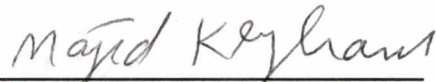


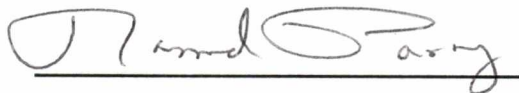
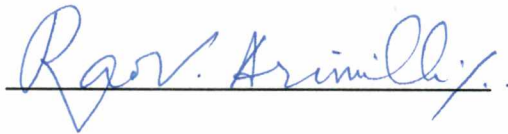
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Date 6-28-93

Experimental and Numerical Investigation of
Heat Transfer in Polymers

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Frank Albert Pitman

August 1993

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Abstract

Two carbon phenolic materials, designated MX 4926 and FM 5055, are experimentally and numerically investigated for mass loss by decomposition, moisture content, and thermal response. A two dimensional transient model is used to calculate temperature, pressure, and decomposition in the polymer with various boundary conditions for comparison with the experimental results from heating and weighing the samples of the carbon phenolics.

The amount of moisture initially contained in a carbon phenolic material and the time required to release the moisture are measured for MX 4926. The mass loss and surface temperature of FM 5055 and MX 4926 samples in a furnace at a number of different temperatures are recorded. A known heat flux is applied to FM 5055 samples to measure the temperature versus time at several locations within the sample. Numerical predictions of mass loss and temperature distribution are compared with the experimental data for verification of the code and its boundary conditions and input material properties.

It was found that 3.1% of the initial mass of the MX 4926 material tested is water. The surface temperature and mass loss for both thin and thick blocks of FM 5055 and MX 4926 provide a means of verifying the two dimensional heating aspects of the numerical code. Heat fluxes applied to the FM 5055 show the importance of material properties in predicting the transient response of the carbon phenolic material with a reasonable accuracy.

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List of Symbols

A	area of control volume face, ft ²
A _i	pre-exponential factor for component i, sec ⁻¹
c _p	specific heat, Btu/lbm R
dx	length of control volume in x direction, ft
dx _e	distance between node i,j and node i+1,j, ft
dx _w	distance between node i,j and node i-1,j, ft
dy	length of control volume in y direction, ft
dy _n	distance between node i,j and node i,j+1, ft
dy _s	distance between node i,j and node i,j-1, ft
E	Young's modulus of elasticity, lbf/ft ²
E _b	black body emissive power
E _i	activation energy, Btu/lbm
F _{ij}	view factor
h	enthalpy, Btu/lbm
h	convective heat transfer coefficient, Btu/ft ² sec R
h _p	pressure coefficient, lbf/ft ²
I	current, amps
J	radiosity
K	permeability, ft ²
k	thermal conductivity, Btu/ft sec R
L	length, feet or inches
M	molecular weight, lbm/lbmole

m	mass, lbm or grams
$\dot{m}$	mass flow rate, lbm/sec
n_i	order of reaction of component i
P	pressure, lbf/ft ²
q	heat flux, Btu/sec
Ra	Rayleigh number
R_u	universal gas constant, Btu/lbmole R
T	temperature, R
t	time, sec
u	velocity in x direction, ft/sec
V	voltage, volts
Vol	volume of control volume, ft ³
v	velocity in y direction, ft/sec
w	width, inches
x	coordinate in x direction, ft
y	coordinate in y direction, ft

Greek Symbols

β	degree of char
ϕ	porosity
ε	emissivity
μ	viscosity, lbm/ft sec
ρ	density, lbm/ft ³ or electrical resistance, ohms-cm
σ	Stefan-Boltzmann constant, Btu/ft ² sec R
Δ	increment
Γ	resin volume fraction

Ψ reaction order

Subscripts

1,2 principle material directions

c char

d dried

e east

f formation

g gas

i,j nodal indices

init initial

n north

ref reference

s south

surr surroundings

v virgin

w west

∞ ambient

Superscripts

- average

0 current time

Chapter 1

Introduction

Background

The need for a material to protect spacecraft against extreme heating conditions has led to the use of carbon phenolic composites. These composites have been shown to be effective in overcoming the aerodynamic heating of spacecraft entering an atmosphere, Ely (1966). Carbon phenolics can also be used effectively as a liner on the nozzles of solid rocket motors, where regenerative cooling is not available. For the material to be used efficiently and safely a thorough knowledge of its properties and behavior under various operating conditions is necessary.

Aerodynamic heating is caused by the conversion of the kinetic energy to heat when a vehicle encounters the resistance of an atmosphere. Table 1.1 from data in April (1969) shows that most of this heat cannot be absorbed by the spacecraft. The liner of a solid rocket motor experiences a similar type of heating due to the high energy flow of combustion gases during operation.

Table 1.1. Aerodynamic heating.

orbital altitude	300 mi
velocity	26,000 ft/sec
kinetic energy	13,500 Btu/lb
heat for 5000 lb vehicle	67,500,000 Btu
vehicle temperature rise	1150 °F
heat absorbed by vehicle	675,000 Btu (1% of total heat)

Transpiration, convective, film, and radiation cooling have been considered, but ablative cooling has been shown to be the most effective means of protecting a vehicle according to Steverding (1965). This method uses a charring ablative material, such as carbon phenolics, to protect the vehicle by the absorption of heat in phase change, as well as by convection, transpiration, and endothermic chemical reactions. A high heat of degradation and a low thermal conductivity are required for the ablator to effectively insulate the vehicle. The ablator decomposes to a char layer of porous carbon and low molecular weight gases, and this process can be divided into three zones: the plastic decomposition zone, the char zone, and the boundary layer. The virgin plastic decomposes into char and pyrolysis gases, and the gases flow through the char zone enabling heat transfer into the boundary layer as shown in Figure 1.1 and described in April (1969).

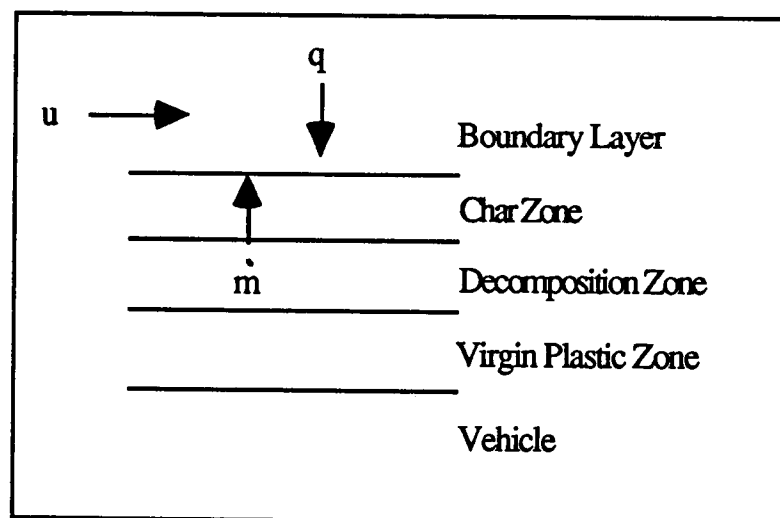


Figure 1.1. Model of a charring ablator.

Accurate prediction of the decomposition of the carbon phenolics is crucial. This work is primarily concerned with the thermal behavior. Two carbon phenolics, FM 5055 and MX 4926, are considered. The material is composed of a resin and a reinforcing material of plys. For a reliable prediction material properties of the composites must be known accurately.

The material properties used are listed in Appendix A. Two of the properties, virgin and char density, have been measured by Acurex, Beck et al (1984), and the Thermophysical Properties Research Lab (TPRL) at Purdue University using a thermogravimetric analysis (TGA) for char values. Elemental compositions of the materials were measured by Galbraith Laboratory. Specific heats were measured at TPRL as a function of temperature using a standard Perkin-Elmer Differential Scanning Calorimeter with sapphire as the reference material. By comparing differential powers to heat the sapphire and the carbon phenolic, the specific heat values were obtained. The values were extrapolated to high temperatures by assuming the carbon phenolic to be equivalent to carbon at these high temperatures.

Virgin thermal conductivities were calculated from knowledge of density, specific heat, and thermal diffusivity. Thermal diffusivity was measured using the laser flash diffusivity method to record the temperature rise of the rear face of a sample when the front face was subjected to a laser burst. Char thermal conductivity has been measured empirically using the Aerotherm Charring Material Thermal Response and Ablation computer program to match thermocouple output in Beck et al (1984). Decomposition kinetic constants were measured by comparing

the CMA code to TGA data. Gas enthalpy was found using the ACE program to make a thermochemical equilibrium calculation assuming that the gas is in thermochemical equilibrium throughout the temperature range used.

Thermal conductivity and specific heat data have also been calculated by Southern Research Institute and are listed in Appendix A. A Comparative Rod Apparatus is used to find conductivity up to 2000 °F, and a Radial Inflow Apparatus is used for 1500 °F to 5000 °F. Specific heat was found from the slope of the enthalpy curve over a selected temperature range. Permeability of FM 5055 was measured using high purity nitrogen and a heating rate of 5-7 °F per minute. Forchheimer's equation with measured upstream and downstream pressures was used to calculate permeability. Porosity was determined by saturation in isopropanol, helium pycnometry, and mercury porosimetry.

Objectives

The two dimensional behavior of carbon phenolics is to be modeled by the numerical code described in chapter two. Previously reported material properties of MX 4926 and FM 5055 are used with the geometry and boundary conditions to model the furnace heating and the heat flux experiments described in chapters four and five, respectively. The accuracy of the properties under different conditions is to be compared, and a reliable two dimensional code is to be verified. The moisture content of the carbon phenolic MX 4926 is to be investigated with respect to its initial quantity and means of escape when heated.

Chapter 2

Numerical Model

Assumptions

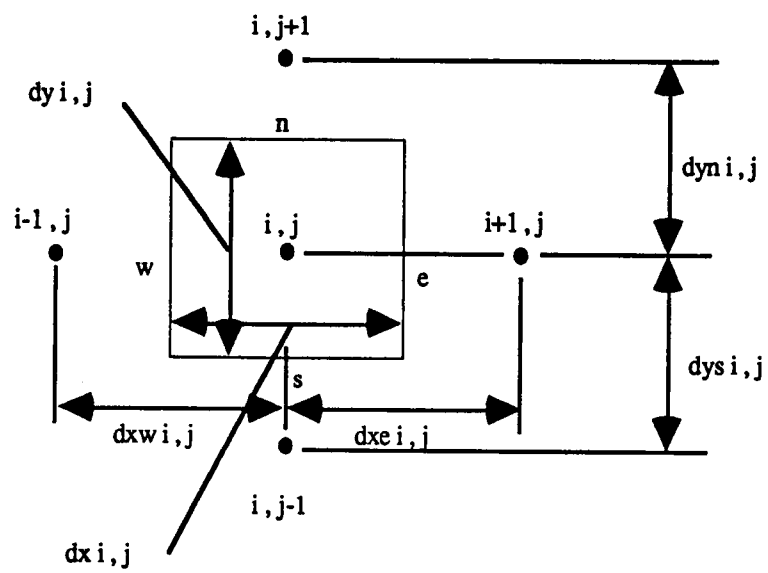
The computer program explained in this chapter is used to predict the thermal response of the carbon phenolic materials, MX 4926 and FM 5055, using thermophysical properties listed in Appendices A.1 to A.3. Two-dimensional, transient heat transfer with variable properties in an orthotropic, porous material is modeled. Boundary conditions regarding radiation, convection, heat flux, and pressure can be set to compare the numerical calculations with experimental data collected and presented in chapters three, four, and five.

The gas and solid are assumed to be in thermal equilibrium, and the reaction kinetics from Beck et al (1984) follow the Arrhenius rate equation. The pyrolysis gas is assumed to obey the equation of state for an ideal gas. Properties are taken to be a combination of virgin and char properties based on decomposition calculations. The Darcy equation is used to model the gas flow within the porous material. The derivation of these equations follows in the next section.

Derivation of Equations

Geometry

The calculation domain is composed of m by n nodes with half control volumes on the boundaries. Figure 2.1 shows the terminology



involved in the assignment of dimensions.

Decomposition

The decomposition of the carbon phenolics is calculated using the Arrhenius relation:

$$\frac{\partial \rho_i}{\partial t} = -A_i [\exp(E_i / RT)] \rho_{vi} \left(\frac{\rho_i - \rho_{ci}}{\rho_{vi}} \right)^{\Psi_i} ; i = 1, 2, 3 \quad (2.1)$$

The polymer is assumed to be composed of three components: 1, 2, and 3. Its density is calculated by:

$$\rho = \Gamma (\rho_1 + \rho_2) + (1 - \Gamma) \rho_3 \quad (2.2)$$

where

Γ = resin volume fraction

ρ_{vi} = initial density of component i

ρ_{ci} = residual density of component i

A_i = pre-exponential factor for component i

E_i = activation energy for component i

Ψ_i = reaction order for reaction of component i

Assuming constant temperature over Δt , for $\Psi_i \neq 1$, the Arrhenius equation is integrated for each of the three components to get the form

$$\rho_i = \rho_{ci} + \left[(\rho_{pi} - \rho_{ci})^{1-\Psi_i} - \frac{1-\Psi_i}{\rho_{vi}^{\Psi_i}} A_i \exp(E_i / RT) \rho_{vi} \Delta t \right]^{\frac{1}{1-\Psi_i}} \quad (2.3)$$

where

Δt = time step

ρ_{pi} = density of component i at previous time step

Constants for this equation were obtained from Beck et al (1984) by matching the TGA data with CMA output. They are listed in Appendices A.1 to A.3. Density is calculated at each time step and for each control volume of the domain.

Energy

The conservation of energy is represented by:

$$\frac{\partial}{\partial t}(\rho h A) + \frac{\partial}{\partial x}(\dot{m}_g h_g) + \frac{\partial}{\partial y}(\dot{m}_g h_g) = \frac{\partial}{\partial x}\left(k_1 A \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_2 A \frac{\partial T}{\partial y}\right) \quad (2.4)$$

The conservation of mass is represented by:

$$\frac{\partial}{\partial t}(\phi \rho_g A) + \frac{\partial}{\partial x}(\dot{m}_g) + \frac{\partial}{\partial y}(\dot{m}_g) = -\frac{\partial \rho}{\partial t} A \quad (2.5)$$

Equations (2.4) and (2.5) are combined to form:

$$\begin{aligned} A \bar{\rho} \bar{c}_p \frac{\partial T}{\partial t} + \frac{\partial}{\partial x}(\dot{m}_g \bar{c}_{pg} T) + \frac{\partial}{\partial y}(\dot{m}_g \bar{c}_{pg} T) &= \frac{\partial}{\partial x}\left(k_1 A \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_2 A \frac{\partial T}{\partial y}\right) + \\ (h_g^o - \bar{h}^o) \frac{\partial \rho}{\partial t} A + \frac{\partial}{\partial x}[\dot{m}_g (\bar{c}_{pg} T^o - h_g^o)] + \frac{\partial}{\partial y}[\dot{m}_g (\bar{c}_{pg} T^o - h_g^o)] &+ h_g^o \frac{\partial \dot{m}_g}{\partial x} + h_g^o \frac{\partial \dot{m}_g}{\partial y} \end{aligned} \quad (2.6)$$

where

$$\bar{c}_p = \frac{\int_{T^o}^T c_p dT}{T - T^o} \quad (2.7)$$

$$\bar{\rho}\bar{c}_p = \beta\rho_c\bar{c}_{pc} + (1-\beta)\rho_v\bar{c}_{pv} \quad (2.8)$$

$$\bar{h} = \frac{\rho_v h_v - \rho_c h_c}{\rho_v - \rho_c} \quad (2.9)$$

The initial enthalpies are calculated using,

$$h_v = h_{vf} + c_{pv}(T_{init} - T_{ref}) \quad (2.10)$$

$$h_c = h_{cf} + c_{pc}(T_{init} - T_{ref}) \quad (2.11)$$

and the enthalpy at any time step is obtained by:

$$h = h^o + \bar{c}_p(T - T^o) \quad (2.12)$$

The properties are calculated with the following concept.

$$k = \beta k_c + (1-\beta)k_v \quad (2.13)$$

$$c_p = \beta c_{pc} + (1-\beta)c_{pv} \quad (2.14)$$

$$\beta = \frac{\rho_v - \rho}{\rho_v - \rho_c} \quad (2.15)$$

Pressure

Conservation of momentum is based on the Darcy equation for flow through a porous medium.

$$-\frac{\partial P}{\partial x} = \frac{\mu u}{K_1} \quad (2.16)$$

$$-\frac{\partial P}{\partial y} = \frac{\mu v}{K_2} \quad (2.17)$$

Combining the momentum equations, (2.16) and (2.17), with the continuity equation (2.5), the following equation for the pore pressure is obtained.

$$\phi A \frac{\partial \rho_g}{\partial t} = \frac{\partial}{\partial x} \left(\frac{\rho_g K_1 A}{\mu} \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{\rho_g K_2 A}{\mu} \frac{\partial P}{\partial y} \right) - A \frac{\partial \rho}{\partial t} \quad (2.18)$$

where the gas density is calculated from the ideal gas equation.

Porosity is determined from equation (2.19). Permeability is interpolated based on the degree of char, and other properties, such as thermal conductivity, heat capacity, and gas viscosity, are interpolated based on temperature.

$$\phi = \phi_{init} + \beta (\phi_c - \phi_{init}) \quad (2.19)$$

Gas Flow

The mass flow rates of the pyrolysis gases are computed using equations (2.20) and (2.21) and are used in the energy equation using the upwind scheme of Patankar (1980) shown in Figure 2.2.

$$\dot{m}_{gx_{ij}} = (P_{i-1,j} - P_{i,j}) \frac{A_{w_{i,j}}}{dx_{w_{i,j}}} \rho_w \frac{K_{1w}}{\mu_w} \quad (2.20)$$

$$\dot{m}_{gy_{i,j}} = (P_{i,j-1} - P_{i,j}) \frac{A_{s_{i,j}}}{dys_{i,j}} \rho_s \frac{K_{2s}}{\mu_s} \quad (2.21)$$

where

$$\rho_w = \left(\frac{M_w P_w}{R_u T_w} \right) \quad (2.22)$$

$$\rho_s = \left(\frac{M_s P_s}{R_u T_s} \right) \quad (2.23)$$

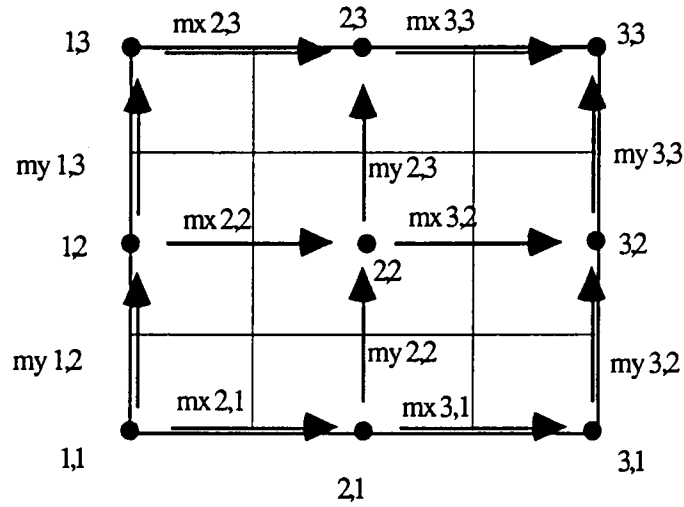


Figure 2.2. Gas flow designation.

Boundary Conditions

The boundary conditions are modeled using the following terms. The boundary node is designated by subscript B, and each side of the calculation domain can be set independently.

Equation (2.24) is substituted into the integrated form of equation (2.6) for the boundary heat flux.

$$q_B'' = q'' + h_c(T_B - T_\infty) + h_R(T_B - T_{\text{surr}}) \quad (2.24)$$

where

q_B'' = boundary heat flux

q'' = input boundary flux

h_c = convective heat transfer coefficient

h_R = Radiative heat transfer coefficient,

$$h_R = \epsilon F \sigma (T_{\text{surr}}^2 + T_B^2)(T_{\text{surr}} + T_B) \quad (2.25)$$

By specifying input values for q'' , h_c , T_∞ , and ϵ , the desired thermal boundary condition is achieved. For example, for a constant temperature boundary condition of T_B , the input values will be $\epsilon = 0$, $q'' = 0$, $T_\infty = T_B$, and $h_c = 10^{30}$.

The boundary mass balance for the pore pressure equation (2.18) is obtained through:

$$\dot{m}_B = \dot{m}_{\text{in}} + Ah_p(P_B - P_\infty) \quad (2.26)$$

where

$\dot{m}_B$ = mass flux on the boundary

$\dot{m}_{\text{in}}$ = input mass flux

h_p = pressure transfer coefficient

A = control volume surface area at the boundary

Similarly, by specifying the input values for $\dot{m}_{\text{in}}$, P_∞ , and h_p , the desired pressure boundary condition can be obtained. For example, for an impermeable surface the input values will be $\dot{m}_{\text{in}} = 0$, $h_p = 0$, while for a constant pressure boundary condition of P_B , the input values will be $\dot{m}_{\text{in}} = 0$, $P_\infty = P_B$, and $h_p = 10^{30}$.

A cutoff time for external heating can be prescribed, and the calculations can be done with or without decomposition, endothermic cooling, or convective cooling.

Features

Major features of the computer program are:

1. The finite difference equations are obtained using the control volume approach of Patankar (1980).
2. Time integration is fully implicit.
3. Diffusion properties are evaluated at the control volume face.
4. The convection terms in the energy equation are based on the upwind scheme of (Patankar, 1980).
5. The non-linear pore pressure equation is iterated to convergence.
6. Convergence is met when successive iterations are within a set tolerance for each node.
7. The in-depth thermal response predictions are based on 9 control volumes in the x-direction, 91 control volumes in the y-direction, and a time step of 0.1 seconds. Half control volumes were used at the boundaries.

The flow chart for the program is presented in Figure 2.3.

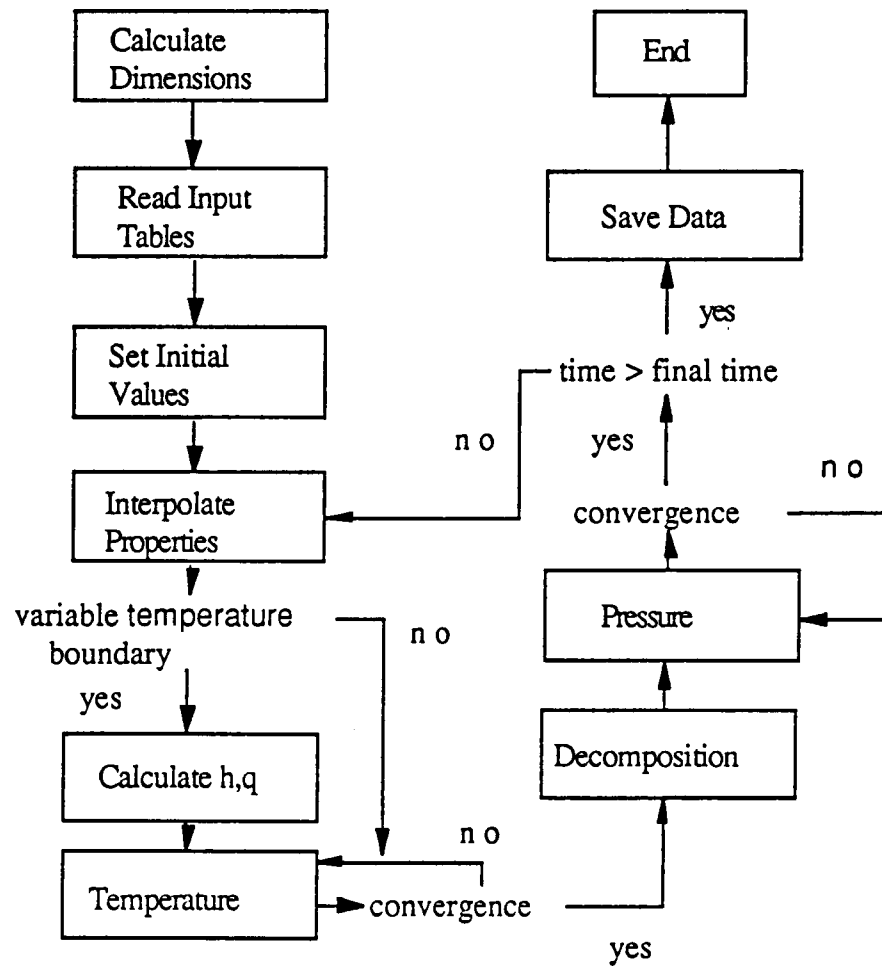


Figure 2.3. Flow chart of the numerical model.

Chapter 3

Drying Mass Loss

Introduction

The water vapor content of carbon phenolic material can have a significant effect on its initial mass and on decomposition predictions, as well as on its mechanical properties. Open pore spaces in the carbon phenolic provide an internal volume through which water can enter and remain under normal atmospheric conditions. The atmospheric conditions that the carbon phenolics are exposed to have a significant effect on their moisture content, and the amount of moisture present is a nonlinear function of relative humidity according to Stokes (1991). The water vapor content depends on the affinity of water for the material, the moisture available to be absorbed, and the diffusion coefficient of water in the material.

Thermal gravimetric analysis can vary according to the moisture content of the material as it goes into testing. Chemical kinetics as done by Beck et al (1984) must account for the moisture in both initial and residual masses to accurately predict the time to attain a degree of char. If exposed to temperatures high enough to vaporize water, the moisture should escape from the material, and the internal pressure and temperature will be affected by the water until it has all been expelled. Seven samples of MX 4926 were tested for water content by heating them to a temperature

above the atmospheric boiling temperature of water and below the decomposition temperature of the material as reported by Beck et al (1984). A sample of MX4926 and a sample of FM 5055 were heated and weighed for comparison of their change in mass subsequent to heating .

Equipment

Seven discs of MX 4926, NARC 0⁰, measuring 0.25 inches thick and 1.5 inches in diameter were used. A Fisher Isotemp Model 175 oven was used to dry the samples, and a Blue M Electric Company furnace was used for heating. A power loss indicator was used to know if heating was interrupted. The samples were weighed on an Ainsworth Delta N-V scale with a 160 gram limit and a 0.0001 gram resolution. The samples were measured with a 0.05 mm resolution micrometer. A Princo Wet Bulb Dry Bulb instrument was used to measure relative humidity.

Experimental Procedure

The dimensions of the MX 4926 discs and the relative humidity were recorded. The initial masses of the carbon phenolic samples were recorded, and they were placed on a wire rack in the center of the oven at 115 °C. The samples were periodically weighed on the scale and replaced in the oven as quickly as possible. Measurements were taken until an asymptotic value appeared to be reached in the mass loss data. Calculation of the mass loss was done using equation (3.1).

$$\% \text{ mass loss} = 100 * \left(\frac{m_{\text{init}} - m}{m_{\text{init}}} \right) \quad (3.1)$$

Results

The percent mass loss for the MX 4926 samples as a function of time is presented in Table 3.1. Figure 3.1 shows the rate at which moisture is lost at 115 °C for sample 3d. 1.03% is lost after the first 24 hours. This lost water was probably located near the surface and in areas of large pore openings where the water could escape easily. The rate of mass loss decreases rapidly after the first day and reaches a maximum of 3.16% after 110 days. This is consistent with the premise that much of the water must be forced through the material to the surface under its own vaporization pressure with the most deeply contained moisture requiring the longest time to escape. It has been shown, Clark (1968), that the pore spaces exist in an interconnected pattern with some being open to the surface and others being isolated in the interior by thin walls of the material. Stokes (1991) found that the percent moisture of a total mass is independent of the surface area of that mass. The relatively smooth decrease in the rate of mass loss indicates that the moisture is probably distributed throughout the pore spaces without large concentrations or absences of moisture in an intermediate pore space. Some small amount of moisture could still be present in the carbon phenolic if its vaporization pressure was insufficient to force it to the surface of the sample.

Mass loss data for six more samples of MX 4926 are shown in Figure 3.2. They have an average mass loss of 0.95% after the first 24 hours and an average mass loss of 3.06% after 92 days. Data collected by Stokes (1991) indicates a moisture content range of 2.4% to 3.2% for 50% relative humidity and 3.1% to 4.6% for 62% relative humidity. The relative humidity

Table 3.1. Drying mass loss for MX 4926.

