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Application of Thermochemical Modeling to Aircraft Interior Polymeric Materials

Won Dokko
Kumar Ramohalli

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

June 1982

Final Report

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16. Abstract

This report summarizes the results from a twelve-month study of the feasibility of applying certain basic concepts in thermochemical modeling to aircraft cabin fire safety. The concepts developed earlier on a NASA-sponsored program were applied to six specific tasks dealing with the thermochemical performance of interior carpets and seat cushions. The specific objective was to predict the burning rate as a function of the material property values, geometry and heat flux; more important, it was the aim to predict and provide rationale for certain special features that have been experimentally observed by the FAA. It was also the specific objective to introduce new concepts that have not been the subject of pursuit at other centers. That is, the novel concepts developed at JPL were highlighted. Three fundamental hypotheses were introduced: the condensed phase degradation of the polymeric material is the overall rate-limiting step; the extent of degradation at the vaporization step (at the surface) is not arbitrary but has to be specified by a scientific criterion such as the vapor pressure equilibrium criterion; and the diffusion/mixing of the pyrolysis products with the oxidizer (air) is the rate-limiting step in the vapor phase combustion. The results indicate that the assumption of condensed-phase reaction as the rate-limiting step is correct, that the thermochemical performance can be predicted using the ingredient properties only, and that a certain theoretical result predicted by this model is in qualitative agreement with experimental observations. For example, it is predicted that a typical carpet can not burn under its own flame but needs augmentation by an external radiation source for sustained burning, and this was observed experimentally.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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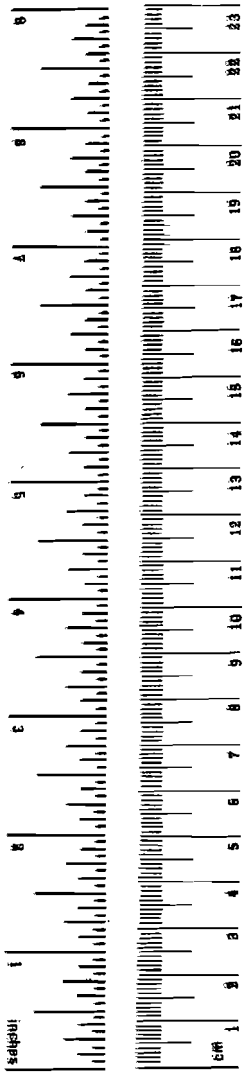
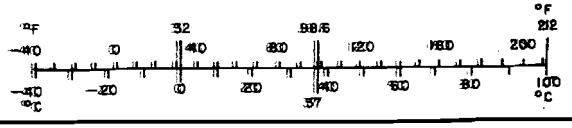


Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

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TABLE OF CONTENTS

Chapter		Page
1.	INTRODUCTION	1
2.	GENERAL APPROACH	1
	(a) Condensed Phase Details	2
	(b) Gas Phase Details	4
	(c) Model Predictions	5
3.	SUPPORTING EXPERIMENTS	5
	(a) Kinetics Constants	5
	(1) Wool Carpet	5
	(2) Seat Cushion (Polyurethane Foam)	7
	(b) Other Data	12
4.	SPECIFIC TASKS IN THE INTERAGENCY AGREEMENT	12
	(a) Burning Rates Under Flaming and Non-flaming Conditions	12
	(1) Carpet	12
	(2) Seat Cushion	18
	(b) Effects of Chemical Fire Retarding Agents on Burning Rate	18
	(c) Integration of the Nomenclature: "Thermal Thickness" and "Thermal Thinness"	21
	(d) Relating the Vaporization Concept to the Spalding B Number	24
	(e) Effect of Pressure on Burning Rates	26
5.	CONCLUSIONS	27
6.	FUTURE WORK	27

Chapter	Page
REFERENCES	30
APPENDIX A - Computer program for calculations for seat cushion	A-1
APPENDIX B - Computer program for calculations for carpet	B-1
APPENDIX C - Experimental DSC data	C-1
APPENDIX D - Experimental TGA data	D-1

LIST OF FIGURES

Figure		Page
1	Thermochemical Model For Condensed Phase Degradation Under Sheet Flame	3
2	Thermogravimetric Analysis Of Carpet Fibers	6
3	Reaction Rate Of Carpet Fibers Deduced From TGA	8
4	SEM Pictures Of Carpet Fibers	9
5	TGA Analysis of Seat Cushion	10
6	Reaction Rate For Seat Cushion Deduced From TGA	11
7	Predicted Burning Rate Of Carpet With Incident Heat Flux	15
8	Predicted Burning Rate Of Carpet	17
9	Carpet Under Self-Sustaining Flame	19
10	Predicted Burning Rate Of Seat Cushion	20
11	Predicted Effect Of Flame-Retardant On The Burning Of Carpet	22
12	Predicted Effect of Flame-Retardant On The Burning Of Seat Cushion	23
13	Schematic Diagram For The Condensed Phase Burning With Convective Flow	25
14	Pressure Dependence Of Burning Rate of Carpet	28
15	Pressure Dependence of Burning Rate of Seat Cushion	29

LIST OF TABLES

Table		Page
1	Arrehenius Constants Obtained From TGA Experiments	13
2	Basic Data Used In The Calculations	14

