Defence Science Journal, Vol 46, No 3, July 1996, pp 161-169

Computer Aided Design & Heat Transfer Analysis of Handguard of a Gun

Ashok K. Choudhary, Shyam Kishor, R.K. Singh*, A.M. Datar**, Sanjay G. Dhande and K. Muralidhar+

Dept of Mechanical Engineering, Indian Institute of Technology, Kanpur-208 016

ABSTRACT

The study presents thermal analysis of the handguard of a gun using finite elements as well as finite differences. The thermal loading corresponds to continuous firing of 300 rounds for 600 s follwed by an inactive period of 300 s. The maximum barrel temperature recorded was around 300 °C. Three different handguard materials, namely, Ryton-4, PEEK-450G, and PEI were tested. The effectiveness of a reflector shield located between the barrel and the handguard was studied. Two major results that emerged from the study are: (i) Ryton-4 gives the lowest temperature rise among the three materials studied, and (ii) The reflector shield is crucial for maintaining the handguard temperature within limits.

Spatial and temporal variation of temperature are qualitatively similar in the two numerical models. Owing to certain factors the finite element predictions for the handguard are on the higher side compared to finite differences. The maximum handguard temperatures as determined in the present model including the reflector are summarized in the Table 1. It is clear that the Ryton-4 as the handguard material can be considered as most desirable.

1. INTRODUCTION

In this study the problem of overheating of the handguard of a gun at the end of 300 rounds of firing was considered. A computer aided thermal analysis of the problem was undertaken and a comparative study of various handguard materials has been performed. With this objective, a geometric model of the barrel-cup-handguard assembly has been developed. This was followed by a two-pronged approach for heat transfer analysis using finite element method (FEM) and finite differences (FD).

The position of a handguard in relation to a gun and the related accessories are shown in Fig. 1. For the purpose of analysis, the geometry of the barrel-cup-handguard assembly was taken to be axisymmetric. This is justified because conduction in the tangential direction is expected to be secondary in comparison to radial and axial conduction. Figure 2 is an axisymmetric section that was used for the analysis. It also shows the FE grid that was used for numerical calculation. The finite element model includes some of the finer features of the geometry such as variable thickness of the handguard, clearances and fillet radii. In comparison, the finite difference geometry was simplified and only major features were implemented as shown in Fig. 3.

Table 1. Maximum Handguard Temperature, °C (Ambient, 30 °C)

Material	FEM	FDM

The energy transfer mechanism from the bullet to the barrel is complicated and was not analysed in the

Received 16 August 1995, revised 11 March 1996

* Defence Materials & Stores Research & Development Establishment, Kanpur
** Armament Research & Development Establishment, Pune
\+ Author to whom all correspondence should be addressed

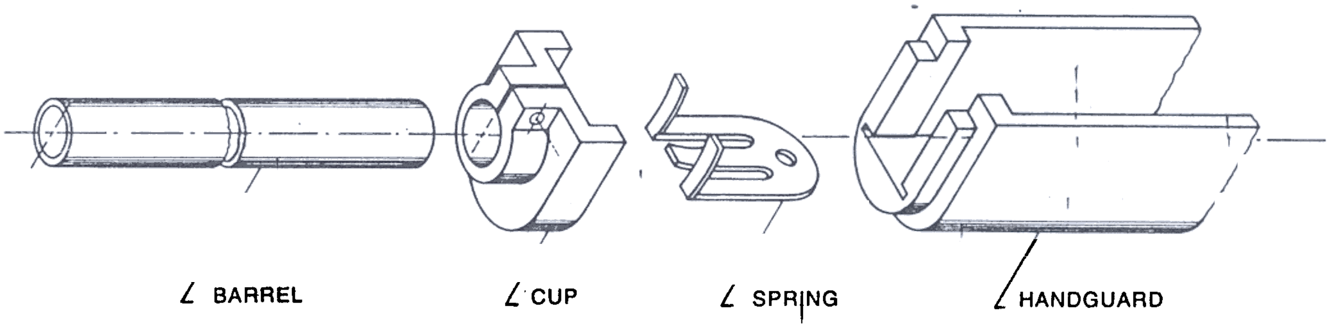

Figure 1. Exploded view of the handguard assembly.

