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MEMORANDUM REPORT BRL-MR-3831

BRL

A COMPUTATIONAL STUDY OF THE EFFECTIVENESS OF COATING MATERIALS FOR KE PROJECTILE FINS SUBJECTED TO THE COMBINED EFFECTS OF INBORE AND AERODYNAMIC HEATING

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

NOTICES

UNCLASSIFIED

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
APRIL 1990

3. REPORT TYPE AND DATES COVERED
Final, May 88 - Aug 88

4. TITLE AND SUBTITLE
A COMPUTATIONAL STUDY OF THE EFFECTIVENESS OF COATING MATERIALS FOR KE PROJECTILE FINS SUBJECTED TO THE COMBINED EFFECTS OF INBORE AND AERODYNAMIC HEATING

5. FUNDING NUMBERS
1L162618AH80
62618A 00 001 AJ

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
BRL-MR-3831

11. SUPPLEMENTARY NOTES
2LT Frank D. Sturek is a member of the U.S. Army, Infantry.

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The objective of this computational study was to examine the inbore and free flight aerodynamic heating of aluminum fins used on large l/d kinetic energy (KE) projectiles. The scope of the study involved the performance of numerical computations to examine the effectiveness of two coating materials for thermal protection of the aluminum fins. A comparison of the predicted unsteady thermal response to the combined effects of inbore and free flight aerodynamic heating was made between a fin coated with the current aluminum oxide coating and a fin coated with a new silicon/fiber mixture. The silicon/fiber coating was found to provide substantially improved thermal protection compared to the standard aluminum oxide coating. A fin coated with the silicon/fiber material was predicted to not reach melt temperature throughout a simulated 3.0 second flight. In comparison, a fin coated with aluminum oxide was predicted to reach melt temperature after less than 1.0 second of flight.

Keywords: Kinetic energy projectiles; Refractory coatings; [illegible] Fins; Thin [illegible] computerized simulation; Thermal respon

14. SUBJECT TERMS
Aerodynamic Heating, Unsteady Heat Conduction; Supersonic Flow; Convective Heat Transfer. (EDC)

15. NUMBER OF PAGES
37

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

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I. INTRODUCTION

Current kinetic energy (KE) penetrator projectile such as the M829 use fins made of aluminum to provide flight stability. Typically, these fins are very thin (3.5 mm is typical) and consequently do not have sufficient mass to absorb and conduct away the high heat loads due to inbore and free flight aerodynamic heating. The fins can ablate and cause erratic flight due to distortion of the fin or lack of sufficient fin area to maintain stability and spin control.

The U.S. Army Ballistic Research Laboratory (BRL) quasi-three-dimensional heat transfer code[1] computationally models both the inbore and free flight aerodynamic heating. The code provides designers of high velocity projectiles the capability to predict the unsteady thermal response of the fins to the flight environment. The code has the ability (although not yet perfected) to simulate melting of the fin with a moving boundary that recedes as the fin material reaches the melting temperature.

Graphs depicting the temperatures on the leading edge of the fin and temperature contours demonstrating the heat transferred throughout the entire fin illustrate the capability of the code and provide a convenient comparison for evaluation of the computational results.

The boundary conditions used for this study are described. Sample computations for heat transfer are shown to illustrate the response of the aluminum fins to inbore and free flight conditions. A comparison was made between an aluminum oxide coated fin and a silicone/fiber coated fin. The results demonstrate that the silicon/fiber coating provides substantial thermal protection compared to that provided by the standard aluminum oxide coating. The results also demonstrate that the computational code provides KE projectile designers a useful tool for the evaluation of the unsteady thermal response of fins for proposed design changes of fin and coating material. The computations were carried out using the Cray 2 supercomputer located at the U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD.

II. THEORY

KE projectile fins are predominately made of high strength aluminum which has the physical properties of high thermal conductivity and relatively low melting point (950 K). These fins have been computationally modeled as having either an aluminum oxide or silicon-fiber coating which is placed on the fin to provide thermal protection from the effects of inbore and aerodynamic heating.

1. INBORE

The quasi-three-dimensional code was first modified to simulate inbore heating. A flame temperature of 3500 K was entered into the code. This represents the flame temperature of the propellant used in the 120mm tank gun.

The equation for determining the temperature at the surface of the aluminum was derived by combining the equations for convection heat transfer from the boundary layer to the coating and the conduction heat transfer from the coating to the aluminum.

T_o = flame temperature of propellant

T_s^+ = temperature of coating

T_s^- = temperature of aluminum fin outer surface

$$\overset{\text{convection}}{\left(T_o - T_s^+\right)} + \overset{\text{conduction}}{\left(T_s^+ - T_s^-\right)} = T_o - T_s^-$$

$Q = hA\Delta T$ convection heat transfer

$Q = kA\frac{\Delta T}{\Delta x}$ conduction heat transfer

where:

Q = heat flux
A = local area over which heat transfer takes place
Δx = thickness of coating
k = thermal conductivity
h = coefficient of convective heat transfer.

Substituting for ΔT

$$\frac{Q}{hA} + \frac{Q\Delta x}{kA} = T_o - T_s^-$$

$$\frac{Q}{A}\left(\frac{1}{h} + \frac{\Delta x}{k}\right) = T_o - T_s^-$$

let

$$R = \frac{1}{h} + \frac{\Delta x}{k}$$

$$R\frac{Q}{A} = T_o - T_s^- \quad .$$

The quantities Q, A, T_o, Δx, k, and h are known since the code solves for Q using information at the last time step. Thus the boundary condition T_s^- is now established.

R is the resistance to heat transfer and was computed using the given coating thickness, thermal conductivity and coefficient of convective heat transfer. The heat transfer coefficient was determined from a previous study.[2] The value used was:

$$h = 6153.6 \frac{Joule}{m^2 - sec - K} \quad .$$

The code simulated the inbore heating for 10 milliseconds. This is approximately the amount of time that the M829 projectile experiences the flame temperature of 3500 K. The temperature data at 10 milliseconds was saved in a data file and used as initial conditions for the free flight case.

2. FREE FLIGHT

The same equations for determining the temperature at the aluminum surface were used in the free flight case. However, T_o was no longer the flame temperature and the coefficient of convective heat transfer changed. T_o became the adiabatic wall temperature. This value was obtained by considering the results of a three dimensional Navier-Stokes solution[3] for a swept fin geometry at Mach 3.5. This solution also demonstrated that there was very little change in the adiabatic wall temperature in the chordwise direction. Therefore a constant value was assumed. The results were extrapolated to the velocities of interest as determined from Firing Table FT 120-D-1 (August 1986). The launch velocity at standard conditions is 1670 m/s.

The adiabatic wall temperature changed with time due to a decrease in velocity of the projectile. Due to the small time difference (1.9 seconds to reach 3000 meters), the variation of the adiabatic wall temperature with time was approximated as the following linear function

$$T_o = T_{aw}(t) = T_{aw_i} - \frac{320}{1.9} \times time$$

where: T_{aw_i} = the value at the gun muzzle velocity.

The initial adiabatic wall temperature was entered into this equation as 1830 K. The value had decreased to 1510 K at a distance of 3000 meters.

The heat transfer coefficient also changed with time using the following linear relationship

$$h_{stag} = h_{stag_i} - \frac{700}{2.0} \times time$$

where:

h_{stag} = convective heat transfer coefficient at the stagnation point on the fin leading edge at an arbitrary time in the trajectory

h_{stag_i} = initial value of the convective heat transfer coefficient at the fin stagnation point at gun launch, based on previous studies.[2,4] [6000.0 $J/(m^2 - sec - K)$]

$time$ = time since gun launch, seconds.

The coefficient of convective heat transfer for the trailing edge remained fairly constant and was assumed to be constant based on previous studies.[2,4]

The change in the coefficient of convective heat transfer as a function of chord-wise position was modeled using a cosine function as:

$$h_{loc} = h_{min} + (h_{max} - h_{min}) \times \frac{1}{2}(\cos(\Delta c \times \pi) + 1.0)$$

where:

h_{loc} = local value of convective heat transfer coefficient

h_{min} = minimum value of h [1800.0 $J/(m^2 - sec - K)$]

h_{max} = maximum value of h ($= h_{stag}$)

Δc = length of chordwise distance for change of h to occur, normalized.

The physical properties used for the materials in this study are given in Table 1.

Table 1. Physical Properties.

Property	*Units*	*Al*	*Al_2O_3*	*Silicon/Fiber*
k	W/m-K	173	12.114	0.3489
ρ	kg/m^3	2800		
c_v	J/kg-K	869		
L_h	J/kg	45188		
Δx	m		0.000127	0.000254

where:

k = thermal conductivity
ρ = density
c_v = specific heat
L_h = latent heat of melt
Δx = coating thickness

III. RESULTS

The initial computational grid is shown in Figure 1. The fin planform and thickness are similar, but not identical, to that of the M829. The fins remained intact during inbore heating with both coatings. The 5 and 10 millisecond temperature contour plots, shown in Figures 2-5, clearly demonstrate that much less heat is transfered to the fin with the silicon/fiber coating than with the aluminum oxide coating. The leading edge of the aluminum oxide coated fin reached a temperature of 460 K while the leading edge of the silicon/fiber coated fin only reached a temperature of between 310 K and 340 K.

The maximum effective range listed for the M829 is 3000 meters and is reached in approximately 1.9 seconds. The free flight temperature contour plots, however, extend to 3.0 seconds to better demonstrate the effectiveness of the silicon/fiber coating. The maximum temperature of the aluminum fin was the melt temperature of aluminum which was input at 950 K. The free flight temperature contour plots are shown in Figures 6-17. During free flight, the aluminum oxide coated fin had already melted a great deal at 1.5 seconds. The silicon/fiber coated fin remained intact through two seconds. Very little, if any, indication of fin melting is apparent either at 2.5 seconds or 3.0 seconds. It is not apparent that the fin had started to melt at these last two time periods since the 9th contour had not appeared.

The temperature as a function of time in free flight at the leading edge of the fin located near the midpoint between the fin root and the fin tip is shown in Figure 18. The leading edge of the aluminum oxide coated fin reached a temperature of 460 K while the leading edge of the silicon/fiber coated fin only reached a temperature of between 310 K and 340 K during the in-bore phase at the selected position. In free flight, the silicon/fiber coated fin reached a maximum temperature of 620 K while the aluminum oxide coated fin reached a maximum temperature of 870 K at the selected position.

IV. CONCLUSIONS

The results of the numerical computations support the following conclusions.

1. Melting did not occur for the aluminum oxide coated fin or the silicon/fiber coated fin while inbore.

2. The silicon/fiber coated fin did not reach melt temperature through the weapon system's maximum effective range while the aluminum oxide coated fin reached melt temperature between 0.5 and 1.0 seconds of flight.

3. The silicon/fiber coating provides substantially enhanced thermal protection compared to the protection provided by the aluminum oxide coating.

V. CLOSING REMARKS

The problem of KE projectile fin ablation is one that will continue to exist with the improvement and redesigning of KE projectiles. Battlefield conditions will require higher velocity and greater effective range of armor piercing rounds. The computer code used in this study can provide designers of these new projectiles the ability to predict the unsteady thermal response of stabilizing fins to the combined effects of inbore and free flight environments. The code is sufficiently flexible to provide the capability to model different fin geometries, construction materials and coating materials. The computational results indicate that the silicon/fiber coating provides substantially enhanced thermal protection compared to the standard aluminum oxide coating. Although the thermal protection provided by the standard aluminum oxide coating is shown to be marginal for the flight conditions considered in this computational study, it should be pointed out that experience has shown that the aluminum oxide coating does provide protection for the aluminum fins. The protective qualities of the aluminum oxide coating are highly effective for protecting the fragile aluminum fin during the inbore phase of flight. The type of protection provided is believed to be primarily abrasion resistence since the fin is initially submerged in the propellant bed. Abrasion resistance is an important consideration for a protective coating. However, the computational results indicate that it would be highly desirable to perform firing tests for silicon/fiber coated fins.