NOMENCLATURE

B	Pre-exponential constant for thermal degradation (sec^{-1})
c_{gas}	Specific heat of vapor phase, at constant pressure (cal $gm^{-1}{}^{\circ}C^{-1}$)
c	Specific heat of solid polymer (cal $gm^{-1}{}^{\circ}C^{-1}$)
c^-, c^+	A point immediately above and below the charring temperature T_c, respectively
D	Energy for complete depolymerization of polymer (cal gm^{-1})
E	Activation energy for thermal degradation of polymer (cal $mole^{-1}$)
FSC	Number of monomer units of degraded polymer at charring temperature
FSV	Number of monomer units in a statistically averaged vaporizing fragment at the surface
k	Thermal conductivity coefficient (cal cm^{-1} $sec^{-1}{}^{\circ}C^{-1}$)
k_ℓ, k_h	Thermal conductivity of charred and uncharred material, respectively
L	Thickness of material (cm)
m	Mean mass of vaporizing species at the surface (gm)
M	Mean molecular weight of vaporizing species at the surface (gm g-$mole^{-1}$)
N	Number of bonds in the polymer at any location normalized with respect to the number in the unaffected state.
P	Mean pressure of the system (atm)
q''_s	Surface heat flux from vapor phase (cal cm^{-2} sec^{-1})
R	Universal gas constant (cal g-$mole^{-1}$ K^{-1})
r	Linear regression rate of polymer solid (cm sec^{-1})
t	Time (sec)
T	Temperature (K)
T_b	Time-averaged peak temperature in vapor phase (K)
T_c	Charring temperature (K)
T_o	Initial temperature (K)
T_s	Surface temperature (K)

x	Distance coordinate normal to the surface (cm)
X^*	Flame standoff distance (cm)
U_{gas}	Flow velocity (cm sec^{-1})
α	Thermal diffusivity (cm^2 sec^{-1})
δ	Thermal thickness (cm)
ϵ	Emittance
ρ	Density (gm cm^{-3})
σ	Stefan-Boltzmann constant (1.355×10^{-12} cal sec^{-1} cm^{-2} K^{-4})

1. INTRODUCTION.

Occasional but serious aircraft cabin fires have raised concerns about the fire safety of the materials used in the aircraft interior. Interest has arisen recently for the performance of these materials under fire conditions, which is becoming an important factor in material design and selection. Naturally then the prediction of the performance through thermochemical modeling has emerged as an economic and logical approach in improving fire safety worthiness for its ultimate aim.

The Federal Aviation Administration (FAA) is currently sponsoring modeling activities at the National Bureau of Standards, Harvard University, University of Notre Dame, University of Dayton Research Institute, and Factory Mutual Research Corporation. The present work performed at Jet Propulsion Laboratory (JPL) is but one part of an overall program sponsored by the FAA. Hence, this work complements and does not substitute for the extensive works performed elsewhere.

Unlike the recent study on structural materials (reference 1), the present work is a new direction of the effort to apply some basic thermochemical principles to the combustion of interior materials, such as carpets and seats, under conditions specified by FAA. The specific objective is to predict the burning rates of these materials under pyrolyzing (non-flaming) and flaming conditions. The effects of flame-retarding agents, external radiant heat flux, and pressure change on the burning rates are also studied.

The significance of this work lies in the new concepts introduced, which can be summarized in terms of three fundamental hypotheses:

1. The importance of the condensed phase degradation is emphasized in predicting the burning rates.

2. The degraded matter vaporizing and leaving the surface (vaporizate) is specifically described using the vapor pressure equilibrium criterion.

3. The gas phase combustion is treated as controlled by diffusion mixing of oxidizer and fuel and no kinetic considerations may be necessary in many cases of practical interest.

The results obtained from this work are in qualitative agreement with the experimental observations made by FAA. Since the current work is limited to theoretical modeling, a detailed quantitative comparison of the predicted values with experimental results has not been made.

2. GENERAL APPROACH.

The thermochemical model used in this work was initially developed (references 2, 3, 4) and applied mainly for the study of behaviour of a class of heterogeneous materials, namely solid propellant combustion. The regression rates of solid propellants predicted by this model were seen to match well with experimental observations. Since the thermochemical performance of interior

materials can be described by the same physico chemical phenomena (i.e., governing equations) as the combustion of propellants, the same theoretical bases are utilized in the present work.

The model differs from those available in the literature in three important aspects. Based on a diverse set of experimental data, the condensed phase degradation is emphasized as the overall rate-limiting reaction. A scientific criterion in specifying the degree of degradation, based on fragment size vaporizing (FSV), is introduced. Lastly, the gas phase reaction is wholly treated as a diffusion (mixing) -controlled process. Since the details are available elsewhere (references 2, 3, 4), only a brief description of the model is given here.

The geometry under consideration is one-dimensional, as shown in Figure 1. In the present work, the steady-state reactions in the condensed phase and gas phase are considered.

(a) Condensed Phase Details.

The heat input for the condensed phase degradation can be the result of either one or both of two heat fluxes incident on the surface, i.e., one from the flame for which the fuel is supplied by the vaporizate from the surfaces, and the other from an external radiation source. The heat is conducted from the surface to the interior, providing the heat needed for the endothermic degradation reaction. The reaction is modeled as a first-order reaction subject to Arrhenius type temperature dependence.

The equation of energy then becomes

$$k \frac{d^2T}{dx^2} + c\rho r \frac{dT}{dx} = D\rho NB \exp(-E/RT) \tag{1}$$

The right hand side of this equation is the heat sink term corresponding to the endothermic first-order degradation reaction described by

$$-\frac{1}{N}\frac{dN}{dt} = B \exp(-E/RT) \tag{2}$$

The symbol N represents the number of bonds per unit mass normalized with respect to that of virgin material.