Time (days)	%Loss ± 0.001	Time (days)	% Mass Loss ± 0.001					
3d	3d	3e-3j	3e	3f	3g	3h	3i	3j
1	1.030	1	0.920	0.935	0.970	0.916	0.987	0.965
2	1.150	2	1.214	1.098	1.173	1.100	1.186	1.146
3	1.330	3	1.394	1.294	1.355	1.286	1.367	1.330
4	1.400	7	1.672	1.572	1.643	1.566	1.662	1.594
8	1.775	8	1.766	1.633	1.713	1.632	1.725	1.659
10	1.902	9	1.829	1.687	1.765	1.688	1.786	1.719
11	1.960	10	1.889	1.743	1.821	1.741	1.841	1.771
14	2.110	14	2.097	1.943	2.041	1.953	2.063	1.984
15	2.127	15	2.149	1.995	2.089	2.001	2.112	2.033
16	2.186	16	2.189	2.028	2.127	2.041	2.148	2.067
17	2.207	17	2.228	2.067	2.161	2.070	2.183	2.105
21	2.331	18	2.271	2.092	2.191	2.098	2.211	2.135
22	2.337	21	2.277	2.110	2.206	2.126	2.273	2.230
23	2.384	22	2.383	2.222	2.293	2.292	2.316	2.252
25	2.471	23	2.397	2.226	2.293	2.293	2.321	2.253
28	2.567	24	2.463	2.295	2.398	2.298	2.418	2.347
30	2.592	25	2.508	2.339	2.440	2.339	2.460	2.389
31	2.595	28	2.597	2.421	2.529	2.433	2.547	2.482
32	2.649	29	2.628	2.451	2.556	2.458	2.575	2.509
35	2.694	30	2.652	2.466	2.576	2.487	2.595	2.530
37	2.677	31	2.647	2.468	2.572	2.477	2.590	2.523
38	2.710	32	2.680	2.500	2.605	2.524	2.619	2.558
39	2.763	35	2.774	2.580	2.690	2.619	2.712	2.652
42	2.844	36	2.788	2.605	2.710	2.632	2.727	2.666
43	2.842	37	2.808	2.617	2.728	2.649	2.747	2.680
44	2.860	38	2.813	2.624	2.732	2.653	2.749	2.690
45	2.890	39	2.821	2.631	2.737	2.677	2.753	2.697
49	2.921	42	2.844	2.648	2.748	2.683	2.773	2.718
50	2.939	43	2.859	2.671	2.769	2.710	2.794	2.737
51	2.937	44	2.879	2.677	2.780	2.722	2.802	2.757
52	2.940	48	2.939	2.741	2.847	2.797	2.871	2.835
56	2.973	49	2.957	2.766	2.858	2.805	2.881	2.839
57	2.977	50	3.000	2.805	2.896	2.815	2.925	2.874
58	2.984	51	3.015	2.823	2.915	2.847	2.939	2.896
59	2.987	52	3.034	2.836	2.928	2.867	2.954	2.914
60	2.987	53	3.046	2.850	2.943	2.878	2.966	2.930
87	3.080	54	3.057	2.861	2.951	2.892	2.979	2.940
110	3.165	56	3.077	2.879	2.969	2.916	2.995	2.954
135	3.155	57	3.085	2.890	2.975	2.928	2.999	2.948
		59	3.094	2.983	2.981	2.931	3.010	2.975
		62	3.117	2.917	3.000	2.952	3.027	3.001
		63	3.128	2.929	3.012	2.984	3.046	3.015
		64	3.129	2.936	3.020	2.986	3.047	3.019
		65	3.129	2.937	3.011	2.983	3.058	3.020
		66	3.128	2.937	3.013	2.982	3.059	3.020
		67	3.132	2.936	3.017	2.988	3.054	3.021
		92	3.167	2.978	3.035	3.040	3.081	3.072

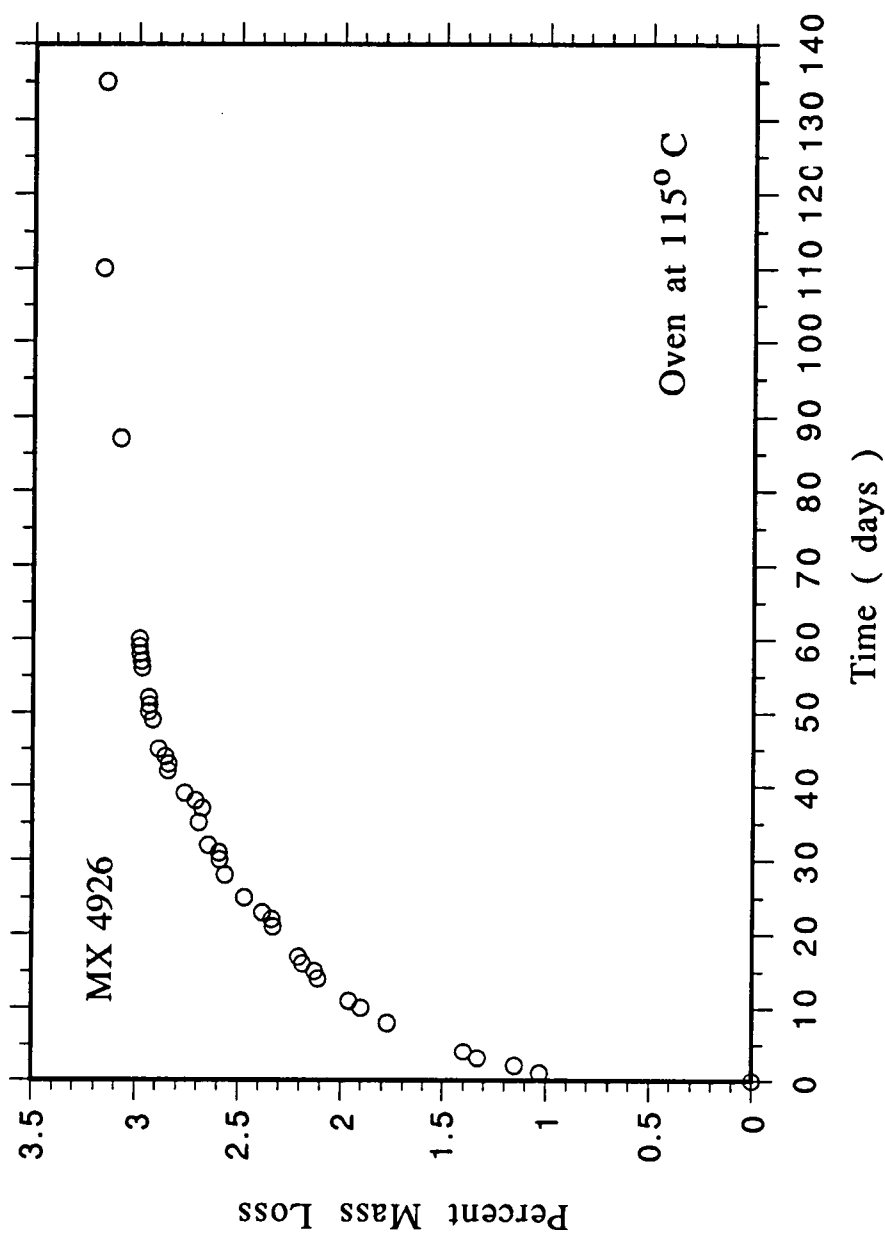


Figure 3.1. Drying mass loss for one sample of MX 4926.

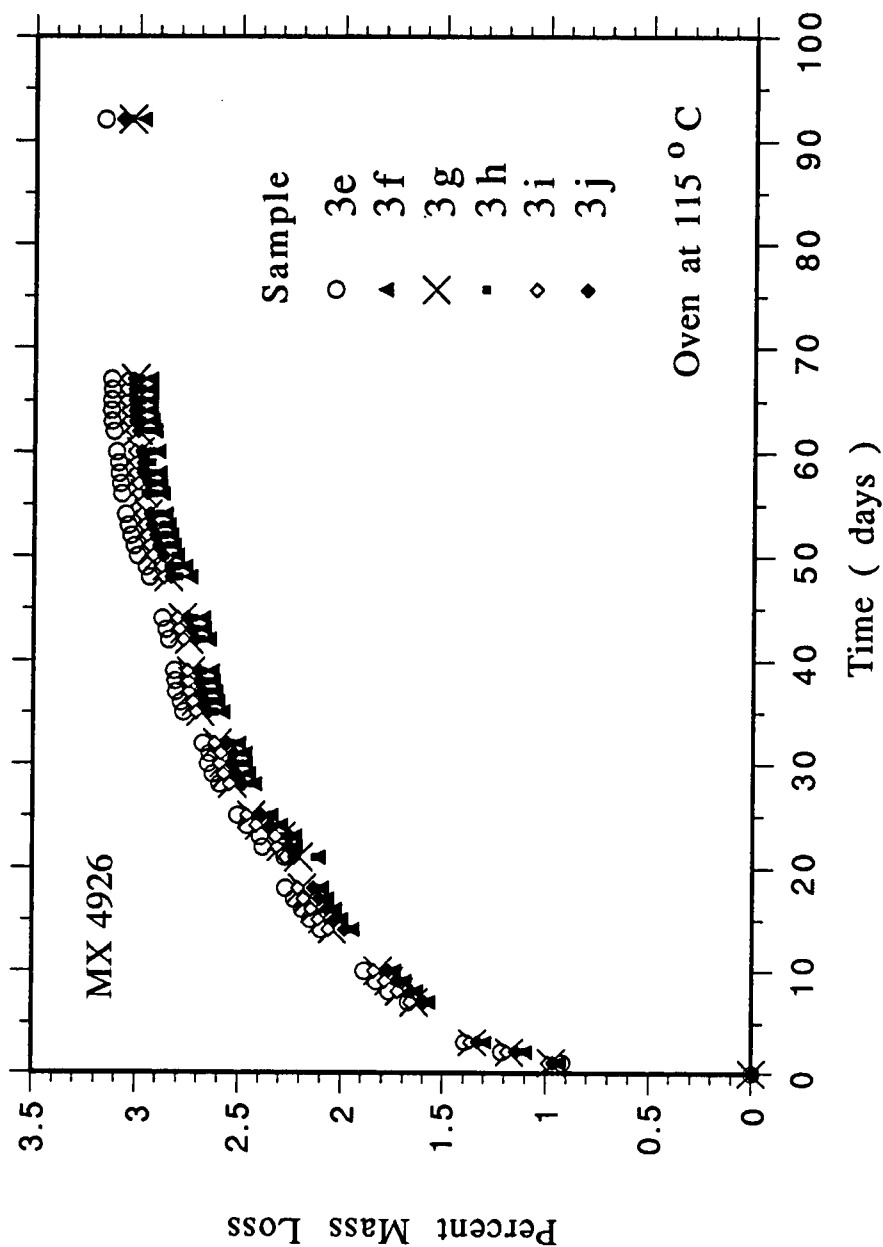


Figure 3.2. Drying mass loss for six samples of MX 4926.

was 50% for the six samples of Figure 3.2, and the relative humidity was 62% for sample 3d in Figure 3.1. This seems to be the reason for a higher mass loss after one day for the sample in Figure 3.1 than for the samples in Figure 3.2. The early mass loss should be a function of the humidity the sample was exposed to just before entering the oven. The samples with a higher final mass loss in Figure 3.2 may have a lower percent of their pore spaces open to the surface, since there was a smaller difference between the samples at early times where pores open to the surface would be responsible for the moisture loss. The samples with a higher final mass loss, such as 3e and 3i, may also have a slightly higher porosity to hold more initial moisture. Heating of the samples was never interrupted except by brief weighings. Variable intervals between measurements indicate this had a negligible effect on rate of mass loss. The loss rate curves have a very similar shape for all of the samples.

FM 5055 could not be measured for moisture loss because of its low starting decomposition temperature, so initial density and mass gain following heating were recorded to compare to the MX 4926. An MX 4926 sample at 66% relative humidity, 3c, was heated at a constant 538 °C for 700 seconds in the furnace. Its mass loss was 16.46%. Assuming a constant temperature in the sample of 538 °C for 700 seconds, the code predicts a 13.2% mass loss by decomposition. If 3.16% of the initial mass were water, then the mass loss due to decomposition would be 13.7%. A block of FM 5055 at 39% relative humidity, Lot Number 1144-1-101, CO2486, RA32, sample 6a, was decomposed at 538 °C for 420 seconds. This resulted in a mass loss of 6.72%. The numerical prediction was 5.70%. One day after decomposition

sample 6a had gained 0.89% in mass with a 38% average humidity, and the MX4926 sample, 3c, gained 1.06% in mass after one day at 60% average relative humidity. FM 5055 appears to have moisture absorbing characteristics similar to those of MX 4926 at these relative humidities.

The theoretical virgin masses based on the densities given in Beck et al (1984) and equation (3.2) are presented in Figure 3.3.

$$m = \rho V, \quad \text{where } \rho = 90.482 \frac{\text{lbm}}{\text{ft}^3} \quad (3.2)$$

This is the density listed in Appendix A.1 for MX 4926 and used in deriving the kinetic constants. The percent mass loss to the fully charred state is 18.89%. An earlier set of data for MX 4926 listed in Table 5-6 in Beck et.al. (1984) shows a virgin density of 87.077 lbm/ft³. This is 3.76% lower than the density in equation (3.2) and predicts a mass loss to a fully charred

Table 3.2. Density of MX 4926.

sample	3d	3e	3f	3g	3h	3i	3j
Initial Mass (gm) $\pm .001$	10.484	10.523	10.490	10.441	10.525	10.384	10.499
Dried Mass (gm) $\pm .001$	10.153	10.189	10.178	10.124	10.205	10.064	10.176
Volume (mm ³) ± 40	7163.7	7239.6	7163.7	7154.3	7239.6	7144.9	7201.6
Initial Density $\pm 10^{-5}$ (gm/mm ³)	1.46 E-03	1.45 E-03	1.46 E-03	1.46 E-03	1.45 E-03	1.45 E-03	1.46 E-03
Dried Density $\pm 10^{-5}$ (gm/mm ³)	1.42 E-03	1.41 E-03	1.42 E-03	1.42E -03	1.41 E-03	1.41 E-03	1.41 E-03

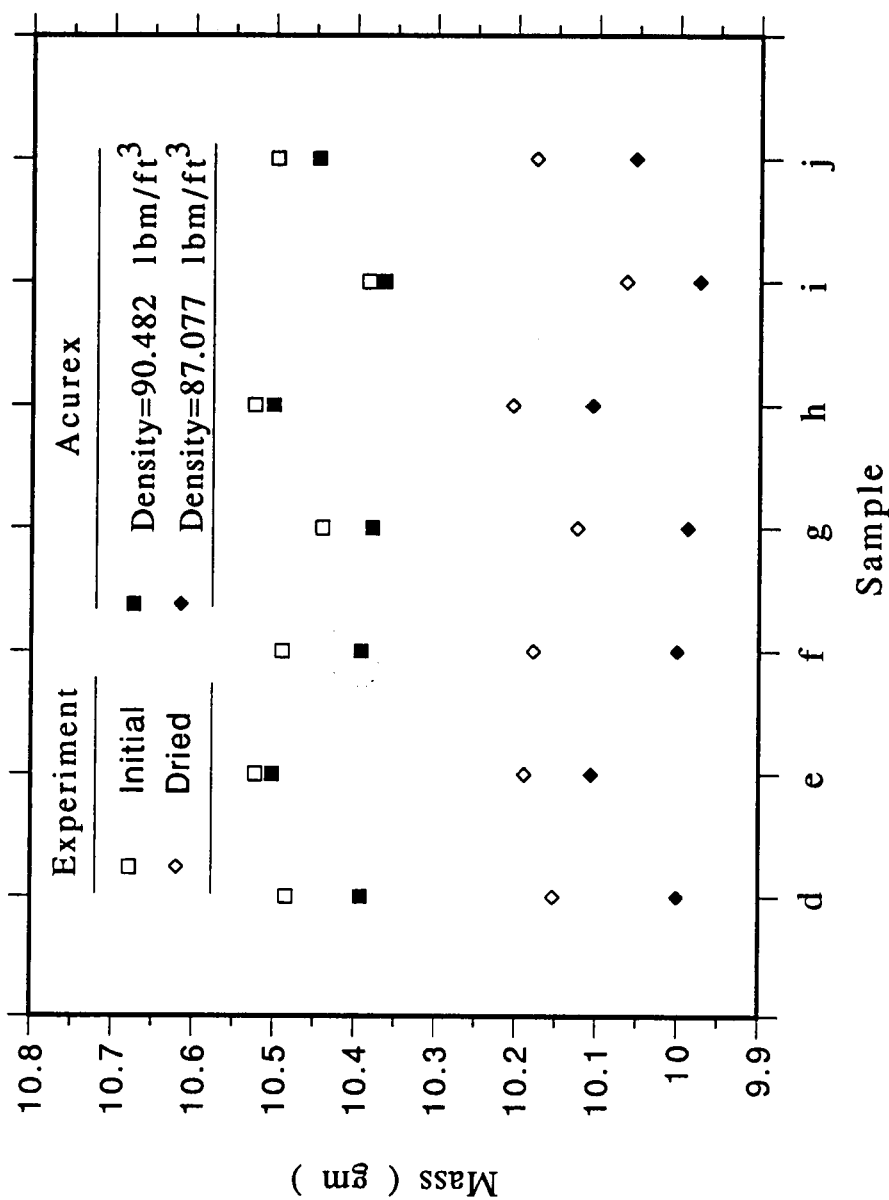


Figure 3.3. Comparison of initial and final dried experimental masses with the theoretical virgin masses using Acurex MX 4926 densities.

state of 16.80%. Density data is shown in Table 3.2, and the average measured densities of MX 4926 before drying are 90.87 lbm/ft³ at 50% humidity and 91.28 lbm/ft³ at 62% humidity and 88.14 lbm/ft³ after drying.

Figure 3.3 shows that the measured masses are consistently higher, but after drying the masses are close to those predicted by the virgin density of Table 5-6 in Beck et al (1984). The different virgin densities in Beck et al (1984) suggest that some moisture is included in the theoretical density of equation (3.2) and may explain the different percent mass losses to the fully charred condition for the two sets of predicted densities for MX 4926. The rates of mass loss due to drying at an oven temperature of 115 °C were fit to the curve given by equation (3.3) and are shown in Figure 3.4 .

$$m = m_{init} \left[1 - \frac{(t - t_d)^2}{t_d^2} \right]^n \quad (3.3)$$

where m = percent mass loss
 m_{init} = percent initial moisture
 t = time, days
 t_d = time for complete drying, days
 n = function of porosity

The value of n is smaller for sample 3d to reflect the assumption that it has a slightly larger fraction of its moisture in pores open to the surface. The properties of the samples do not appear to vary greatly since the drying mass loss is similar for all the samples.

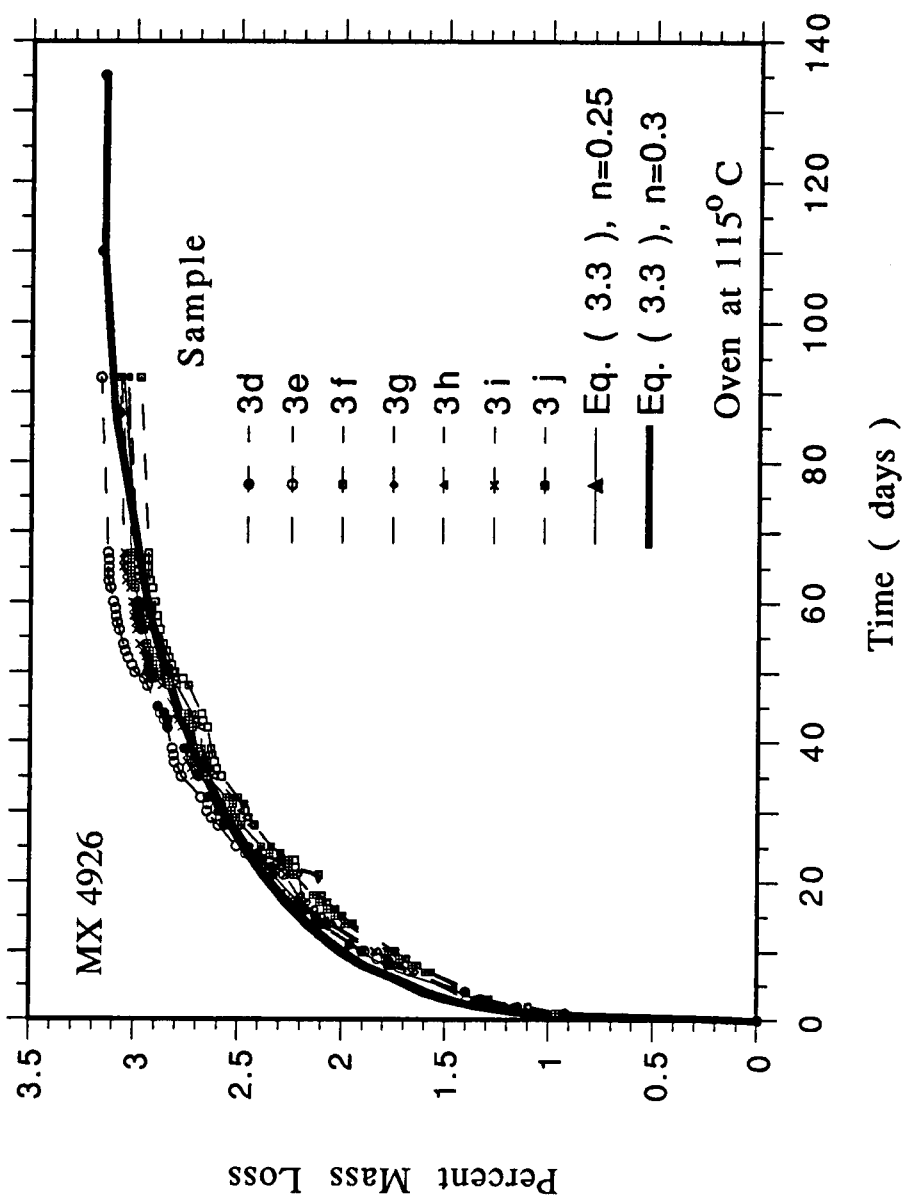


Figure 3.4. Experimental mass loss versus equation (3.3).

Chapter 4

Decomposition

Equipment

A series of experiments were conducted to measure the surface temperature at a point on the center of a number of blocks of carbon phenolic material. Samples of FM 5055 and MX 4926 were used for the tests in which mass loss and surface temperature were recorded. In the performance of these tests a Blue M Electric Company furnace with a maximum temperature of 2000 °F and an exhaust hood mounted over it was used to heat the carbon phenolic blocks. A thermocouple mounted in the roof of the interior of the furnace was used as a controller to maintain constant temperature. Type K 28 AWG thermocouple wire with glass insulation was used with an Omega 2166A Digital Thermometer, and Omega CC High Temperature Cement was used to hold the thermocouple bead on the carbon phenolic block. 18 gauge steel wire was used to produce holding stands to place the blocks in the desired location within the furnace as shown in Figure 4.1. An Ainsworth digital scale with a limit of 160 grams was used to weigh the blocks, and a Medana stopwatch was used to time the heating duration in the furnace. A micrometer with a 0.05 mm resolution and a Princo Wet Bulb Dry Bulb relative humidity instrument were also used.

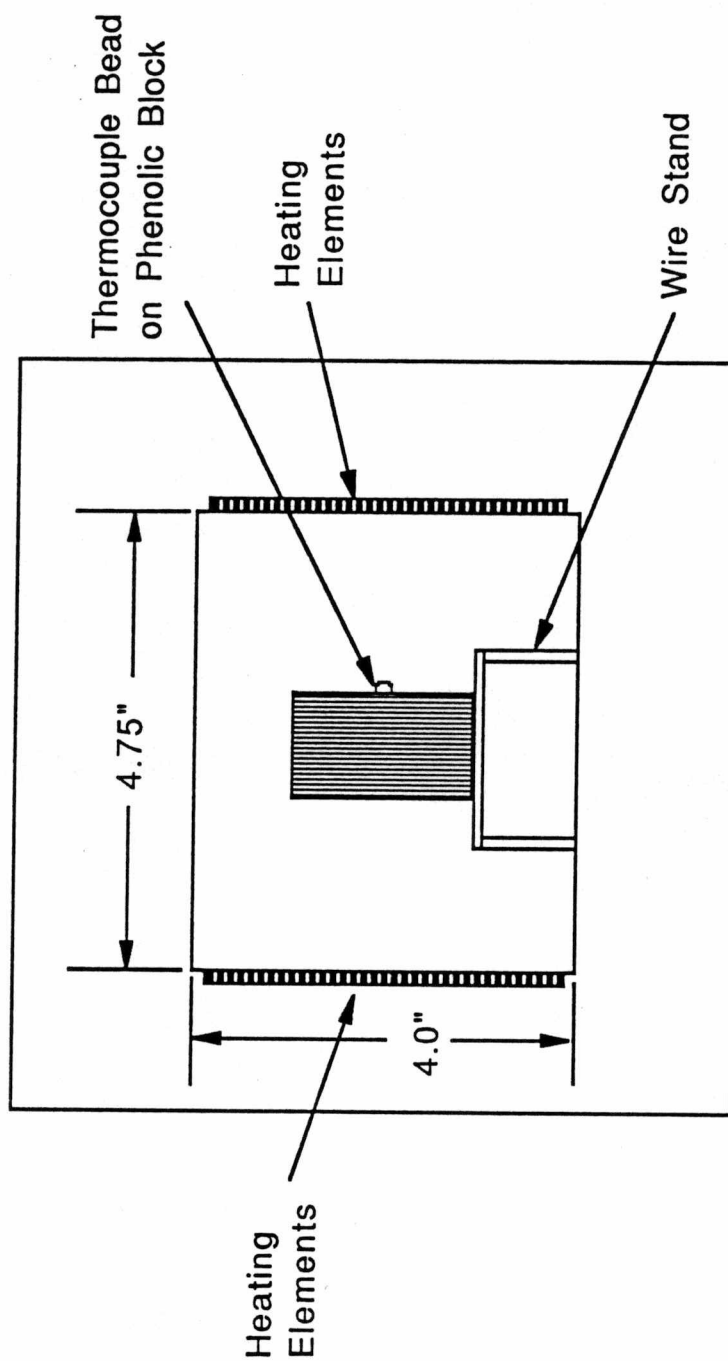


Figure 4.1. Furnace diagram.

Experimental Procedure

The type K thermocouple beads were cemented to the blocks with an 8 mm diameter coverage of cement and cured at room temperature for 24 hours. The accuracy of the Omega Thermometer was verified with a mercury thermometer. The blocks were measured with the micrometer on all sides to determine volume, and the relative humidity was recorded before the block was placed in the furnace. The wire stand was placed in the furnace. The furnace was preheated to the desired temperature, and the initial mass of the block was recorded.

The block was placed in the furnace, and the stopwatch was started. Temperature measurements were recorded at even intervals. At the end of the heating period, the block was removed as quickly as possible from the furnace and placed on the scale. Mass was recorded thirty seconds after removal from the furnace. This sequence was repeated for a number of blocks of FM 5055 and MX 4926 at several different furnace temperatures. Percent mass loss was calculated by equation (3.1). One MX 4926 sample, 7e, was decomposed without a thermocouple for mass loss comparison.

Numerical Comparison

The computer program of chapter two was modified to calculate boundary heating based on radiation heat transfer in a six-sided enclosure to model the furnace conditions. Symmetry was assumed in the horizontal and vertical directions to allow calculation over one quarter of the actual block. Furnace walls were assumed to be reradiating surfaces. The following equations were used to find a heat flux input for sides 1 and 2 of

the carbon phenolic test specimen in Figure 4.2.

$$\frac{E_{b1} - J_1}{\frac{1 - \epsilon_1}{A_1 \epsilon_1}} = \frac{J_1 - J_4}{\frac{1}{A_1 F_{14}}} + \frac{J_1 - J_5}{\frac{1}{A_1 F_{15}}} + \frac{J_1 - J_6}{\frac{1}{A_1 F_{16}}} \quad (4.1)$$

$$\frac{E_{b2} - J_2}{\frac{1 - \epsilon_2}{A_2 \epsilon_2}} = \frac{J_2 - J_3}{\frac{1}{A_2 F_{23}}} + \frac{J_2 - J_4}{\frac{1}{A_2 F_{24}}} + \frac{J_2 - J_5}{\frac{1}{A_2 F_{25}}} \quad (4.2)$$

$$0 = \frac{J_3 - J_2}{\frac{1}{A_3 F_{32}}} + \frac{J_3 - J_4}{\frac{1}{A_3 F_{34}}} + \frac{J_3 - J_5}{\frac{1}{A_3 F_{35}}} + \frac{J_3 - J_6}{\frac{1}{A_3 F_{36}}} \quad (4.3)$$

$$0 = \frac{J_4 - J_2}{\frac{1}{A_4 F_{42}}} + \frac{J_4 - J_3}{\frac{1}{A_4 F_{43}}} + \frac{J_4 - J_5}{\frac{1}{A_4 F_{45}}} + \frac{J_4 - J_6}{\frac{1}{A_4 F_{46}}} + \frac{J_4 - J_1}{\frac{1}{A_4 F_{41}}} \quad (4.4)$$

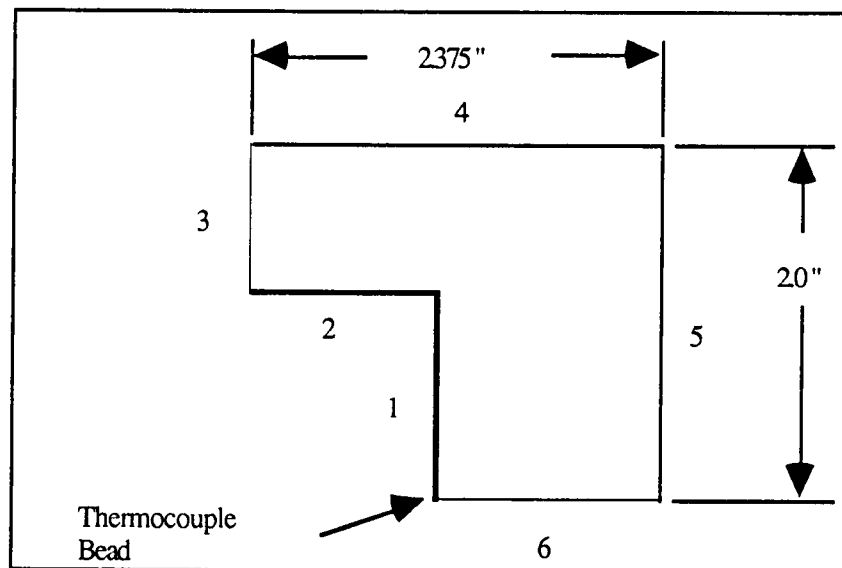


Figure 4.2. Heat flux domain for numerical calculation.

$$\frac{E_{b5} - J_5}{\frac{1 - \epsilon_5}{A_5 \epsilon_5}} = \frac{J_5 - J_1}{\frac{1}{A_5 F_{51}}} + \frac{J_5 - J_3}{\frac{1}{A_5 F_{53}}} + \frac{J_5 - J_4}{\frac{1}{A_5 F_{54}}} + \frac{J_5 - J_6}{\frac{1}{A_5 F_{56}}} + \frac{J_5 - J_2}{\frac{1}{A_5 F_{52}}} \quad (4.5)$$

$$0 = \frac{J_6 - J_1}{\frac{1}{A_6 F_{61}}} + \frac{J_6 - J_4}{\frac{1}{A_6 F_{64}}} + \frac{J_6 - J_5}{\frac{1}{A_6 F_{65}}} + \frac{J_6 - J_3}{\frac{1}{A_6 F_{63}}} \quad (4.6)$$

The heater coil temperature, surface 5, was assumed to be at the furnace set temperature with an emissivity of 0.9. This is clearly a major simplification since the coil is actually at a much higher temperature. The heater coil is cycling on and off in order to maintain the set temperature, and this periodic nature of the heating could not be modeled in the code.