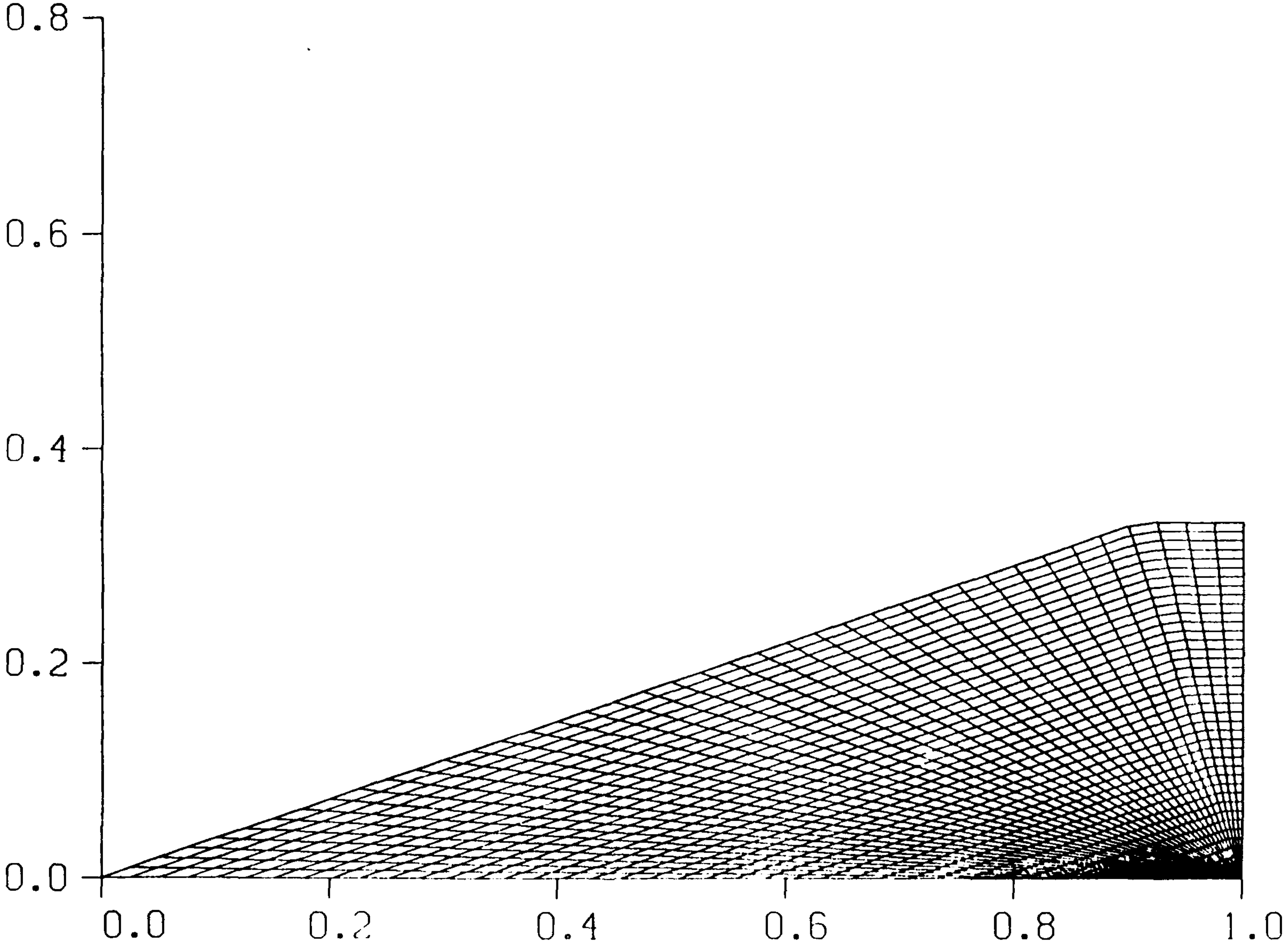

Figure 1. Computational grid.

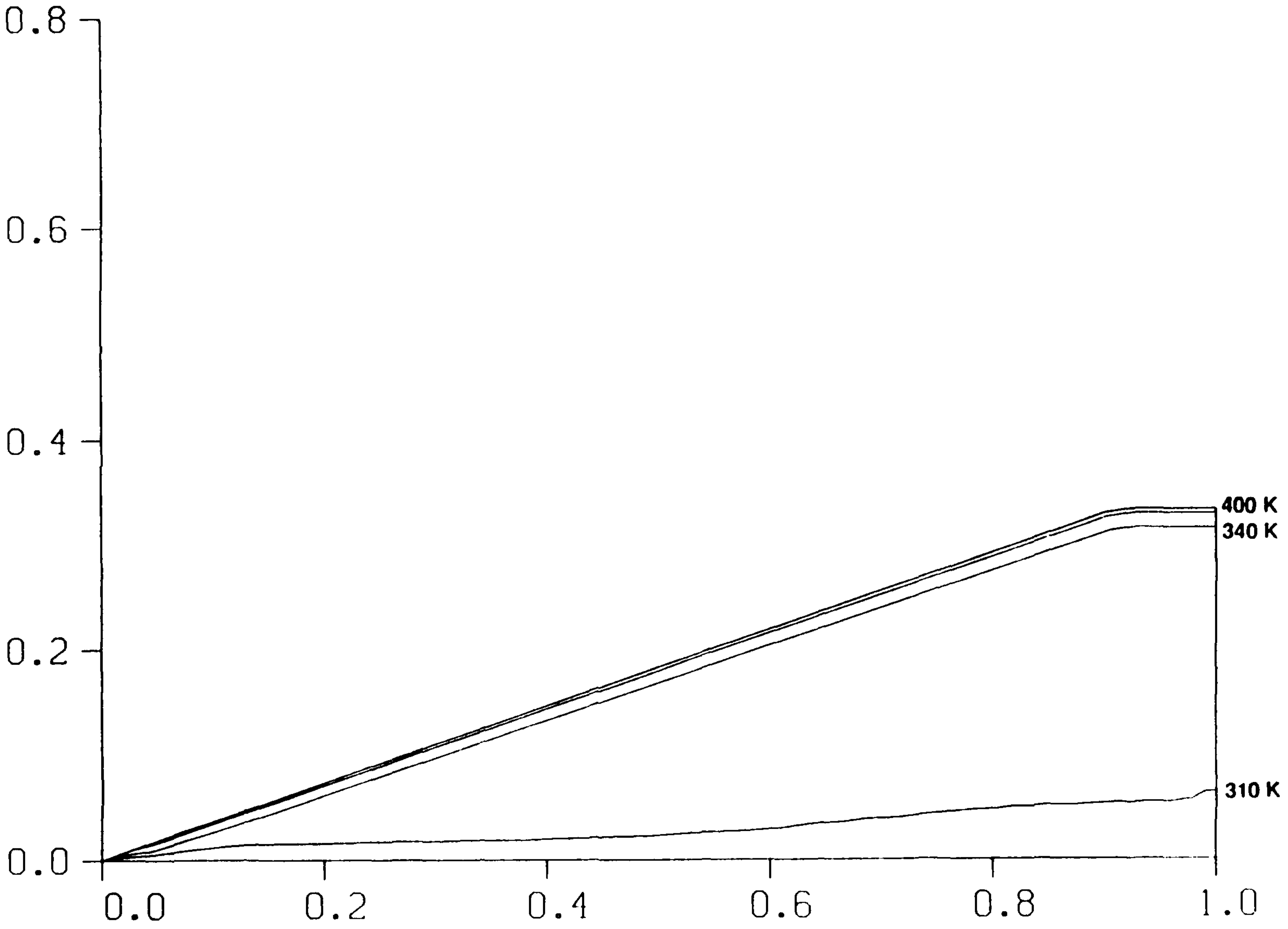

Figure 2. In-Bore temperature contours, aluminum oxide coating, time = 5 milliseconds.

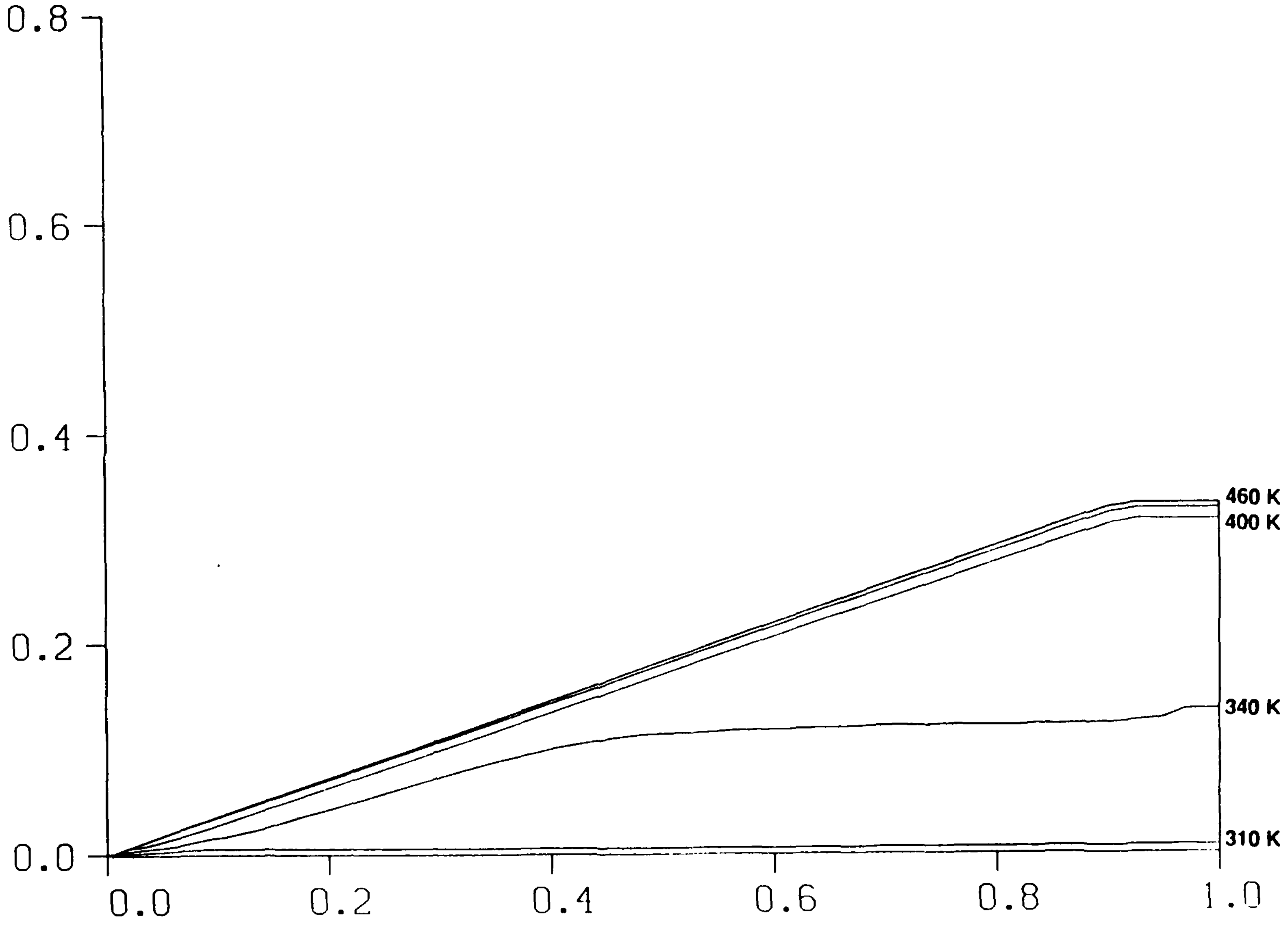

Figure 3. In-Bore temperature contours, aluminum oxide coating, time = 10 milliseconds.