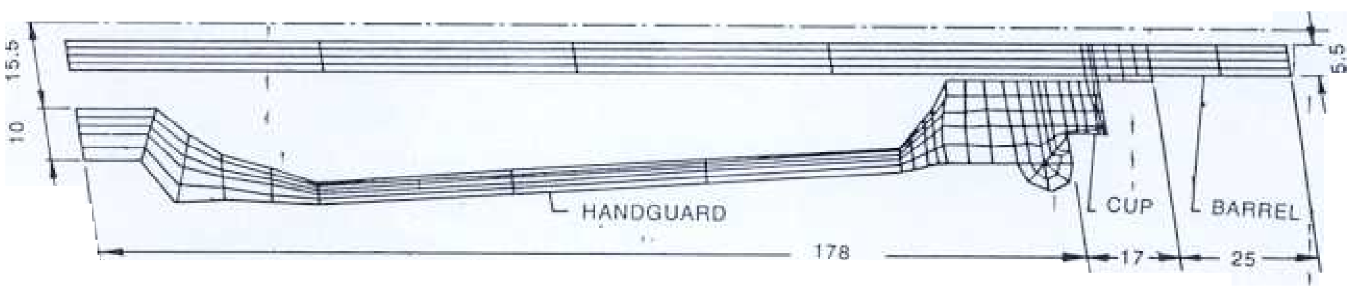

Figure 2. Finite element mesh.

present work. Instead, the conduction problem was initiated at the barrel which was subjected to a prescribed heating load. The path of heat transfer (i.e, the network) from the barrel to the handguard is presented in Fig. 4. It shows that the heating of the handguard takes place via a cup and by direct radiation from the barrel.

The thermal loading on the barrel is decided using the following method. The energy released per bullet was 1500 cal and 300 bullets were fired in 600 s. Using the inside area of the barrel and a 30 per cent energy conversion effectiveness from the bullet, it was possible to estimate the heat flux on the inner surface of the barrel. This value of Q was taken to be 72,500 W/m^2 in the present study. It produces a maximum temperature of approximately 300 °C in the barrel. This heat flux was assumed to be distributed as a saw-tooth profile as shown in Fig. 5. The ambient temperature in all the calculations was 30 °C.

2. FINITE ELEMENT MODEL

Finite element calculations for transient heat conduction were carried out using NISA software. The geometry was two-dimensional and axisymmetric, and hence 8-noded isoparametric axisymmetric solid elements were used[1]. Time marching was accomplished by Crank-Nicolson scheme with automatic time step control to resolve rapid transients. Nonlinearities arising from dependence of heat transfer coefficient and thermal conductivity on temperature were included in the analysis. The former accounts for heat transfer by natural convection as well as radiation either to the ambient or to another surface. For the results presented here the number of elements used were 197, number of nodes 680 and the time step 0.25 s. On a PC-486

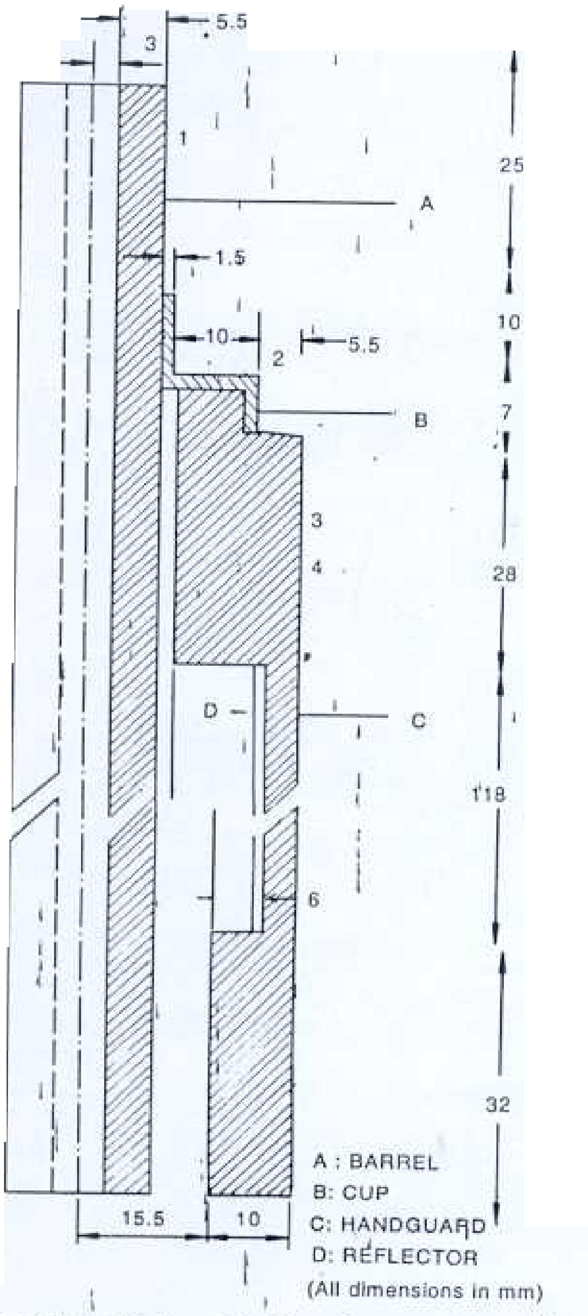

Figure 3. Geometrical model of barrel, cup and handguard assemblies (finite difference). Numbers 1, 2, 3, 4 denote points at which temperatures are recorded.

machine, a single run takes eight hours of computing time.