The natural convection heat transfer coefficients were calculated from correlations given by Incropera and DeWitt (1990) for a horizontal heated surface,

$$h = \frac{k(0.54Ra^{0.25})}{L} \quad (4.7)$$

and a vertical heated surface.

$$h = \frac{k(0.59Ra^{0.25})}{L} \quad (4.8)$$

By measuring the interior temperature of the furnace with a thermocouple, it was determined that assuming the initial air temperature to be the average of the room temperature and the set furnace temperature results in a more accurate representation of the temperature following the block insertion. The air temperature was raised linearly over the first 120 seconds until it reached the maximum furnace temperature.

Results

Table 4.1 lists the mass data, and Figure 4.3 compares the numerical calculations with the measured mass loss. The numerical boundary heated solution incorporates equations (4.1) to (4.8), and the constant temperature column shows the upper theoretical limit on mass loss. For FM 5055 samples the numerical constant temperature mass losses are significantly higher than the boundary heated results. However, for MX 4926 , the isothermal mass loss predictions are lower than the experimental values.

For FM 5055 samples in Table 4.1 the initial masses differ by less than 3.6% and show good consistency. At 260 °C the experimental percent mass loss is 0.13 higher than the numerical. At 399 °C experimental percent mass loss is 0.58 higher than numerical for 900 seconds and 1.18 higher for 1800 seconds. At 538 °C experimental percent mass loss is 1.02 higher than numerical for 420 seconds and 2.7 higher for 900 seconds. Sample 6b experimental mass loss is lower than expected, and this may be due to the furnace door having been opened to check the thermocouple wire. The samples show a trend of larger differences between experimental and numerical masses at higher temperatures and after longer times. If the difference is due to moisture content, then the longer times and higher temperatures would create higher porosity and allow more moisture to vaporize and escape. It should be noted that the experimental mass losses should be higher than the numerical calculations, due to the fact that the decomposition kinetics are for the dry samples and can not account for the water.

Table 4.1. Mass loss for MX 4926 and FM 5055 in constant temperature furnace.

Sample	Temperature (°C) Time (sec)	Initial Mass (gm) ±0.20	Final Mass (gm) ±0.20	% Mass Loss Experiment ±0.28	% Mass Loss Numerical	% Mass Loss Constant Temperature
FM 5055 2"x2"x1"						
6a	538	95.62	89.20	6.72	5.70	18.5
	420 sec					
6b	399	96.77	91.00	5.97	5.98	10.5
	900 sec					
6c	538	97.45	83.28	14.5	11.8	19.1
	900 sec					
6d	260	97.92	94.61	3.38	3.25	5.0
	1020 sec					
6e	399	97.36	90.90	6.64	5.98	10.5
	900 sec					
6f	593	96.43	82.56	14.4	11.1	19.7
	630 sec					
6i	399	98.30	91.93	6.48	5.98	10.5
	900 sec					
6j	538	98.77	84.44	14.5	11.8	19.1
	900 sec					
6k	399	99.20	89.96	9.32	8.14	12.4
	1800 sec					
MX 4926 2"x2"x0.5"						
7a	260	49.71	47.15	5.15	0.055	0.1
	1200 sec					
7b	399	50.25	45.42	9.61	2.68	5.5
	1200 sec					
7c	399	43.30	38.90	10.2	2.68	5.5
	1200 sec					
7d	538	50.41	41.83	17.0	7.37	14.0
	1200 sec					
7e	399	48.55	45.534	6.21	2.68	5.5
	1200 sec					

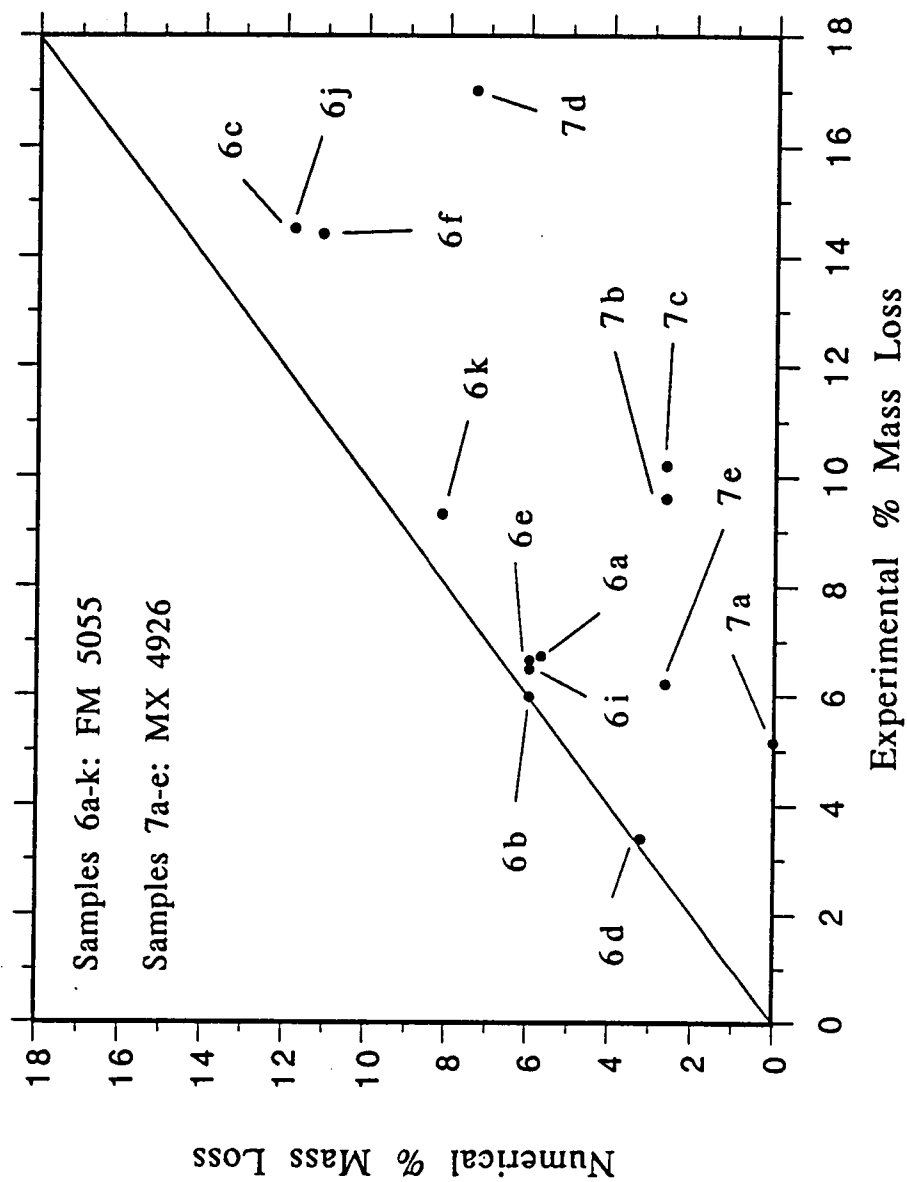


Figure 4.3. Experimental and numerical % mass loss for furnace heating.

Some uncertainty exists for the mass measurements due to the thermocouple wire cemented to the block. This is especially true for the MX 4926 samples since their smaller mass will be proportionately affected by the wire to a greater extent. The thermocouples broke loose from samples 7a, 7b, and 7c before final masses were determined. This led to the large percent mass loss recorded for them. Sample 7e, initially at 59% relative humidity, was heated without a thermocouple to avoid this problem. It shows much better agreement with the numerical prediction of 2.68% mass loss. The initial and final densities were measured as 91.13 lbm/ft³ and 85.47 lbm/ft³, respectively. For a dry density of 88.14 lbm/ft³ as found in chapter three, the experimental mass loss due to decomposition would be 3.0%. The average FM 5055 initial density was 91.82 lbm/ft³, and the average MX 4926 initial density was 91.11 lbm/ft³. There is a good correlation between numerical and experimental masses.

The numerical and experimental sample surface temperatures should compare well when the mass losses do. The carbon phenolic blocks were placed in the furnace with the ply layers perpendicular to the direction of the heating coils. Figure 4.4 for FM 5055 shows close agreement between experimental and numerical temperatures up to 300 seconds, then the numerical values are below the experimental temperatures. Figure 4.4 shows that surface temperatures for samples 6e, 6i, and 6k at 399 °C are consistent, and numerical temperatures follow the curve well, especially at early times. Figure 4.5 shows that experimental temperatures for 6c and 6j at 538 °C are fairly consistent also. The 593 °C case shows less agreement between experimental and numerical

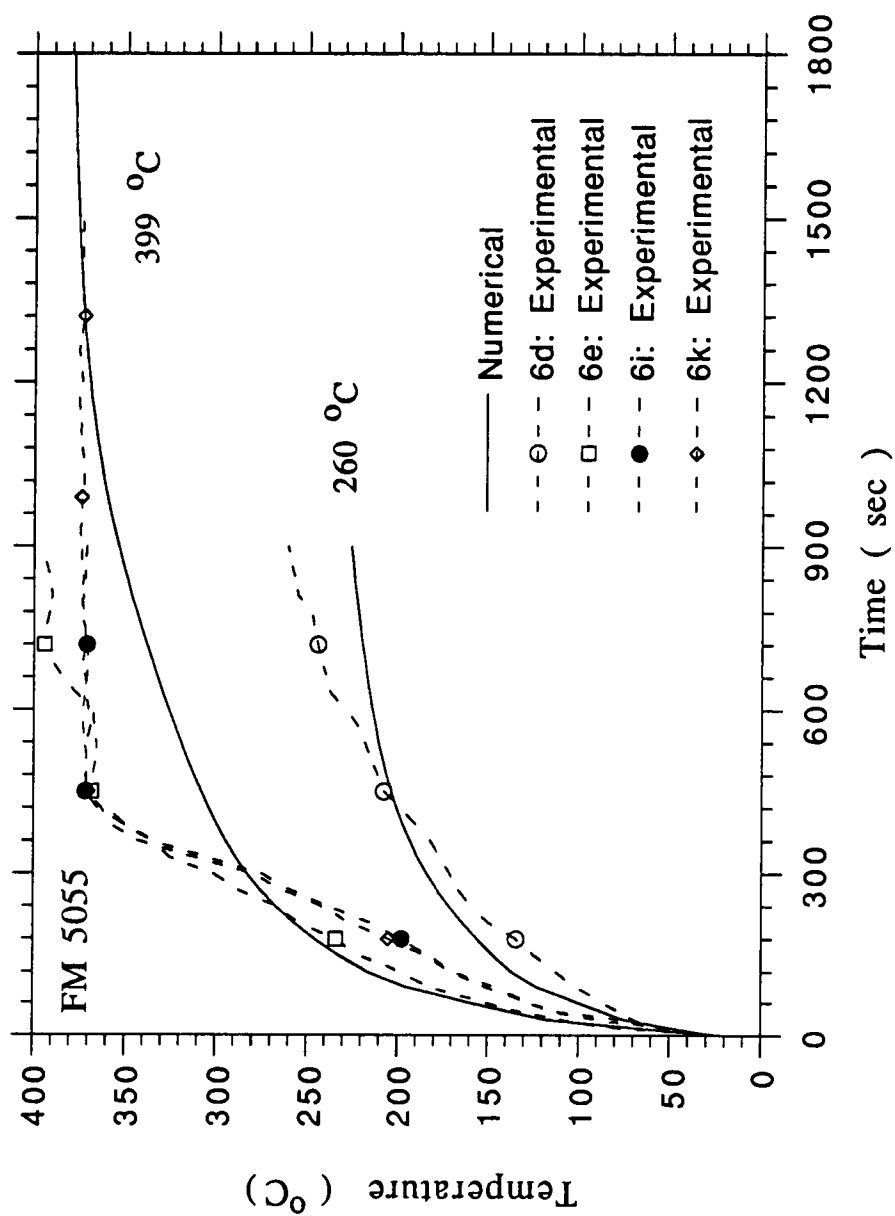


Figure 4.4. Surface temperature for furnace heating of FM 5055 at 260 °C and 399 °C.

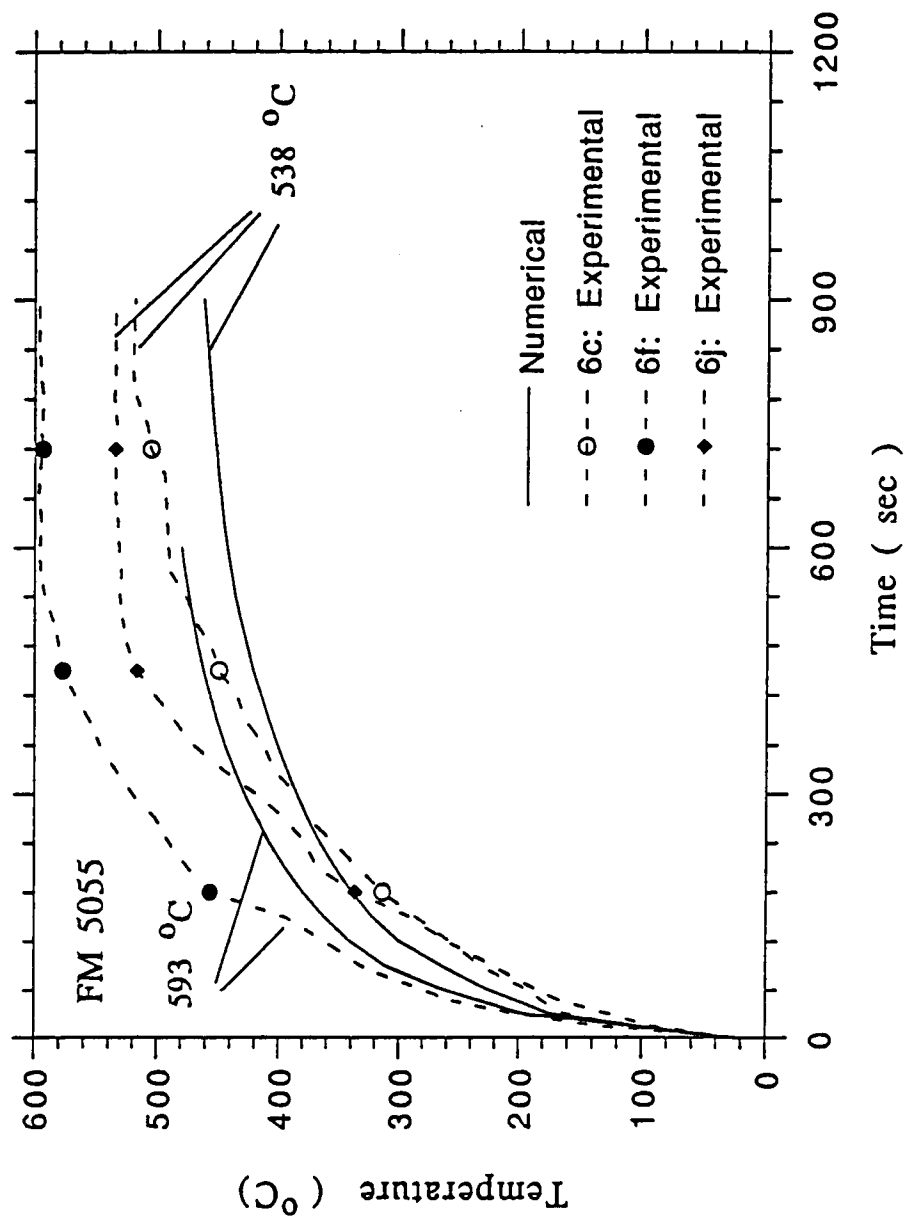


Figure 4.5. Surface temperature for furnace heating of FM 5055 at 538 °C and 593 °C.

temperatures. Figure 4.6 shows the temperature comparisons for the MX 4926 samples. Experimental and numerical values are very close for the low furnace temperature of 260 °C, and the two samples heated at 399 °C show good experimental consistency. The 538 °C case has the least agreement with numerical predictions, but it is still reasonably close.

The experimental temperatures are higher than expected for the higher temperature cases. This can be explained by the fact that the furnace heating coils cycled on and off to maintain the temperature. When the coils were on, the block was receiving more heat than it would at a steady temperature, and at higher temperatures the coils had to turn on much more to maintain the set temperature. The final experimental temperatures are slightly higher than numerical calculations for all cases except sample 6k. The thermal properties of the cement may contribute to the differences. The emissivity of the carbon phenolic and the furnace walls had to be approximated, and the convection heat transfer coefficient was approximated by equations (4.7) and (4.8). The thermocouple lag time may be a factor in the first minutes of rapid temperature increase where experimental values are lower, and the experiment is modeled as two-dimensional when it is actually three-dimensional. The numerical results are also a direct function of the material properties in the Appendix, which appear to be fairly accurate as far as this comparison indicates.

During heating of FM 5055 the phenomenon of plylift, separation of the material along the plane of the ply layers, was experienced. Table 4.2

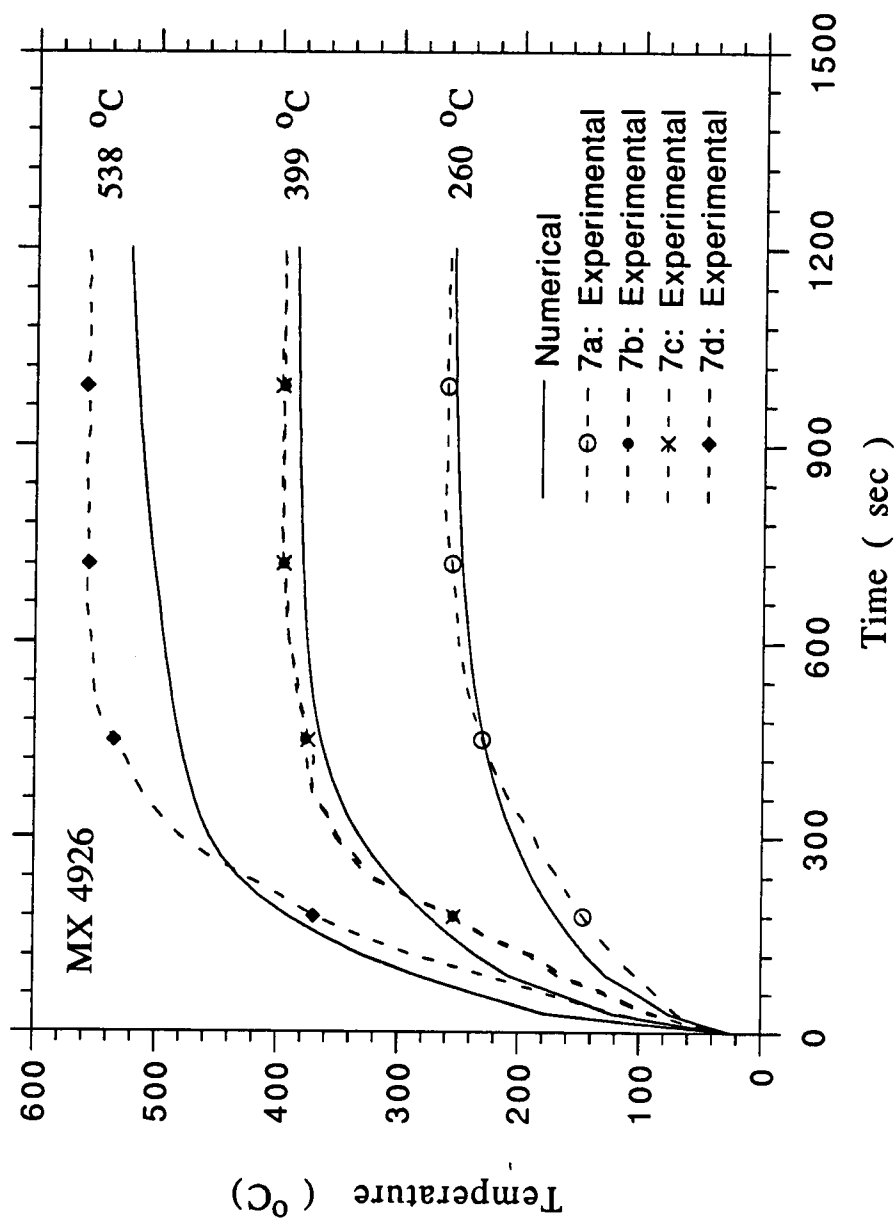


Figure 4.6. Surface temperature for furnace heating of MX 4926.

Table 4.2. Occurrence of plylift.

Sample	Plylift	Numerical		
		Time (sec)	Temperature (°F)	Pressure (psi)
6a	some	180	490	1360
6b	some	300	507	1074
6c	extreme	180	490	1360
6d	extreme	900	420	750
6e	some	300	507	1074
6f	extreme	120	567	1332
6i	some	300	507	1074
6j	some	180	490	1360
6k	slight	300	507	1074

compares the calculated internal temperatures and corresponding pressures for each sample to the occurrence of plylift. The presence of pressure in the numerical predictions high enough to cause plylift based on across ply tensile strength, Stokes (1987), correlates well with the observations. The stress limit is reported as 1000 psi at 500 °F and 500 psi at 1000 °F for FM 5055. This and the reasonably good agreement between numerical and experimental mass losses and temperatures indicates that the code is modeling the thermal response of the carbon phenolic samples with a reasonable accuracy.

Chapter 5

In-Depth Thermal Response

Objectives

Samples of FM 5055 carbon phenolic were tested by supplying a heat flux to one side, and the following objectives were to be met:

1. Compare measured in-depth transient temperatures with those of the numerical model for several applied heat fluxes.
2. Analyze the accuracy of the published thermal conductivities and specific heats for the material.
3. Examine the effects of heating on mass loss.
4. Determine the reliability of the resistance heating scheme.

Experimental Apparatus

Power Supply

The components of the experimental setup are shown in Figure 5.1. A Sorensen AC Regulator, model ACR 3000, was used to supply power to a transformer, rated for an input of 120 VAC. A Hewlett Packard 6634A system DC power supply was used to close the 15 amp Electrolet Killart relay to close the circuit to the heating element. Voltage was stepped down using a Square D Company dry type 2 KVA single phase transformer capable of supplying 1800 W at a high current and a low voltage. A 250 amp current shunt was placed in series with the circuit to provide current

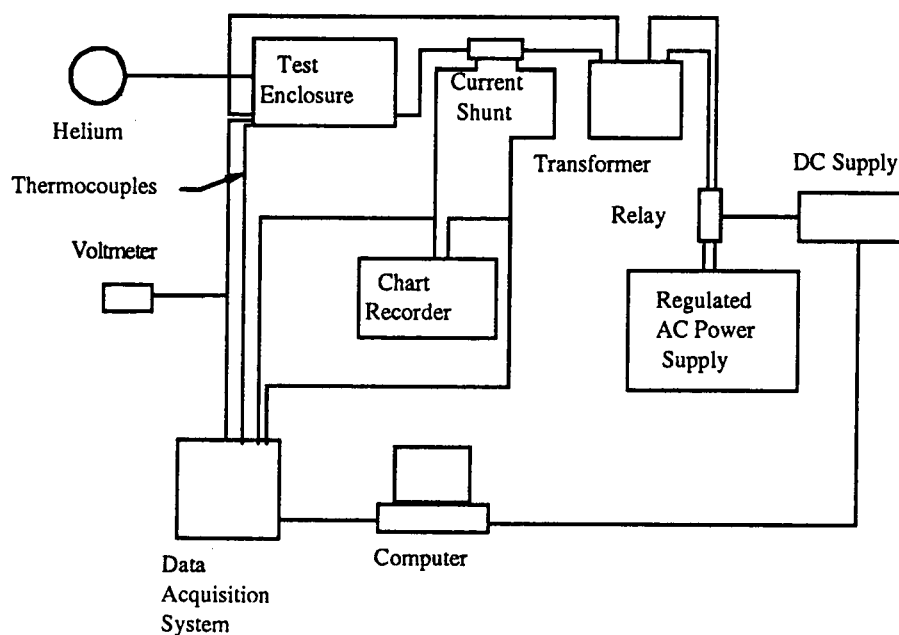


Figure 5.1. Schematic of testing apparatus.

measurements.

Test Enclosure

A steel cover with a 0.25 inch thick plexiglas front window was placed over the test area. Copper bars, measuring 0.25 by 0.5 by 8.0 inches, were held in place by C clamps insulated from the current flow by small squares of mica. To create the heated surface 1 mil stainless steel foil, 0.025 mm thick, was clamped between the copper bars by tightening screws in the bars. Two FM 5055 carbon phenolic samples were clamped onto the upper and lower sides of the steel foil with C clamps as shown in Figure 5.2.

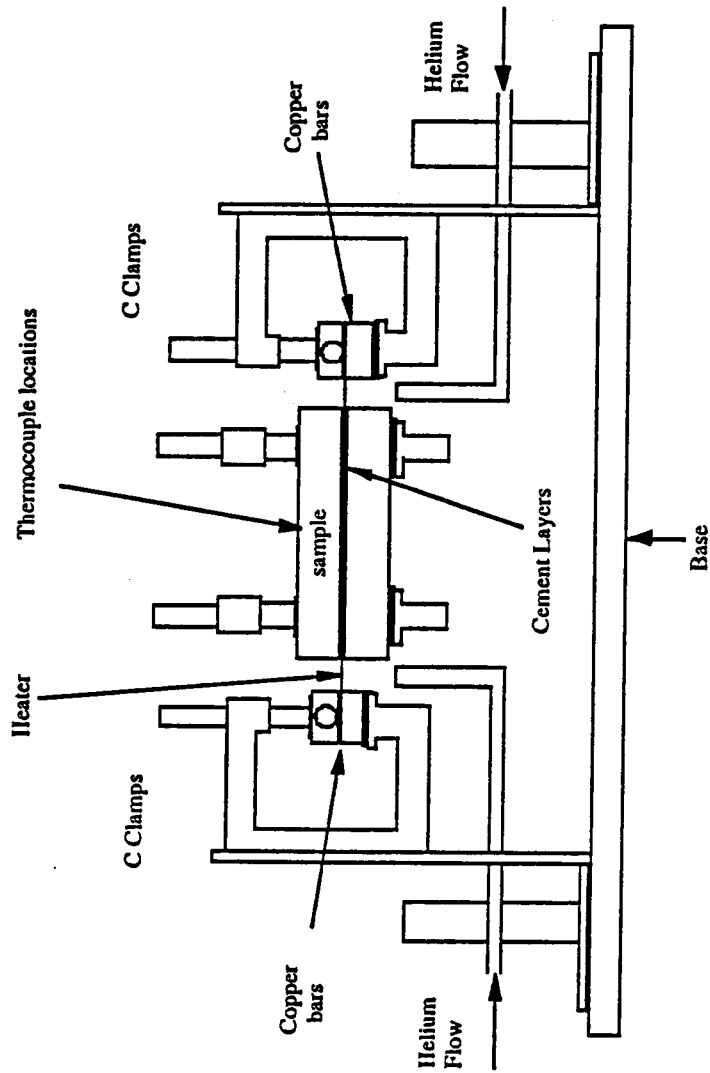


Figure 5.2. Front profile of sample holder.

The upper sample was instrumented with five type K 36 AWG thermocouples, as can be seen in Figure 5.3. Two were inserted on one side and three on the other for minimal interference in the sample. The samples were oriented so that the plane of the plies was parallel to the heating surface. The holes were made by drilling 0.76 mm diameter holes in which to insert and cement the thermocouples. Voltage drop across the steel foil was measured by two copper wires, one on each side of the foil, held in place by copper tubing attached to the copper bars. A pair of tubes with funnels on the ends was connected to a 291 cubic foot helium tank to cool the edges of the steel foil next to the copper bars to prevent melting of the stainless steel foil.

Data Acquisition System

A Hewlett Packard 9000 Series 217 computer with the Hewlett Packard 9133 Hard Disk Drive was used to control the power supply and Data Acquisition/Control Unit. The Hewlett Packard 3456A Digital Voltmeter with the Hewlett Packard 3497A Data Acquisition/Control Unit was used to measure the voltage drop, the voltage across the current shunt, and voltage readings from the five type K thermocouples. A Kaye Ice Point Reference was used to measure the reference voltage for conversion of the thermocouple voltage readings to temperature. Voltage drop across the steel foil was also measured using a Metex M-3610 voltmeter. Voltage across the current shunt was also measured using a Kiethley 177 Microvolt DMM with a Gould Brush 2400 chart recorder to obtain current as a function of time. Using a Panasonic Newvicon Omnipro video camera the heating process was filmed from the perspective shown in Figure 5.2.

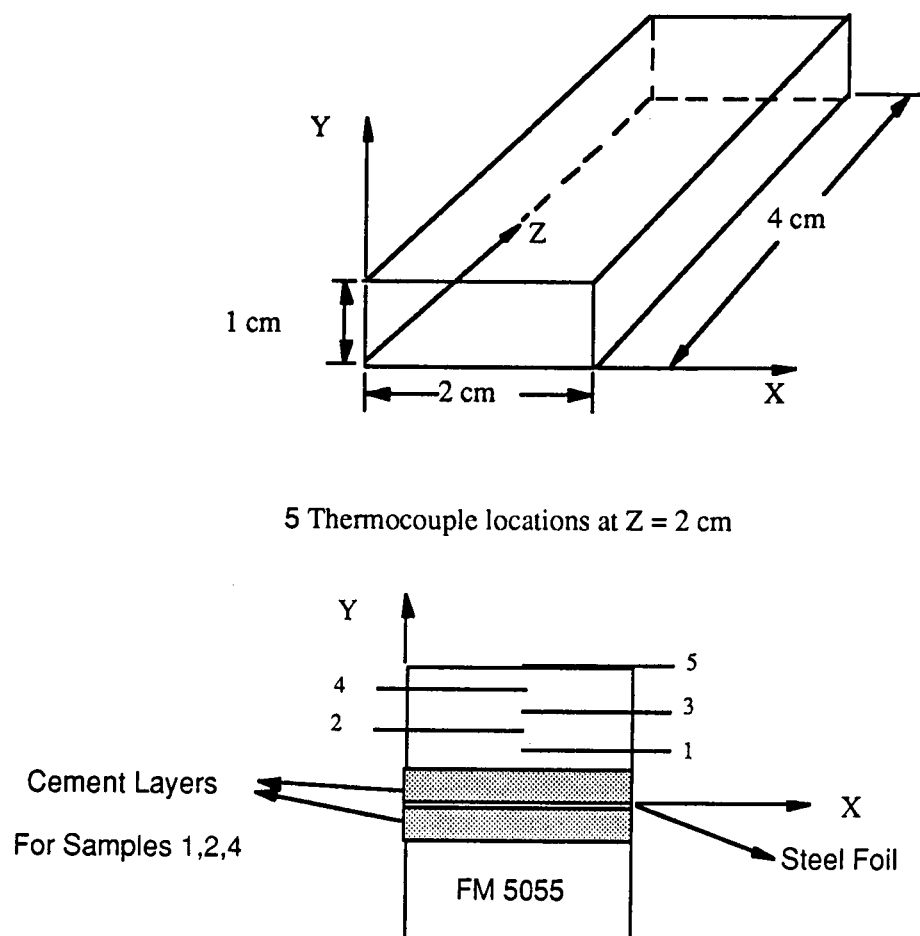


Figure 5.3. Details of the test sample preparation.