The boundary conditions for the differential equations are

$$T = T_s \text{ at } x = o, \qquad T = T_o \text{ at } x = \infty \tag{3}$$

$$N = 1 - \frac{1}{FSV} \text{ at } x = o, \qquad N = 1 \text{ at } x = \infty \tag{4}$$

The symbol FSV stands for fragment size vaporizing, whose importance is well known from earlier works (references 2,3). The formula for FSV was evolved after some study of hydrocarbon vapor pressure data published by the American

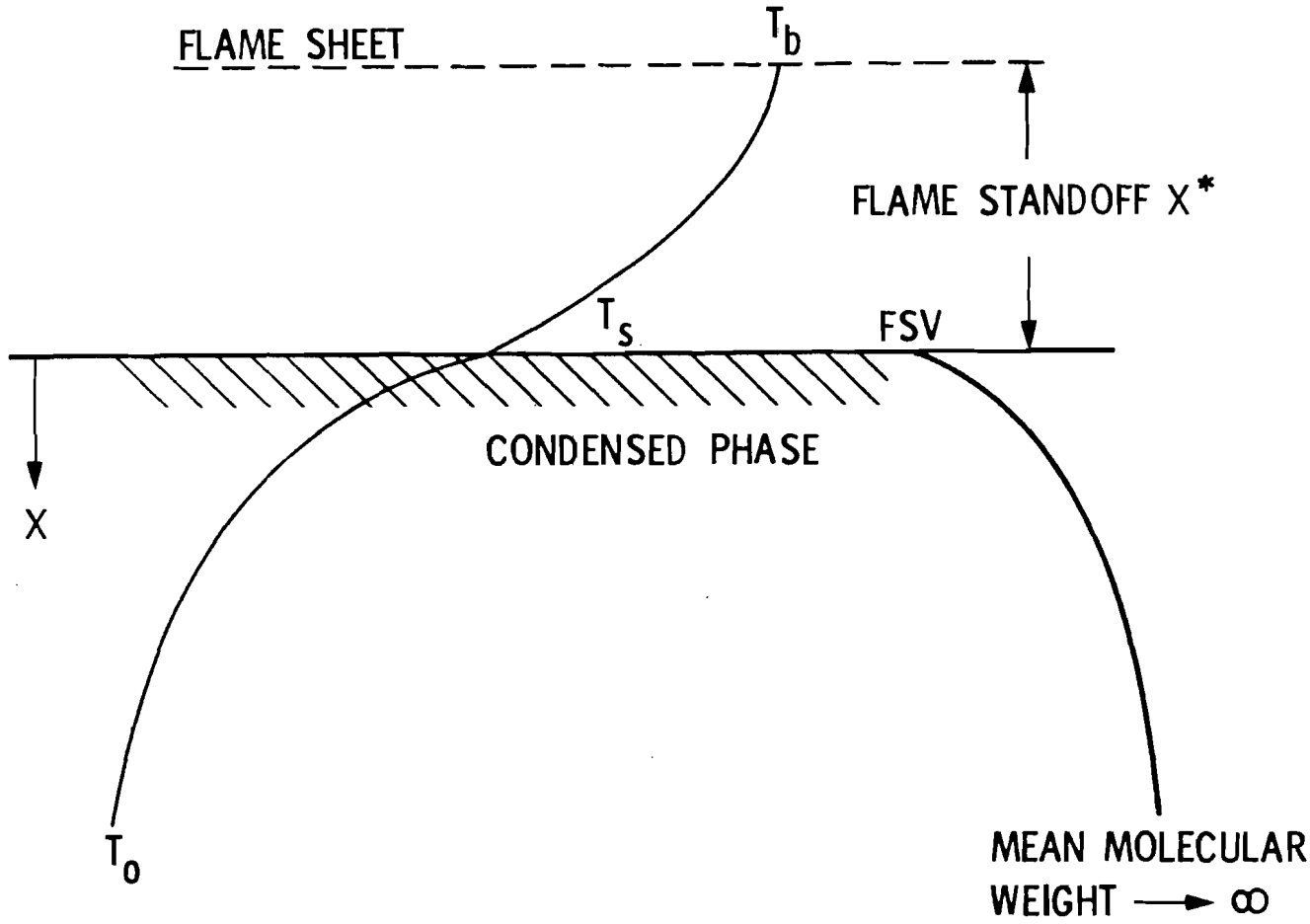


FIGURE 1. THE THERMOCHEMICAL MODEL FOR CONDENSED PHASE DEGRADATION UNDER SHEET FLAME.

Petroleum Institute (reference 5), which predicts the fragment weight of the vaporizate as a function of surface temperature T_s(K) and pressure P (atm).

$$m = 32.8\ P^{-0.2615} x \exp\ (3.67 \times 10^{-3} T_s) \tag{5}$$

FSV is obtained after dividing the fragment weight m by the molecular weight of the monomer M. Thus,

$$FSV = m/M \tag{6}$$

The heat flux at the surface to maintain a regression rate r has to be

$$q_s = r\rho c\ (T_s - T_o) + D\rho r/FSV + \varepsilon\sigma T_s^4 \tag{7}$$

The solution for the constant k has been worked out (reference 2) by singular perturbation methods with matching the solutions for the inner (surface) and outer (deep solid) regions. For the steady-state system, the regression rate r is

$$r = \sqrt{\frac{(k/\rho c)\ B \exp\ (-E/RT_s)}{\left(\frac{E}{RT_s}\right)\left(\frac{T_s-T_o}{T_s}\right)\ \left[\left\{1 + \frac{D}{c(T_s-T_o)}\right\}\ln\left(\frac{FSV}{FSV-1}\right) - \frac{D}{c(T_s-T_o)FSV}\right]}} \tag{8}$$

(b) <u>Gas Phase Details.</u>

In the gas phase, the flame may or may not appear depending on the condition of heat flux, oxygen concentration and regression rate. In the case where the flame does not appear, the only heat available for the condensed phase degradation is from an external radiation source. In the case where the flame is present, the heat from the combustion zone will be conducted through the gas phase to the condensed phase.