3. FINITE DIFFERENCE MODEL

Computer program for the finite difference model was developed in 'C' language. The geometric model was once again axisymmetric as shown in Fig. 3. The thermal model treats the cup as a radial fin with variable area and the handguard as a plane fin of variable

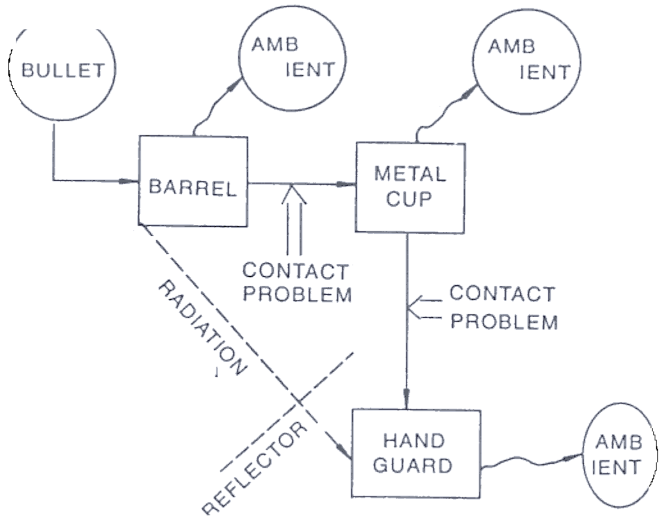

Figure 4. Schematic diagram of heat flow network.

cross-section[2]. Contact resistance, principally at the cup-handguard interface, was also accounted for. Radiative heating of the handguard due to the barrel was included in the governing equations. The governing equations were discretised to second order accuracy in space and first order accuracy in time. Discretised equations in the barrel, cup and handguard were solved simultaneously within each time step. The levels of grid

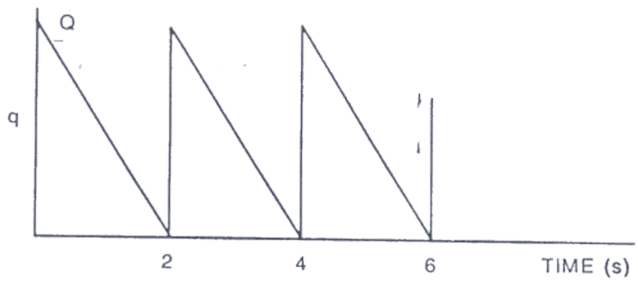

Figure 5. Saw-tooth profile for heat flux ($Q = 72500\ W/m^2$).

and time refinement are comparable to those in the finite element model. On a PC-386 machine, a single run takes 2 hours of computing time.

Both methods include radiation from the barrel to the ambient and barrel to handguard and a temperature-dependent heat transfer coefficient owing to natural convection from the gun assembly to the ambient. In contrast to this, contact resistance was taken to be zero in the FE model while it was non-zero in the

FD model. The blockage of radiation from the barrel to handguard was included in both models. In the absence of the reflector, the handguard temperature rise was large and rapid. This was a source of delayed convergence in the FE model and results for this case have not been presented. The FD model did not experience this difficulty.

It is worth asking which of the two model (FD vs FEM) is expected to give realistic answers. Clearly FEM represents geometry with greater accuracy but with FD, the thermal model, especially at the contact areas is superior. Hence the comparison is inconclusive in principle. The difference between the two results for temperature reported above must be viewed as the extent of scatter and uncertainty in numerical analysis of this problem.

4. THERMAL PROPERTIES

Barrel, cup and handguard properties used in the present calculation are summarised in Table 2. The surface properties necessary for radiation calculations are given in Table 3.

Table 2. Thermal properties of barrel, cup and handguard material

Item	Material	Thermal conductivity k(W/m.K)	Density kg/m^3	Specific heat C_p(J/kg. K)
Barrel	E-19 steel	25	7860	490
Cup	E-19 steel	25	7860	490
Handguard	PEEK-450G	0.25	1320	1340
Handguard	Ryton-4	0.30	1670	1340
Handguard	PEI	0.30	1270	1465

Table 3. Radiative properties

Material	Emissivity
Barrel	0.85
Cup	0.85
Handguard	
PEEK-450G	0.90
Ryton-4	0.90
PEI	0.90
Reflector-barrel	0.10
Reflector-Handguard	0.10

The free convection correlation required for specifying heat transfer from the outer surfaces exposed to the ambient is taken from handbooks[3] as:

$$h = C\left(\frac{\Delta T}{d}\right)^{0.25}$$

where ΔT is in °C and h (W/m^2 K) is heat transfer coefficient.