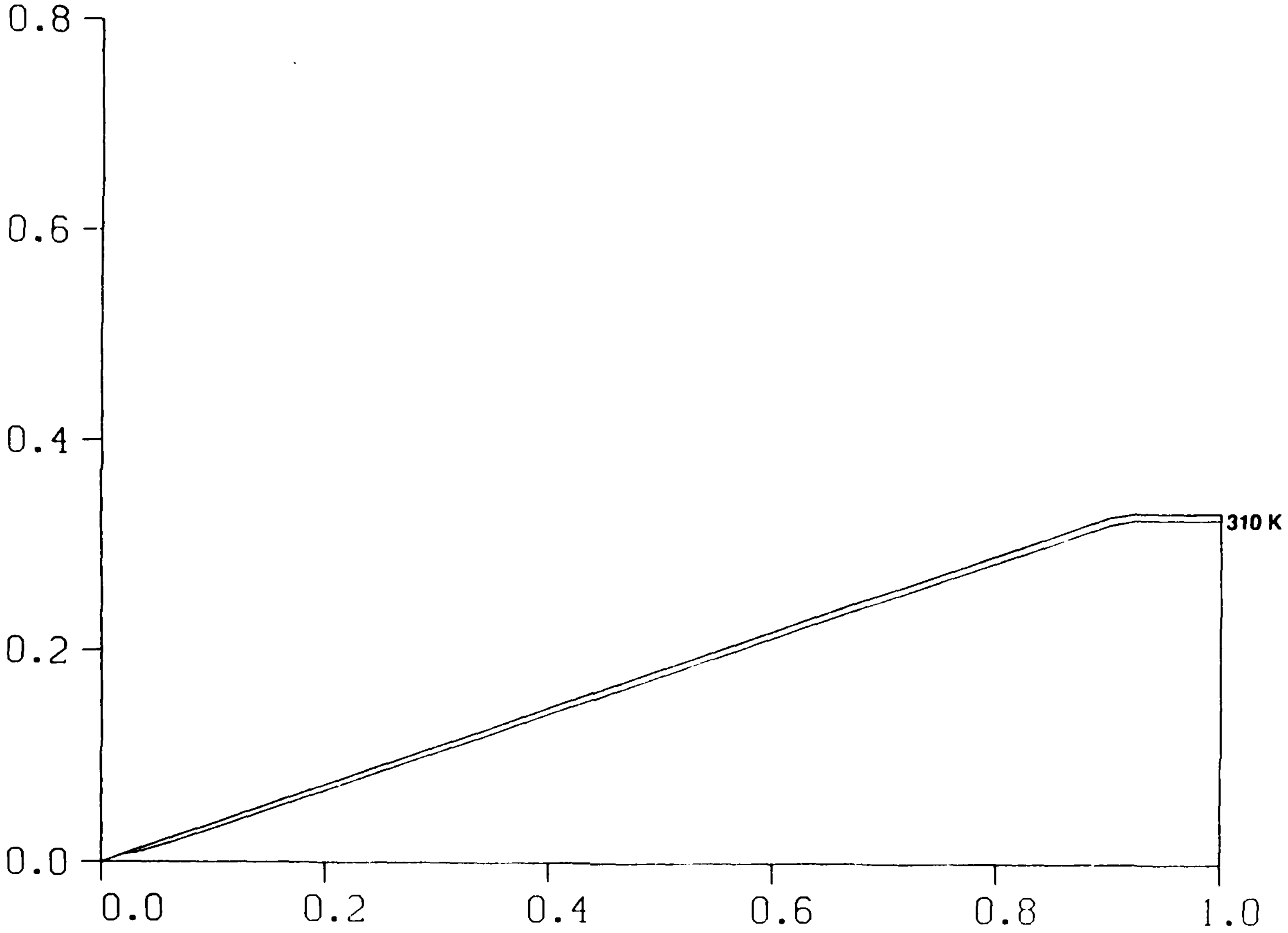

Figure 4. In Bore temperature contours, silicon/fiber coating, time = 5 milliseconds.

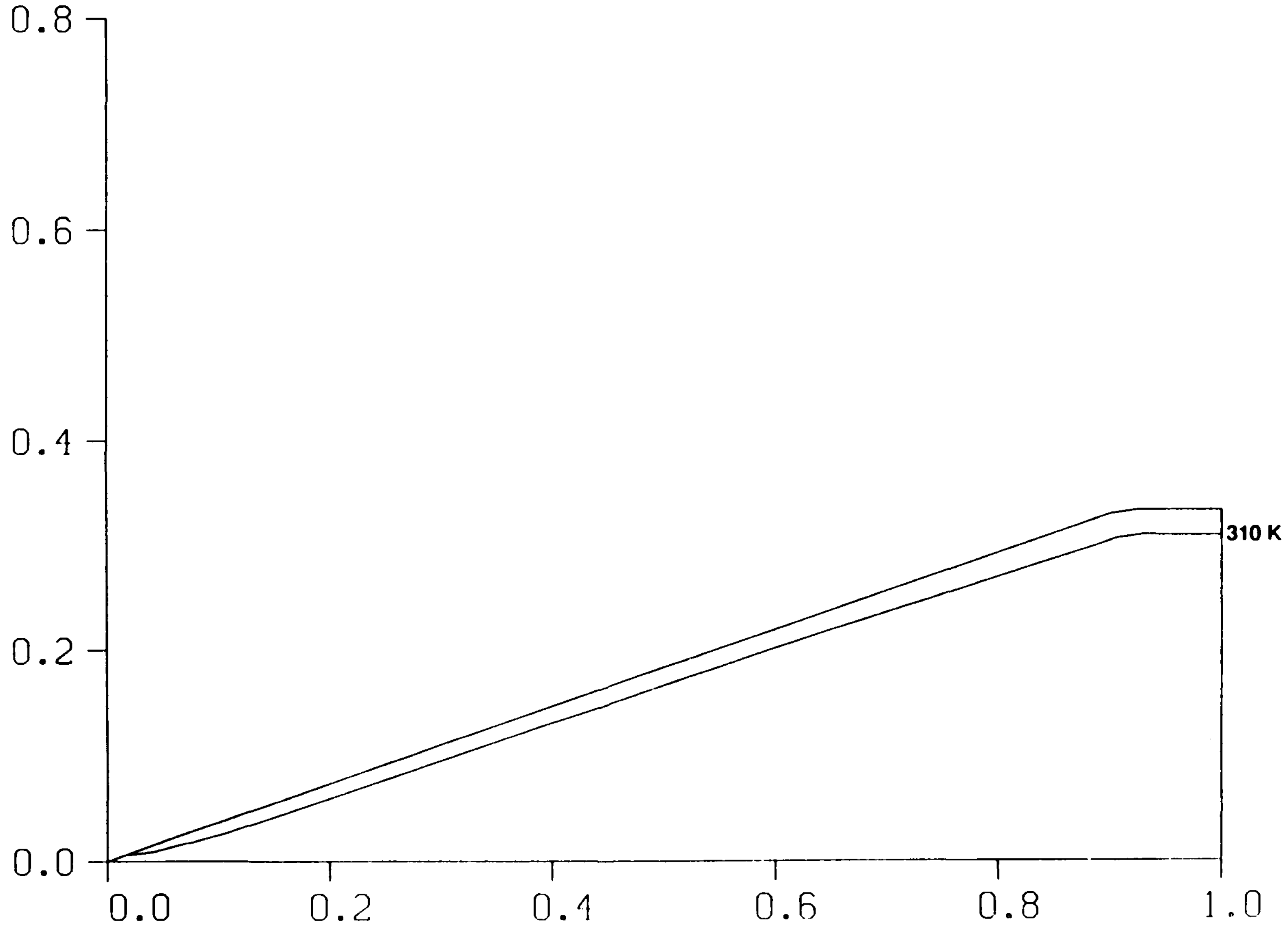

Figure 5. In-Bore temperature contours, silicon/fiber coating, time = 10 milliseconds.

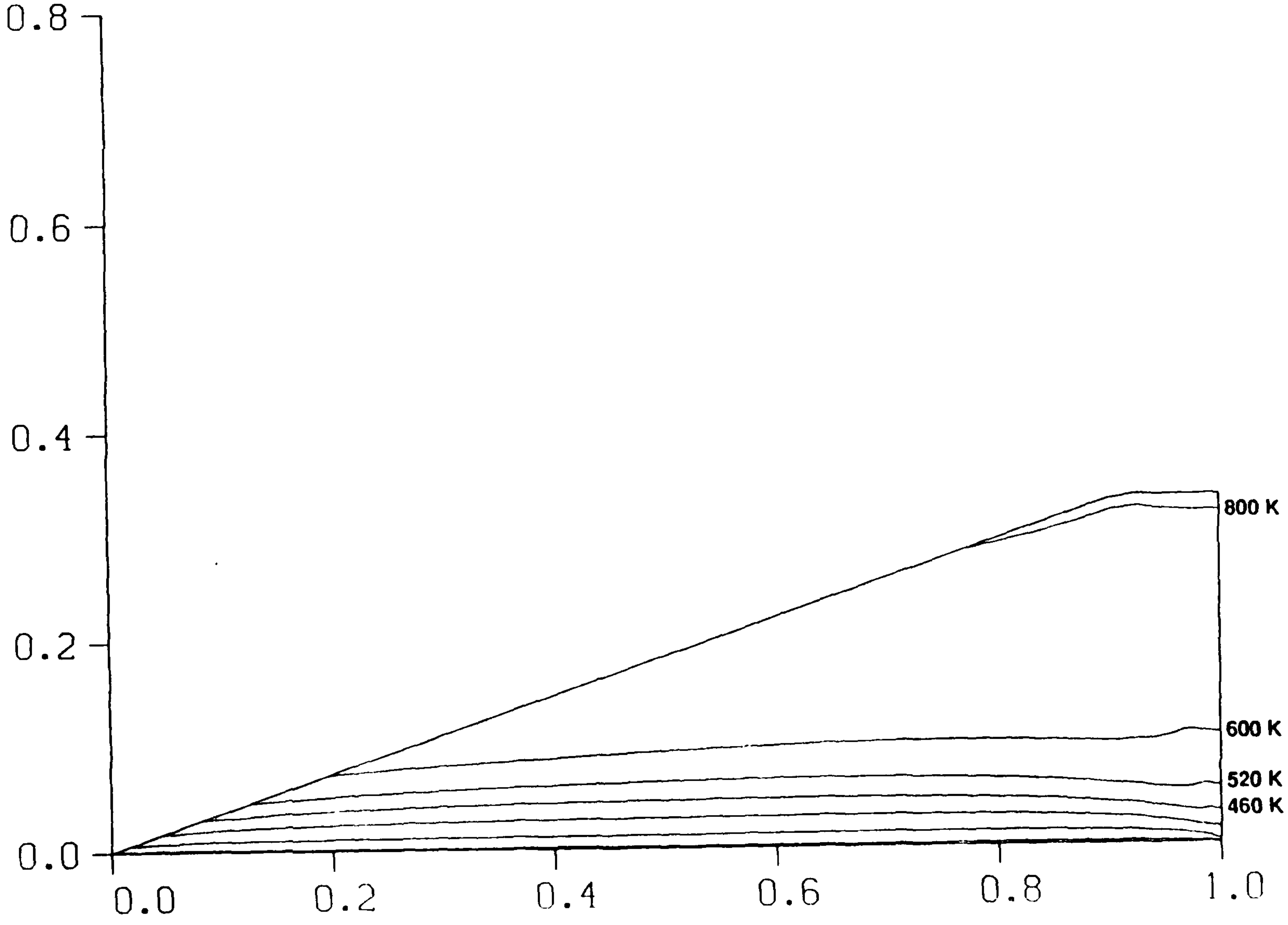

Figure 6. Free flight temperature contours, aluminum oxide coating, time = 0.5 seconds.