Considering the relatively larger time needed for transport/mixing of oxidizer than the time for the combustion reaction, the flame above the pyrolyzing material is taken as diffusion controlled. Following the familiar flame-sheet approximation, it is modeled that the vapors leaving the surface do not combust until the gases mix well with the oxidizer to reach a distance X* (flame standoff distance) from the surface, and they combust completely in a thin zone (flame sheet thickness << X*). The temperature of the flame sheet is T_b.

The energy equation for the region between the flame sheet and the surface is given by

$$k_{gas}\ \left(\frac{d^2T}{dx^2}\right) + \rho_{gas}\ c_{gas}\ U_{gas}\ \left(\frac{dT}{dx}\right) = o \tag{9}$$

The continuity equation is

$$\rho_{gas} U_{gas} = \rho r \text{ (from condensed phase)} \tag{10}$$

with boundary conditions

$$T = T_s \text{ at } x = o, \; T = T_b \text{ at } x = X^* \tag{11}$$

The solution to equation (9) is

$$q_s = k_{gas} \left(\frac{dT}{dx}\right)_s = \frac{\rho_{gas} U_{gas}(T_b - T_s) \exp (U_{gas} X^* / \alpha_{gas})}{1 - \exp (U_{gas} X^* / \alpha_{gas})} \tag{12}$$

where α_{gas} is thermal diffusivity ($k/\rho c$) of gas.

(c) Model Predictions.

As can be seen from the solutions, i.e., Equations (8) and (12), there are several input variables needed to compute the regression rate. But most of them are already known or approximated with reasonable accuracy. Thus the most characteristic parameters in this work seem to be the Arrhenius constants, B and E. Values of these constants are obtained using a thermogravimetric analyzer (TGA) as discussed in the next section.

3. SUPPORTING EXPERIMENTS.

(a) Kinetics Constants.

Small scale laboratory experiments were performed to deduce a number of essential input data. The first one was thermogravimetric analysis (TGA). The experiment is to heat up a small sample suspended inside a furnace and record the weight change as a function of temperature. The kinetic constants were deduced then from an Arrhenius plot, a plot of log (-dw/wdt) versus reciprocal of absolute temperature. The equipment used in this work was Perkin-Elmer's TGS System 4. By attaching a pair of flowmeters for nitrogen and air to the TGA equipment and varying their flow rates, the effect of oxygen concentration could be studied. The whole system was evacuated with a mechanical pump before purging to ensure a homogeneous atmosphere surrounding the sample.

(1) Wool Carpet (Supplied by the FAA to JPL). The thermogravimetric analysis (TGA) curves for carpet wool are shown in Figure 2. The effect of the presence of oxygen is quite readily seen by comparing the three curves obtained under nitrogen, air and a mixture of 1 percent oxygen and 99 percent nitrogen. Some interesting facts can be observed from this figure. The first one is that, in pure nitrogen, approximately 20 percent of the original mass reamins as char at and above 650°C. In air, on the other hand, there is no residue remaining by the time the temperature reaches 700°C. The presence of oxygen from air, however, does not mean the enhanced reaction rates for the entire temperature range. Rather it seems to contribute to preserving the oxidizing