Experimental Procedure

Preparation

The transformer coils were connected to produce a voltage to current ratio to match the 0.07Ω resistance of the steel foil for maximum efficiency. The HP thermocouple readings were calibrated against a mercury thermometer. Instrumented samples were x-rayed so that the precise location of the thermocouple beads could be measured. The resulting data is shown in Table 5.1. Measurements were made with a micrometer with a 0.05 mm resolution. The thermocouple beads and wire sections which were to be inserted into the sample were coated with cement to maintain a constant shape. No. 10 Sauereisen high temperature cement

Table 5.1. Thermocouple locations.

Sample Number width (mm) ± 0.05 height (mm) ± 0.05	Thermocouple Number	X Location (mm) ± 0.05	Y Location (mm) ± 0.05
1 20.12 9.98 cement=0.66 mm	1	8.130	2.840
	2	10.31	4.320
	3	5.870	6.530
	4	10.31	8.280
	5	10.16	10.64
2 20.27 10.03 cement=2.0 mm	1	8.130	4.440
	2	10.52	5.730
	3	6.020	7.870
	4	10.47	9.620
	5	10.36	12.03
3 20.27 10.03 mica=0.03 mm	1	9.930	1.936
	2	10.87	4.346
	3	9.400	5.796
	4	9.650	7.696
	5	10.80	10.01
4 20.32 10.06 cement=0.46 mm	1	10.85	2.720
	2	9.320	4.960
	3	8.740	5.880
	4	8.530	8.320
	5	9.530	10.52

was chosen for its service temperature of 2400 °F, high electrical resistance, specific heat of 0.235 Btu/lbm-R, and thermal conductivity of 0.00046 Btu/sec-ft-R to minimize interference in temperature measurements. No. 10 cement was used to hold the thermocouples in place inside the samples. Initial masses of the uninstrumented samples were recorded. A thin layer of cement was placed on both sides of the stainless steel foil, with exactly the same width as the sample, to inhibit any leakage of electric current into samples 1, 2, and 4. For sample 3 a 0.03 mm thick layer of mica was placed between the samples and the foil. Thin sheets of mica were placed between the ends of the samples and the copper bars.

Operation

The ice point reference unit was running continuously before the experiment to assure an accurate reading of the reference thermocouple. The Hewlett Packard Digital Voltmeter and all the other recording devices were turned on, and the zero offsets of the meters were recorded. The video camera was run to record the date and then left on to record with the stopwatch display. The power supply voltage was set, and the program was started on the HP computer. A stopwatch was operated by hand to record heating time in the event that the steel foil melted before the programmed time duration was reached.

The helium flow was started. The computer closed the relay, and the heat flux was supplied to the sample at the determined power level and for the desired time. The pyrolysis gases released were videotaped for all runs. Voltage, current, and thermocouple temperatures were recorded. Final mass of the uninstrumented sample was then recorded when it cooled to

room temperature.

Data Reduction

The thermocouple voltages were recorded by the Hewlett Packard Digital Voltmeter, and the HP computer program converted them to temperatures, °C, by subtracting the ice point reference voltage and using the following polynomial:

$$T = P_0 + V (P_1 + V (P_2 + V (P_3 + V (P_4 + V (P_5 + V (P_6 + V (P_7 + V (P_8 + V (P_9))))))))) \quad (5.1)$$

where

$$\begin{aligned} P_0 &= -5.115307103E-2 \\ P_1 &= 2.485028007E+4 \\ P_2 &= -3.826622822E+5 \\ P_3 &= 9.966105673E+7 \\ P_4 &= -1.082062357E+10 \\ P_5 &= 6.039285524E+11 \\ P_6 &= -1.910899962E+13 \\ P_7 &= 3.478234730E+14 \\ P_8 &= -3.399102821E+15 \\ P_9 &= 1.382851398E+16 \end{aligned}$$

Voltage drop across the steel foil was recorded by the HP computer program at the start and end of the run. Current was also recorded by the HP computer at the start and end of the run. Current in amps was obtained by multiplying the recorded voltage by a conversion factor of 5000. Time was measured by the HP computer at the start of the power, at the start of the

thermocouple readings, and at the conclusion of the run when power was turned off. A time for each thermocouple reading was assigned by the HP computer program. After the run was completed, the number of thermocouple readings, times, and thermocouple temperatures were written to an ASCII data file using the HP 9133 Hard Disk Drive.

Results

Power Calculations

Voltages, currents, and heat fluxes are listed in Table 5.2 for each sample. Current measurements are included in Appendix C. The initial peak of high current is due to the lower resistance of the steel foil at room temperature. Within the first few seconds the foil reaches an equilibrium resistance, yielding an almost constant current. The gradual rise near the end of heating may be the effect of current leakage into either the cement or the sample resulting in a lower overall resistance. Resistance for the

Table 5.2. Heat flux calculations.

Sample	Meter Voltage (V)	HP Voltage (V)	Average Voltage (V)	Average Current (A)	Power (W)	Area (cm ²)	Heat Flux per sample (W/cm ²)	Cement (mm)
1	7.25	7.16 initial	7.20 ±0.05	71.1 ±1	511.8	8.40 ±.01	30.5±0.6	0.66
2	7.40	7.38 average	7.39 ±0.01	74.4 ±1	549.8	8.34 ±.01	33.0±0.6	2.0
3	7.72	7.67 initial	7.70 ±0.025	78.2 ±1	602.1	8.26 ±.01	36.5±0.6	none*
4	7.28	7.11 initial	7.20 ±0.04	71.3 ±1	513.4	8.40 ±.01	30.6±0.6	0.46

* 0.03 mm of mica

circuit was calculated by equation (5.2).

$$R = \frac{\rho L}{2.54 w t} = \frac{V}{I} \quad (5.2)$$

where ρ = electrical resistance = 0.00008 Ω cm for stainless steel

t = thickness, inches

w = width, inches

L = length, inches

Several metals, including steel, zirconium, Inconel 600, and constantan, were tested for maximum sustainable heat flux and durability. Stainless steel, with a melting temperature of 2700 °F, was chosen.

When a test sample was placed on the foil, the steel melted at the gap between the copper bars and the sample. 20 W/cm² was the maximum flux allowable. With a flow of helium gas to cool the gap a sustainable heat flux of over 30 W/cm² was achieved. Mica and No. 10 Sauereisen cement were used to electrically isolate the sample from the heater while allowing a high heat flux. As will be discussed later, this was difficult to accomplish. Heat flux per sample for the test was calculated using equation (5.3).

$$q'' = \frac{V I}{2 A} \quad (5.3)$$

Temperatures

The temperature data for the four samples is presented in this section of the results. Two sets of numerical predictions are presented. One set is based on specific heat and thermal conductivity data as reported by Acurex Corporation, and the other is based on data measured at Southern Research Institute, (SRI). These properties are listed in appendix A. The

temperatures calculated with the Acurex data are somewhat lower at all locations. The virgin heat capacity and charred across ply thermal conductivity reported by Acurex are higher than those measured by SRI.

Figure 5.4 shows that sample 1 experimental temperatures at 2.84 mm are very close to the numerical prediction up to 15 seconds. The temperature increases above numerical calculations after that. This may be due to electrical leakage reaching the sample. The numerical temperatures are higher than the experimental temperatures for the other four thermocouple locations as can be seen in Figures 5.5 and 5.6.

In Figure 5.7 the first thermocouple at 4.44 mm for sample 2 is much cooler than the first thermocouple in sample 1. The thick layer of cement resulted in less decomposition than for sample 1, and the numerical and experimental temperatures follow the same slope. The numerical calculations are very close for all the thermocouple locations in sample 2 as seen in Figure 5.8.

As should be expected, due to the highest heat flux and the least electrical insulation, 0.03 mm layer of mica, the highest temperature was measured in sample 3 as shown in Figure 5.9. At 1.94 mm the first thermocouple is close to numerical calculations up to 15 seconds, then the experimental temperatures have a greater rate of increase. At 15 seconds the surface temperature next to the mica is calculated to be about 750 °C. In Chowdury (1941) the resistivity of mica is said to be lost between 700 °C and 900 °C due to vaporization of its water of crystallization. This would allow electrical leakage and alter the experimental temperatures. Figure 5.10

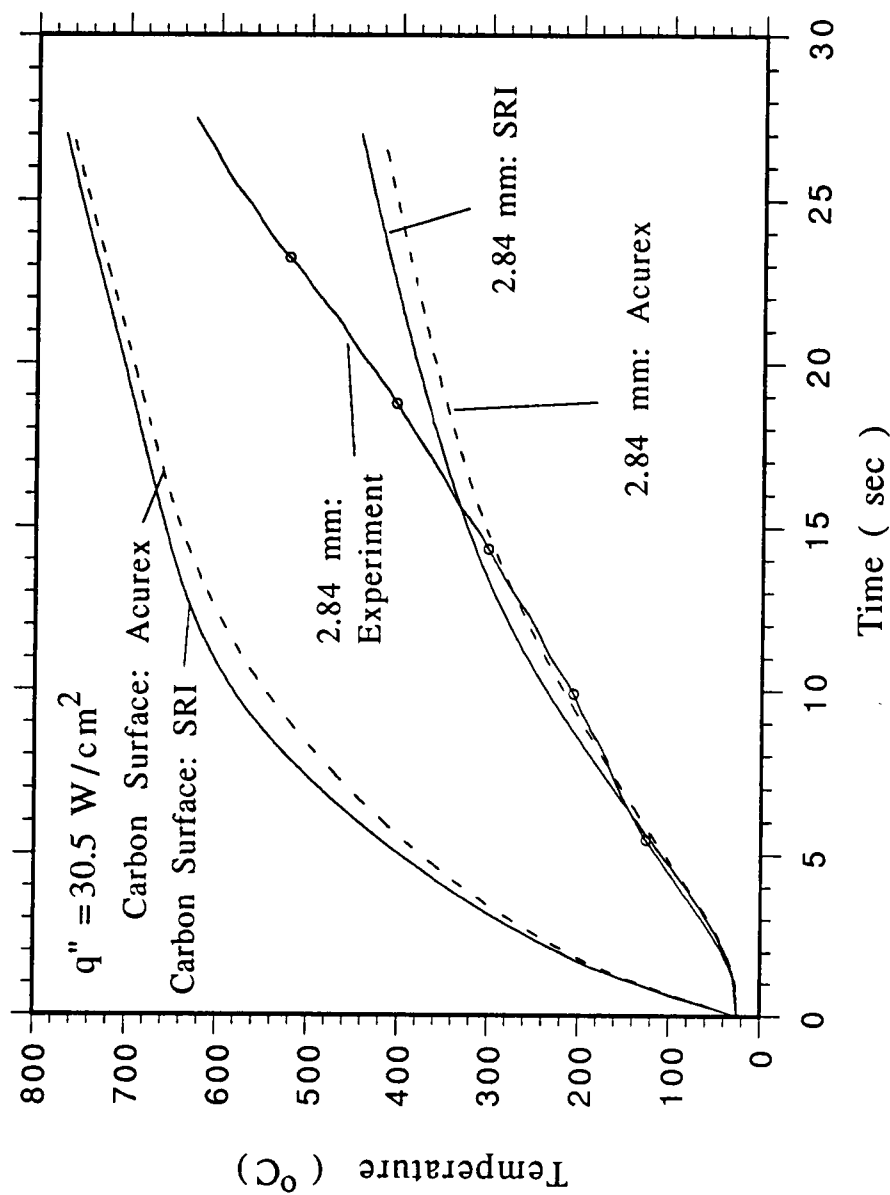


Figure 5.4. Temperatures at the surface of the carbon phenolic and first thermocouple location for sample 1.

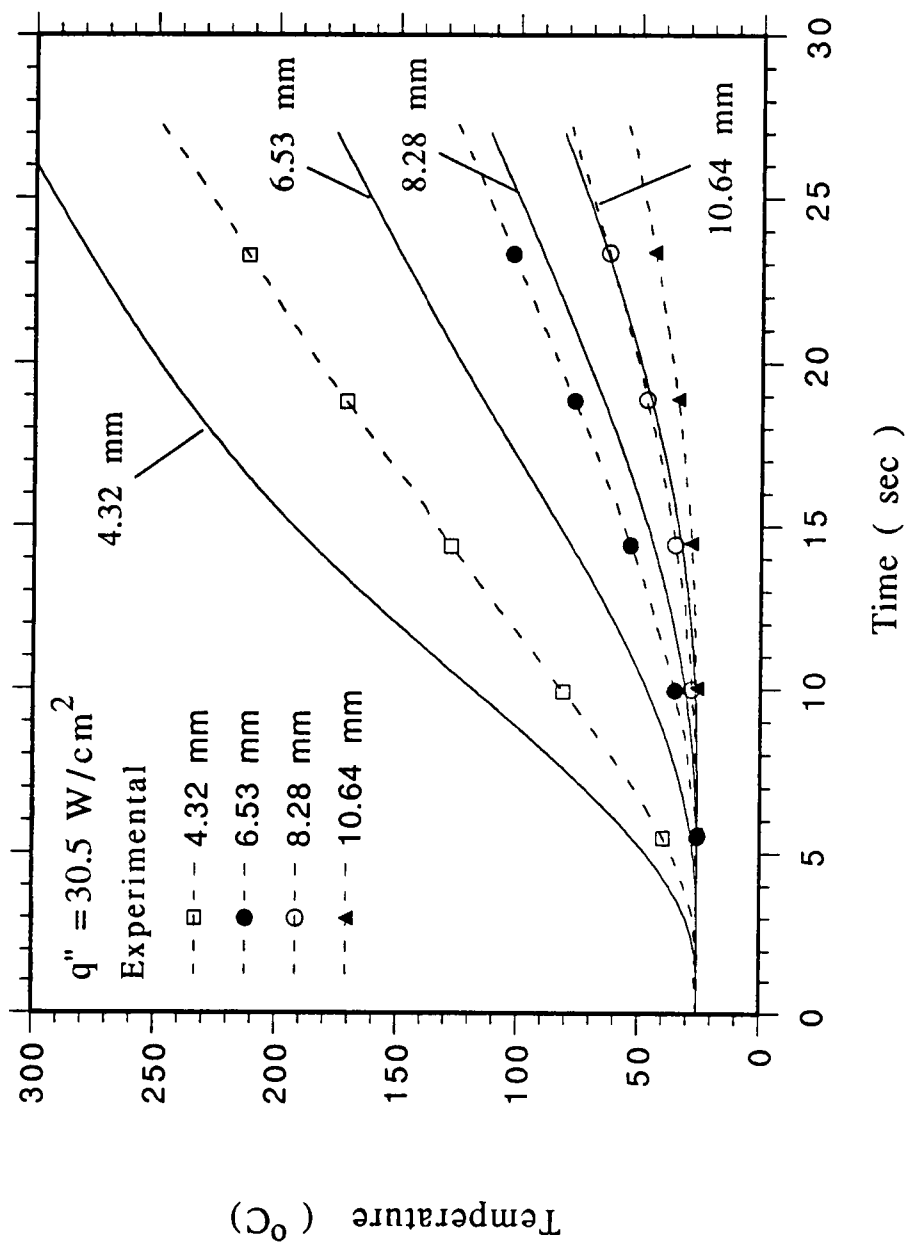


Figure 5.5. Comparison of experimental temperatures and numerical temperatures using SRI data for sample 1.

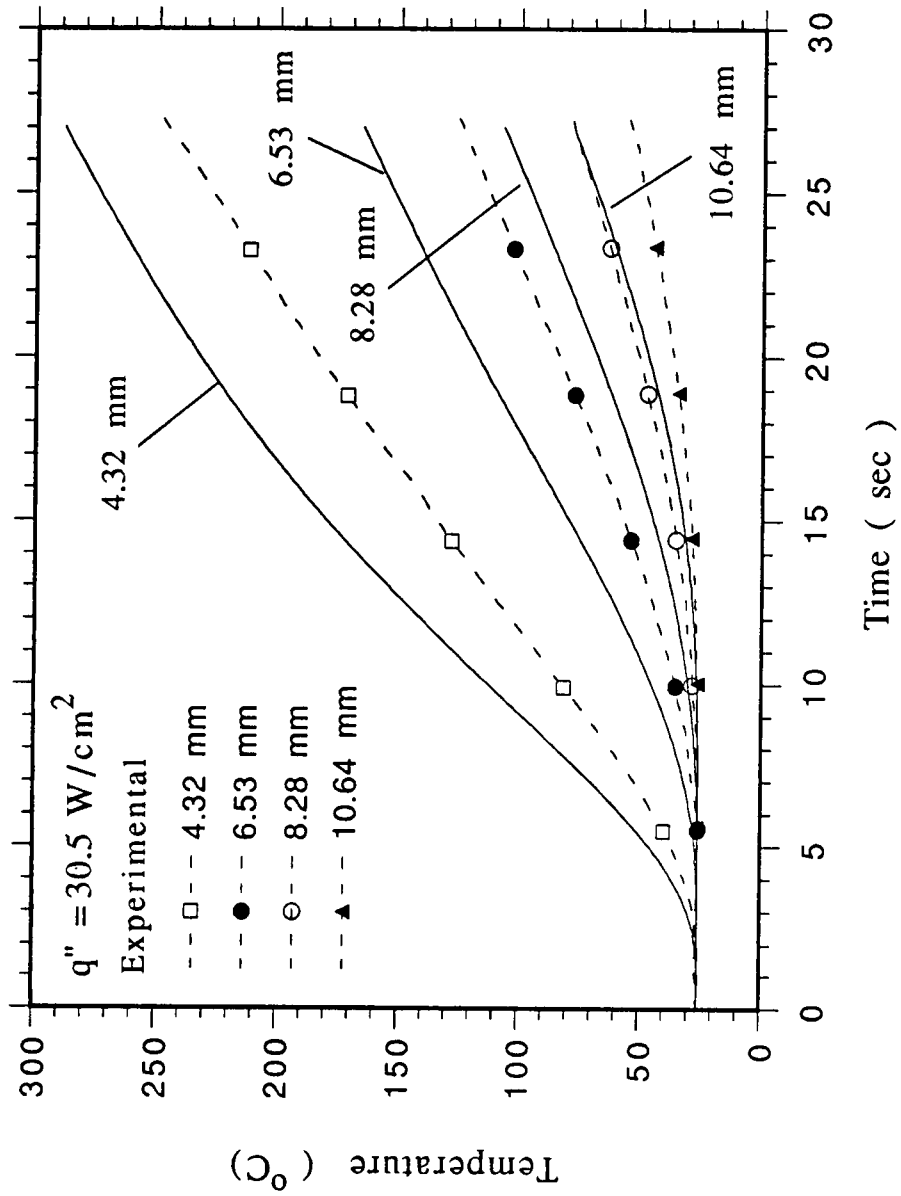


Figure 5.6. Comparison of experimental temperatures and numerical temperatures using Acurex data for sample 1.

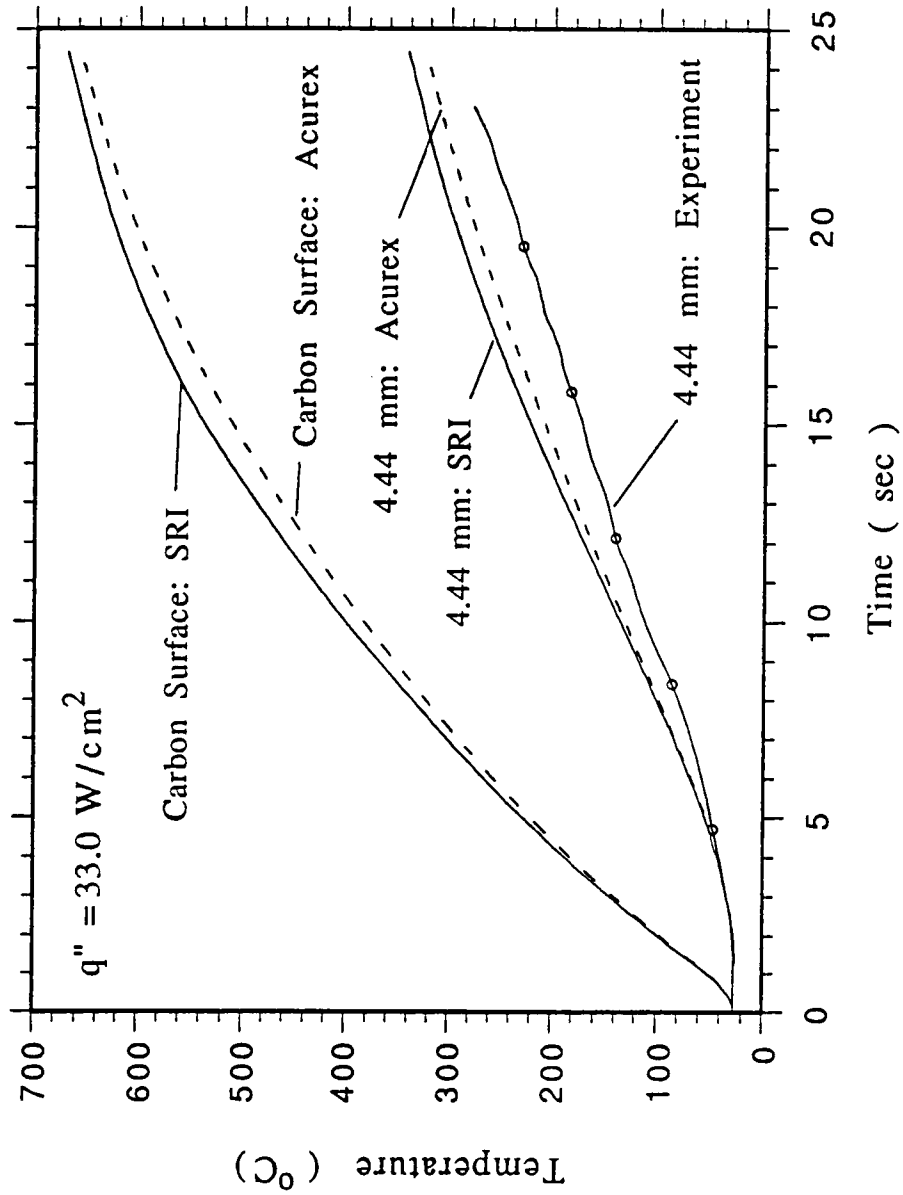


Figure 5.7. Temperatures at the surface of the carbon phenolic and the first thermocouple location for sample 2.

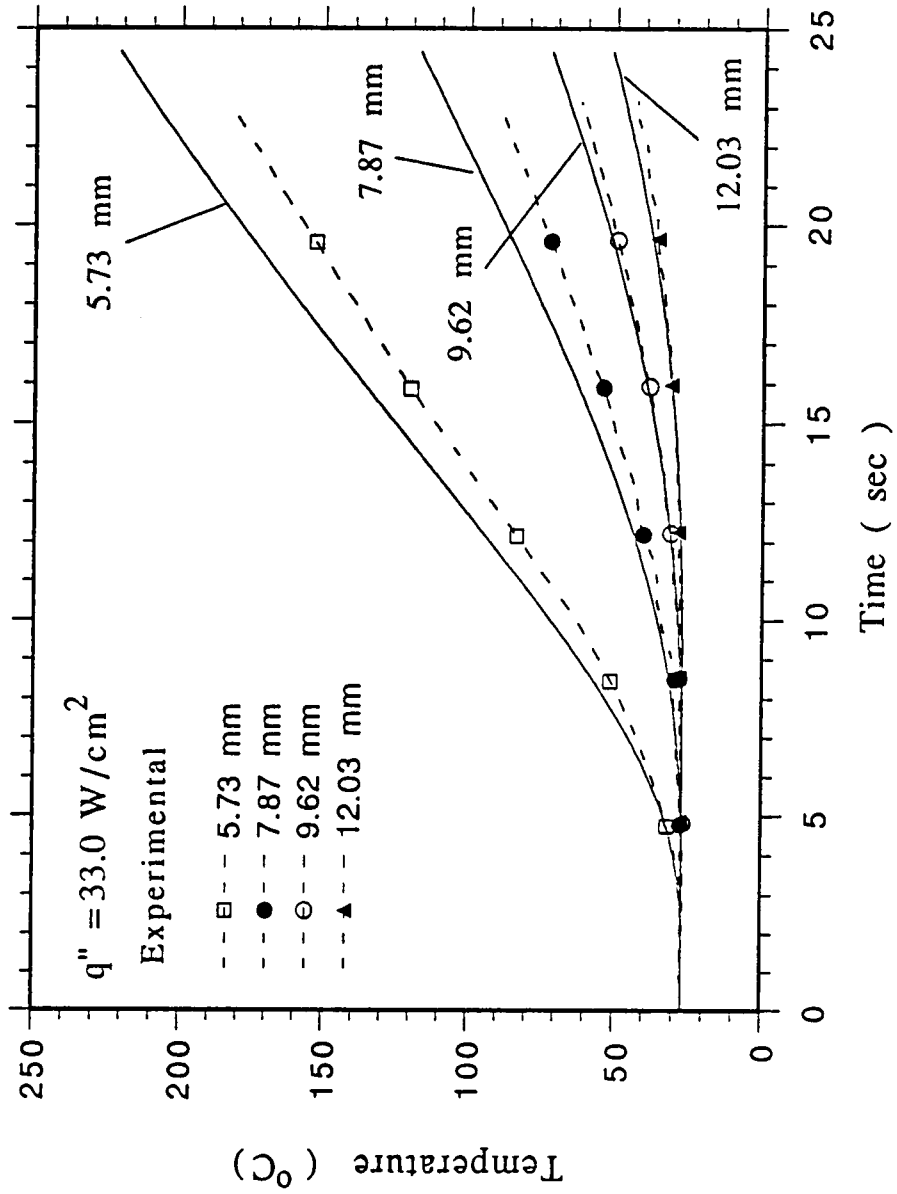


Figure 5.8. Comparison of experimental temperatures and numerical temperatures using Acurex data for sample 2.

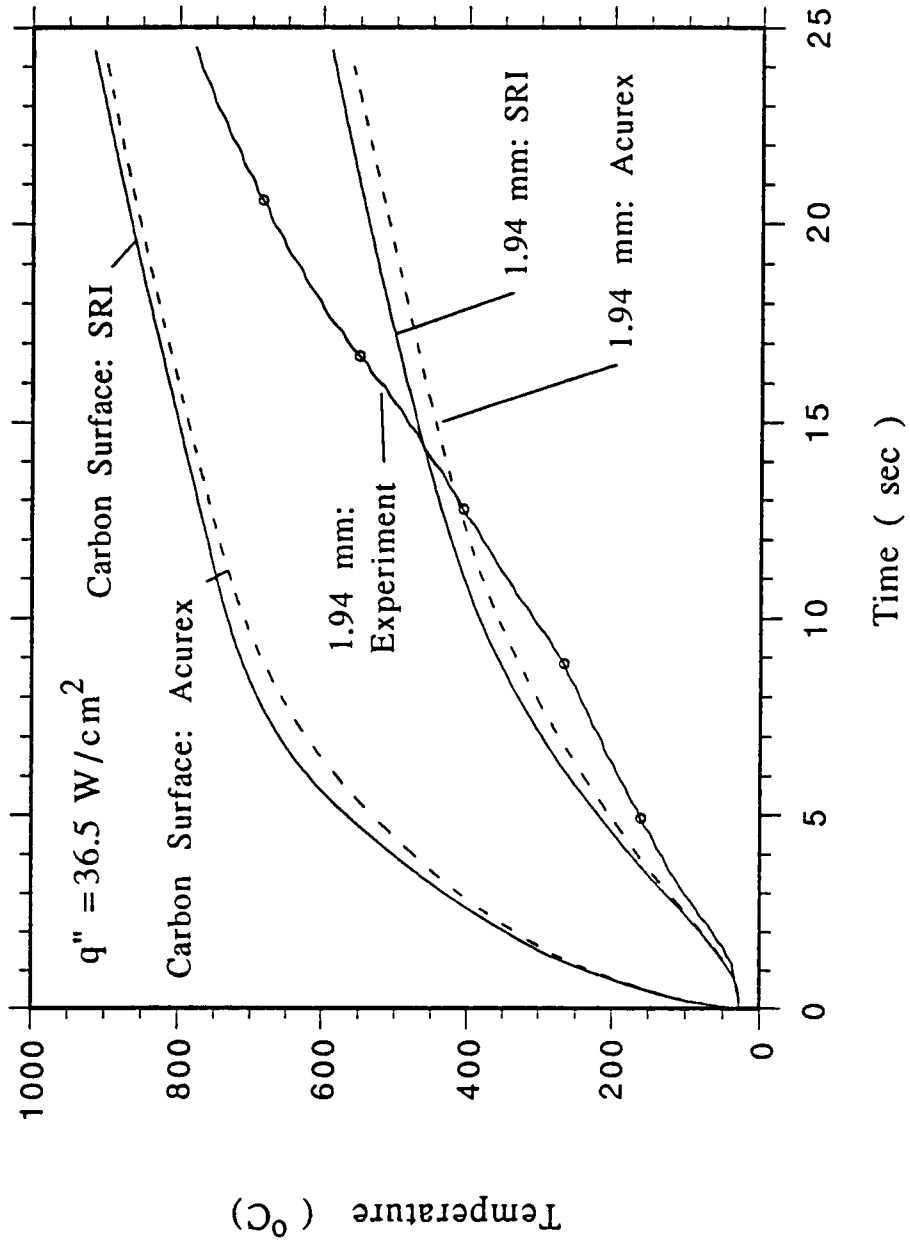


Figure 5.9. Temperatures at the surface of the carbon phenolic and at the first thermocouple location for sample 3.