In the finite difference model contact resistance between any pair of surfaces (1) and (2) is included in the form[2],

$$-kT_n = h_c\,(T_1 - T_2)$$

where T_n is the partial derivative of T with respect to n and h_c is the heat transfer coefficient corresponding to contact resistance between surfaces (1) and (2). A typical value of h_c between barrel and cup for a nominal values of contact pressure is 333.3 W/m^2 K. A typical value of h_c between cup and handguard for a nominal values of contact pressure is 50 W/m^2 K.

Radiative boundary conditions between the barrel and the handguard are implemented in a similar manner with the radiation heat transfer coefficient h_r specified as[2]:

$$h_{rg} = \frac{S\,(T_b^4 - T_g^4)}{A_g\,(T_b - T_g)\left[\frac{1}{e_b} + \frac{A_b}{A_g}\left(\frac{1}{e_g} - 1\right) + \frac{A_b}{A_g}\left(\frac{1}{e_{sb}} + \frac{1}{e_{sg}} - 1\right)\right]}$$

Here, S is Stefan-Boltzmann constant;

e is emissivity and A is area;

Suffixes b, g and s stand for barrel, cup and handguard, respectively; and

Suffixes sb and sg stand for shield on barrel side and shield on handguard side, respectively.

5. RESULTS & DISCUSSION

Temperature at selected points on the barrel, cup and handguard as a function of time are plotted in the Figs 6-13. These points are marked as 1, 2, 3 and 4 in Fig. 3 and are simultaneously referred in the temperature plots. For each handguard material, results have been presented with and without radiation exchange between the barrel and the handguard. An expanded view of temperature versus time for the handguard is enclosed for each configuration. The case of no radiation exchange must be viewed as the limiting case of perfect reflector. The qualitative agreement between the FE and FD models is excellent. Graphs have been presented for the FD model alone in this paper.

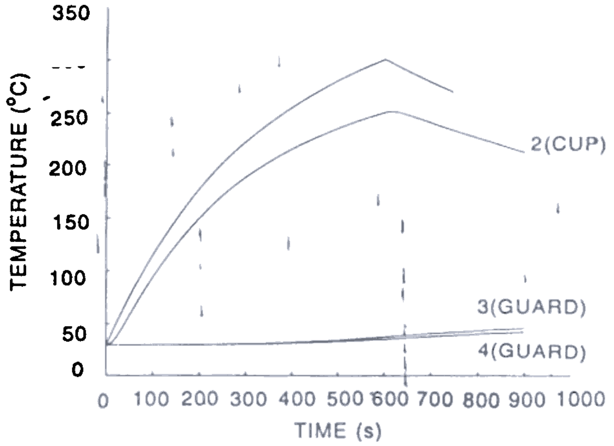

Figure 6a. Variation of temperature with time (Ryton-4).

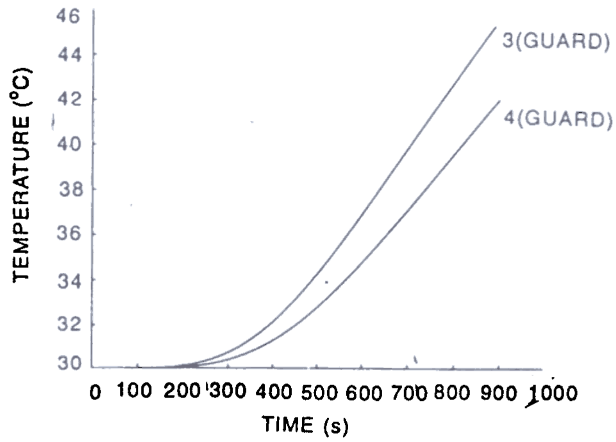

Figure 6b. Variation of temperature with time (Ryton-4).