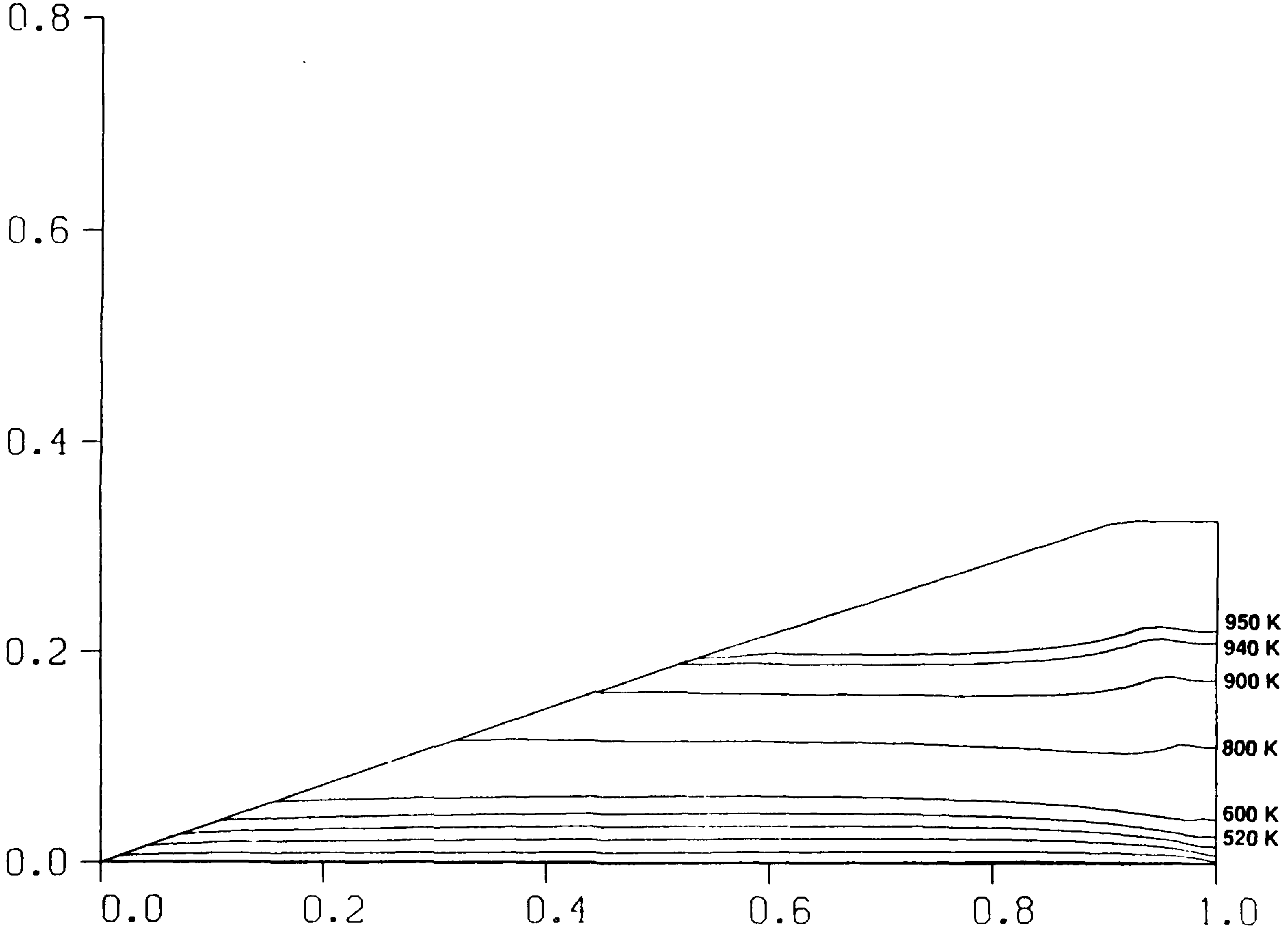

Figure 7. Free flight temperature contours, aluminum oxide coating, time = 1.0 second.

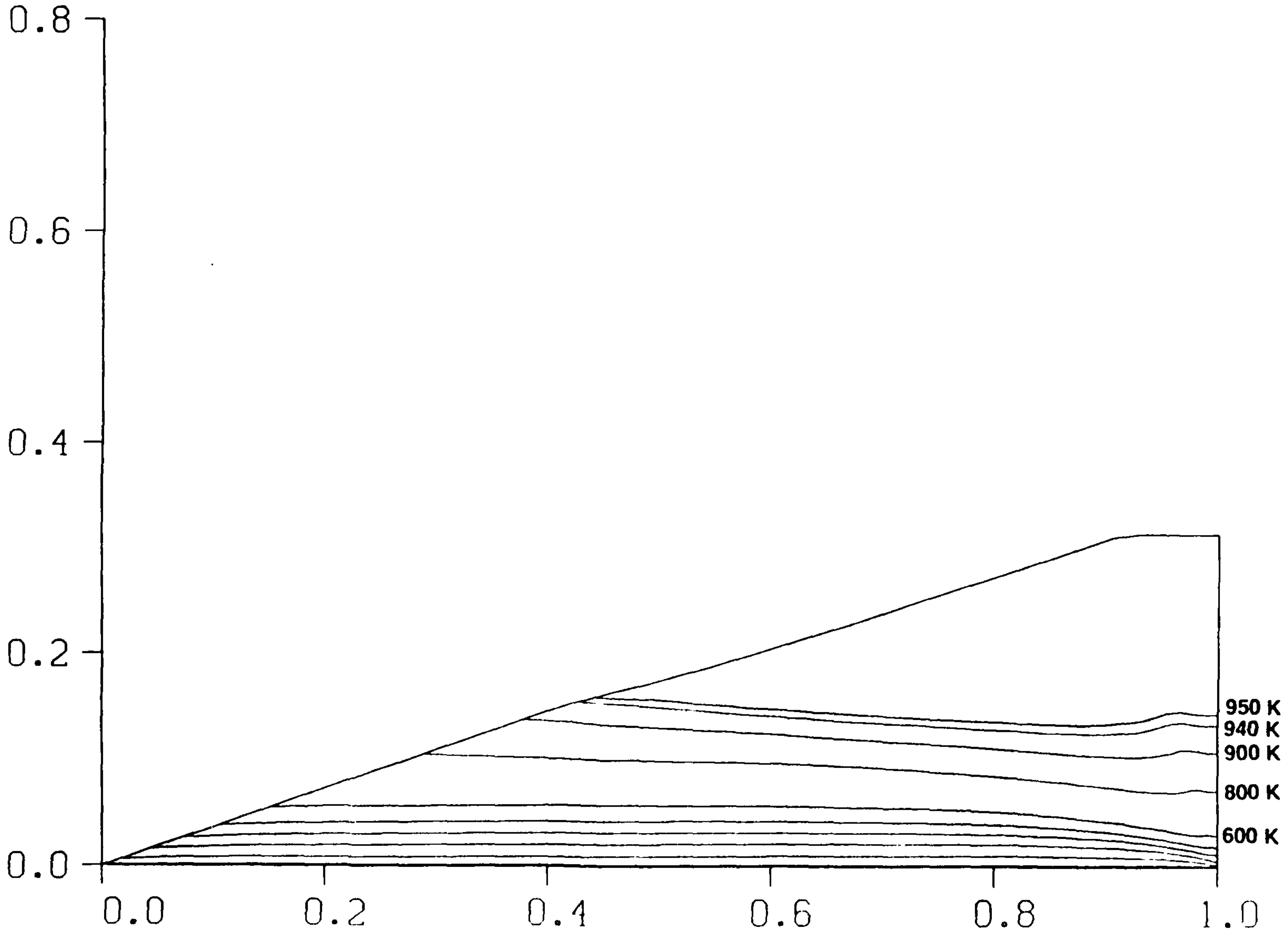

Figure 8. Free flight temperature contours, aluminum oxide coating, time = 1.5 seconds.

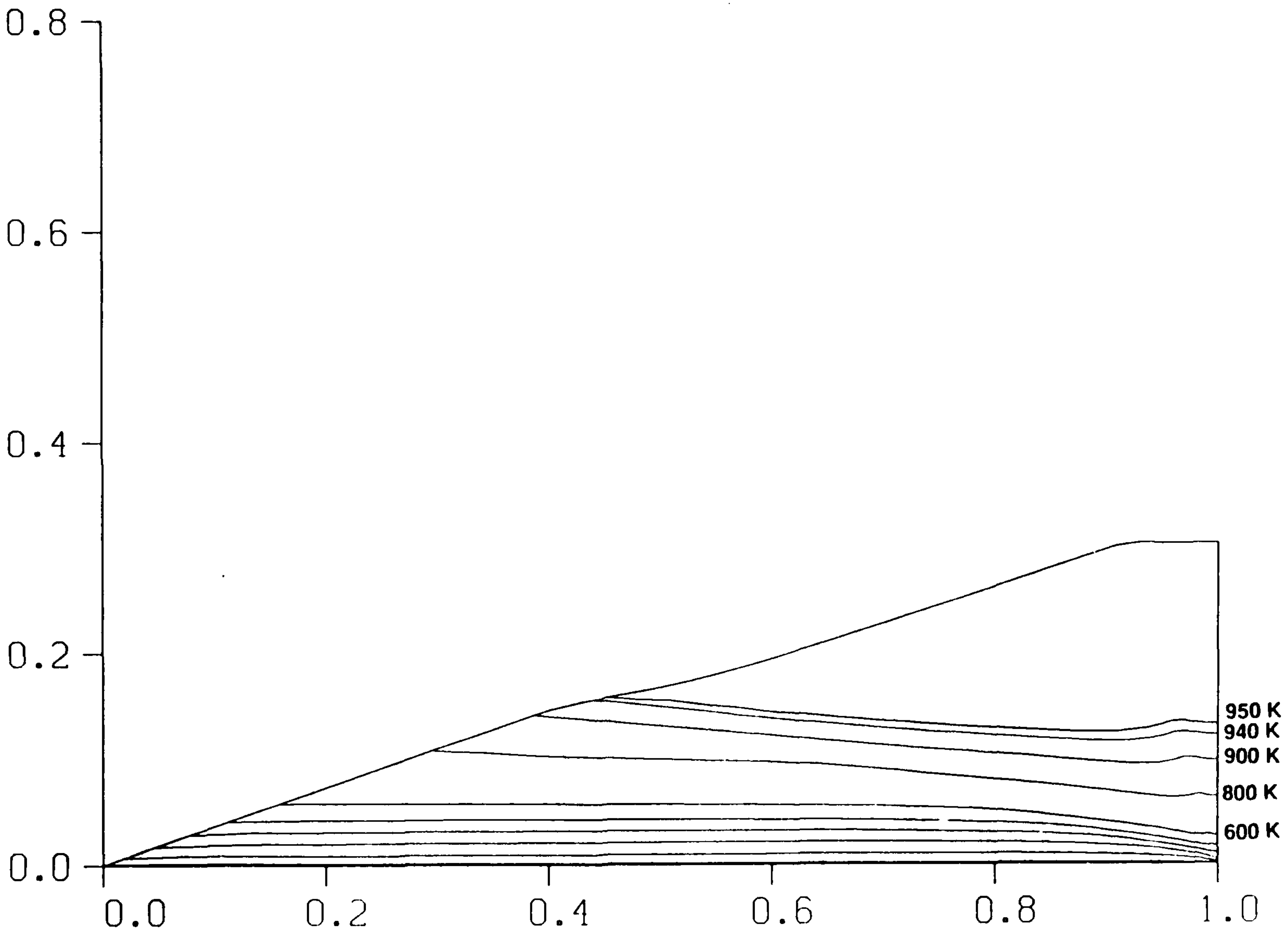

Figure 9. Free flight temperature contours, aluminum oxide coating, time = 2.0 seconds.