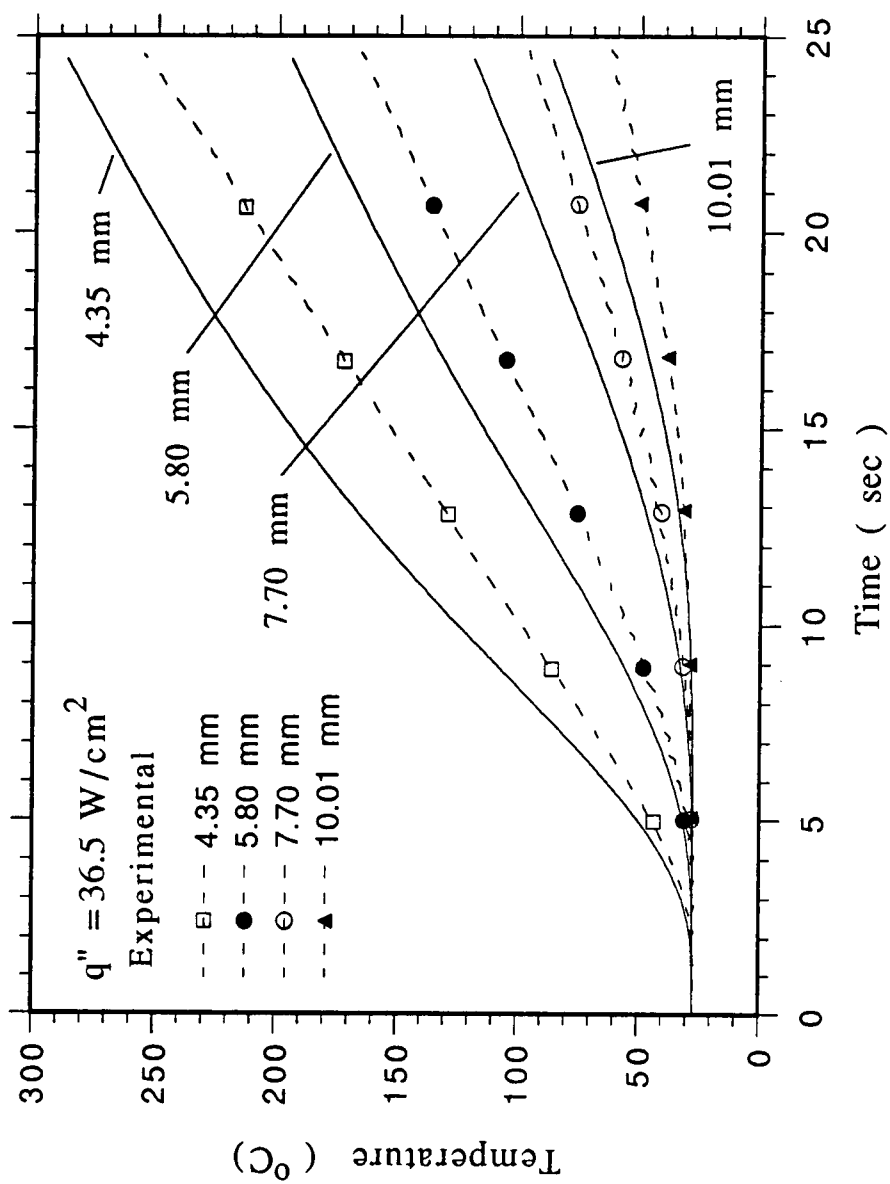


Figure 5.10. Comparison of experimental temperatures and numerical temperatures using Acurex data for sample 3.

shows that numerical temperatures are higher than experimental values for the other four thermocouples as well.

Sample 4 predicted temperature at 2.72 mm in Figure 5.11 are fairly close to experimental data, but the slope of the experimental temperature is increasing while the numerical slope is decreasing. This may again be due to some electrical leakage in the latter end of the test. Figure 5.13 shows experimental temperatures for the first thermocouple of samples 1 and 4 at nearly the same heat flux. Both have a similar slope and shape, but the higher values were measured for the sample 1 thermocouple that did not go to the end of the hole. The curves also come from tests with different layers of cement, and if the properties of the cement vary due to the mixing and drying, the electrical properties may have been different just as the mechanical properties can be under such conditions. Numerical calculations were done to compare the effect of including convective cooling for sample 4. Figure 5.14 shows that the temperatures decrease with convective cooling. The effect is mainly in the latter half of the test period and at high temperatures where decomposition results in the generation and flow of the pyrolysis gases.

The numerical temperatures of the carbon phenolic sample surfaces are plotted in Figure 5.15. Sample 2 has the lowest temperatures as expected with the thick cement layer, and sample 3, highest heat flux, has the highest temperatures. Sample 3 has an average heating rate of 125 °F/sec up to 10 seconds.

Figure 5.16 shows the degree of char for each test. This shows that sample 3 has much more decomposition than sample 2, and the char

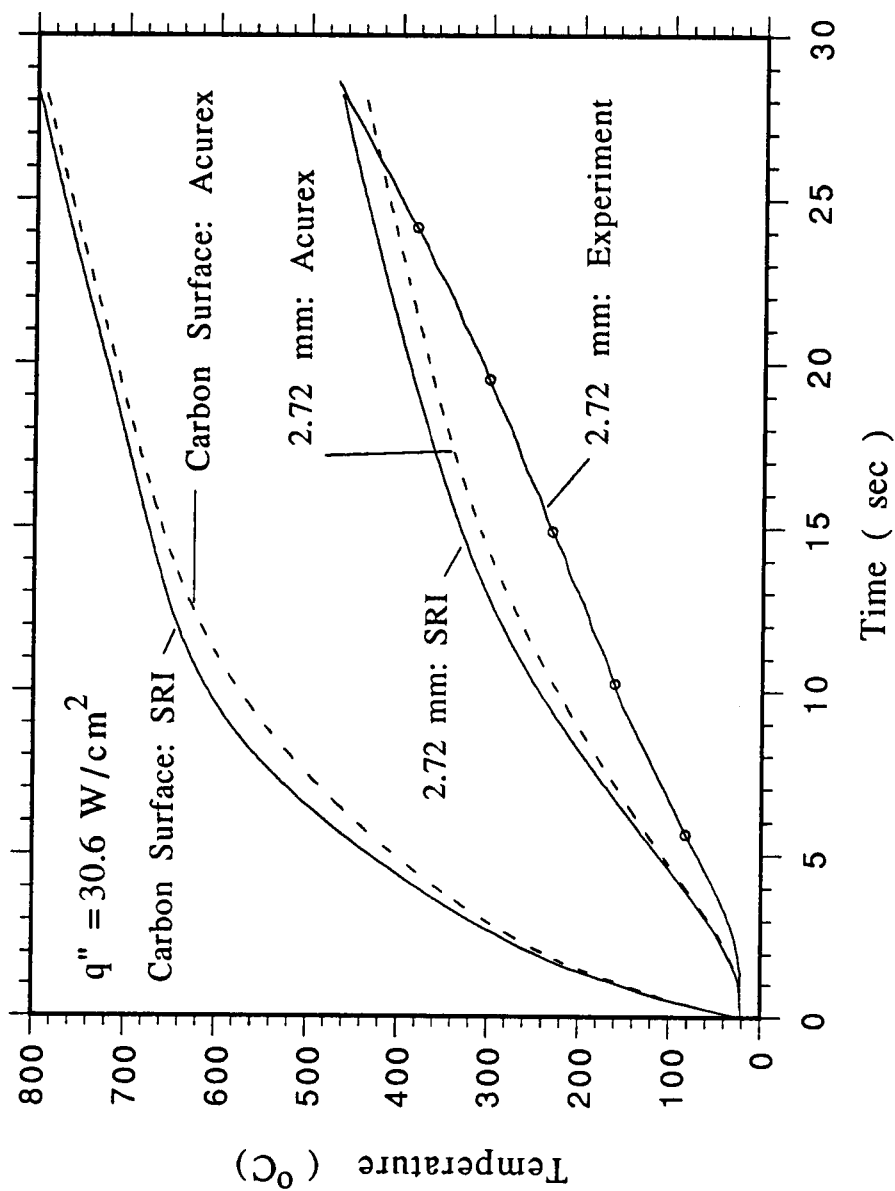


Figure 5.11. Temperatures at the carbon phenolic surface and at the first thermocouple location for sample 4.

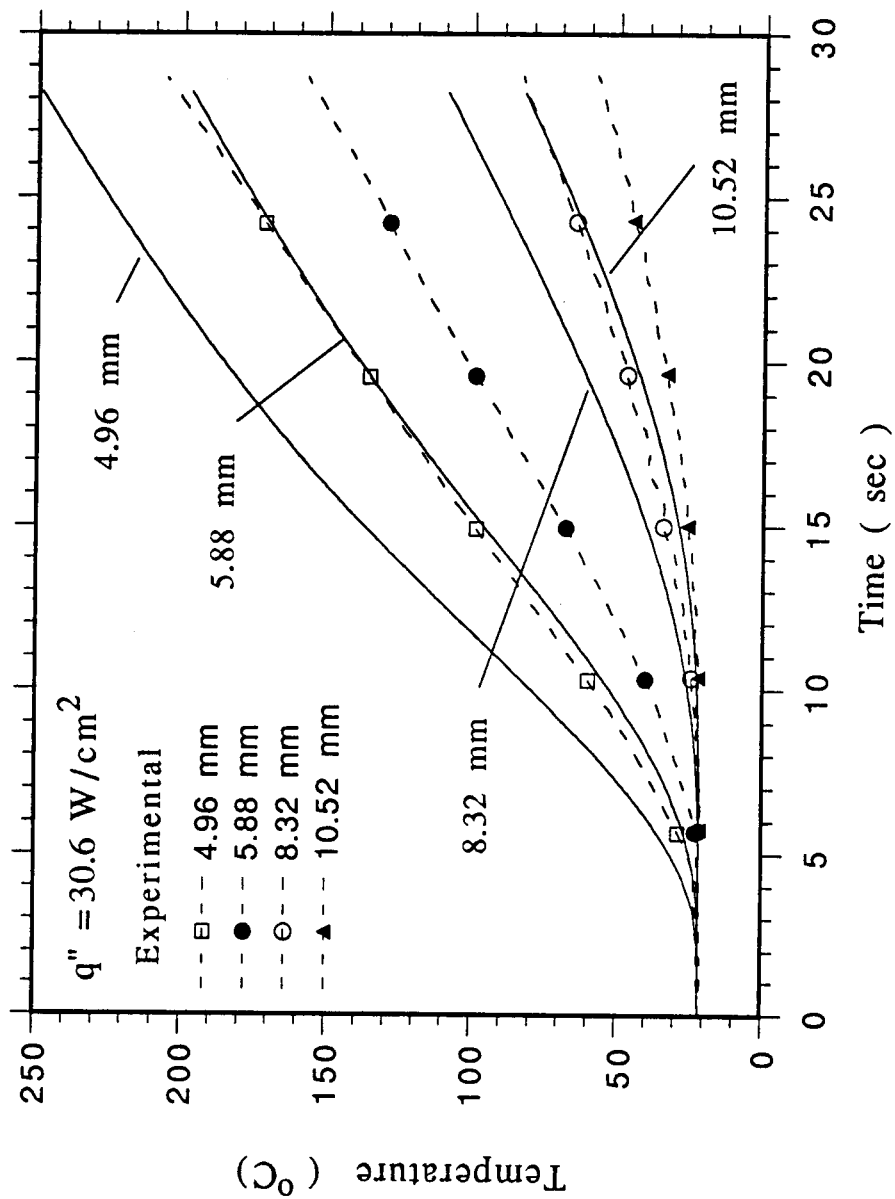


Figure 5.12. Comparison of experimental temperatures and numerical temperatures using Acurex data for sample 4.

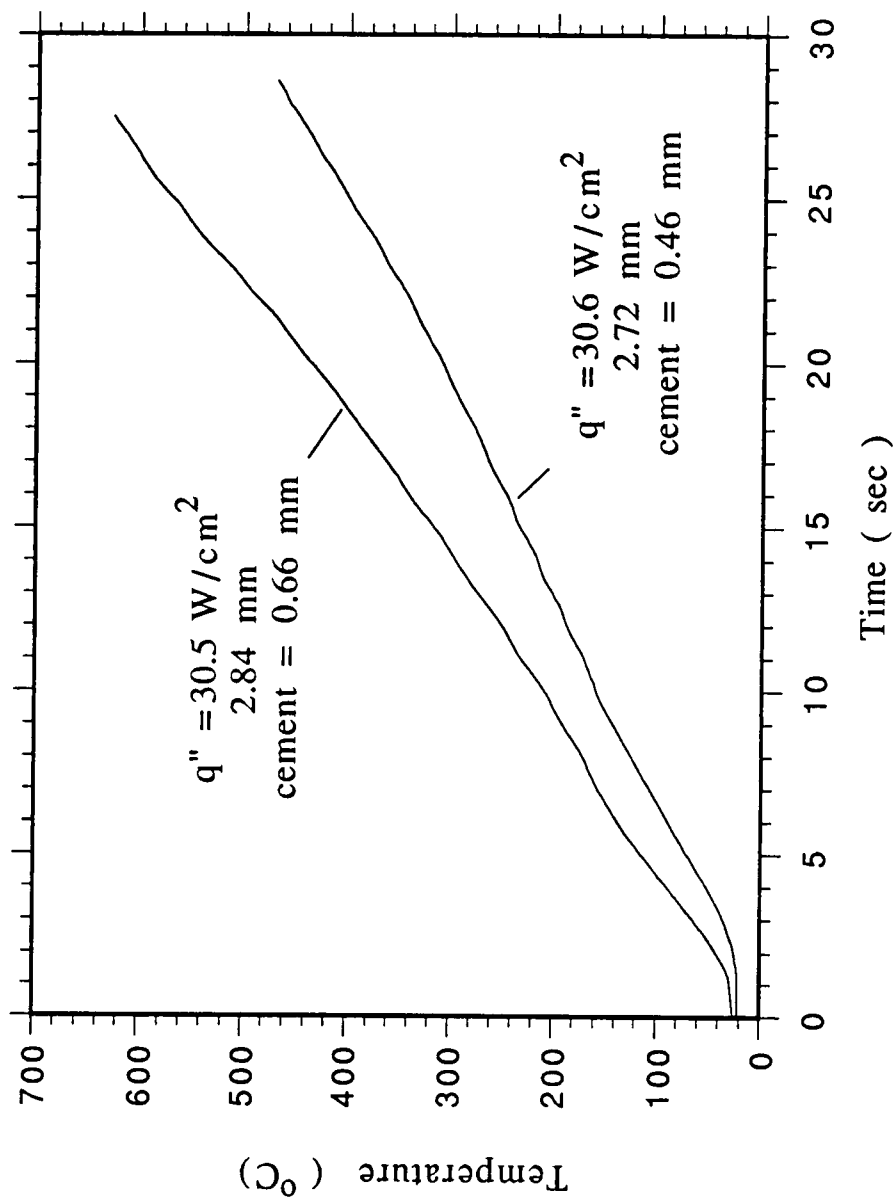


Figure 5.13. Experimental temperatures for the first thermocouples of sample 1 at 30.5 W/cm^2 and sample 4 at 30.6 W/cm^2 .

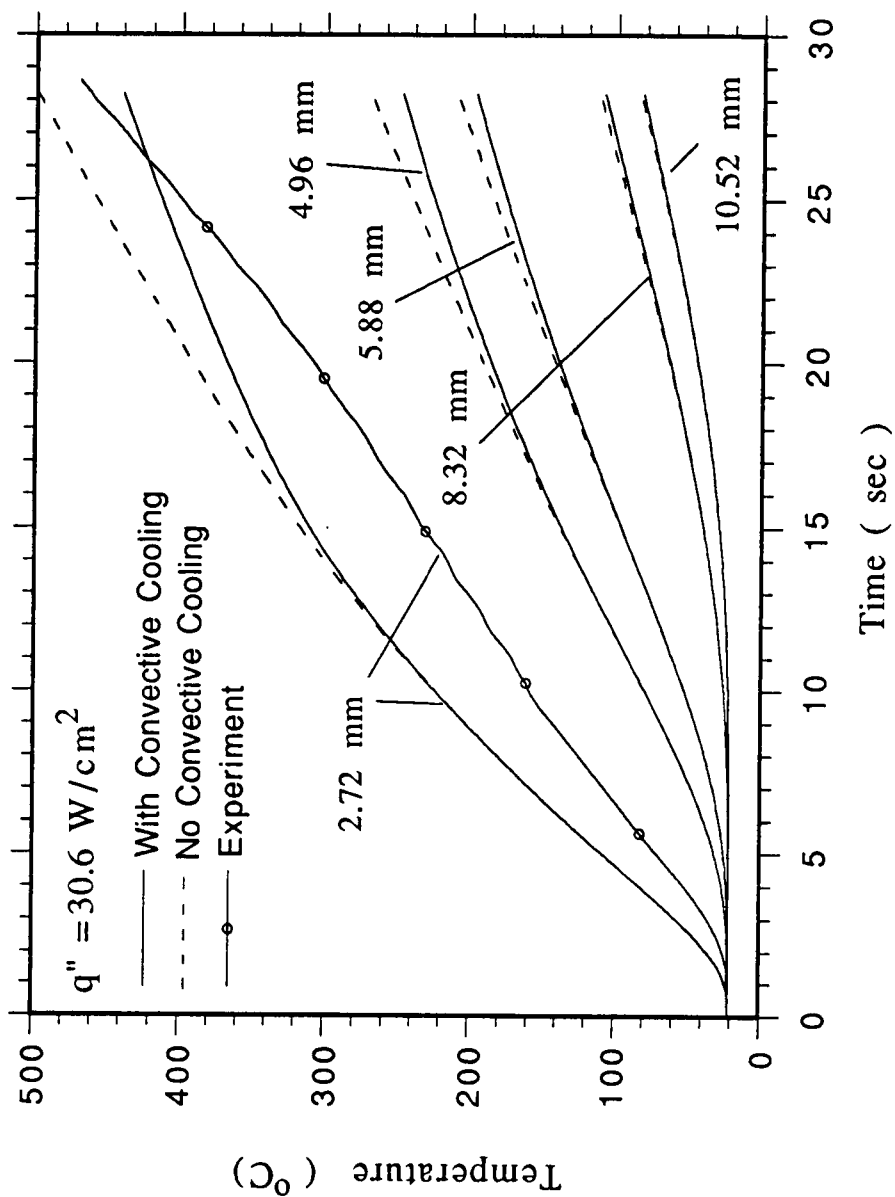


Figure 5.14. Comparison of numerical temperatures with and without convection using Acurex data and experimental data for sample 4.

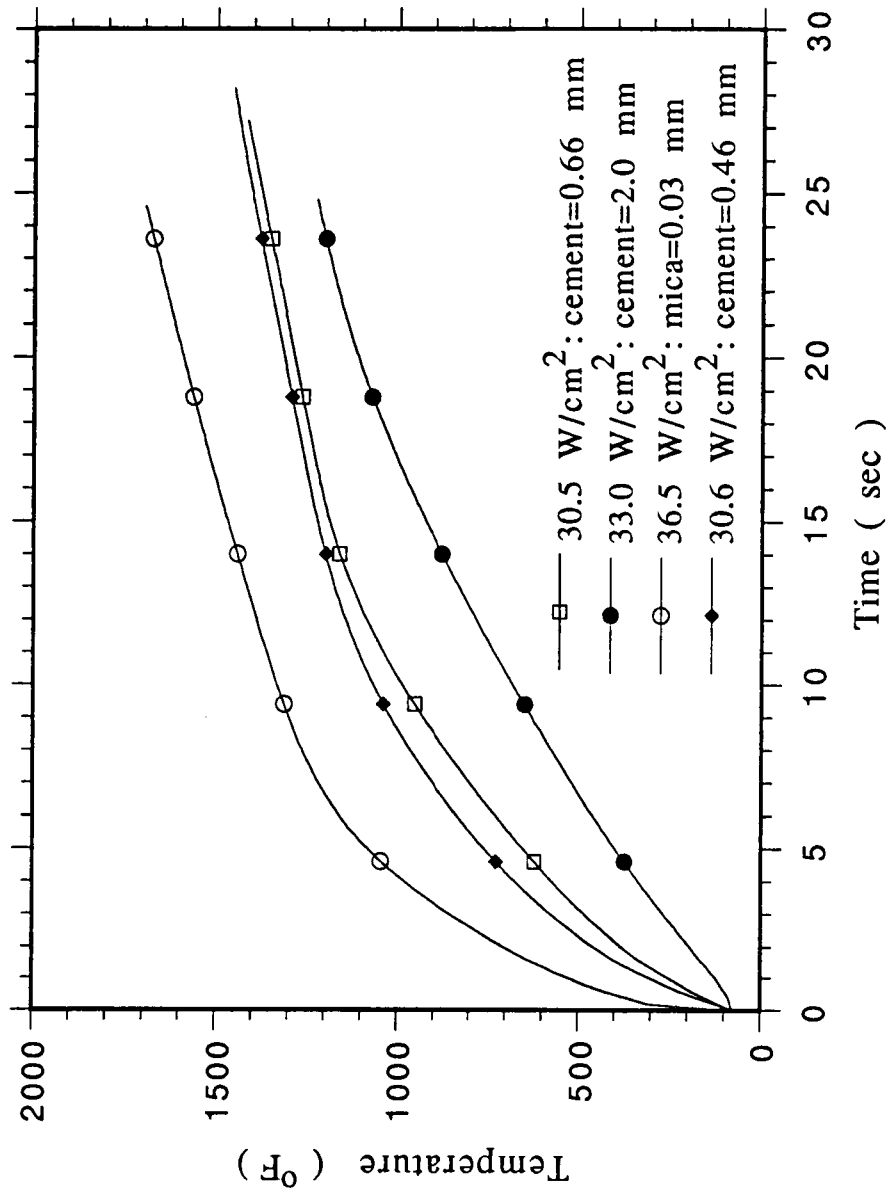


Figure 5.15. Carbon surface numerical temperatures for all samples using Acurex data.

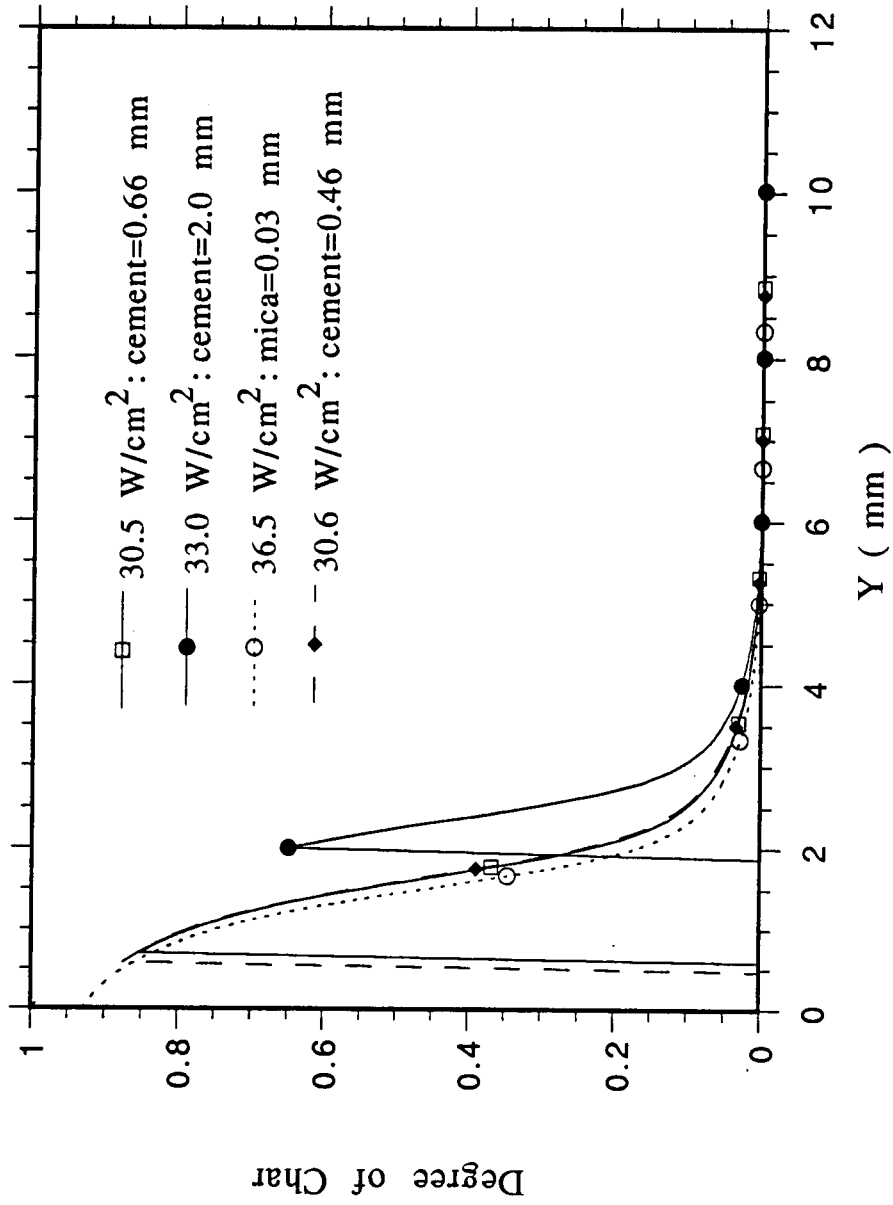


Figure 5.16. Degree of char at the end of heating along the centerline in the X direction.

properties have more importance for sample 3 numerical predictions. Except for the first thermocouple, all the thermocouples are located in a region of conduction heat transfer with almost no decomposition.

The centerline ($x=1$ cm) calculated temperature profiles at the end of the heating period for the four samples are plotted in Figure 5.17. Temperatures at the steel foil surface are very close for all tests, and an almost linear decrease can be seen for the region of cement which was assumed to have constant properties. Figure 5.18 shows the centerline ($x=1$ cm) calculated pressure profiles at the end of the heating period for the four samples. The carbon phenolic surface in contact with the cement or the heater was assumed to be an impermeable boundary. The assumption of an impermeable boundary probably overestimates the seal between the sample and the cement and computes somewhat higher pressures. Figure 5.19 shows the numerical gas mass flow along the centerline in which most of the gas flow is toward the foil in the region opened up by decomposition. Calculations show that most of the total gas flow is in the fill direction (X) due to higher permeability in that direction.

Mass Loss

Mass losses are shown in Table 5.3 and densities are listed in Table 5.4. The experimental mass loss for sample 1 is 3.81%, and the numerical calculation is 1.73% at the end of the 27.0 second heating period. The lower numerical value is probably due to some moisture present in the sample and the fact that the experimental mass measurement was made when the sample had cooled to room temperature. More decomposition had taken place after the power was turned off. Mass loss for sample 4 is 3.57%

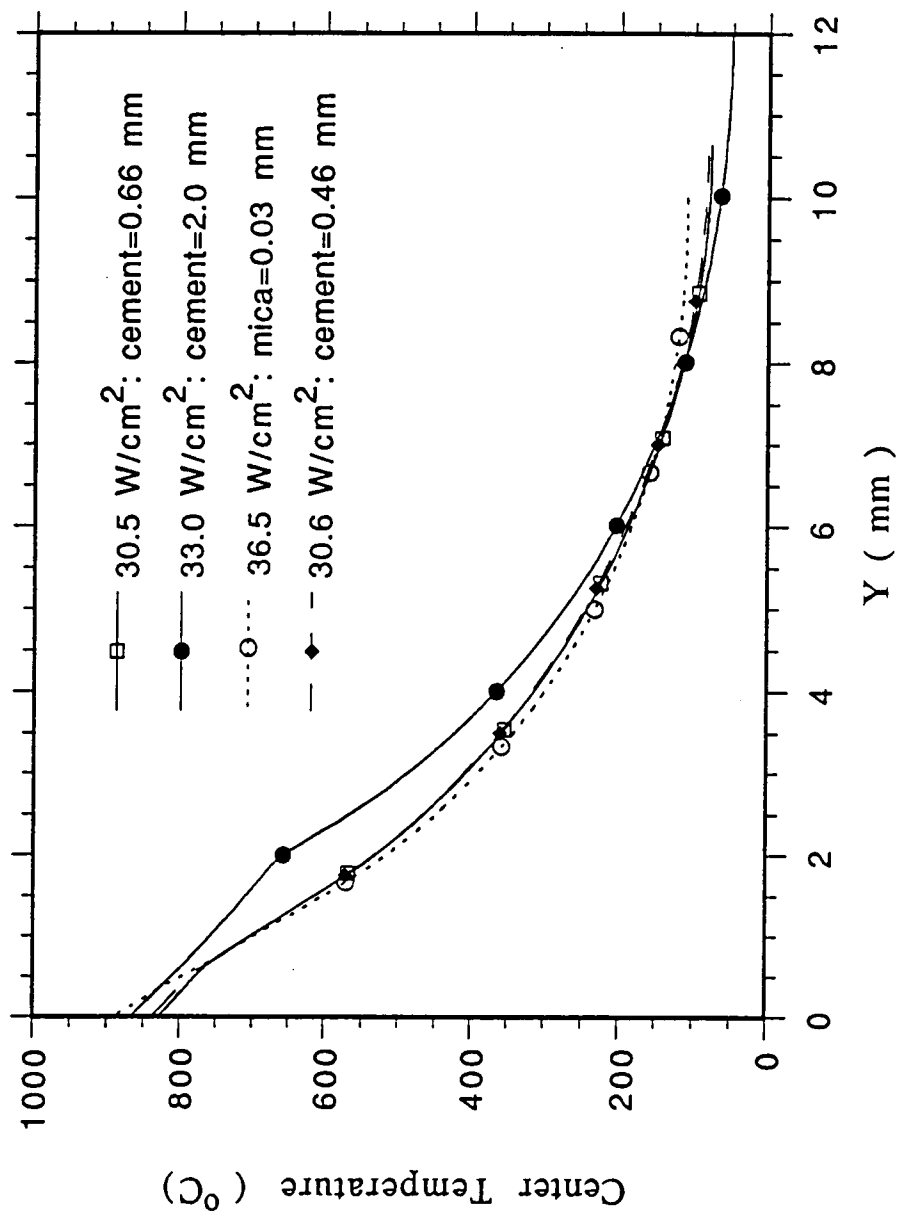


Figure 5.17. Temperature at the end of heating along the centerline in the X direction.