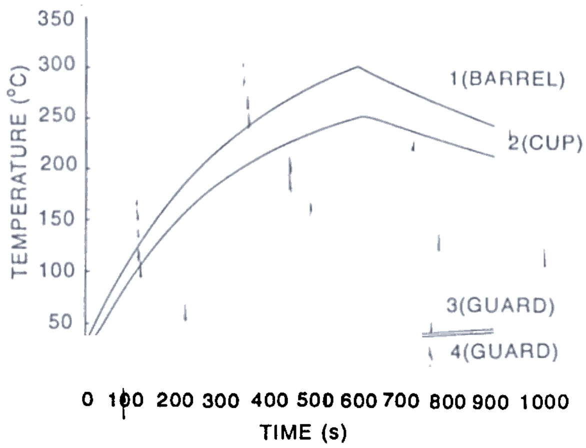

Figure 7a. Variation of temperature with time (PEEK-450G).

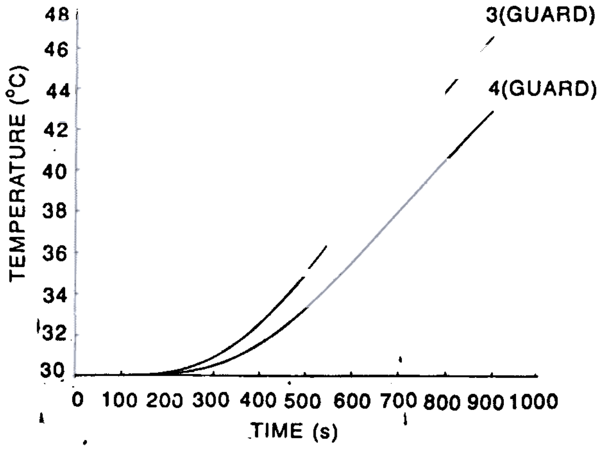

Figure 7b. Variation of temperature with time (PEEK-450G).

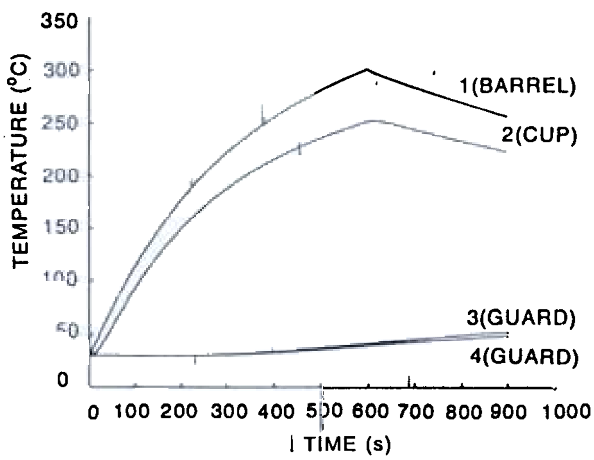

Figure 8a. Variation of temperature with time (PEI).

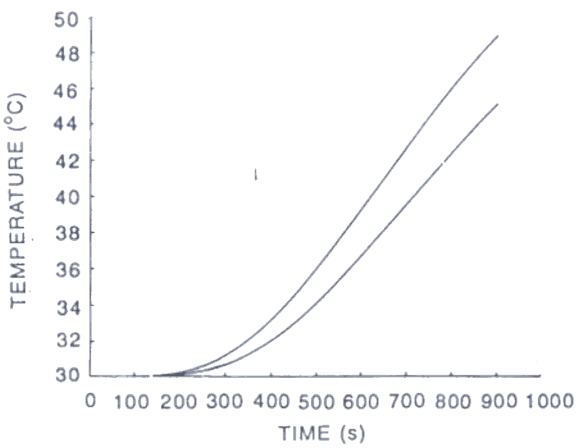

Figure 8b. Variation of temperature with time (PEI).

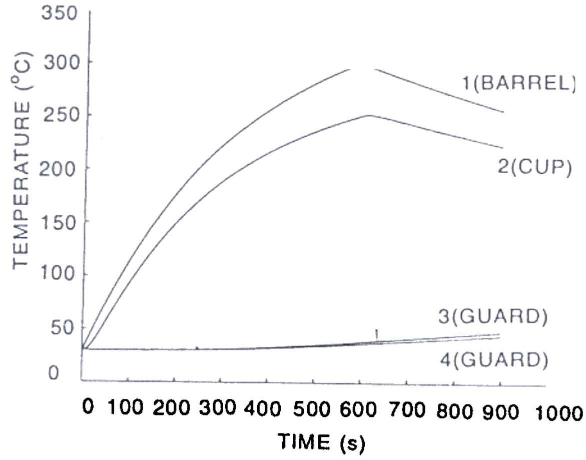

Figure 9a. Variation of temperature with time (Ryton-4) radiation.