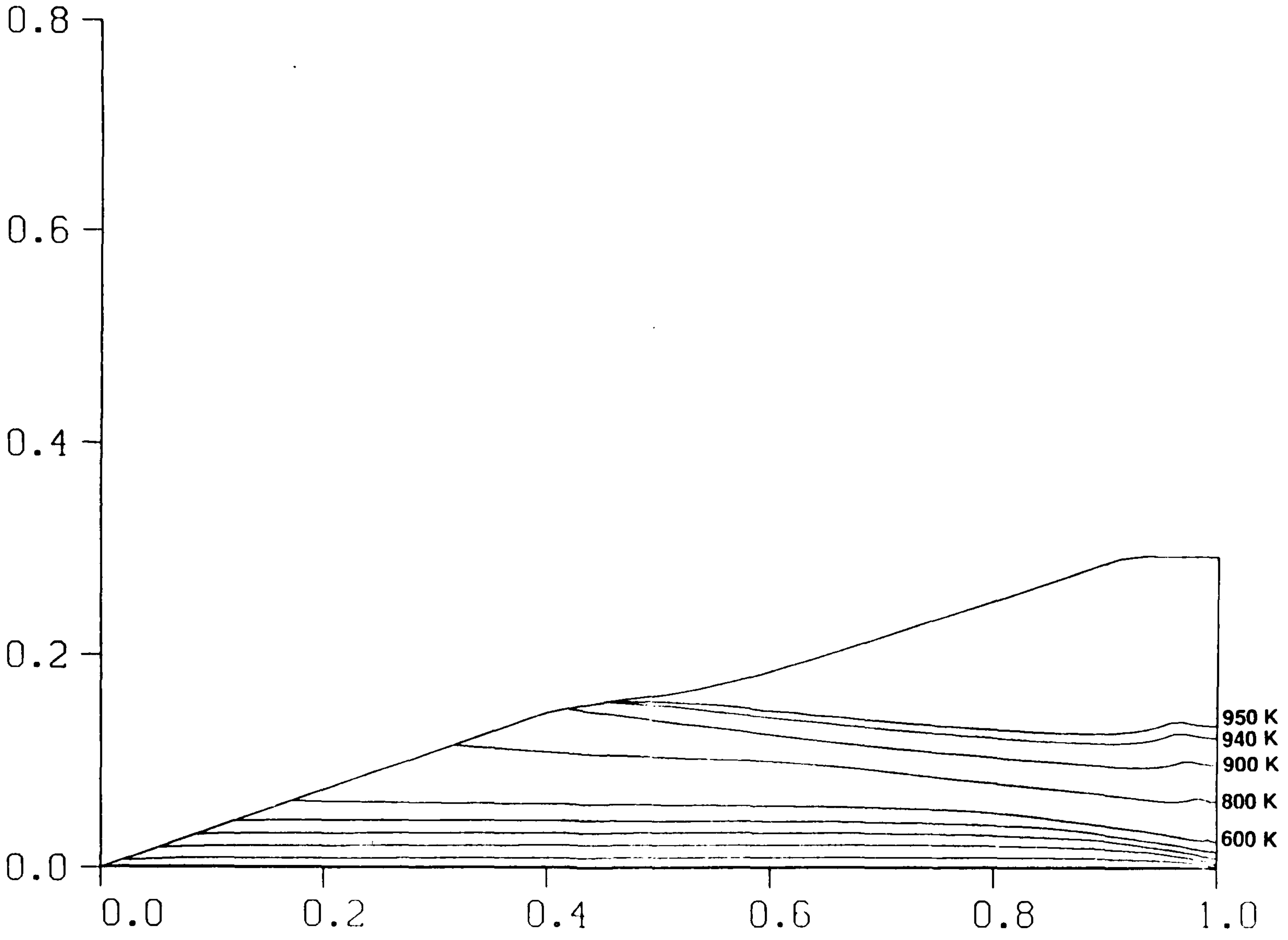

Figure 10. Free flight temperature contours, aluminum oxide coating, time = 2.5 seconds.

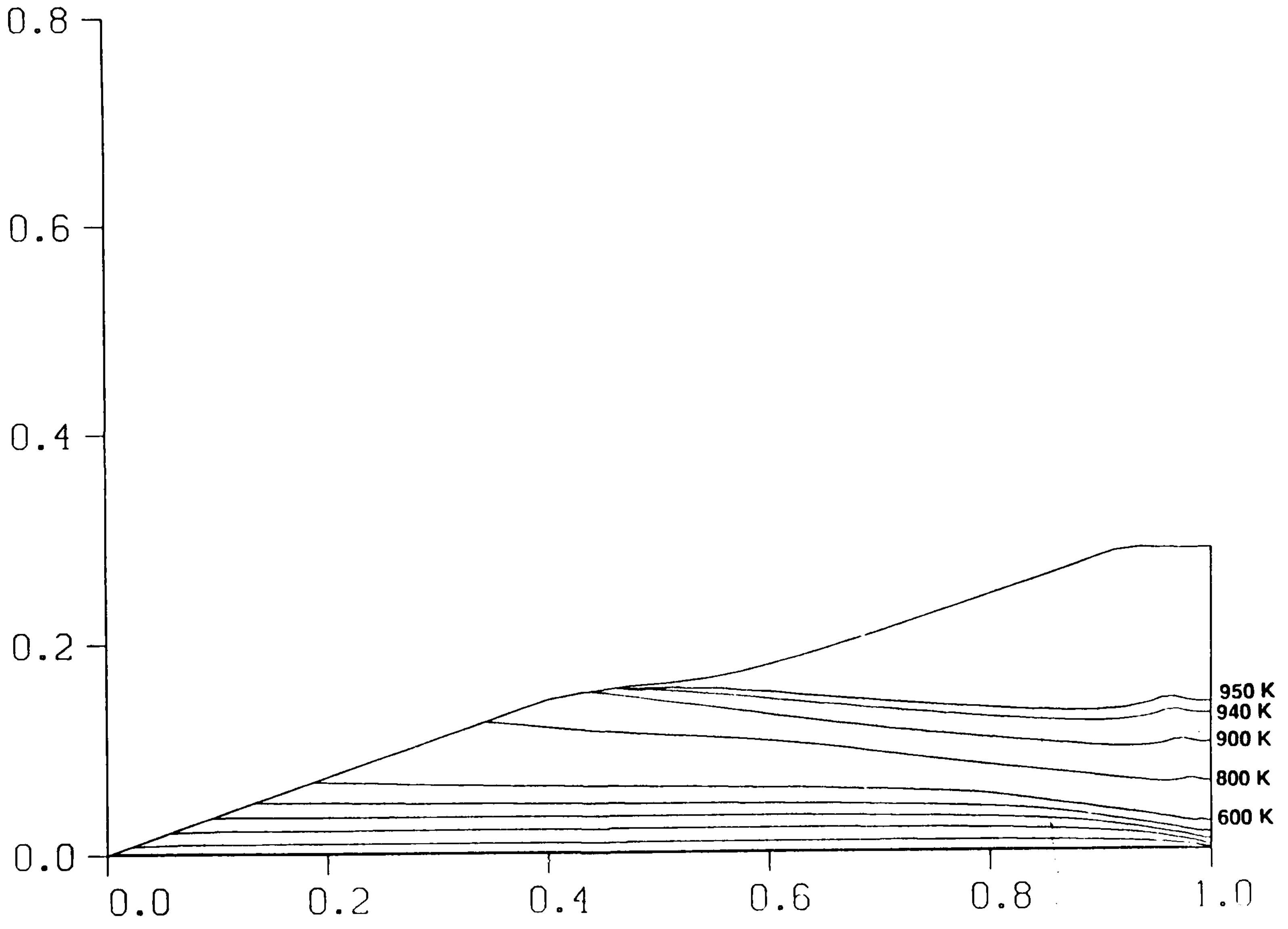

Figure 11. Free flight temperature contours, aluminum oxide coating, time = 3.0 seconds.