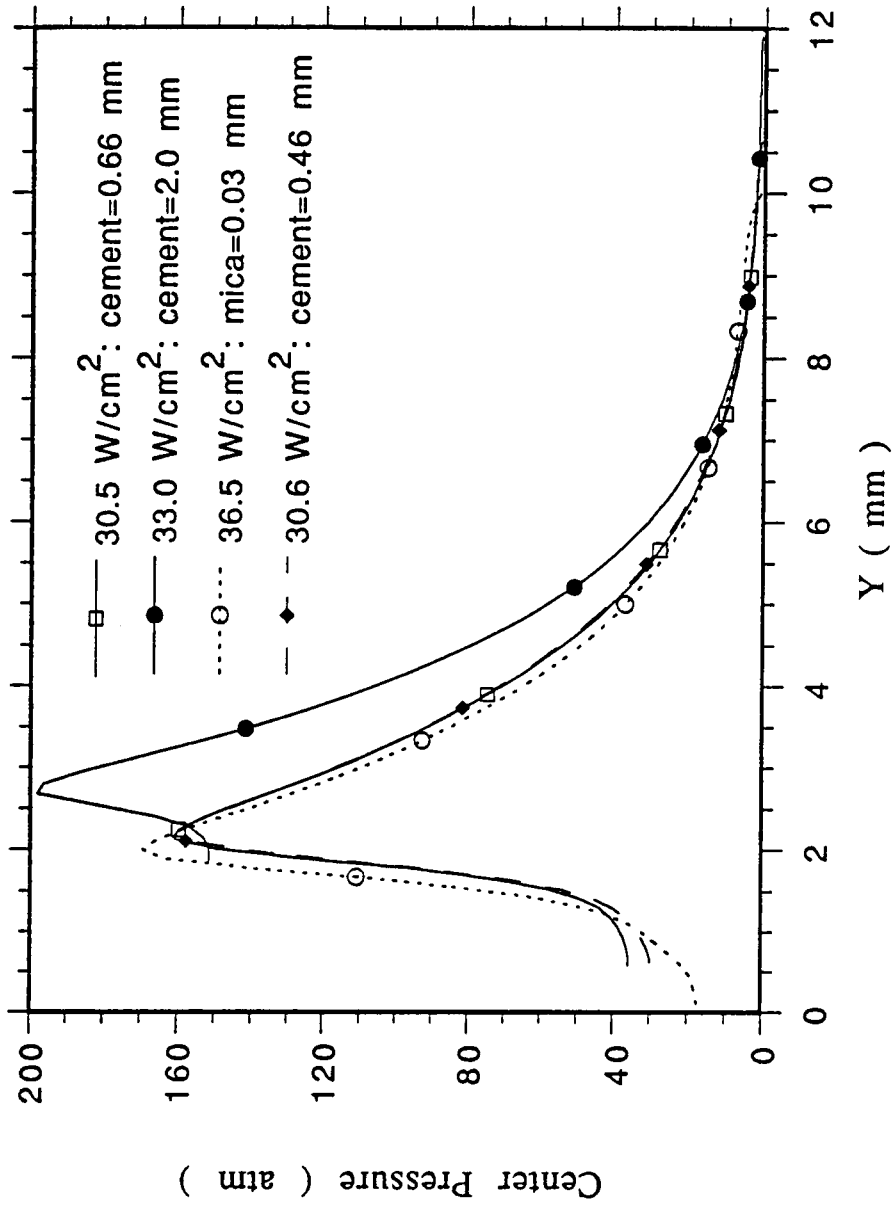


Figure 5.18. Pressure at the end of heating along the centerline in the X direction.

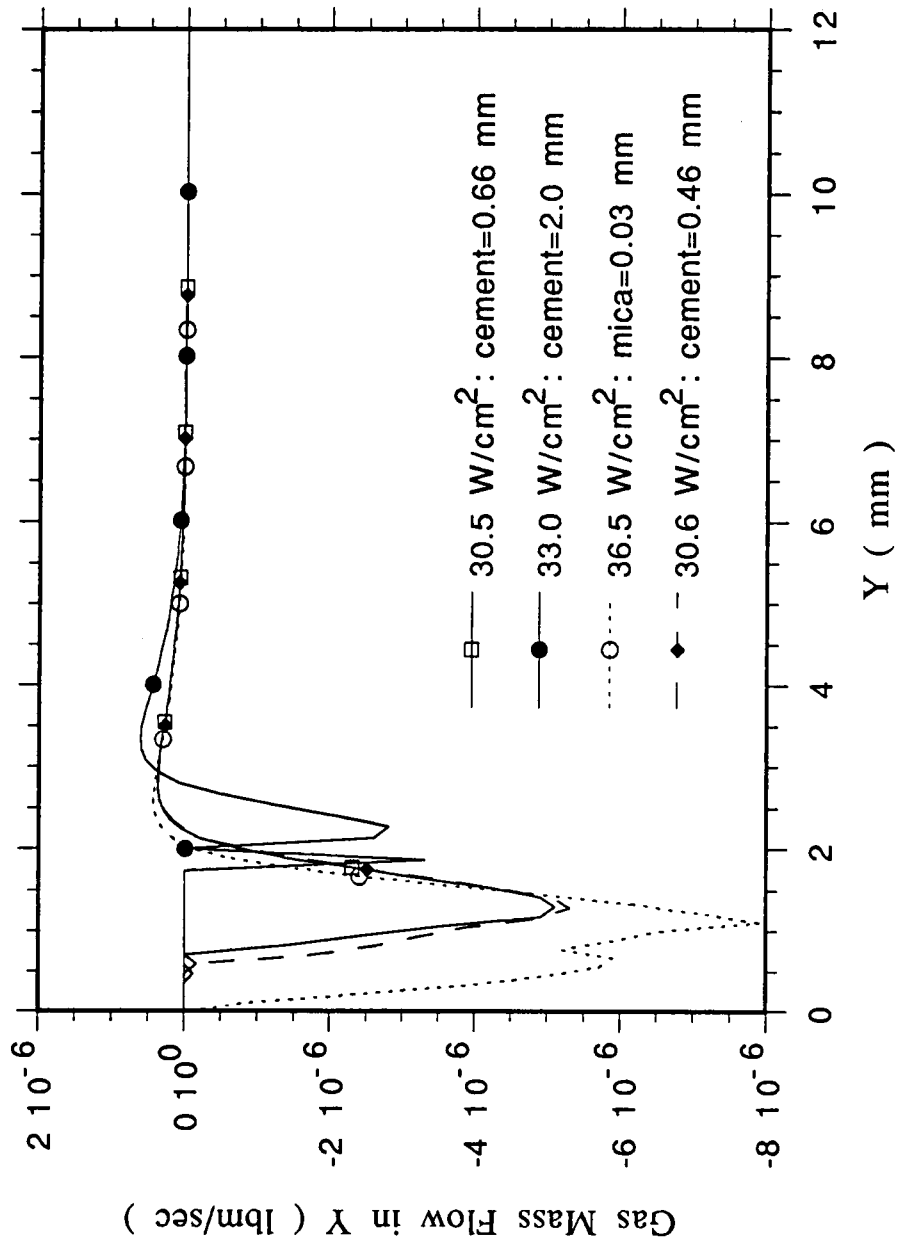


Figure 5.19. Gas mass flow in the Y direction at the end of heating at the centerline in the X direction for 6% of the width in X.

Table 5.3. Mass loss due to heat flux for FM 5055.

Sample	Heat Flux (W/cm ²) ±0.6	Time (sec)	Initial Mass (gm) ±0.0005	Final Mass (gm) ±0.0005	Mass Loss %	Numerical Mass Loss %
1	30.5	27.0	11.8230	11.3727	3.81	1.73
2	33.0	24.4	11.8240	11.4315	3.32	0.70
3	36.5	24.4	11.8238	11.2150	5.15	2.24
4	30.6	28.2	11.8219	11.3998	3.57	1.97

Table 5.4. FM 5055 density.

Sample	Volume (mm ³) ±40	Initial Density (lbm/ft ³) ±0.50	Initial Mass (gm) ±0.0005	Theoretical Initial Mass (gm) ±0.060	Percent Moisture ±0.01
1	8034	91.79	11.8230	11.542	2.38
2	8128	90.69	11.8240	11.677	1.24
3	8132	90.66	11.8238	11.683	1.19
4	8150	90.40	11.8219	11.708	0.97

experimentally and 1.97% numerically. Although the heat flux was 0.1 W/cm² higher than for sample 1 and lasted 1.2 seconds longer, the experimental mass loss is lower. This is probably due to a higher initial moisture content of sample 1 as shown in Table 5.4. The last column in Table 5.4 is based on the difference between measured initial density and virgin density given by Beck et al (1984). The higher numerical mass loss for sample 4 is due primarily to the smaller thickness of cement used with sample 4 than with sample 1. The numerical mass loss up to 60 seconds for sample 4 is plotted in Figure 5.20 to show the effect of the continuing decomposition after the input heat flux ends. The 2.78% decomposition mass loss at 60 seconds added to 0.97% assumed total moisture in Table 5.4 yields a 3.75% mass loss compared to the 3.57% loss actually measured. With

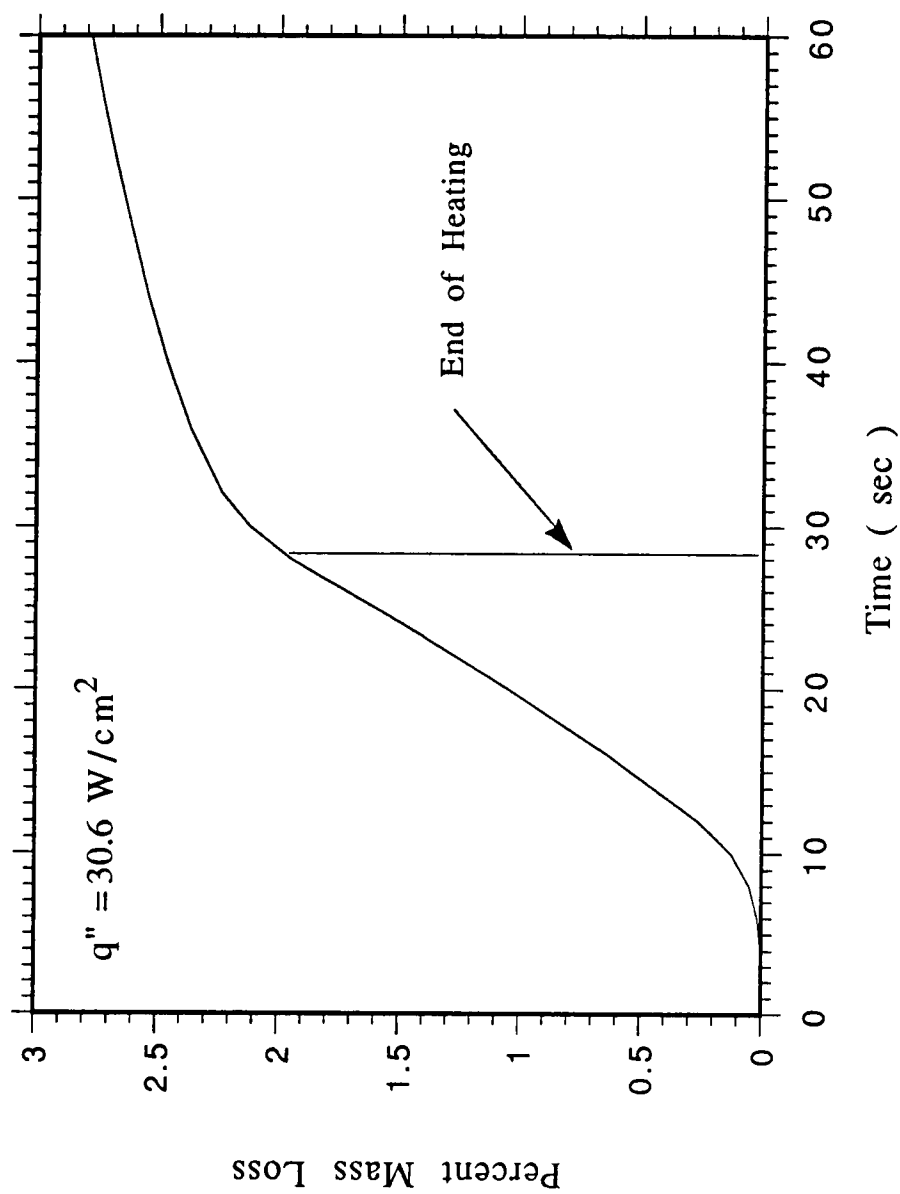


Figure 5.20. Numerical mass loss for sample 4.

115 °C on the nonheated side, probably not all of the moisture in the FM 5055 samples was driven out. The comparison between the experimental and numerical values for the mass is considered to be very good.

The numerical mass loss plus the calculated moisture content for sample 2 is 1.94%, while the experimental loss is 3.32%. Sample 3 has the highest mass loss experimentally and numerically as is expected with the highest heat flux input.

Pressures

The centerline ($x=1\text{cm}$) predicted pressures for the four samples at each thermocouple location are presented in Figures 5.21 to 5.24. The initial period shows the time for heat to reach each location. Pressures in samples 1 and 4 are similar as expected for similar heating, and the local maximum in the pressure at thermocouple 1 is probably a result of decomposition increasing porosity and permeability sufficiently to relieve some pressure through gas flow out of the carbon phenolic. The local maximum is most pronounced for sample 3, with the highest heat flux and decomposition. It is nonexistent for sample 2 with lower temperatures and less decomposition. Figures 5.16 and 5.19 show the degree of char and gas flow distributions for each sample in support of this.

The maximum pressures calculated in Figure 5.18 and the temperatures in Figure 5.17 for the same locations are above the limit of tensile strength as reported by Stokes (1988), but the C clamps may exert sufficient compressive force to prevent noticeable separation of plies.

Figure 5.25 shows that the experimental temperatures on the unheated surface have good consistency. Sample 2, with the thick cement

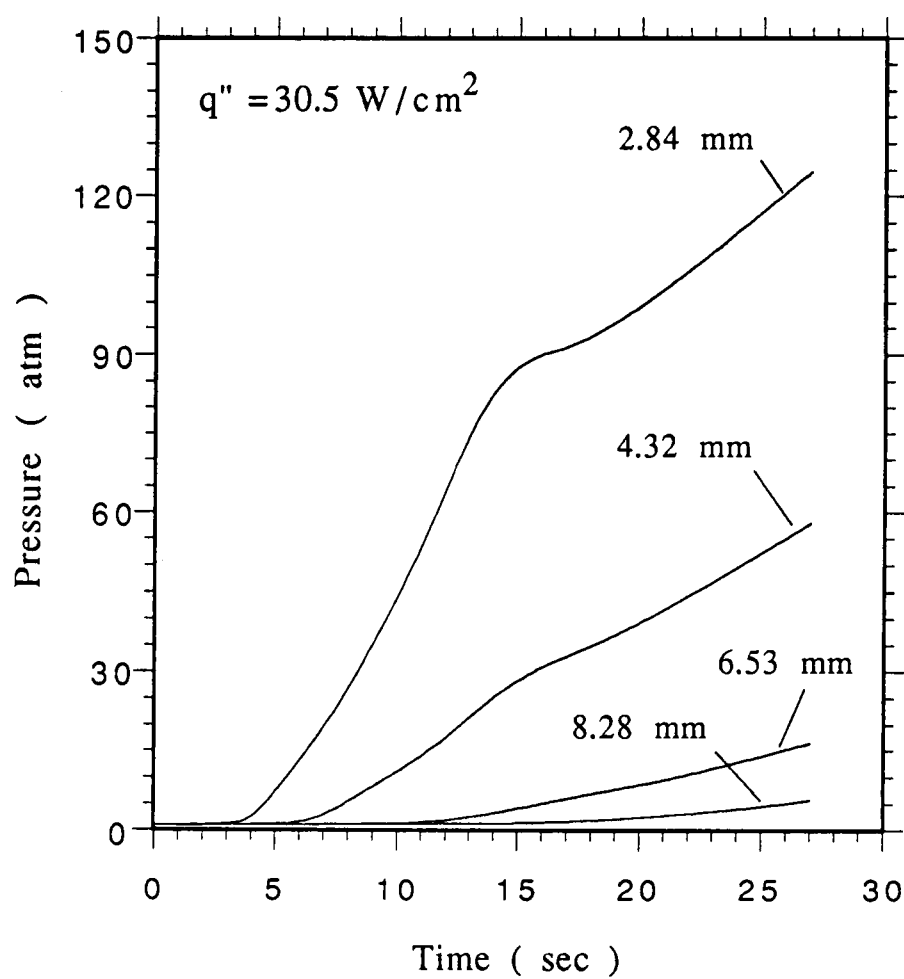


Figure 5.21. Pressure predictions for sample 1 using Acurex data.

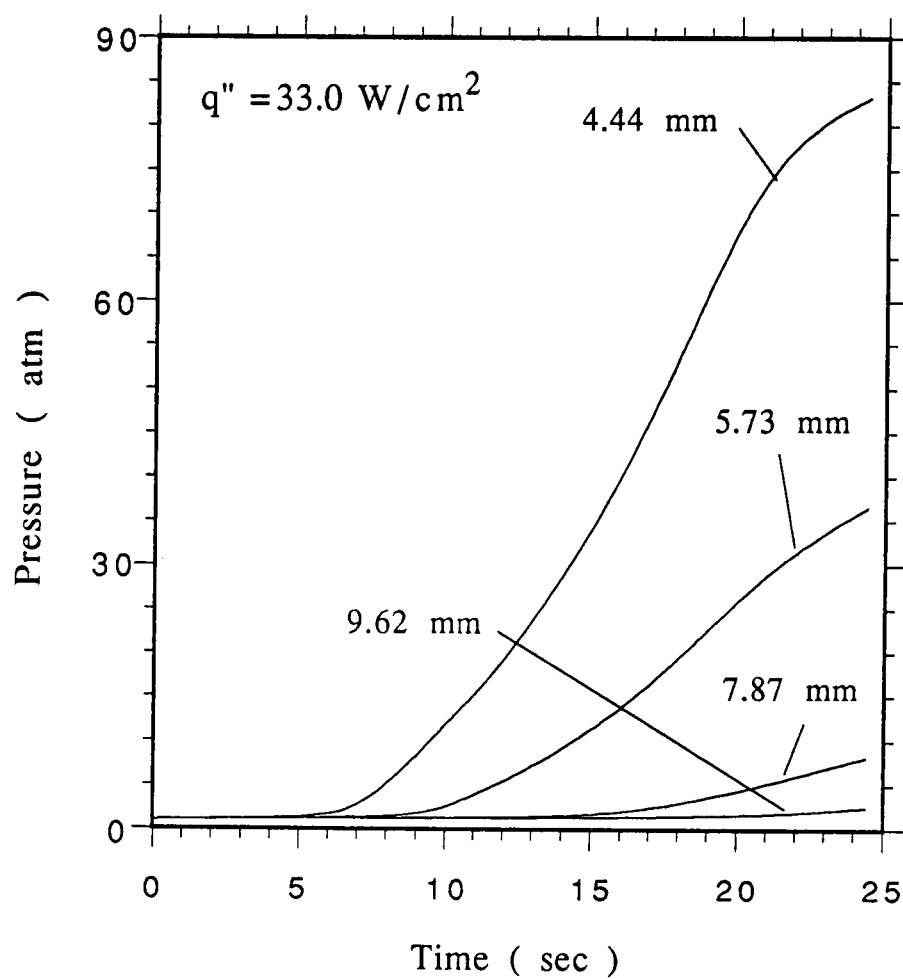


Figure 5.22. Pressure predictions for sample 2 using Acurex data.

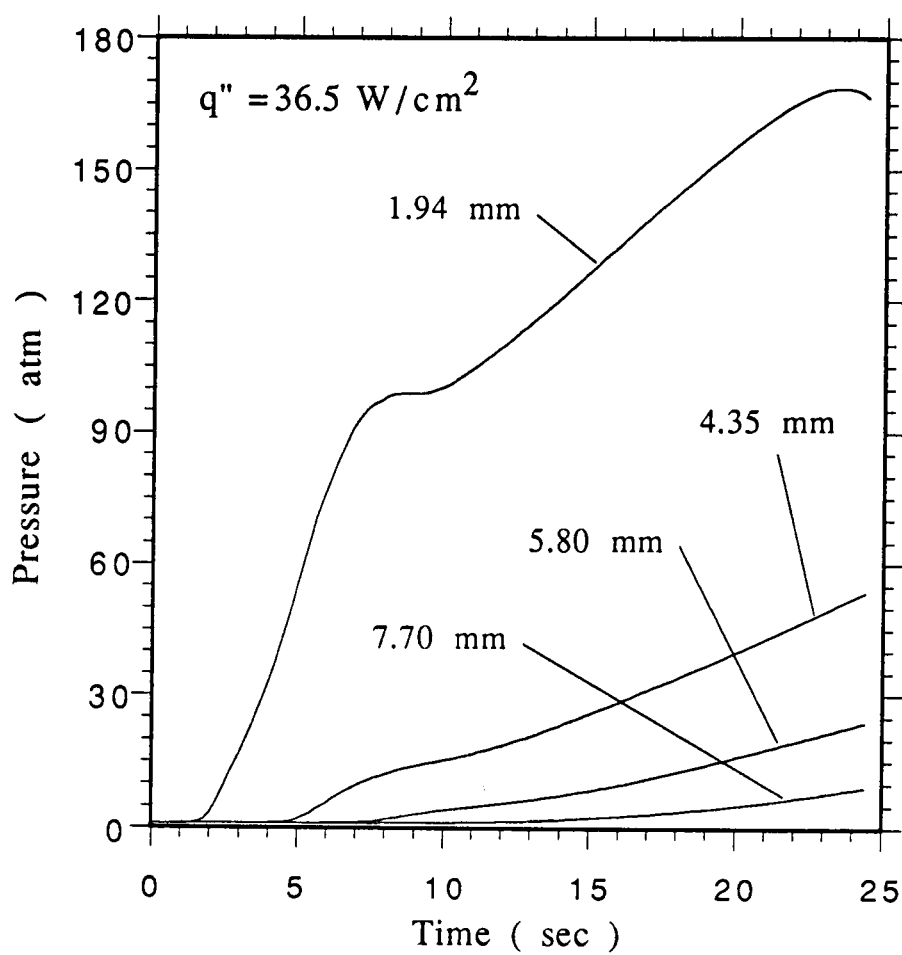


Figure 5.23. Pressure predictions for sample 3 using Acurex data.

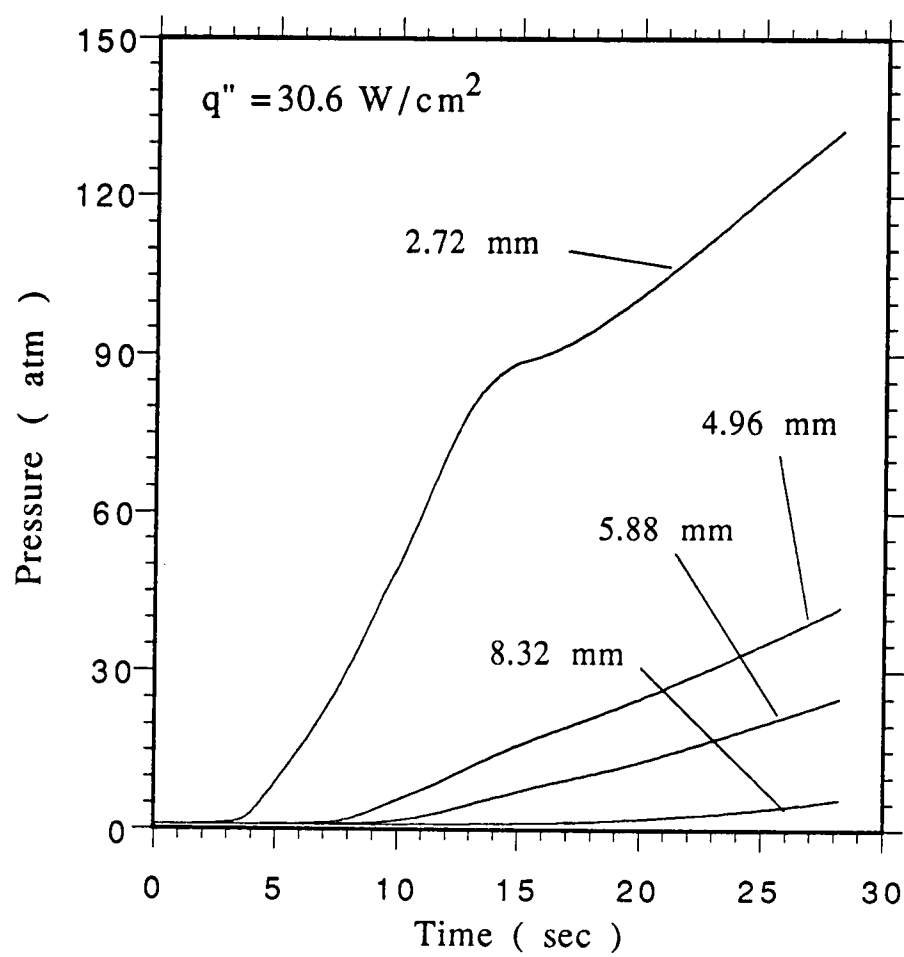


Figure 5.24. Pressure predictions for sample 4 using Acurex data.

layer, has the lowest temperature, and sample 3 has the highest temperature and clearly shows the fluctuations due to the breakdown of the electrical resistance of the mica for time greater than 12 seconds. Smaller amplitude oscillations can be observed in the measured back face temperatures of the other samples. This indicates that electrical leakage, to some extent, was a problem in all the experiments.

The fact that the experimental temperatures were lower than the numerical calculations may be due to uncertainties in the natural convection heat transfer coefficient at the back face ($0.00046 \text{ Btu/ft}^2\text{-sec-R}$), heat absorbed by the ends of the C clamps, 49.8 mm^2 each in area, thermocouple lag time, uncertainties in the thermophysical properties, and experimental uncertainty in the measurement of the thermocouple bead locations. For the numerical model one control volume is 0.13 mm , about equal to the uncertainty in the measurement. Exact location is further complicated because the bead is approximately two control volumes in diameter. During heating the moisture in the samples will absorb heat to vaporize. If 3% of the initial mass were water, then the percent of total heat supplied that would be used to vaporize the water is indicated in Table 5.5. If accounted for, this vaporization would lower the numerical

Table 5.5. Heat absorbed by water vaporization.

Sample	Total Heat Supplied (J)	Heat to vaporize the water (J)	Percent of total heat needed for vaporization
1	6621	800.2	12.1%
2	6457	800.2	12.4%
3	7160	800.2	11.2%
4	6938	800.1	11.5%

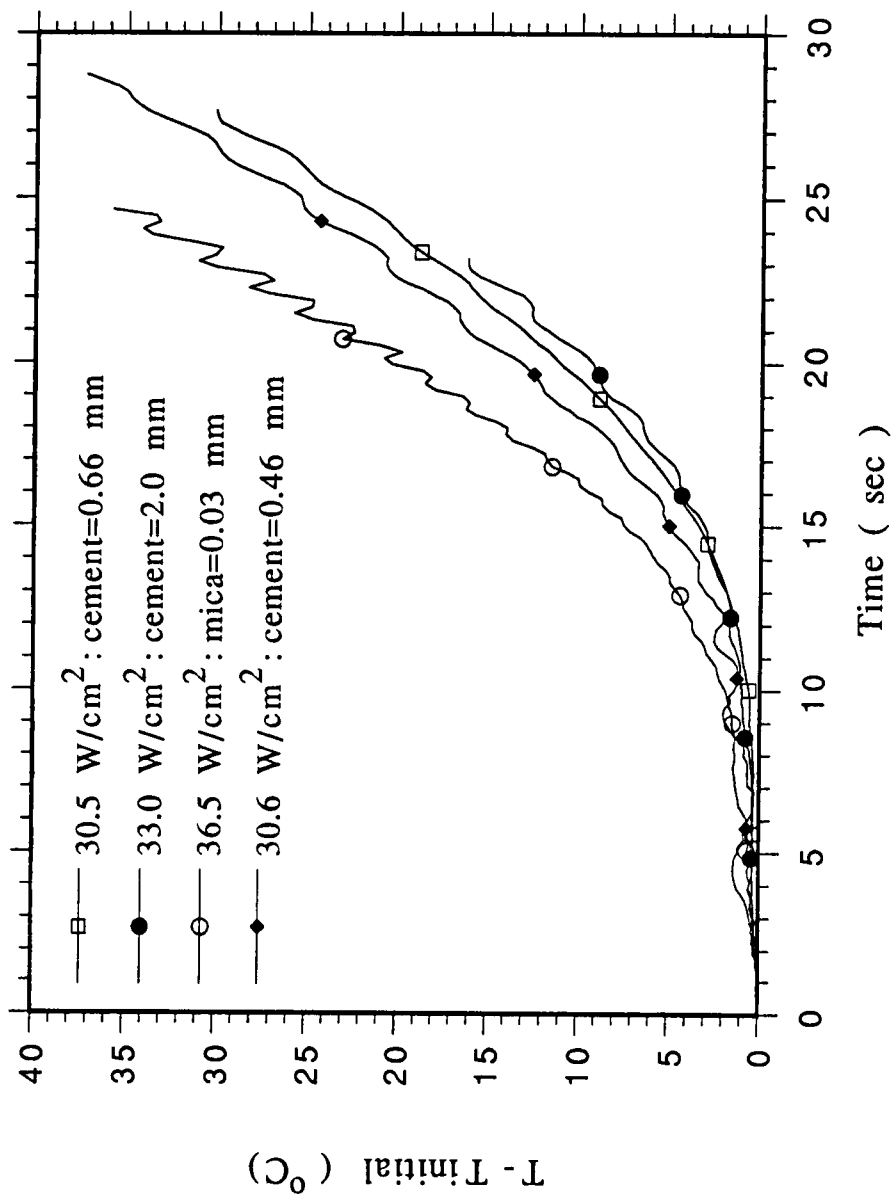


Figure 5.25. Back surface experimental temperatures.

predictions and decrease the difference between numerical and experimental temperatures. Figures 5.7 and 5.8 show the best agreement between experimental and numerical temperatures for sample 2. It was subjected to temperatures which would not vaporize all the water, and the experimental temperatures were not affected as much by vaporization as they were for the other samples. The properties of the mica and cement do not seem to be as constant as assumed. For the first thermocouple electrical leakage is a major concern in matching the experimental and numerical temperatures. Considering these uncertainties there is a good correlation between the numerical predictions and the experimental data.