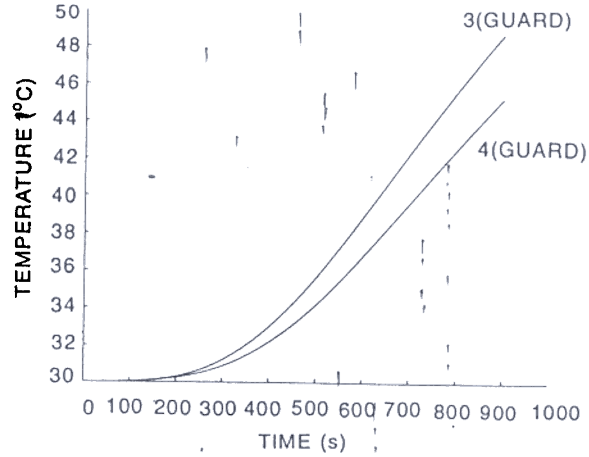

Figure 9b. Variation of temperature with time (Ryton-4) radiation.

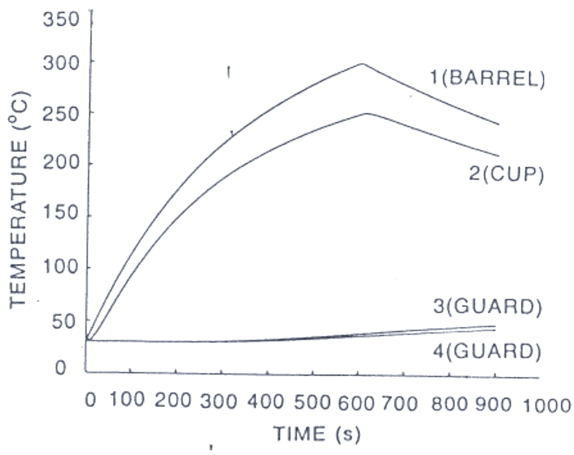

Figure 10a. Variation of temperature with time (PEEK450G), radiation.

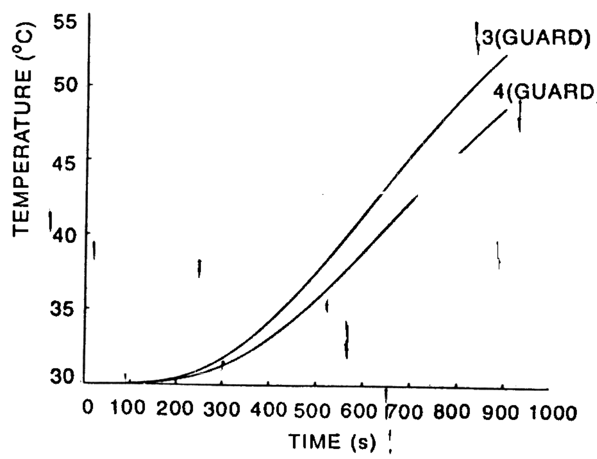

Figure 10b. Variation of temperature with time (PEEK450G), radiation.

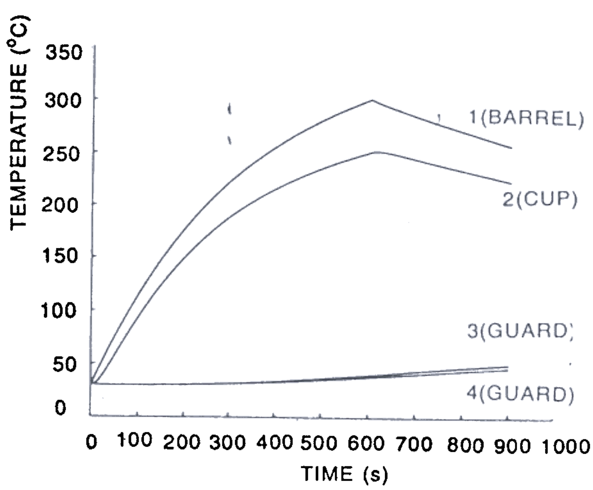

Figure 11a. Variation of temperature with time (PEI), radiation.

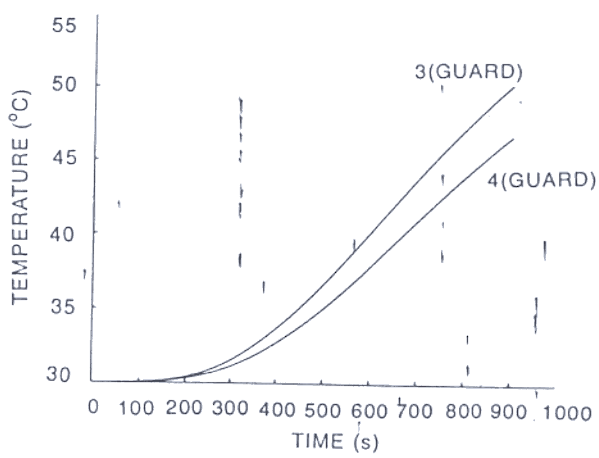

Figure 11b. Variation of temperature with time (PEI), radiation.