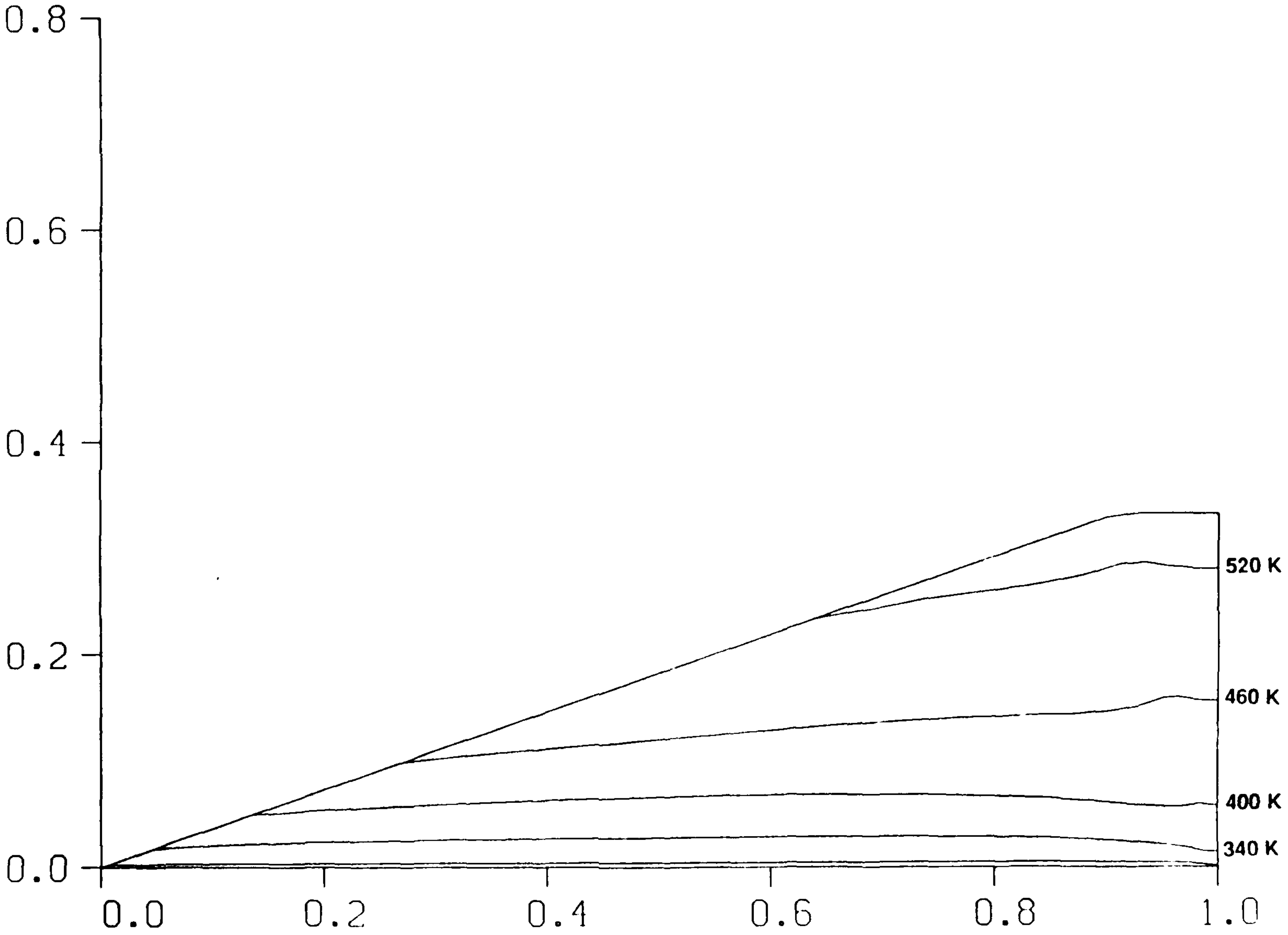

Figure 12. Free flight temperature contours, silicon/fiber coating, time = 0.5 seconds.

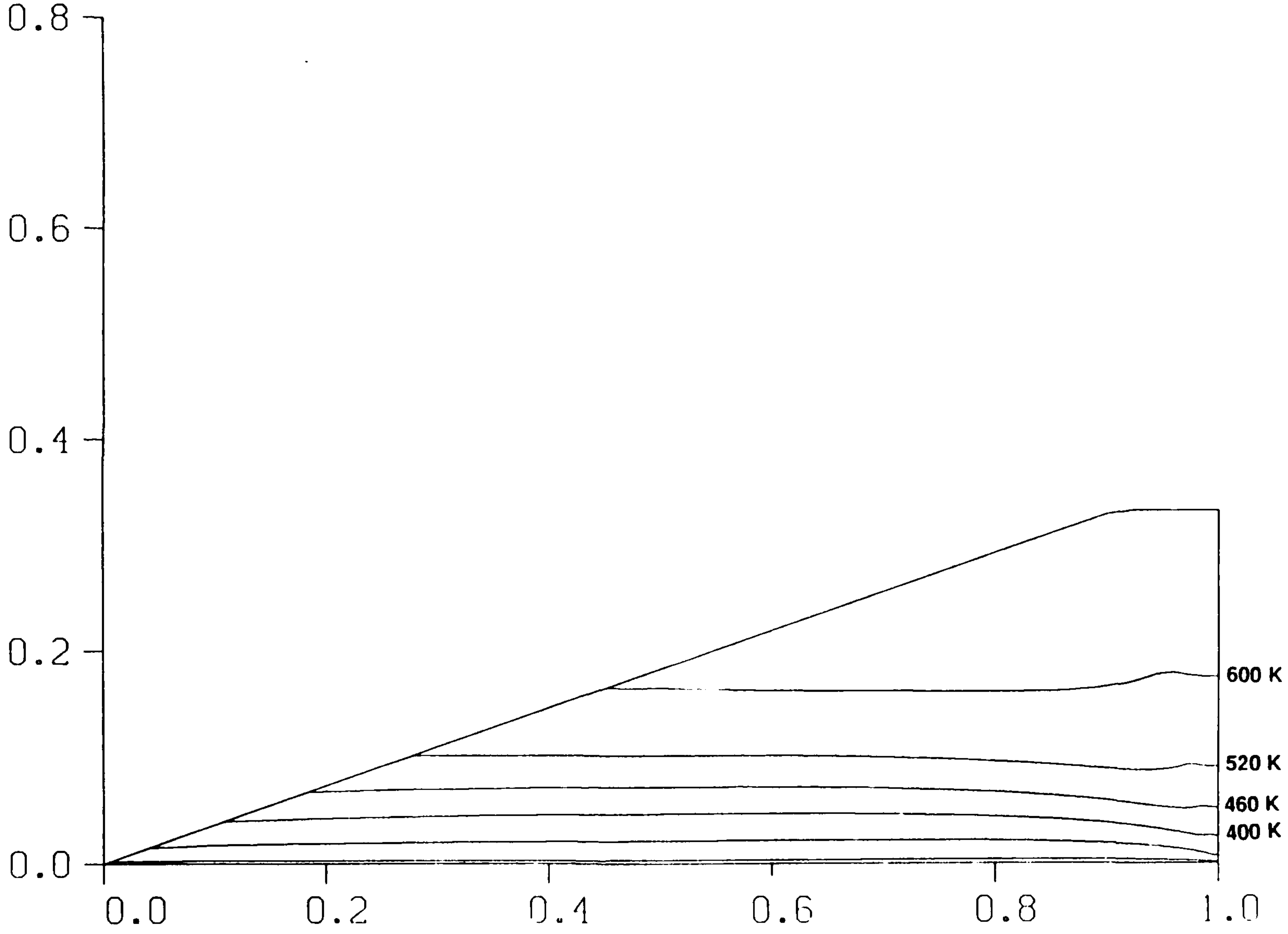

Figure 13. Free flight temperature contours, silicon/fiber coating, time = 1.0 second.

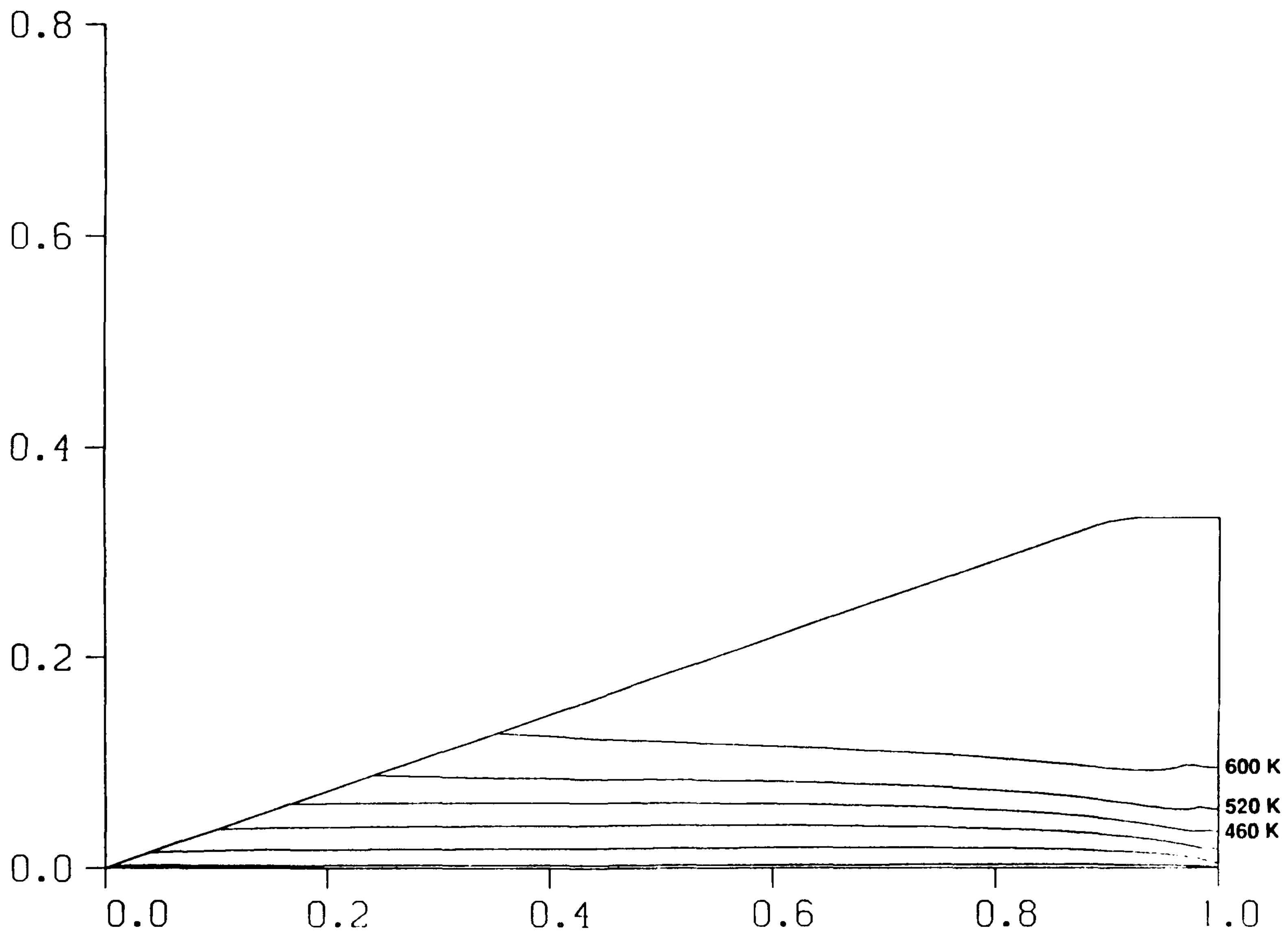

Figure 14. Free flight temperature contours, silicon/fiber coating, time = 1.5 seconds.