Chapter 6

Conclusions

1. In drying experiments with an oven temperature of 115 °C, the MX 4926 samples with 50% initial relative humidity, on average lost 3.06% in mass due to moisture and samples with 62% initial relative humidity, on average lost 3.16% of their mass . The rate of mass loss fits the equation:

$$m = m_{\text{init}} \left[1 - \frac{(t - t_d)^2}{t_d^2} \right]^n ,$$

where m = percent mass loss
 m_{init} = percent initial moisture
 t = time, days
 t_d = time for complete drying, days
 n = function of porosity

2. Average density of MX 4926 discs was found to be 90.87 lbm/ft³ at 50% relative humidity and 91.28 lbm/ft³ at 62% relative humidity before drying. The average dried density was found to be 88.14 lbm/ft³. The average measured density of MX 4926 blocks was found to be 91.11 lbm/ft³.

3. The average measured initial density of FM 5055 was found to be 91.82 lbm/ft³ compared to a dry density of 89.606 lbm/ft³ as reported by Beck et al (1984).

4. In decomposition experiments the predictions of the surface temperature for MX 4926 and FM 5055 closely approximate the measured

values within the limitations described in chapter four.

5. Mass loss of the FM 5055 and MX 4926 sample 7e in decomposition experiments agrees with the numerical predictions and indicates a moisture content as observed in the drying experiments of the MX 4926 discs.
6. Plylift was observed during furnace heating of the FM 5055, and the numerical pressure calculations correspond to its occurrence.
7. Numerical mass loss due to decomposition and moisture content based on theoretical density of FM 5055 compare well with measured mass loss.
8. In the in-depth experiments, the numerical temperatures are closest for sample 2 with the least decomposition. With electrical leakage the first thermocouple temperatures increase above predictions, and locations farther from the foil are below predictions. The fact that the experimental temperatures were lower than the numerical calculations may be due to uncertainties in the natural convection heat transfer coefficient at the back face ($0.00046 \text{ Btu/ft}^2\text{-sec-R}$), heat absorbed by the ends of the C clamps, 49.8 mm^2 each in area, thermocouple lag time, uncertainties in the thermophysical properties, and experimental uncertainty in the measurement of the thermocouple bead locations. Considering the stated uncertainties there is a good correlation between the numerical predictions and the experimental data.

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17. Stokes, E.H., "The Physical, Mechanical, and Thermal Properties of the FM 5055 404 Aft Inlet Ring", Southern Research Institute, SRI-EAS-88-201-6032-1, March 1988.
18. Stokes, E.H., "Prediction of Plylift Temperature in Two Dimensional Polymeric Composites", Southern Research Institute, 1989 JANNAF

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19. Stokes, E.H., and Puckett, A.N., "Mechanical and Thermal Property Differences Between TEM-7 and FSM-1 and Possible Implications to Plylift", 1991 JANNAF Rocket Nozzle Technology Subcommittee Meeting, November 5-7, 1991.
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Appendices

Appendix A.1.

MX 4926 PROPERTIES

Reference: Beck, Johnson, Gordon and Laub, "IUS Nozzle Materials Thermal Characterization", Acurex Final Report FR-84-21/A TD, August 1984.

DECOMPOSITION KINETIC DATA, From Reference, Table C-1.

React	ρ_{vi} lb/ft ³	ρ_{ci} lb/ft ³	A_i 1/sec	Ψ_i	E_i/R R	T REACT R
1	23.696	0.0	2.125E4	2.79	20479.0	717.14
2	16.984	0.0	1.9409E7	2.88	30714.0	1075.8
3	118.73	115.014	4.2862E14	1.63	75214.0	1860.1

VIRGIN HEAT OF FORMATION, From Reference, Appendix C.3
-349.92 BTU/lbm

CHAR HEAT OF FORMATION, From Reference, Appendix C.3
0.0 BTU/lbm

RESIN FRACTION, From Reference, Appendix C
0.36192

VIRGIN WITH PLY THERMAL CONDUCTIVITY, From Reference, Table C-5.

T, R	k, BTU/ft-s-R
500	0.0002641
800	0.0002920
1000	0.0003190
1200	0.0003220
1500	0.0003220
2000	0.0003220

VIRGIN ACROSS PLY THERMAL CONDUCTIVITY, From Reference, Table C-5.

T, R	k, BTU/ft-s-R
500	0.0000880
800	0.0001001
1000	0.0001202
1200	0.0001214
1500	0.0001214
2000	0.0001214

CHAR WITH PLY THERMAL CONDUCTIVITY, From Reference, Table C-5.

T, R	k, BTU/ft-s-R
500	0.000322
800	0.000322
1000	0.000322
1200	0.000322
1500	0.000322
2000	0.000400
2500	0.000620
3000	0.001040
3500	0.001480
4000	0.001900

CHAR ACROSS PLY THERMAL CONDUCTIVITY, From Reference, Table C-5.

T, R	k, BTU/ft-s-R
500	0.0001214
800	0.0001214
1000	0.0001214
1200	0.0001260
1500	0.0001329
2000	0.0001835
2500	0.0003543
3000	0.0004986
3500	0.0006794
4000	0.0007958

VIRGIN HEAT CAPACITY, From Reference, Table C-4.

T, R	c, BTU/lbm-R
460.0	0.4100
2000.0	0.4100
3000.0	0.4930
3500.0	0.4955
4000.0	0.4980

CHAR HEAT CAPACITY, From Reference, Table C-4.

T, R	c, BTU/lbm-R
460.0	0.4100
2000	0.4100
3000	0.4930
3500	0.4955
4000	0.4980

PYROLYSIS GAS ENTHALPY, From Reference, Table C-3.

T, R	h, BTU/lbm
530.0	-1574.2
1000.0	-1175.4
1500.0	-665.1
2000.0	-66.00
2500.0	470.00
3000.0	880.00
3500.0	1260.0
4050.0	1711.1
4500.0	2165.1
4950.0	2707.7
5400.0	3415.3
5850.0	4379.2
6300.0	5698.5
6750.0	7462.8
7300.0	9717.4

Appendix A.2.

FM 5055 PROPERTIES

- Reference 1: Beck, Johnson, Gordon and Laub, "IUS Nozzle Materials Thermal Characterization", Acurex Final Report FR-84-21/A TD, August 1984.
- Reference 2: Stokes, E.H., "Gas Permeability of FM 5055 (Pre-Avtec Shutdown) Carbon Phenolic Composite in the Fill Direction as a Function of Across-Ply Compressive Load", Southern Research Institute, SRI-MME-91-056-6672-003, January 1991.
- Reference 3: Stokes, E.H., "The Physical, Mechanical, and Thermal Properties of the FM 5055 404 Aft Inlet Ring", Southern Research Institute, SRI-EAS-88-201-6032-1, March 1988.
- Reference 4: Stokes, E. H., "Compressibility of Carbon Phenolic Pyrolysis Gas Products and a Discussion of Other Factors Contributing to Internal Gas Pressure Calculations", JANNAF RNTS Meeting, Pasadena, CA, 1990.
- Reference 5: Ross, Robert and Strobel, Forrest, "CMA90S Input Guide and User's Manual", Acurex Corporation, Aerotherm Division, Huntsville Operations, December 1990.

DECOMPOSITION KINETIC DATA, From Reference 1, Table 5-1.

React	ρ_{vi} lb/ft ³	ρ_{ci} lb/ft ³	A_i 1/sec	Ψ_i	E_i/R R	T REACT R
1	15.476	0.0	0.2171E2	1.92	0.8329E4	536.14
2	0.0	0.0	1.0	1.00	1.0	9999.9
3	139.282	118.981	0.9535E11	3.10	0.3480E5	1009.4

VIRGIN HEAT OF FORMATION, From Reference 1, Section 5.1.3.
-391.72 BTU/lbm

CHAR HEAT OF FORMATION, From Reference 1, Section 5.1.3.
0.0 BTU/lbm

RESIN FRACTION, From Reference 1, Section 5.1.1.
0.40124

VIRGIN WITH PLY THERMAL CONDUCTIVITY, From Reference 3, Fig 3.2-2.

T, R	k, BTU/ft-s-R
610.0	0.000181
760.0	0.000238
860.0	0.000248
960.0	0.000248
1060.0	0.000245
1160.0	0.000241

VIRGIN ACROSS PLY THERMAL CONDUCTIVITY, From Reference 3, Fig 3.2-1.

T, R	k, BTU/ft-s-R
610.0	0.000130
760.0	0.000148
860.0	0.000157
960.0	0.000164
1060.0	0.000167
1160.0	0.000162

CHAR WITH PLY THERMAL CONDUCTIVITY, From Reference 3, Fig 3.2-5.

T, R	k, BTU/ft-s-R
660.0	0.000257
860.0	0.000299
1060.0	0.000324
1260.0	0.000354
1460.0	0.000377
1660.0	0.000403
1960.0	0.000440

CHAR ACROSS PLY THERMAL CONDUCTIVITY, From Reference 3, Fig 3.2-4.

T, R	k, BTU/ft-s-R
660.0	0.000153
860.0	0.000188
1060.0	0.000218
1260.0	0.000243
1460.0	0.000264
1660.0	0.000269
1960.0	0.000269

VIRGIN HEAT CAPACITY, From Reference 3, Fig 3.3-2.

T, R	c, BTU/lbm-R
560.0	0.230
660.0	0.285
760.0	0.310
860.0	0.328
960.0	0.345
1060.0	0.355

CHAR HEAT CAPACITY, From Reference 3, Fig 3.3-4.

T, R	c, BTU/lbm-R
560.0	0.205
660.0	0.240
760.0	0.272
860.0	0.295
960.0	0.320
1060.0	0.345
1160.0	0.360
1260.0	0.375
1360.0	0.388
1460.0	0.400
1560.0	0.410
1660.0	0.420
1760.0	0.424
1860.0	0.429
1960.0	0.432

PYROLYSIS GAS ENTHALPY, From Reference 1, Table 5-3.

T, R	h, BTU/lbm
900.0	-1182.5
1080.0	-940.0

T, R	h, BTU/lbm
1260.0	-693.6
1440.0	-428.1
1620.0	-172.6
1800.0	83.6
1980.0	351.3
2160.0	614.8
2340.0	870.0
2520.0	1140.0
2700.0	1375.0
3600.0	2654.5
4500.0	3519.5
5400.0	4604.2
6300.0	6554.3
6750.0	8224.1

POROSITY OF SOLID, From Reference 3, Table 3.13-2.

Degree of Char	Phi
0.000	0.01
1.000	0.345

WITH PLY PERMEABILITY, From Reference 2, Reduced data, Table 3.2.1.

Heating rate = 0.1 °F/sec

Degree of Char	K, ft ²
0.00000	9.078E-17
0.00045	7.393E-17
0.00297	7.571E-17
0.01049	6.984E-17
0.02909	6.963E-17
0.06751	6.343E-17
0.13191	4.803E-17
0.21441	2.503E-17
0.72533	1.662E-14
0.82908	2.287E-14
0.89303	9.506E-14
0.93131	2.184E-13
0.99182	1.131E-12

ACROSS PLY PERMEABILITY, With ply permeability divided by 100.

Degree of Char	K, ft ²
0.00000	9.078E-19
0.00045	7.393E-19
0.00297	7.571E-19
0.01049	6.984E-19
0.02909	6.963E-19
0.06751	6.343E-19
0.13191	4.803E-19
0.21441	2.503E-19
0.72533	1.662E-16
0.82908	2.287E-16
0.89303	9.506E-16
0.93131	2.184E-15
0.99182	1.131E-14

PYROLYSIS GAS MOLECULAR WEIGHT, From Reference 4, Fig. 7.

T, R	M, lbm/mole
1210.0	32.0
1460.0	26.0

PYROLYSIS GAS VISCOSITY, From Reference 5, Sample 2.

T, R	μ , lbf-s/ft ²
500.0	3.366E-7
720.0	4.127E-7
2880.0	9.988E-7
3600.0	1.151E-6
4320.0	1.299E-6
5040.0	1.450E-6
5760.0	1.618E-6
6500.0	1.713E-6

THERMAL EXPANSION (IN/IN), From Reference 3, Figure 3.15.1-9.

Heating rate = 10 °F/sec

T, R	strain
530.000	0.
560.000	5.00000E-05
660.000	9.50000E-04
760.000	2.20000E-03
860.000	5.30000E-03
960.000	0.0195000
1060.00	5.00000E-02
1160.00	5.02000E-02
1260.00	4.85000E-02
1360.00	5.10000E-02
1460.00	5.40000E-02
1560.00	4.40000E-02
1660.00	1.04300E-02
1860.00	-2.00000E-03
2060.00	-8.30000E-03
2260.00	-1.14000E-02
2460.00	-1.30000E-02
2960.00	-1.60000E-02
3460.00	-1.70000E-02
3960.00	-1.82000E-02
4460.00	-2.12000E-02
4960.00	-3.00000E-02
5460.00	-3.95000E-02

Appendix A.3.

FM 5055 PROPERTIES (Acurex Data)

Reference: Beck, Johnson, Gordon and Laub, "IUS Nozzle Materials Thermal Characterization", Acurex Final Report FR-84-21/A TD, August 1984.

DECOMPOSITION KINETIC DATA, From Reference, Table 5-1.

	ρ_{vi}	ρ_{ci}	A_i	Ψ_i	E_i/R	T REACT
React	lb/ft ³	lb/ft ³	1/sec		R	R
1	15.476	0.0	0.2171E2	1.92	0.8329E4	536.14
2	0.0	0.0	1.0	1.00	1.0	9999.9
3	139.282	118.981	0.9535E11	3.10	0.3480E5	1009.4

VIRGIN HEAT OF FORMATION, From Reference, Section 5.1.3.
-391.72 BTU/lbm

CHAR HEAT OF FORMATION, From Reference, Section 5.1.3.
0.0 BTU/lbm

RESIN FRACTION, From Reference, Section 5.1.1.
0.40124

VIRGIN WITH PLY THERMAL CONDUCTIVITY, From Reference, Table 5-5.

T, R	k, BTU/ft-s-R
500.0	0.0001729
800.0	0.0002190
1000.0	0.0002320
1200.0	0.0002500
1500.0	0.0002500
2000.0	0.0002500

VIRGIN ACROSS PLY THERMAL CONDUCTIVITY, From Reference, Table 5-5.

T, R	k, BTU/ft-s-R
500.0	0.0001295
800.0	0.0001721
1000.0	0.0001761
1200.0	0.0001784
1500.0	0.0001830
2000.0	0.0001830

CHAR WITH PLY THERMAL CONDUCTIVITY, From Reference, Table 5-5.

T, R	k, BTU/ft-s-R
500.0	0.0002500
800.0	0.0002500
1000.0	0.0002500
1200.0	0.0002700
1500.0	0.0003000
2000.0	0.0004000
2500.0	0.0006000
3000.0	0.0009000

T, R	k, BTU/ft-s-R
3500.0	0.0013500
4000.0	0.0016000
4500.0	0.0018100
5000.0	0.0020200

CHAR ACROSS PLY THERMAL CONDUCTIVITY, From Reference, Table 5-5.

T, R	k, BTU/ft-s-R
500.0	0.0001830
800.0	0.0001830
1000.0	0.0001830
1200.0	0.0001824
1500.0	0.0001814
2000.0	0.0002969
2500.0	0.0004763
3000.0	0.0006525
3500.0	0.0007417
4000.0	0.0008576
4500.0	0.0009645
5000.0	0.0010714

VIRGIN HEAT CAPACITY, From Reference, Table 5-4.

T, R	c, BTU/lbm-R
460.0	0.250
530.0	0.257
800.0	0.351
1000.0	0.421
1160.0	0.450
1500.0	0.460
2000.0	0.470
2500.0	0.482
3000.0	0.493
3500.0	0.495
4000.0	0.498
5000.0	0.500

CHAR HEAT CAPACITY, From Reference, Table 5-4.

T, R	c, BTU/lbm-R
460.0	0.175
530.0	0.187
800.0	0.261
1000.0	0.315
1160.0	0.342
1500.0	0.400
2000.0	0.434
2500.0	0.464
3000.0	0.493
3500.0	0.495
4000.0	0.498
5000.0	0.500

Appendix B

Input and Output

Entries in the input file listed in this appendix are explained below.

C Title of input file
 sample 4 'sam4in' at heat flux = 30.6W/cm²
 INPUT DATA FOR FM 5055 with convection, decomposition, and radiation

C node numbers in x and y, inner radius, outer radius, height,
 C progression ratio in x and y

M	N	RI(FT)	RO(FT)	H(FT)	PX DIRECTX	PY DIRECTY
9	91	10.0	10.03312	0.0345	1.0 1.0	1.0 1.0

C boundary pressure, char porosity, strain coefficient, Stefan-
 C Boltzmann constant, initial pressure, heats of formation

PINF	PHIC	PNU	EPSIG	PINIT (lbf/ft ²)	HV	HFC
2120.0	0.345	0.31	4.7583E-13	2120.0	-391.2	0.0

C initial and residual density of components 1,2,3

RHOI 1	RHOI 2	RHOI 3	RHOR 1	RHOR 2	RHOR 3 (LBM/FT ³)
15.476	0.0	139.282	0.0	0.0	118.981

C volume fraction, activation energy, reaction order kinetic constants

GAMMA	E 1	E 2	E 3	PSI 1	PSI 2	PSI 3
0.40124	8329.0	1.0	34800.0	0.92	1.0	3.1

C kinetic constants, decomposition cutoff temperatures, enthalpy
 C reference temperature

B1	B2	B3	T1CUT	T2CUT	T3CUT	TREF (R)
21.71	1.0	.9535E+11	536.14	9999.9	1009.4	530.0

C relaxation factor, convergence tolerance, decomposition factor,
 C choose to read permeability, read stress, rectangular coordinates,
 C constant heat transfer coefficient =HCOEFF= 0

WP	ERROR	REWDTR	EXP PERMEABILITY	STRESS RECTANGLE	HCOEFF
1.0	0.01	1.0	1.0	1.0	1 0

C time step, heating rate, initial temperature, initial porosity
 C ,initial permeability, and heat cutoff time

DELT(SEC)	HRATE	TI (R)	PHI	PERMI	TCUT (SEC)
0.1	0.0	530.7	0.01	9E-17	900.0

C write to output file parameters for time step,x nodes,y nodes,time,
 C include endothermic term = 0, include convective term = 0

JSTEP	MSTEP	NSTEP	LPSTEP	NOENDO	NOCONV
1	2	5	2	0	0

C assign corner boundary conditions to match a side

CORNERS	1,1	1,N	M,N	M,1 (1=X,2=Y)
	1	2	2	1

C ambient temperature for each side

TINFW	TINFN	TINFE	TINFS (R)
530.7	530.7	530.7	530.7

C surrounding temperature for radiation for each side

TSURRW	TSURRN	TSURRE	TSURRS (R)
530.7	530.7	530.7	530.7

C heat flux for each side

CONSTANT HEAT INPUT (BTU/FT²-SEC) W,N,E,S
0.0 0.0 0.0 26.93

C view factors for each side

VIEW FACTORS SIDE 1,2,3,4,5,6
1.0 1.0 1.0 1.0 1.0 1.0

C emissivity for each side

EMISSIVITY SIDE 1,2,3,4,5,6
0.00 0.9000 0.9000 0.00 0.000 0.000

C heat transfer coefficient for each side

HEAT TRANSFER COEFFICIENT (BTU/FT-SEC) W,N,E,S
0.00 0.000460 0.000703 0.00

C pressure coefficient(0.0 = impermeable, 1.0 = permeable)

PRESSURE COEFFICIENT W,N,E,S
0.0 1.0 1.0 0.0

C input mass flow on each boundary

MASS FLOW IN (LB/SEC) W,N,E,S
0.0 0.0 0.0 0.0

Each set of properties is read into an array for later interpolation of the properties. The title and number of entries precedes the values as shown below.

VIRGIN HEAT CAPACITY (BTU/LBM-R)

6

560.000	0.23000
660.000	0.285000
760.000	0.310000
860.000	0.328000
960.000	0.345000
1060.00	0.355000

sample 4 'sam4in' at heat flux = 30.6W/cm²

INPUT DATA FOR FM 5055 with convection, decomposition, and radiation

```

M N RI(FT) RO(FT) H(FT) PX DIRECTX PY DIRECTY
9 91 10.0 10.03312 0.0345 1.0 1.0 1.0 1.0
PINF PHIC PNU EPSIG PINIT ( lbf/ft^2 ) HFV HFC
2120.0 0.345 0.31 4.7583E-13 2120.0 -391.2 0.0
RHOI1 RHOI2 RHOI3 RHOR1 RHOR2 RHOR3 ( LBM/FT^3 )
15.476 0.0 139.282 0.0 0.0 118.981
GAMMA E1 E2 E3 PSI1 PSI2 PSI3
0.40124 8329.0 1.0 34800.0 92 1.0 3.1
B1 B2 B3 T1CUT T2CUT T3CUT TREF (R)
21.71 1.0 .9535E+11 536.14 9999.9 1009.4 530.0
WP ERROR REWDTR EXP PERMEABILITY STRESS RECTANGLE HCOEFF
1.0 0.01 1.0 1.0 1.0 1.0 1 0
DELT(SEC) HRATE TI (R) PHII PERMI TCUT (SEC)
0.1 0.0 530.7 0.01 9E-17 900.0
JSTEP MSTEP NSTEP LPSTEP NOENDO NOCONV
1 2 5 2 0 0
CORNERS 1,1 1,N M,N M,1 (1=X,2=Y)
1 2 2 1
TINFW TINFN TINFE TINFS (R)
530.7 530.7 530.7 530.7
TSURRW TSURRN TSURRE TSURRS (R)
530.7 530.7 530.7 530.7
CONSTANT HEAT INPUT (BTU/FT^2-SEC) W,N,E,S
0.0 0.0 0.0 26.93
VIEW FACTORS SIDE 1,2,3,4,5,6
1.0 1.0 1.0 1.0 1.0 1.0
EMISSIVITY SIDE 1,2,3,4,5,6
0.00 0.9000 0.9000 0.00 0.000 0.000
HEAT TRANSFER COEFFICIENT (BTU/FT-SEC) W,N,E,S
0.00 0.000460 0.000703 0.00
PRESSURE COEFFICIENT W,N,E,S
0.0 1.0 1.0 0.0
MASS FLOW IN (LB/SEC) W,N,E,S
0.0 0.0 0.0 0.0
VIRGIN HEAT CAPACITY ( BTU/LBM-R)
6
560.000 0.23000
660.000 0.285000
760.000 0.310000
860.000 0.328000
960.000 0.345000
1060.00 0.355000
CHAR HEAT CAPACITY ( BTU/LBM-R )
15
560.000 0.205000
660.000 0.240000
760.000 0.272000

```

860.000	0.295000
960.000	0.320000
1060.00	0.345000
1160.00	0.360000
1260.00	0.375000
1360.00	0.388000
1460.00	0.400000
1560.00	0.410000
1660.00	0.420000
1760.00	0.424000
1860.00	0.429000
1960.00	0.432000

CHAR ACROSS PLY THERMAL CONDUCTIVITY (BTU/FT-SEC-R)

5

660.000	1.53000E-04
860.000	1.88000E-04
1060.00	2.18000E-04
1260.00	2.43000E-04
1460.00	2.64000E-04

VIRGIN ACROSS PLY THERMAL CONDUCTIVITY (BTU/FT-SEC-R)

6

610.000	1.30000E-04
760.000	1.48000E-04
860.000	1.57000E-04
960.000	1.64000E-04
1060.00	1.67000E-04
1160.00	1.62000E-04

VIRGIN WITH PLY THERMAL CONDUCTIVITY (BTU/FT-SEC-R)

6

610.000	1.81000E-04
760.000	2.38000E-04
860.000	2.48000E-04
960.000	2.48000E-04
1060.00	2.45000E-04
1160.00	2.41000E-04

CHAR WITH PLY THERMAL CONDUCTIVITY (BTU/FT-SEC-R)

7

660.000	2.57000E-04
860.000	2.99000E-04
1060.00	3.24000E-04
1260.00	3.54000E-04
1460.00	3.77000E-04
1660.00	4.03000E-04
1960.00	4.40000E-04

PYROLYSIS GAS ENTHALPY (BTU/LBM)

10

530.000	-1574.20
1000.00	-1175.40
1500.00	-665.100
2000.00	-66.0000
2160.00	151.000

2500.00	470.000
---------	---------

3000.00	880.000
---------	---------

3500.00	1260.000
---------	----------

4050.00	1711.700
---------	----------

4500.00	2165.100
---------	----------

AIR CONDUCTIVITY (BTU/FT²-SEC)

15

541.000	4.22000E-06
---------	-------------

631.000	4.81500E-06
---------	-------------

721.000	5.42500E-06
---------	-------------

811.000	5.98700E-06
---------	-------------

901.000	6.53200E-06
---------	-------------

991.000	7.04600E-06
---------	-------------

1081.00	7.52800E-06
---------	-------------

1171.00	7.97700E-06
---------	-------------

1261.00	8.41000E-06
---------	-------------

1351.00	8.81100E-06
---------	-------------

1441.00	9.19700E-06
---------	-------------

1531.00	9.56500E-06
---------	-------------

1621.00	9.95100E-06
---------	-------------

1711.00	1.03200E-05
---------	-------------

1801.00	1.07100E-05
---------	-------------

COMPRESSIVE MODULUS (LBF/FT²)

17

0.00000	2.01000E+06
---------	-------------

0.00003	2.12000E+06
---------	-------------

0.00009	2.01000E+06
---------	-------------

0.00053	1.75000E+06
---------	-------------

0.00167	1.06000E+06
---------	-------------

0.00519	3.90000E+05
---------	-------------

0.01115	2.70000E+05
---------	-------------

0.02107	2.40000E+05
---------	-------------

0.02378	2.50000E+05
---------	-------------

0.04364	2.00000E+05
---------	-------------

0.06964	1.60000E+05
---------	-------------

0.09332	1.40000E+05
---------	-------------

0.12849	1.30000E+05
---------	-------------

0.17602	1.20000E+05
---------	-------------

0.26711	1.00000E+05
---------	-------------

0.42852	9.70000E+04
---------	-------------

0.59953	9.90000E+04
---------	-------------

PERMEABILITY WITH PLY (CM²)

18

0.00000	8.43400E-14
---------	-------------

0.00045	6.86800E-14
---------	-------------

0.00297	7.03400E-14
---------	-------------

0.01049	6.48800E-14
---------	-------------

0.02909	6.46900E-14
---------	-------------

0.06751	5.89300E-14
---------	-------------

0.13191	4.46200E-14
---------	-------------

0.21441	2.32500E-14
---------	-------------

0.72533	1.54400E-11
0.82908	2.12500E-11
0.89303	8.83100E-11
0.93131	2.02900E-10
0.95460	3.66100E-10
0.96917	5.98900E-10
0.97855	7.99600E-10
0.98474	8.75600E-10
0.98893	1.05000E-09
0.99182	1.21700E-09

THERMAL EXPANSION (IN/IN)

23

530.000	0.
560.000	5.00000E-05
660.000	9.50000E-04
760.000	2.20000E-03
860.000	5.30000E-03
960.000	0.0195000
1060.00	5.00000E-02
1160.00	5.02000E-02
1260.00	4.85000E-02
1360.00	5.10000E-02
1460.00	5.40000E-02
1560.00	4.40000E-02
1660.00	1.04300E-02
1860.00	-2.00000E-03
2060.00	-8.30000E-03
2260.00	-1.14000E-02
2460.00	-1.30000E-02
2960.00	-1.60000E-02
3460.00	-1.70000E-02
3960.00	-1.82000E-02
4460.00	-2.12000E-02
4960.00	-3.00000E-02
5460.00	-3.95000E-02

PYROLYSIS GAS VISCOSITY (LBF-SEC/FT^2)

8

500.000	3.36600E-07
720.000	4.12700E-07
2880.00	9.98800E-07
3600.00	1.15100E-06
4320.00	1.29900E-06
5040.00	1.45000E-06
5760.00	1.61800E-06
6500.00	1.71300E-06

PYROLYSIS GAS MOLECULAR WEIGHT (LBM/MOLE)

2

1210.000	32.0
1460.000	26.0

sample 4 'sam4in' at heat flux = 30.6W/cm²
 OUTPUT DATA FOR FM 5055 with convection, decomposition, and
 radiation

M	N	RI(FT)	RO(FT)	H(FT)	PX DIRECTX	PY DIRECTY		
9	91	10.00000	10.03312	0.03450	1.00	1.00	1.00	1.00
PINF	PHIC	PNU	EPSIG	PINIT (lbf/ft ²)	HFV		HFC	
2120.0	0.345	0.310	0.4758E-12	2120.000	-391.200		0.000	
RHOI1	RHOI2	RHOI3		RHOR1	RHOR2		RHOR3 (LBM/FT ³)	
15.476	0.000	139.282	0.000	0.000			118.981	
GAMMA	E1	E2	E3	PSI1	PSI2		PSI3	
0.40124	0.833E+04	1.0	0.348E+05	1.920	1.000		3.100	
B1	B2	B3	T1CUT	T2CUT	T3CUT		TREF (R)	
0.217E+02	1.0	0.954E+11	536.14	9900.00	1009.00		530.00	
WP	ERROR	REWDTR	EXP PERMEABILITY	STRESS	RECTANGLE		HCOEFF	
1.000	0.100E-01	1.0000	1.000	1.000	1.0		0.0	
DELT(SEC)	HRATE	TI (R)	PHII	PERMI			TCUT (SEC)	
0.100	0.000	530.700	0.010	0.900E-16			900.000	
JSTEP	MSTEP	NSTEP		LPSTEP			NOENDO	NOCONV
1	2	5		2			0	0
CORNERS 1,1 1,N M,N M,1 (1=X,2=Y)								
1.000	2.000	2.000	1.000					
TINFW	TINFN	TINFE		TINFS (R)				
530.700	530.700	530.700		530.700				
TSURRW	TSURRN	TSURRE		TSURRS (R)				
530.700	530.700	530.700		530.700				
CONSTANT HEAT INPUT (BTU/FT ² -SEC) W,N,E,S								
0.000	0.000	0.000	26.930					
VIEW FACTORS SIDE 1,2,3,4,5,6								
1.000	1.000	1.000	1.000	1.000	1.000			
EMISSIVITY SIDE 1,2,3,4,5,6								
0.000	0.900	0.900	0.000	0.000	0.000			
HEAT TRANSFER COEFFICIENT (BTU/FT-SEC) W,N,E,S								
0.000	0.00046	0.000703	0.000					
PRESSURE COEFFICIENT W,N,E,S								
0.000	1.000	1.000	0.000					
MASS FLOW IN (LB/SEC) W,N,E,S								
0.000	0.000	0.000	0.000					
Y COORDINATES (FT) :								
0.000E+00	0.383E-03	0.767E-03	0.115E-02					
0.153E-02	0.192E-02	0.230E-02	0.268E-02					
0.307E-02	0.345E-02	0.383E-02	0.422E-02					
0.460E-02	0.498E-02	0.537E-02	0.575E-02					
0.613E-02	0.652E-02	0.690E-02	0.728E-02					
0.767E-02	0.805E-02	0.843E-02	0.882E-02					
0.920E-02	0.958E-02	0.997E-02	0.103E-01					
0.107E-01	0.111E-01	0.115E-01	0.119E-01					
0.123E-01	0.126E-01	0.130E-01	0.134E-01					
0.138E-01	0.142E-01	0.146E-01	0.149E-01					
0.153E-01	0.157E-01	0.161E-01	0.165E-01					
0.169E-01	0.172E-01	0.176E-01	0.180E-01					

0.184E-01	0.188E-01	0.192E-01	0.195E-01
0.199E-01	0.203E-01	0.207E-01	0.211E-01
0.215E-01	0.218E-01	0.222E-01	0.226E-01
0.230E-01	0.234E-01	0.238E-01	0.241E-01
0.245E-01	0.249E-01	0.253E-01	0.257E-01
0.261E-01	0.264E-01	0.268E-01	0.272E-01
0.276E-01	0.280E-01	0.284E-01	0.287E-01
0.291E-01	0.295E-01	0.299E-01	0.303E-01
0.307E-01	0.310E-01	0.314E-01	0.318E-01
0.322E-01	0.326E-01	0.330E-01	0.333E-01
0.337E-01	0.341E-01	0.345E-01	

X COORDINATES (FT) :

0.100E+02	0.100E+02	0.100E+02	0.100E+02
0.100E+02	0.100E+02	0.100E+02	0.100E+02
0.100E+02			

TEMP INF = 70.7 F TIME = 0.00 SEC

TEMPERATURE (F)

J= 91	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 86	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 81	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 76	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 71	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 66	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 61	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 56	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 51	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 46	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 41	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 36	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 31	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 26	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 21	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 16	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 11	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 6	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02
J= 1	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02	0.70700D+02

PRESSURE (PSI)

J= 91	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02
J= 86	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02
J= 81	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02
J= 76	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02
J= 71	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02
J= 66	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02
J= 61	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02
J= 56	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02
J= 51	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02
J= 46	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02
J= 41	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02
J= 36	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02	0.14722D+02

J= 31 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 26 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 21 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 16 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 11 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 6 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 1 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02

TOTAL FLOW (LB/SEC) IN X , Y DIRECTIONS :
 FLOW OUT 0. , 0.