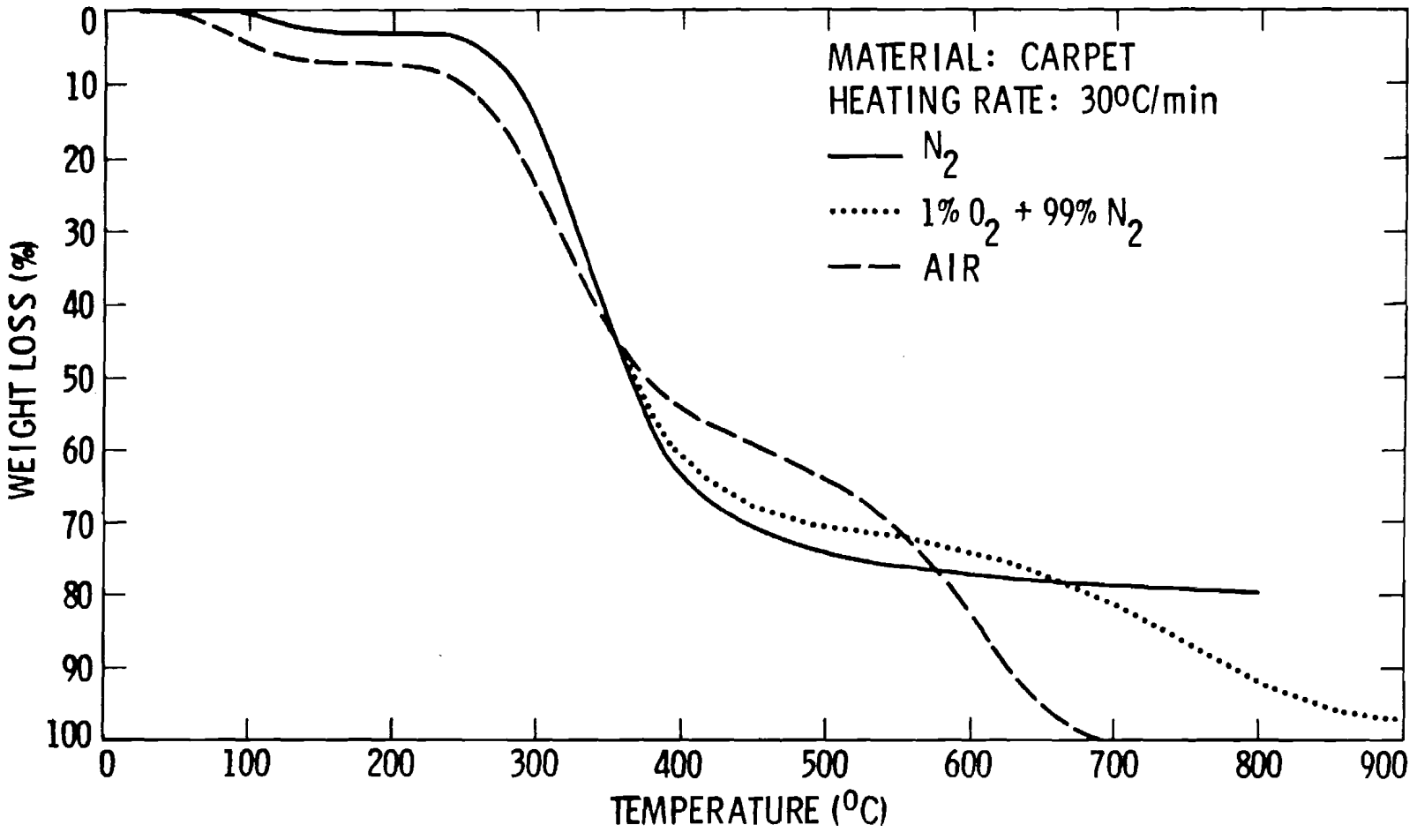


FIGURE 2. THERMOGRAVIMETRIC ANALYSIS OF CARPET FIBERS.

mass temporarily, in this case in the temperature range from 360°C to 575°C. When the oxygen concentration is reduced to 1 percent, the result is the combination of two characteristics, i.e., the carpet behaves like that in pure nitrogen up to 670°C, then burns up almost completely before it reaches 900°C.

This can be elucidated further by using the Arrhenius plot as shown in Figure 3. In pure nitrogen, the degradation reaction takes place in two distinct steps; it increases first and then decreases as the temperature goes higher. For the first step, the conventional Arrhenius expression is

$$r = 7.2 \times \exp(-9{,}270/RT) \qquad T<641K \qquad (13)$$

For the second step, it is

$$r = 3.84 \times 10^{-8} \times \exp(15{,}000/RT) \qquad T>641K \qquad (14)$$

The reaction of the second step might be described as the one with the negative activation energy. But further TGA tests under isothermal conditions show that there are no chain reactions in these high temperature ranges whose termination rates may increase preferentially with temperature to justify the negative activation energy hypothesis. Rather it was found that the wool fibers fuse and coalesce resulting in the decrease of surface area, thus increasing the diffusion and thermal resistances. The SEM (Scanning Electron Microscope) pictures of Figure 4 verify the existence of molten state.

In air, however, the degradation reaction takes place in three steps. In the low temperature region, the reaction rate is the same as that in pure nitrogen. In the medium temperature region, the reaction rate decreases with temperature as in nitrogen, but the rate itself is much lower than in nitrogen. In the high temperature region, the reaction rate increases again with temperature. These observations can be explained in the following way. The degradation in the low temperature region is pyrolysis which is not affected by the presence of oxygen. The lower reaction rates in the medium temperature range seems to be due to the crosslinking caused by oxygen diffusing through the molten phase. The high temperature reaction rate can be simply termed as the char oxidation, expressed by

$$r = 3{,}300 \times \exp(-22{,}000/RT) \qquad T>748K \qquad (15)$$

(2) Seat Cushion (Polyurethane Foam). Similar tests were performed for seat cushions. The TGA curves are shown in Figure 5 and the Arrhenius plots in Figure 6. As observed in the case of wool, the first phase of degradation of foam in low temperature is the same in air or in pure nitrogen. The difference in reaction rates appears in the next phase. In the absence of oxygen, the degraded foam goes through a melt transition and becomes liquid tar followed by very active boiling-like decomposition (reference 6). In the presence of oxygen, it was observed (reference 7) that the black cellular char is formed and undergoes further oxidation. But the residue of our specimen looked more like tar rather than char. This explains why there is no intermediate transition observed for the foam: the condensed phase material at the surface is a thin layer of liquid tar which does not go through a charring process. (The SEM