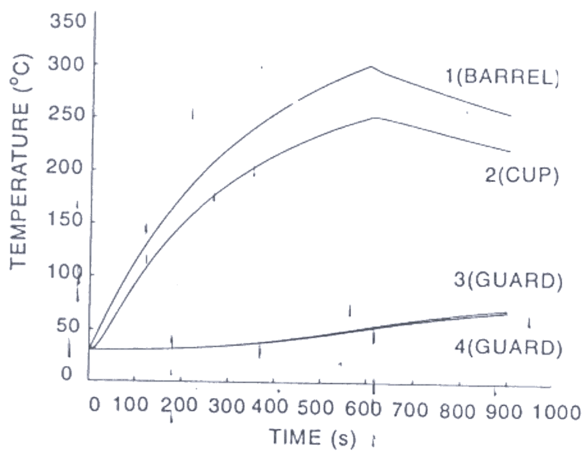

Figure 12a. Variation of temperature with time (Ryton-4), radiation, no reflector.

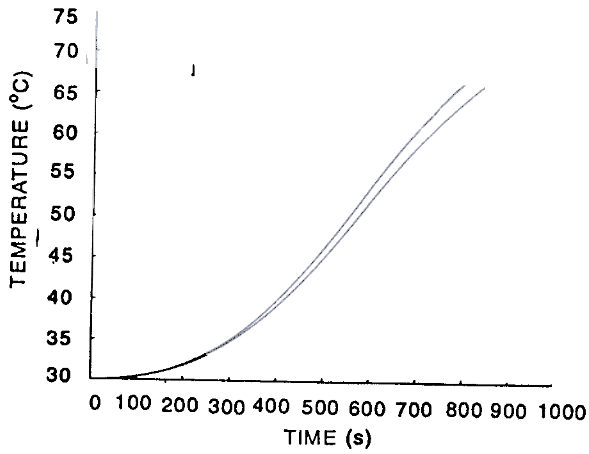

Figure 12b. Variation of temperature with time (Ryton-4), radiation, no reflector.

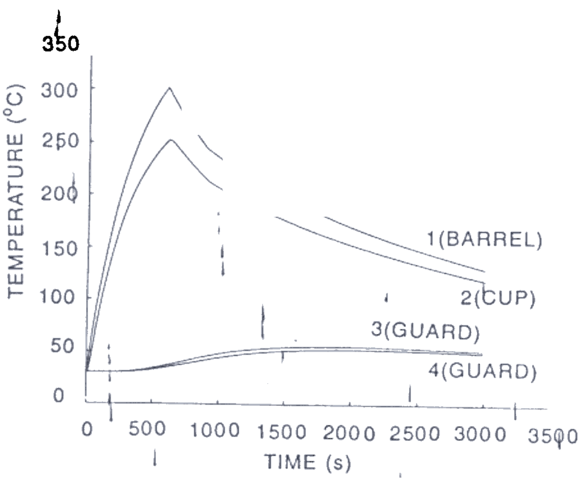

Figure 13a. Variation of temperature with time (Ryton-4), radiation.

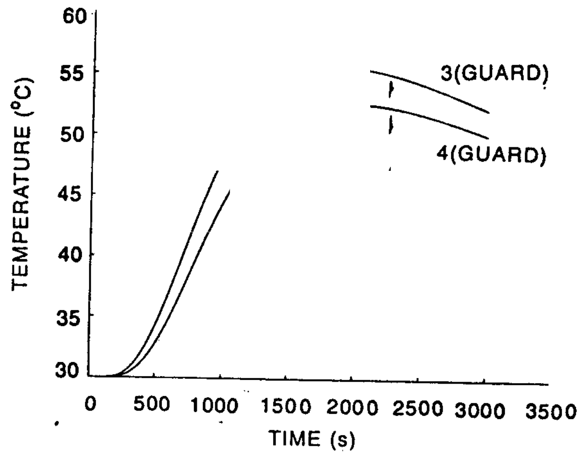

Figure 13b. Variation of temperature with time (Ryton-4), radiation.

Figures 6-8 show the results obtained using finite differences and without any radiation interaction. Figures 9-11 are also finite difference results including the presence of the reflector and radiation calculation. Figure 12 is an exceptional run with radiation but without the reflector. The large increase in handguard temperature clearly underlines the utility of the reflector. Figure 13 shows temperature variation with time for an extended period of 3,000 s. It can be seen that it takes around 2,000 s before temperatures in the handguard, especially close to the metal cup, start decreasing. In comparison barrel and cup temperatures decrease as soon as firing is stopped, that is, at the end of 600 s.