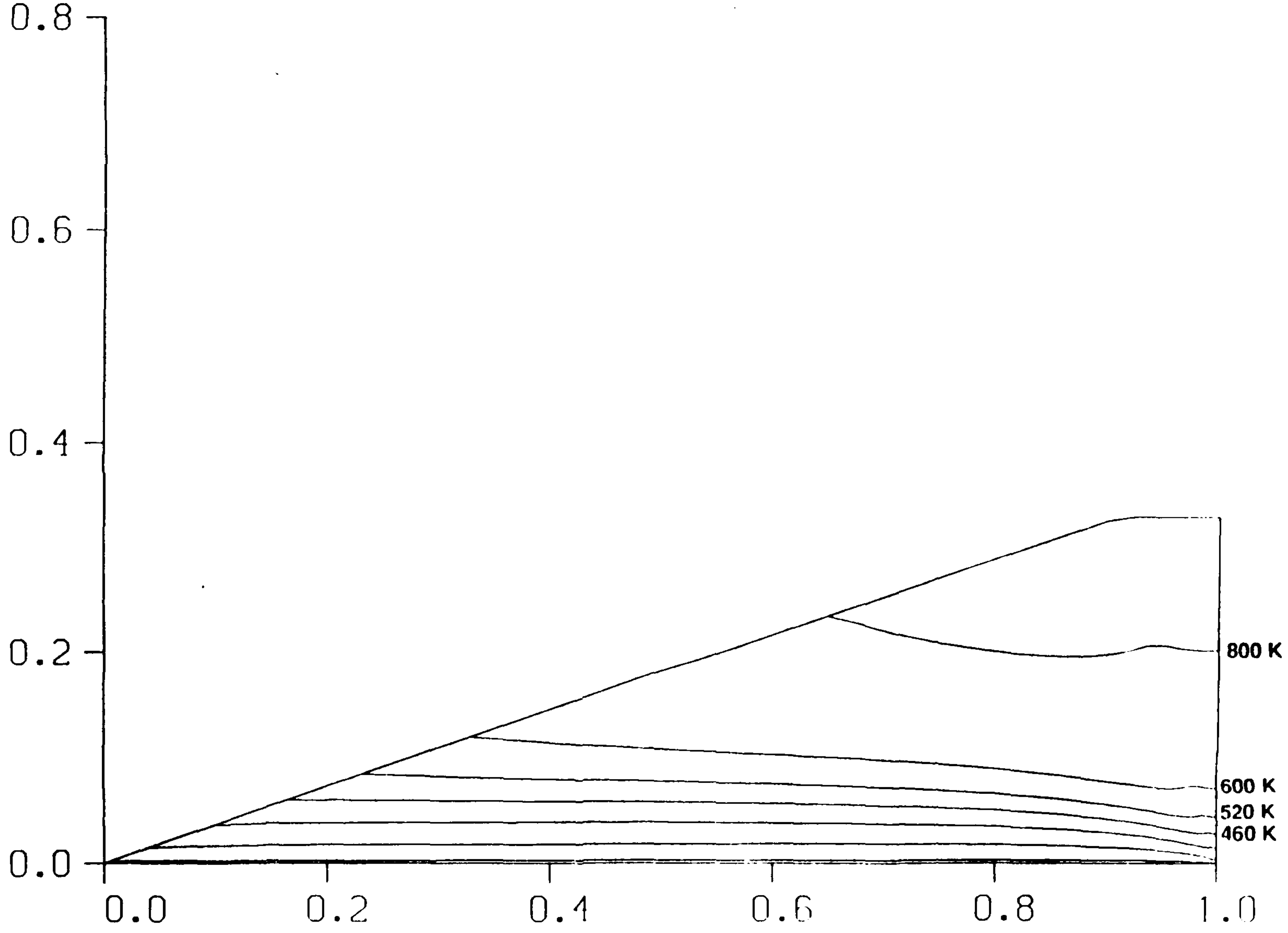

Figure 15. Free flight temperature contours, silicon/fiber coating, time = 2.0 seconds.

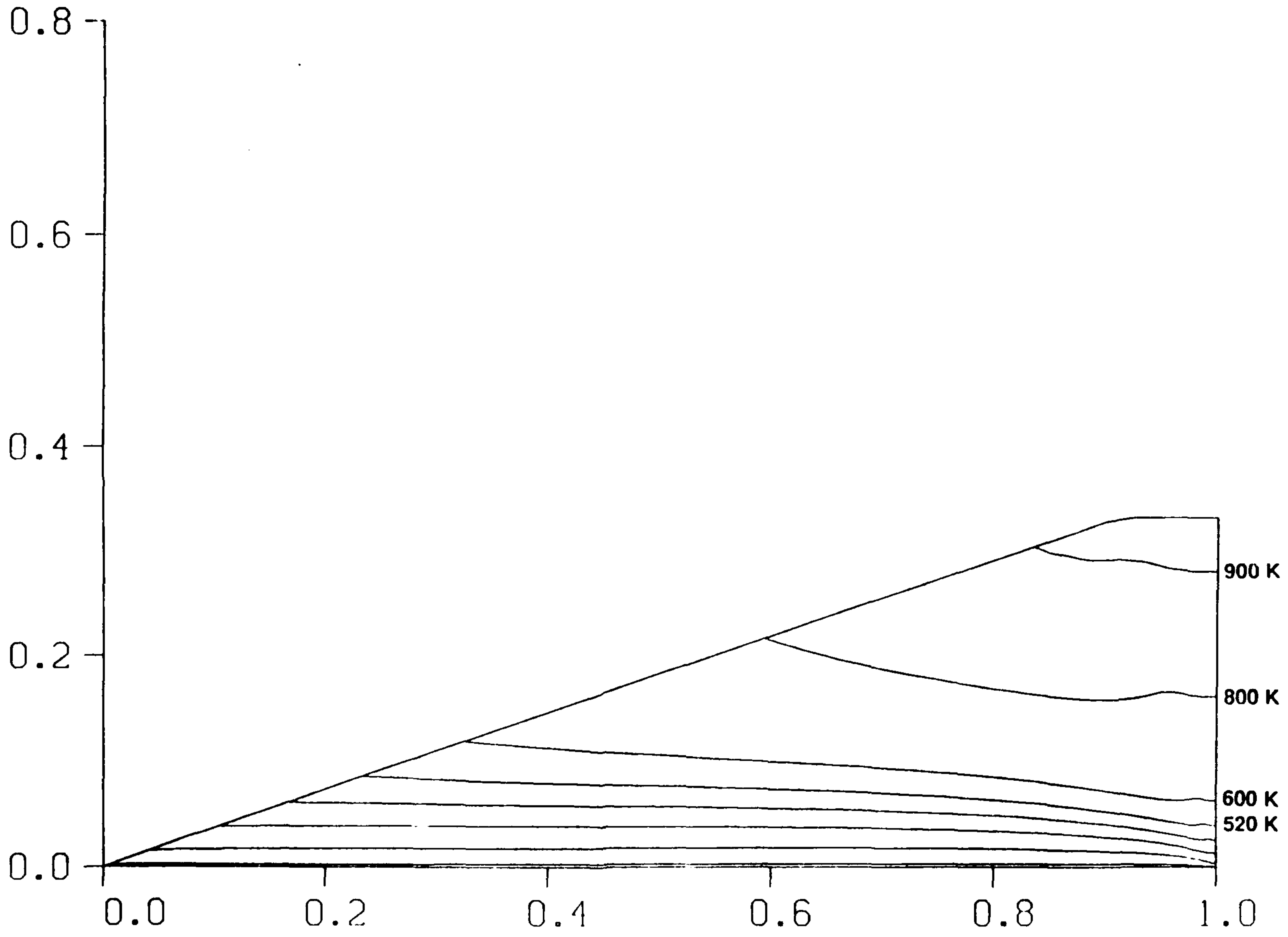

Figure 16. Free flight temperature contours, silicon/fiber coating, time = 2.5 seconds.

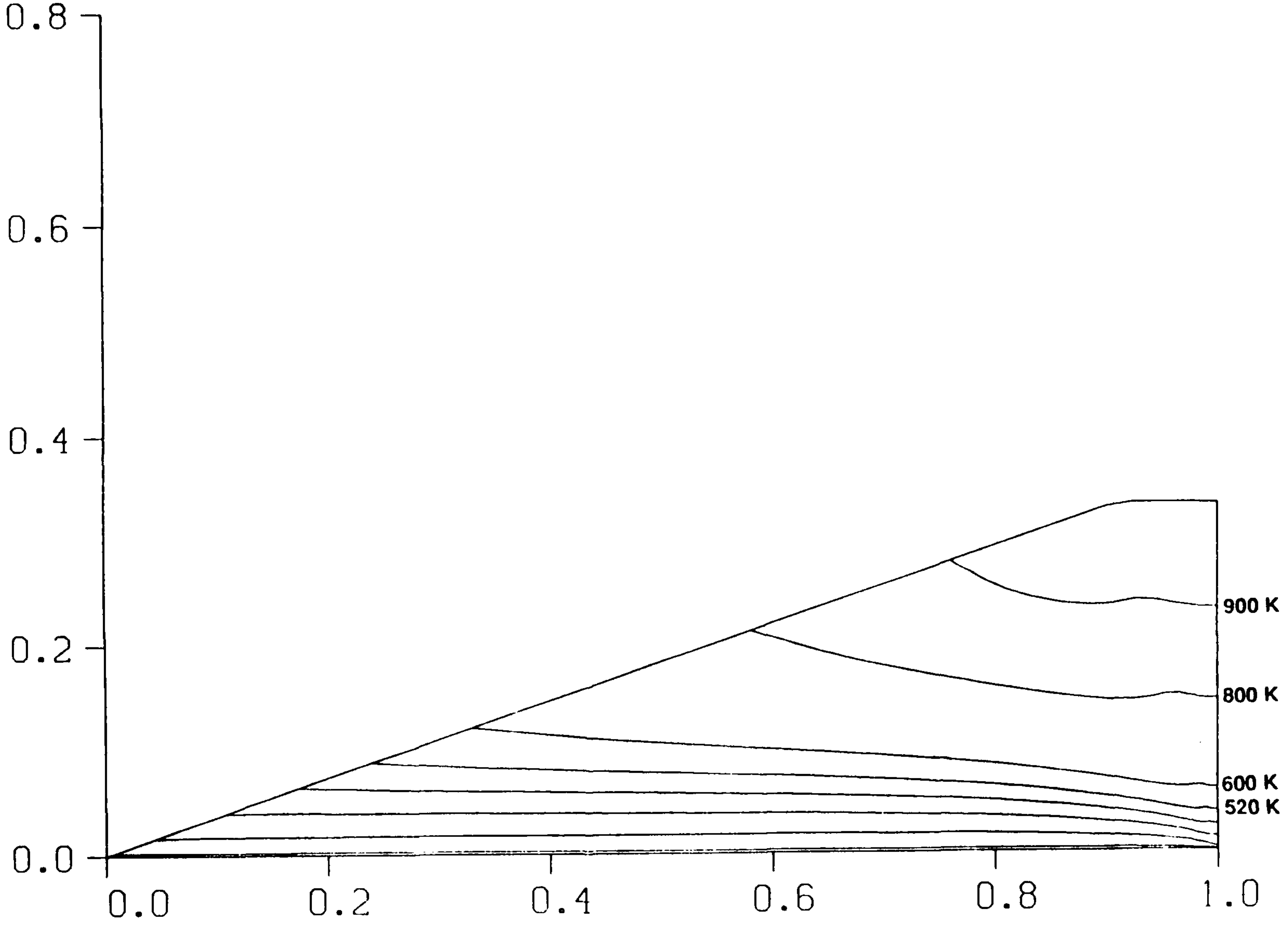

Figure 17. Free flight temperature contours, silicon/fiber coating, time = 3.0 seconds.