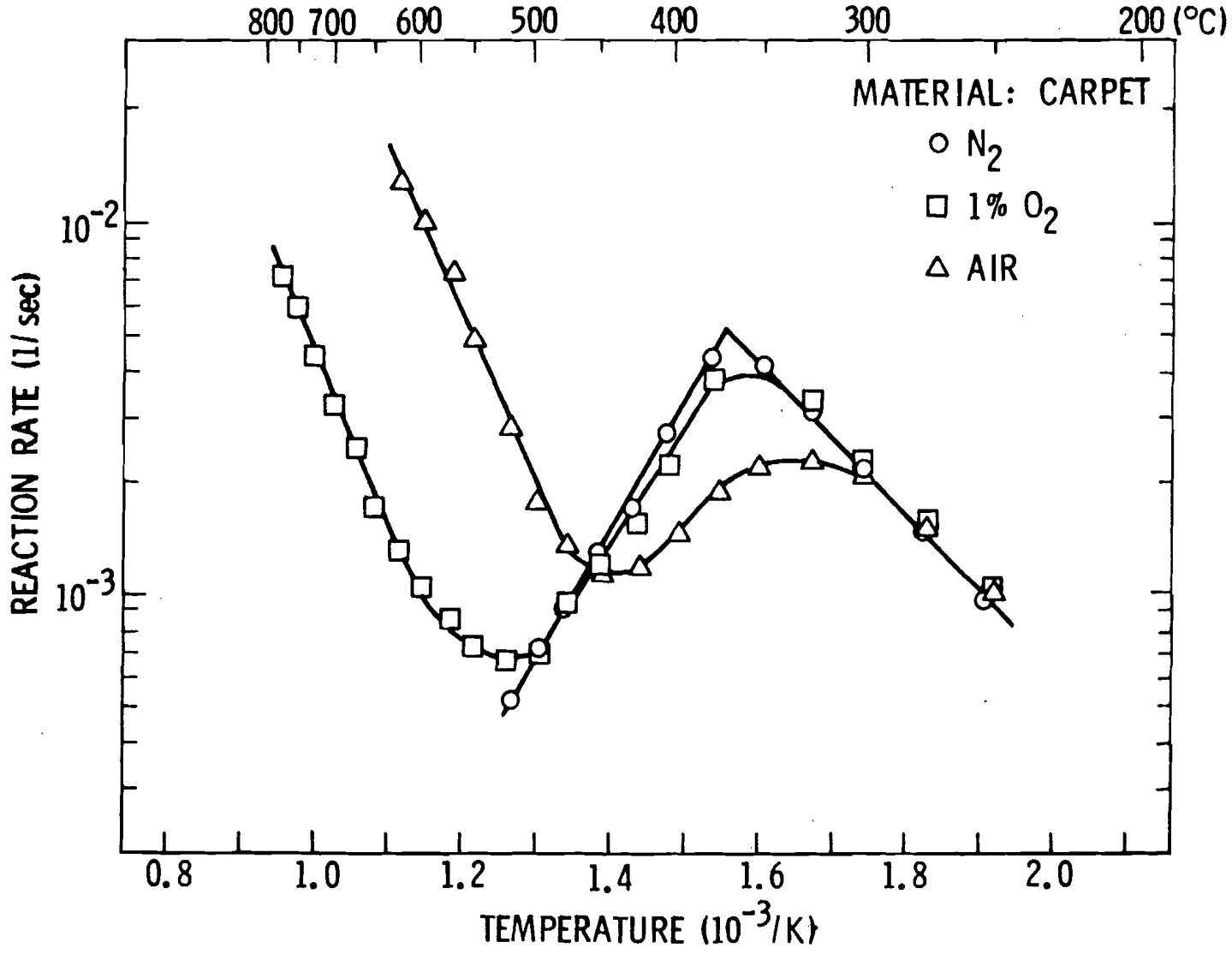
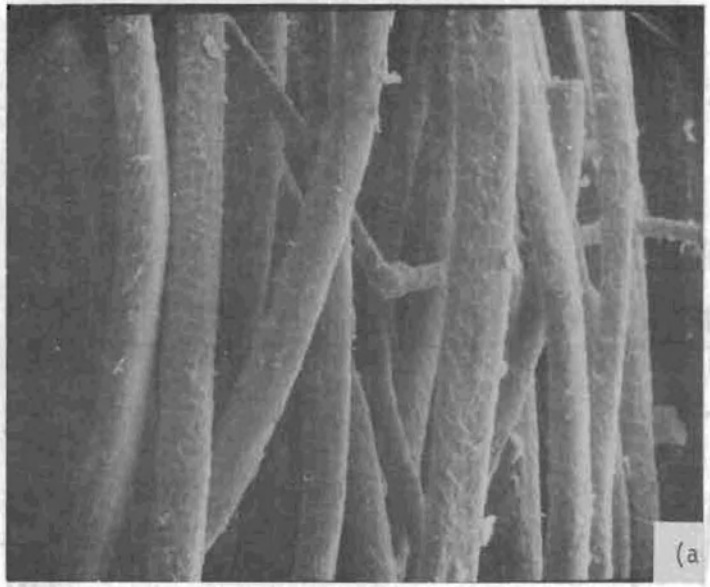
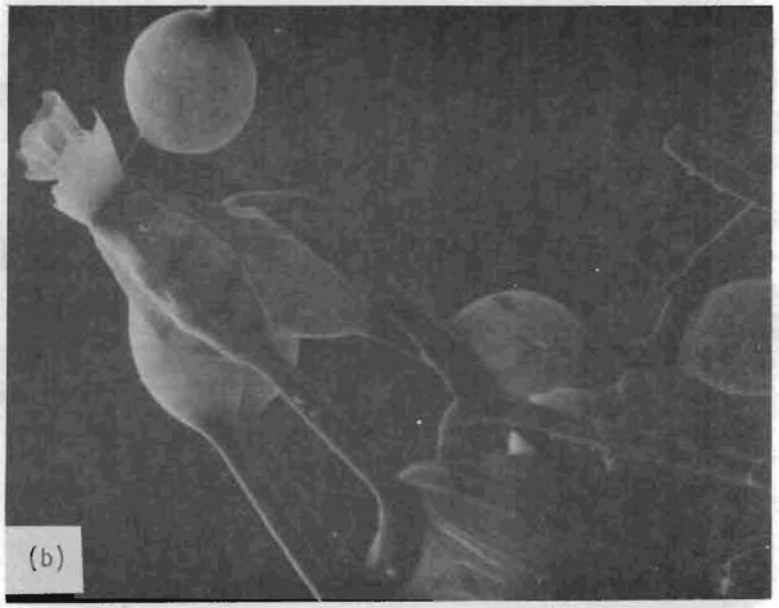


FIGURE 3. REACTION RATE OF CARPET FIBERS DEDUCED FROM TGA.