The salient features of the results presented here have been summarised in Table 4 in terms of the maximum temperature attained in each of the components, namely barrel, cup and handguard, at representative locations.

6. CONCLUSIONS

Based on the calculations reported here, the following conclusions can be drawn:

1. PPS-40 (Ryton-4), used as handguard material, gives the best performances in the sense that its temperature rise is within acceptable limits. For an ambient temperature of 30 °C, an upper limit of 54 °C (measured) for the handguard has been specified by

Table 4. Summary of temperature in °C over 900 s

Item	Imperfect reflector	Perfect reflector	No reflector
(a) Handguard material : Ryton-4			
Finite element			
Barrel	234.60	233.10	
Cup	160.10	157.90	
Handguard	56.98	51.09	
Finite difference			
Barrel	301.18	301.40	301.18
Cup	251.88	252.03	251.88
Handguard	48.75	45.67	71.39
(b) Handguard material : PEEK-450G			
Finite element			
Barrel	236.80	235.20	
Cup	163.30	161.10	
Handguard	58.45	51.11	
Finite difference			
Barrel	301.18	301.32	
Cup	251.88	251.98	
Handguard	52.38	46.69	
(c) Handguard material : PEI			
Finite element			
Barrel	235.30	233.70	
Cup	161.10	158.58	
Handguard	61.59	53.49	
Finite difference			
Barrel	301.18	301.37	
Cup	251.88	252.01	
Handguard	52.48	49.03	

* Run not possible due to excessive computer run time

ARDE, Pune. The FD solution is well within the limit. The FEM solution marginally exceeds this value. However this is not serious for the following reasons:

(a) FEM uses perfect contact at the material interfaces and hence predicts a higher handguard temperature, and

(b) A measured temperature limit of 54 °C will actually correspond to a higher true local temperature since one must include attenuation of varying temperature by a thermocouple.

2. The handguard temperature rises sharply in the absence of the reflector. Hence, the presence of a reflector is a crucial component.

REFERENCES

1 Lapidus, L. & Pinder, G.F. Numerical solution of partial differential equations in science and engineering. John Wiley, New York, 1982.

2. Bayazitoglu, Y. & Ozisik, M.N. Elements of heat transfer. McGraw Hill, New York, 1988.

3. Gelhart, B.; Jaluria, Y.; Mhajan, R.L. & Sammekia, B. Buoyancy induced flows and heat transport. Hemisphere Publishing Company, New York, 1988.

Contributors

Mr Shyam Kishor did his MTech in Design of Process Machines from MNR Engineering College, Allahabad, in 1994. He worked at the Department of Mechanical Engineering, IIT, Kanpur, during 1994-96. His current research interest includes CAD of thermal systems and computational fluid dynamics. At present, he is working with the Flow Consultants India at Pune.

Dr RK Singh obtained his MTech (Chem) from IIT, Delhi, in 1972, PhD in Plastics Technology from Chemical Technology Institute, Moscow, in 1977 and Post-Doctorate from Royal Institute of Technology, Stockholm, during 1977-78. He served as Pool Officer at the Centre for Material Science & Technology, IIT, Delhi, during 1978-80. He joined DRDO at the Defence Materials & Stores Research & Development Establishment, Kanpur. He has published 40 research papers in national and international journals.

Mr Anil Datar is a BE from College of Engineering, Pune and did his MSc in Gun System Design from RMCS, Cranfield University, UK. He won prestigeous ROF Trophy for his performance there. He also has Master's Diploma in Business Administration to his credit. For last ten years, he has been working in the field of weapon design and has specialised in the area of small arms. Presently, he is working as Deputy Director at the Armament Research & Development Establishment, Pune. He is Chartered Engineer and member of Institution of Mechanical Engineering (India).

Dr Sanjay G Dhande obtained his BE (Mechanical Engineering) from University of Ponna, in 1969. He was awarded the Institution of Engineers Gold Medal in 1970. He obtained his PhD (Mechanical Engineering) from IIT, Kanpur, in 1974. He is presently a Professor of Mechanical Engineering and Computer Science at IIT, Kanpur. His research interests are geometric modelling for engineering analysis, design for manufacturability, computer graphics and simulation.

Dr K Muralidhar is presently Professor at the Department of Mechanical Engineering, IIT, Kanpur, where he has worked for nine years. Earlier, he held a Post-Doctoral Fellowship at Lawrence Berkely Laboratory, California, USA. His research interests are in the field of fluid mechanics and thermal sciences.