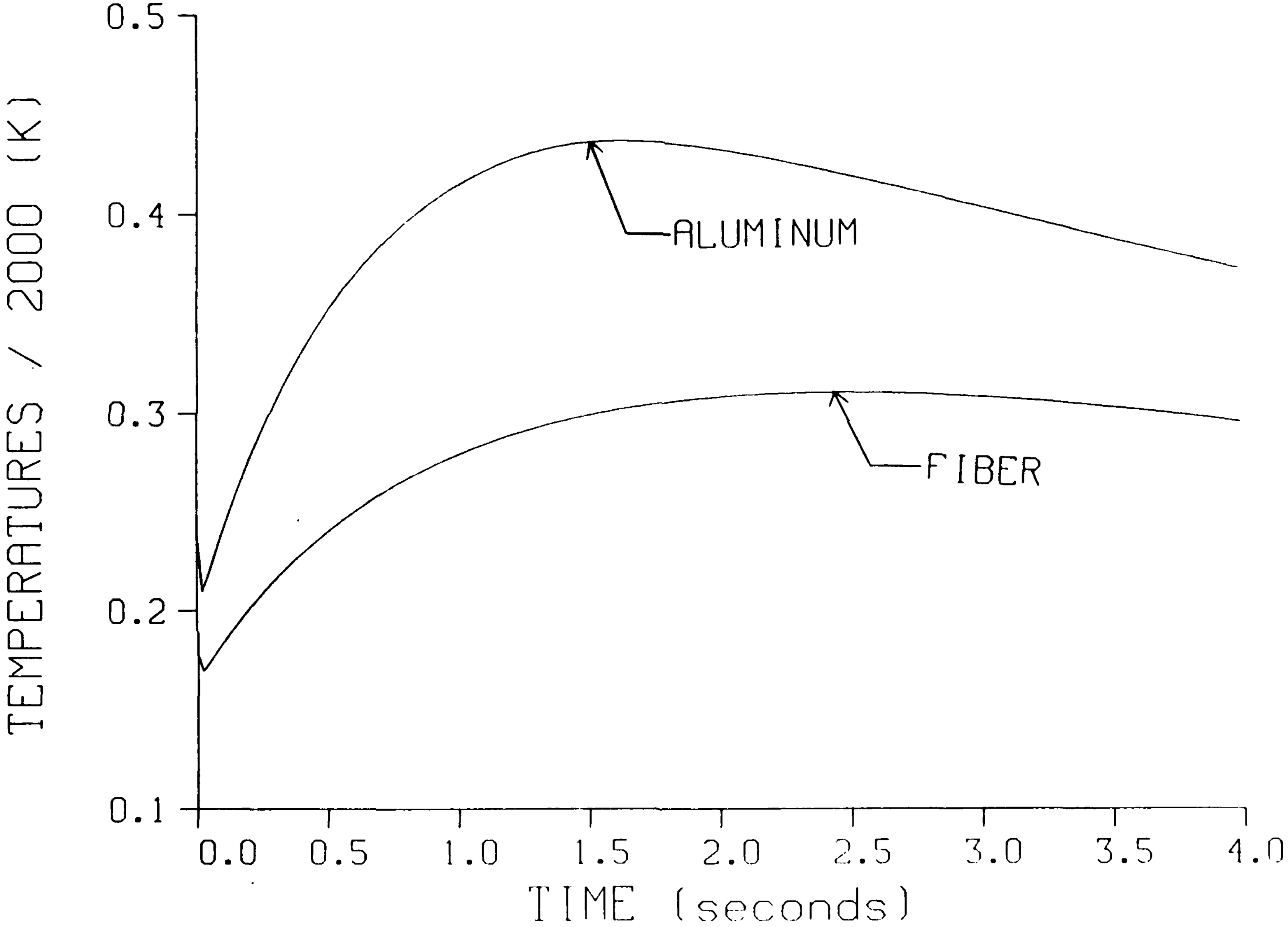

Figure 18. Temperature at the fin leading edge versus flight time (midway between the root and tip of the fin).

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1. Sturek, W.B., Dwyer, H.A., and Ferry, E.N., Jr., "Prediction of In-Bore and Aerodynamic Heating of KE Projectile Fins," Memorandum Report, US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, to be published.
2. Weinacht, P., Sturek, W.B., and Wooden, P.A. "Computational Study of Inbore and Inflight Heating for the 105mm M774 Projectile Modified Swept Fin," ARBRL-MR-03377, US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland. August 1984. (AD A146568)
3. Weinacht, P., Private Communications, US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland.
4. Sturek, W.B., Kayser, L.D., and Weinacht, P., "Computational Study of Swept-Fin Aerodynamic Heating for the 105mm M774," ARBRL-MR-03315, US Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, October 1983. (AD A134992)

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APPENDIX A: CODE IMPLEMENTATION ON THE BRL SUPERCOMPUTER

The heat transfer code is currently installed and running on the Cray 2 and Cray X-MP/48 Supercomputers at BRL. The code is maintained using a Unix Makefile. This recompiles and links only the code sections which have been changed since the last time the program was complied and linked. This provides an efficient way to accurately maintain the source code. The Makefile creates the executable code which is then run on the Cray. A copy of this Makefile follows:

```
#echo
#echo
#echo
#echo   !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
#echo
#echo   The Subroutines Are Being Compiled With Optimization Turned On
#echo
#echo   !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
#echo
#
#
#
#geom.h phyvar.h solver.h
#include/geom.h include/phyvar.h include/solver.h
#include/geom.h include/phyvar.h include/solver.h
#
#

2dfin:  nmangfa.o nequafa.o nmathfa.o
        segldr -o 2dfin nequafa.o nmangfa.o nmathfa.o

#
#

        echo
        echo
        echo  '            LINKING PROGRAM'
        echo
        echo
        echo
        echo  '            OPTIMIZATION ON'
        echo
        echo  '            DONE'

#
```

```
nmangfa.o: mangfa.f include/geom.h include/phyvar.h
include/solver.h
        echo '          COMPILING MANGFA.F'
        /lib/cpp -P mangfa.f>nmangfa.f
        cft77 nmangfa.f

#
#
#

nequafa.o: equafa.f include/geom.h include/phyvar.h
include/solver.h
        echo '          COMPILING EQUAFA.F'
        /lib/cpp -P equafa.f>nequafa.f
        cft77 nequafa.f

#
#
#

nmathfa.o: mathfa.f include/geom.h include/phyvar.h
include/solver.h
        echo '          COMPILING MATHFA.F'
        /lib/cpp -P mathfa.f>nmathfa.f
        cft77 nmathfa.f
```

Everything in the Makefile which is preceded with a "#" is a comment. The following line from the Makefile sets up the dependencies for the executable code.

```
2dfin:  nmangfa.o nequafa.o nmathfa.o
        segldr -o 2dfin nequafa.o nmangfa.o nmathfa.o
```

What this means is. the executable code "2dfin" depends on the three object code files which follow it. They are linked using the Cray 2 linker "segldr." All through the Makefile you see lines which are "indented" from the first column. These MUST be indented with a "tab" character, NOT by spaces. This is a restriction of the Makefile, not the operating system.

The following line sets up the dependencies of the "nmangfa" object code. This line means the object code depends on the Fortran source code file and the four include files which are located in a subdirectory called "include."

```
nmangfa.o: mangfa.f include/geom.h include/phyvar.h
include/solver.h
        echo '          COMPILING MANGFA.F'
        /lib/cpp -P mangfa.f>nmangfa.f
        cft77 nmangfa.f
```

Due to the length of the code and the numerous "common" statements, the code is set up to use "include" statements. This allows changes to be made in the ".h" file and the Makefile then causes these changes to be made throughout the entire code. However, the include statement is not part of standard Fortran, so the code is first run through the C-Preprocessor which actually brings in the common blocks stored in the ".h" files. This is done with the "/lib/cpp -P....." line of the Makefile. The output of this preprocessor is redirected to the file "nxxxxx. f" which is the Fortran source code with the common blocks replacing the include statements.

To use the include statements, the following line

```
#include"include/xxxx.h"
```

must be in the Fortran code, where "xxxx.h" is the name of the file to be included and is located in a subdirectory called "include." This line goes in the Fortran code in the place you want the ".h" file to be inserted. It must start in the FIRST column, not the seventh like the Fortran code does.

Due to the length of time necessary for some runs of the code to complete, it is submitted to the batch queues of the Cray. This also protects the run from an unexpected system crash since the code's point of execution is quickly saved if the system crashes, and its execution continues at that point when the system is brought back up. Running the code in this way also permits you to use the terminal for other work while the code is running. To submit the code for execution, a short JCL file is created which contains the path to the executable code and any input data files. The JCL file also contains the name of the queue in which to run the code, and the maximum amount of CPU time to allocate to it. There is also a line in the JCL file to start and stop timing statistics. This makes it easier to determine if the code can run in a faster queue the next time it is submitted since the queues are based on the amount of CPU time required and the amount of memory required. An example of the JCL file follows:

```
# QSUB-q crayque    # submit job to the pipe queue
# QSUB-eo           # standard error goes to standard out
# QSUB-lm 1mw       # establish per-process memory size limit
# QSUB-lM 1mw       # establish per-request memory size limit
# QSUB-lt 3000      # establish per-process cpu time limit (seconds)
# QSUB-lT 3000      # establish per-request cpu time limit (seconds)
# QSUB              # end of QSUB parameters


cd /lfd/sb/eferry/Q3F
2dfin < inp
```

The first line of the JCL file sends the job to the queue "crayque." This is a "pipe" queue. There are a series of six queues that the job may run in. The system looks at the requirements of the job and compares this to the limitations of the six queues. The job is then submitted into the most appropriate queue. The next line combines the standard error file and the standard output file into one, the standard output file. The next two lines set up the memory requirements for the code. Here, the requirements are 1 mega-word. The fifth and sixth lines in this JCL file set the maximum time limit of execution to 3000 seconds CPU time. The next line supplies the path to the code to be run. The "2dfin" is the actual executable code, and the "< inp" redirects Unix standard input from the file "inp" rather than from the keyboard of the terminal.

As the code is executing, the real time of flight is being calculated at each time step. When this time just exceeds predetermined values, a data file (for040.dat) is written out with the fin's grid geometry and the temperature at all the grid points. This file can be plotted to the screen from either of the Crays using a program called "disgrid." This file can also be shipped to an Iris Silicon Graphics work station using ftp (file transfer protocol). On the Iris, this file can be graphically displayed using an Iris version of "disgrid." This "for040.dat" file can also be plotted using a program called "gen" which gives a smooth blending of colors representing the temperatures across the grid. The "for040.dat" files can also be run through another program called "plotc" which creates a "plotc.dat" file containing specific temperature contour levels specified within the program. This "plotc.dat" file can be plotted on the Crays using a program called "discont," and, like the "for040.dat" files, the "plotc.dat" file can be ftp'd to the Iris and be plotted by an Iris version of "discont." The code on the Iris which creates these displays is written in Fortran and calls on the Iris' extensive graphics library to visually display the current state of the fin. This can be done in one of two ways. One way is to view single data files at a time. This is helpful to make sure the code appears to be running correctly before you let it go to its completion. It is also useful for creating hard copies of the fin on a Tektronix 4692 color inkjet printer. A second method by which the data can be viewed is accomplished by reading in all the data files at one time and display them in rapid succession. This allows the viewer to get a feel as to how the heat is transferring through the fin.

The second method of display uses a mode called "double buffered mode" to make the successive images appear on the screen more fluidly. In this mode, as one image is being viewed, the next image is being drawn in a buffer "behind" it. This image is invisible until the buffers are swapped. When the buffers are swapped, the old image gets pushed to the back. This method is very useful to more easily see how the fin changes from one time to the next. This is especially useful to observe the quasi-3d melting process.

The "gen" program on the Iris workstation was written by Harry Dwyer using GSS on an IBM compatible PC, and was ported to the Iris by Earl N. Ferry, Jr. The program uses a method of shading on the Iris known as Gouraud shading to achieve smooth contours. This is accomplished by creating a color map and interpolating the temperatures of the grid onto the indices of the color map. These indices are then used as color shades for the fill routine. This method of coloring the grid creates a smooth blend of colors for the different temperatures.

The heat transfer code also creates a file called "tdat.dat." This file contains the temperatures of specific grid points at each time interval. This file can be plotted on the Crays using a program called "dta.x." This program plots this file as temperature vs. time for the selected points.

The programs which are run on the Crays to plot the grids and contours are written in Fortran and currently use DISSPLA. These programs also present another hard copy option. The "disgrid" and "discont" programs have the option to create a file which can be ftp'd to the Vax and be printed on a QMS Laser printer.

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