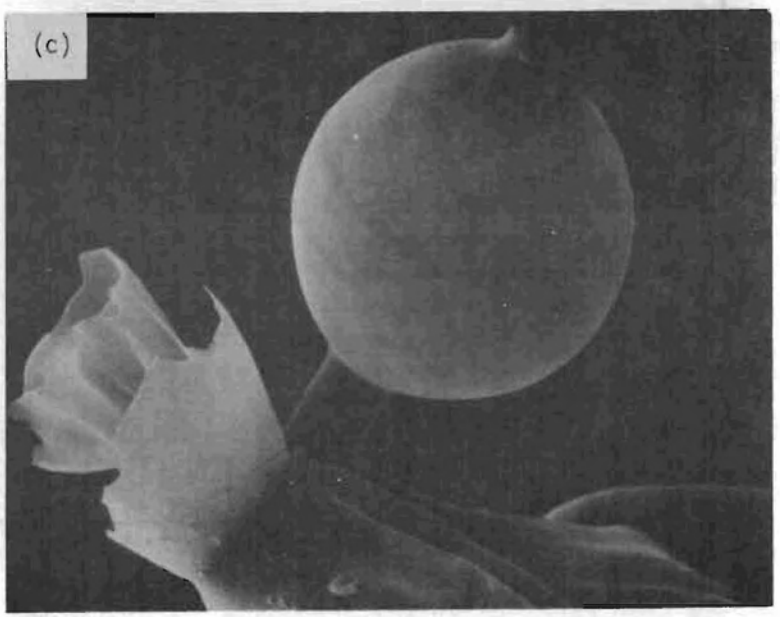


FIGURE 4. SCANNING ELECTRON MICROSCOPE PICTURES OF CARPET FIBERS; (a) AS RECEIVED, 200X, (b) AFTER PYROLYSIS IN NITROGEN, 650°C AND QUENCHING, 200X, (c) PART OF (b) BUT WITH MAGNIFICATION 500X.

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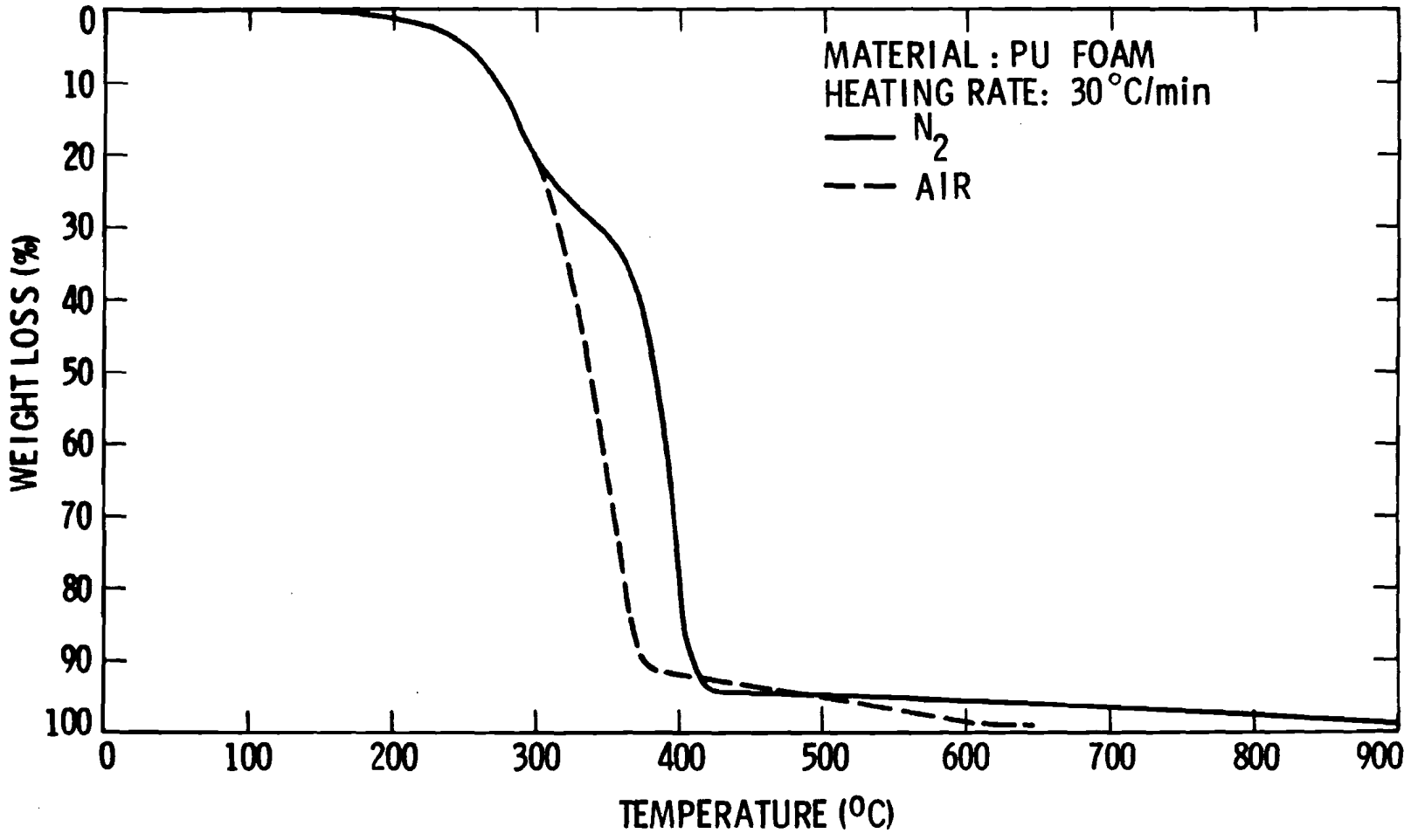