TIME (SEC)	SURR TEMP	DEGREE OF CHAR	MASS LOSS	MAX PRESS (PSF)	SURFACE TEMP (F)	STRAIN
0.00	70.7	0.00000	0.00000	14.722	70.700	0.000D+00

TEMP INF = 70.7 F TIME = 1.00 SEC
 TEMPERATURE (F)

J= 91 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02
 J= 86 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02
 J= 81 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02
 J= 76 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02
 J= 71 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02
 J= 66 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02
 J= 61 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02
 J= 56 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02
 J= 51 0.70701D+02 0.70701D+02 0.70701D+02 0.70701D+02 0.70701D+02
 J= 46 0.70705D+02 0.70705D+02 0.70705D+02 0.70705D+02 0.70705D+02
 J= 41 0.70727D+02 0.70727D+02 0.70727D+02 0.70727D+02 0.70726D+02
 J= 36 0.70826D+02 0.70826D+02 0.70826D+02 0.70825D+02 0.70823D+02
 J= 31 0.71242D+02 0.71242D+02 0.71242D+02 0.71241D+02 0.71233D+02
 J= 26 0.72815D+02 0.72815D+02 0.72815D+02 0.72814D+02 0.72786D+02
 J= 21 0.78020D+02 0.78020D+02 0.78020D+02 0.78017D+02 0.77933D+02
 J= 16 0.92617D+02 0.92617D+02 0.92617D+02 0.92612D+02 0.92415D+02
 J= 11 0.12965D+03 0.12965D+03 0.12965D+03 0.12964D+03 0.12922D+03
 J= 6 0.26175D+03 0.26175D+03 0.26175D+03 0.26172D+03 0.26075D+03
 J= 1 0.35832D+03 0.35832D+03 0.35832D+03 0.35829D+03 0.35725D+03

PRESSURE (PSI)

J= 91 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 86 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 81 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 76 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 71 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 66 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 61 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 56 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 51 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 46 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 41 0.14723D+02 0.14723D+02 0.14723D+02 0.14723D+02 0.14722D+02
 J= 36 0.14726D+02 0.14726D+02 0.14726D+02 0.14726D+02 0.14722D+02

J= 31 0.14739D+02 0.14739D+02 0.14738D+02 0.14736D+02 0.14722D+02
 J= 26 0.14787D+02 0.14787D+02 0.14785D+02 0.14777D+02 0.14722D+02
 J= 21 0.15048D+02 0.15048D+02 0.15041D+02 0.14998D+02 0.14722D+02
 J= 16 0.15755D+02 0.15752D+02 0.15721D+02 0.15546D+02 0.14722D+02
 J= 11 0.17800D+02 0.17783D+02 0.17659D+02 0.17067D+02 0.14722D+02
 J= 6 0.25574D+02 0.25543D+02 0.25315D+02 0.23987D+02 0.14722D+02
 J= 1 0.22701D+02 0.22701D+02 0.22701D+02 0.22700D+02 0.22671D+02

TOTAL FLOW (LB/SEC) IN X , Y DIRECTIONS :
 FLOW OUT 3.0705499221944D-09 , 0.

TIME (SEC)	SURR TEMP	DEGREE OF CHAR	MASS LOSS	MAX PRESS (PSF)	SURFACE TEMP (F)	STRAIN
1.00	70.7	0.00000	0.00000	25.574	358.316	0.000D+00

TEMP INF = 70.7 F TIME = 2.00 SEC

TEMPERATURE (F)

J= 91 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02
 J= 86 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02
 J= 81 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02
 J= 76 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02
 J= 71 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02
 J= 66 0.70701D+02 0.70701D+02 0.70701D+02 0.70701D+02 0.70701D+02
 J= 61 0.70705D+02 0.70705D+02 0.70705D+02 0.70705D+02 0.70705D+02
 J= 56 0.70719D+02 0.70719D+02 0.70719D+02 0.70719D+02 0.70719D+02
 J= 51 0.70767D+02 0.70767D+02 0.70767D+02 0.70766D+02 0.70765D+02
 J= 46 0.70919D+02 0.70919D+02 0.70919D+02 0.70919D+02 0.70914D+02
 J= 41 0.71371D+02 0.71371D+02 0.71371D+02 0.71370D+02 0.71356D+02
 J= 36 0.72603D+02 0.72603D+02 0.72603D+02 0.72600D+02 0.72565D+02
 J= 31 0.75672D+02 0.75672D+02 0.75671D+02 0.75665D+02 0.75581D+02
 J= 26 0.82582D+02 0.82582D+02 0.82582D+02 0.82571D+02 0.82392D+02
 J= 21 0.96552D+02 0.96553D+02 0.96552D+02 0.96536D+02 0.96221D+02
 J= 16 0.12599D+03 0.12599D+03 0.12599D+03 0.12596D+03 0.12532D+03
 J= 11 0.21205D+03 0.21205D+03 0.21205D+03 0.21198D+03 0.21034D+03
 J= 6 0.39603D+03 0.39603D+03 0.39602D+03 0.39588D+03 0.39330D+03
 J= 1 0.49955D+03 0.49955D+03 0.49954D+03 0.49937D+03 0.49669D+03

PRESSURE (PSI)

J= 91 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 86 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 81 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 76 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 71 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 66 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 61 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 56 0.14723D+02 0.14723D+02 0.14723D+02 0.14723D+02 0.14722D+02
 J= 51 0.14724D+02 0.14724D+02 0.14724D+02 0.14724D+02 0.14722D+02
 J= 46 0.14729D+02 0.14729D+02 0.14729D+02 0.14728D+02 0.14722D+02
 J= 41 0.14743D+02 0.14742D+02 0.14742D+02 0.14738D+02 0.14722D+02
 J= 36 0.14780D+02 0.14780D+02 0.14777D+02 0.14766D+02 0.14722D+02

J= 31 0.14899D+02 0.14898D+02 0.14890D+02 0.14855D+02 0.14722D+02
 J= 26 0.15421D+02 0.15416D+02 0.15383D+02 0.15245D+02 0.14722D+02
 J= 21 0.16286D+02 0.16266D+02 0.16165D+02 0.15810D+02 0.14722D+02
 J= 16 0.18671D+02 0.18595D+02 0.18265D+02 0.17308D+02 0.14722D+02
 J= 11 0.35357D+02 0.34927D+02 0.33178D+02 0.28423D+02 0.14722D+02
 J= 6 0.77676D+02 0.77103D+02 0.74531D+02 0.65624D+02 0.14722D+02
 J= 1 0.26619D+02 0.26619D+02 0.26619D+02 0.26614D+02 0.26540D+02

TOTAL FLOW (LB/SEC) IN X , Y DIRECTIONS :
 FLOW OUT 1.7453741493461D-08 , 0.

TIME (SEC)	SURR TEMP	DEGREE OF CHAR	MASS LOSS	MAX PRESS (PSF)	SURFACE TEMP (F)	STRAIN
2.00	70.7	0.00001	0.00000	77.676	499.539	0.000D+00

TEMP INF = 70.7 F TIME = 3.00 SEC
 TEMPERATURE (F)

J= 91 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02
 J= 86 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02 0.70700D+02
 J= 81 0.70701D+02 0.70701D+02 0.70701D+02 0.70701D+02 0.70701D+02
 J= 76 0.70702D+02 0.70702D+02 0.70702D+02 0.70702D+02 0.70702D+02
 J= 71 0.70708D+02 0.70708D+02 0.70708D+02 0.70708D+02 0.70707D+02
 J= 66 0.70723D+02 0.70723D+02 0.70723D+02 0.70723D+02 0.70723D+02
 J= 61 0.70768D+02 0.70768D+02 0.70768D+02 0.70768D+02 0.70766D+02
 J= 56 0.70890D+02 0.70890D+02 0.70890D+02 0.70889D+02 0.70885D+02
 J= 51 0.71199D+02 0.71199D+02 0.71199D+02 0.71197D+02 0.71186D+02
 J= 46 0.71937D+02 0.71937D+02 0.71937D+02 0.71933D+02 0.71906D+02
 J= 41 0.73586D+02 0.73586D+02 0.73586D+02 0.73578D+02 0.73518D+02
 J= 36 0.77021D+02 0.77021D+02 0.77020D+02 0.77006D+02 0.76882D+02
 J= 31 0.83667D+02 0.83667D+02 0.83665D+02 0.83643D+02 0.83411D+02
 J= 26 0.95584D+02 0.95584D+02 0.95582D+02 0.95551D+02 0.95176D+02
 J= 21 0.11760D+03 0.11760D+03 0.11760D+03 0.11755D+03 0.11685D+03
 J= 16 0.17464D+03 0.17465D+03 0.17464D+03 0.17452D+03 0.17283D+03
 J= 11 0.30159D+03 0.30159D+03 0.30158D+03 0.30133D+03 0.29815D+03
 J= 6 0.50181D+03 0.50179D+03 0.50176D+03 0.50138D+03 0.49691D+03
 J= 1 0.60881D+03 0.60879D+03 0.60876D+03 0.60834D+03 0.60375D+03

PRESSURE (PSI)

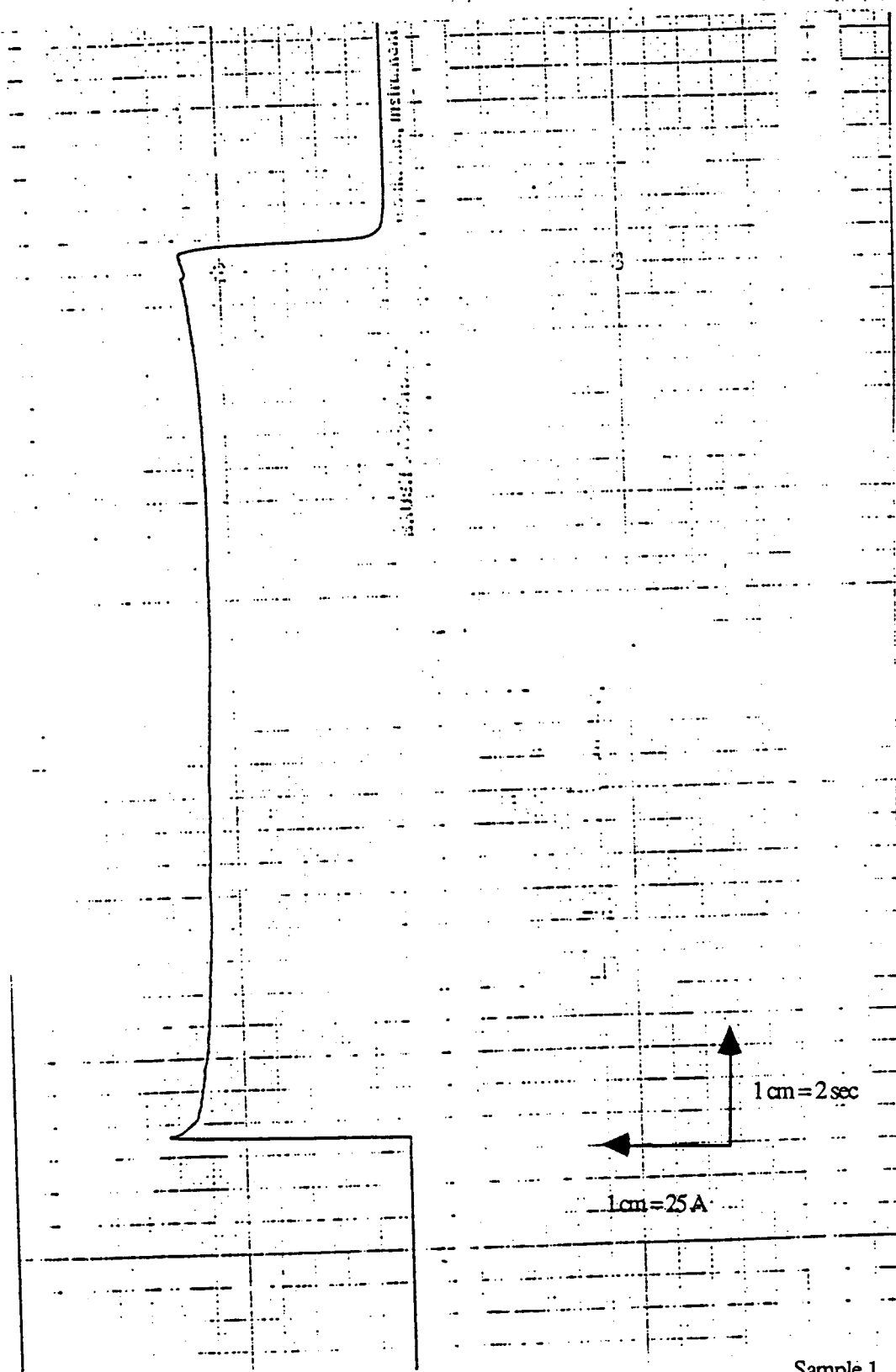
J= 91 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 86 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 81 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 76 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 71 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02 0.14722D+02
 J= 66 0.14723D+02 0.14723D+02 0.14723D+02 0.14723D+02 0.14722D+02
 J= 61 0.14724D+02 0.14724D+02 0.14724D+02 0.14724D+02 0.14722D+02
 J= 56 0.14728D+02 0.14728D+02 0.14728D+02 0.14727D+02 0.14722D+02
 J= 51 0.14737D+02 0.14737D+02 0.14736D+02 0.14733D+02 0.14722D+02
 J= 46 0.14760D+02 0.14759D+02 0.14757D+02 0.14749D+02 0.14722D+02
 J= 41 0.14810D+02 0.14809D+02 0.14803D+02 0.14783D+02 0.14722D+02
 J= 36 0.15057D+02 0.15054D+02 0.15036D+02 0.14970D+02 0.14722D+02

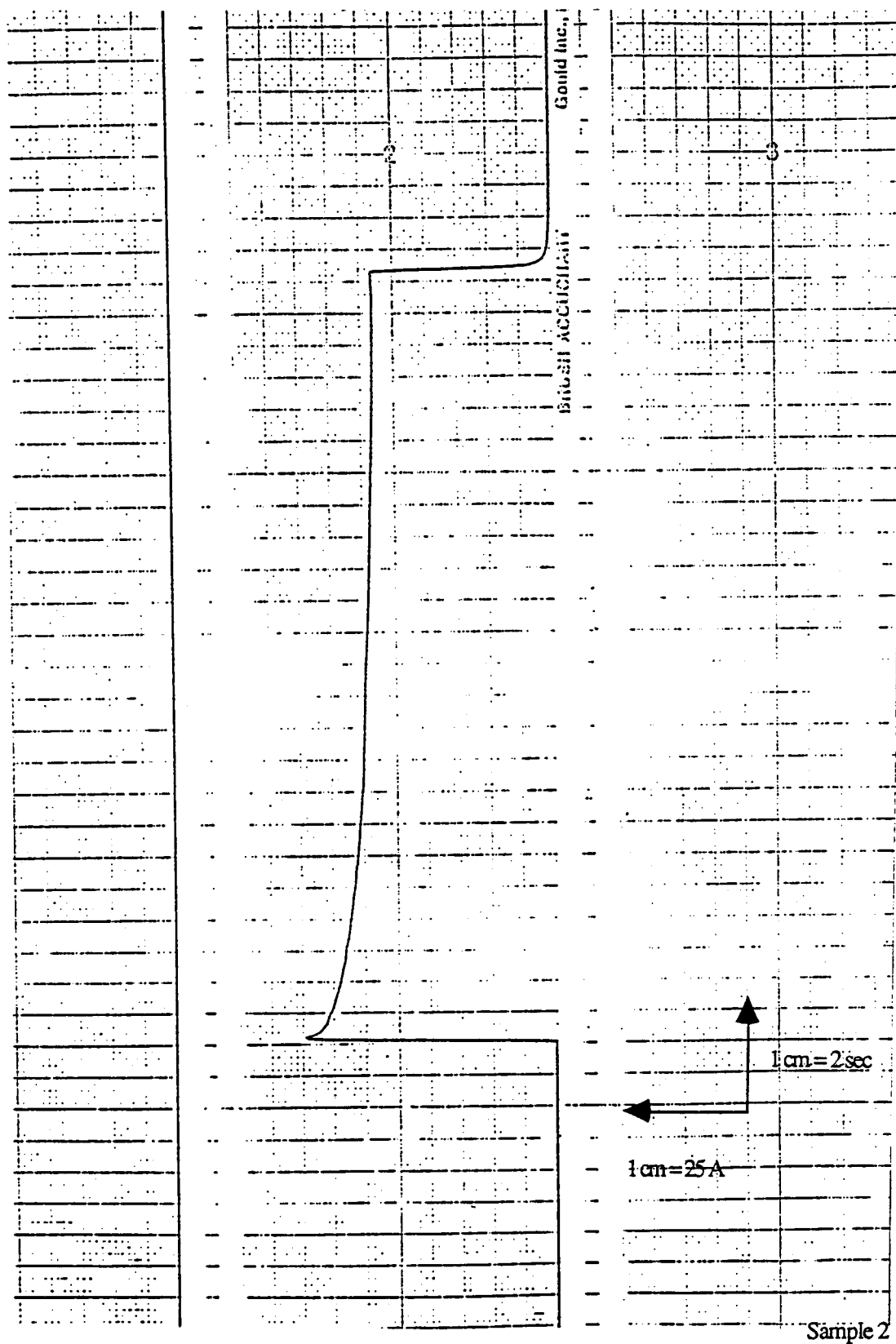
J= 31 0.15641D+02 0.15628D+02 0.15567D+02 0.15359D+02 0.14722D+02
 J= 26 0.16511D+02 0.16476D+02 0.16322D+02 0.15877D+02 0.14722D+02
 J= 21 0.18755D+02 0.18629D+02 0.18176D+02 0.17118D+02 0.14722D+02
 J= 16 0.39379D+02 0.38227D+02 0.34535D+02 0.27655D+02 0.14722D+02
 J= 11 0.11834D+03 0.11529D+03 0.10481D+03 0.81869D+02 0.14722D+02
 J= 6 0.21525D+03 0.21170D+03 0.19878D+03 0.16558D+03 0.14722D+02
 J= 1 0.29650D+02 0.29650D+02 0.29649D+02 0.29637D+02 0.29510D+02

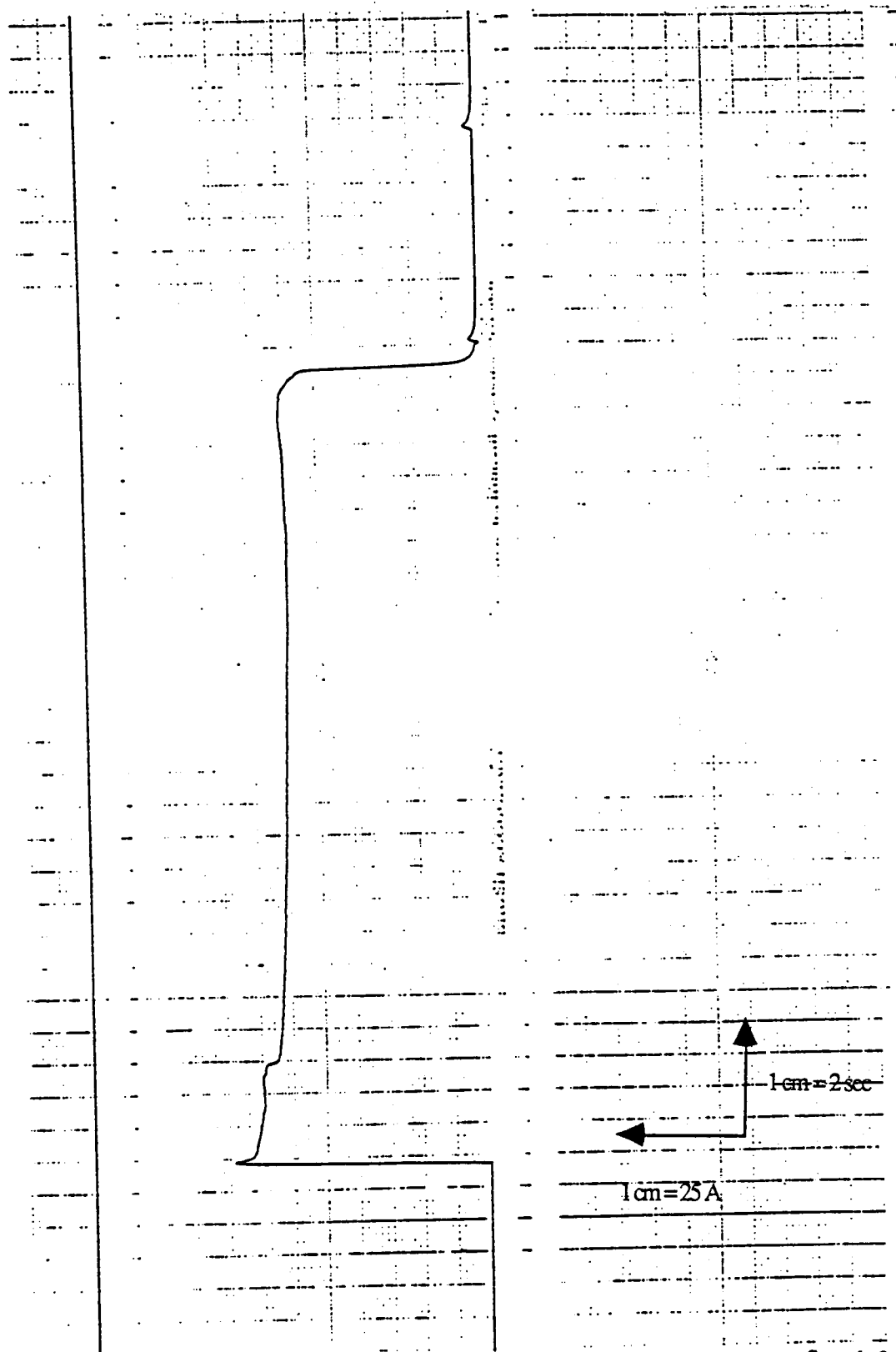
TOTAL FLOW (LB/SEC) IN X , Y DIRECTIONS :
 FLOW OUT 9.6497660410684D-08 , 0.

TIME (SEC)	SURR TEMP	DEGREE OF CHAR	MASS LOSS	MAX PRESS (PSF)	SURFACE TEMP (F)	STRAIN
3.00	70.7	0.00003	0.00001	215.247	608.763	0.000D+00

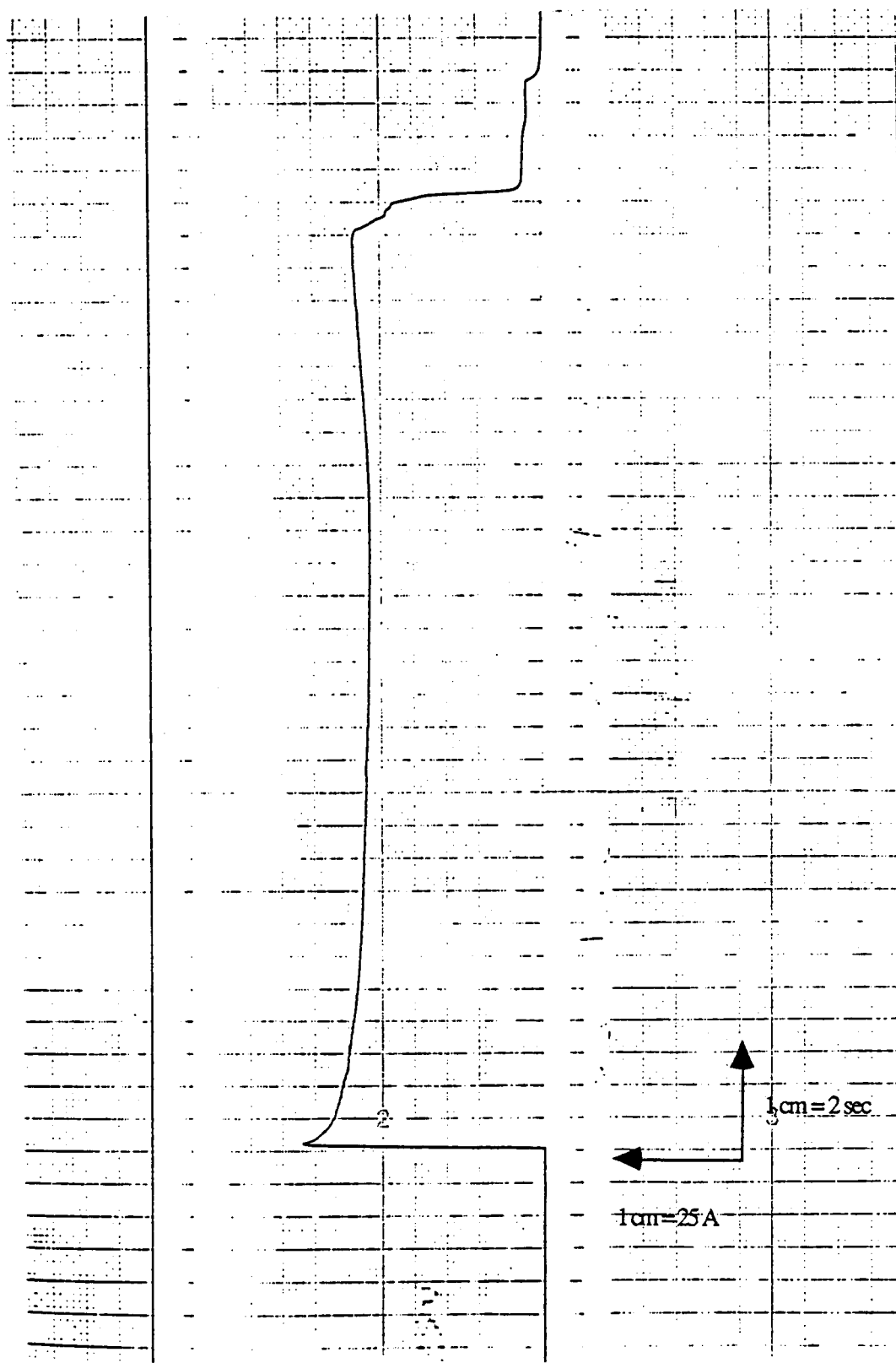
Appendix C







Sample 3



Sample 4

Vita

Frank Albert Pitman graduated from Darlington High School in Rome, Georgia in 1983. He earned a Bachelor of Science degree in Aerospace Engineering at the University of Colorado in Boulder in 1987 and a Master of Science degree in Aeronautical and Astronautical Engineering at Purdue University in 1988. He received a Master of Science degree in Mechanical Engineering from the University of Tennessee in 1993.