FIGURE 5. TGA ANALYSIS OF SEAT CUSHION (POLYURETHANE FOAM).

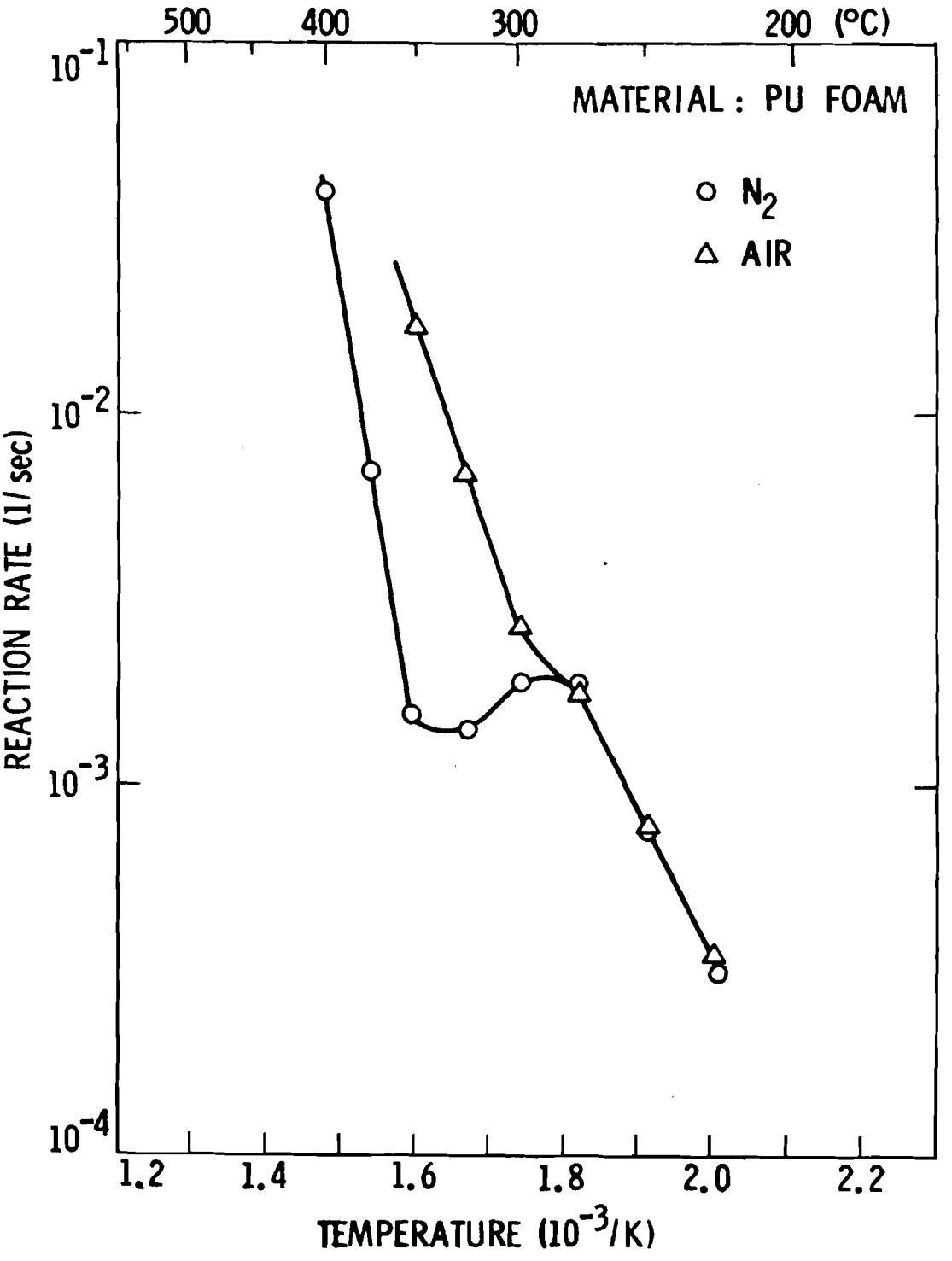


FIGURE 6. REACTION RATE FOR SEAT CUSHION DEDUCED FROM TGA.

show that the melting of wool fibers does not lead to the total agglomeration in any case.)

From the above TGA experiments, the reaction rates of the first phase both in air and in pure nitrogen can be written as

$$r = 95{,}000 \times \exp(-19{,}400/RT) \qquad T<548K \tag{16}$$

In pure nitrogen, the reaction rate after phase change can be described as

$$r = 1.9\times10^{18} \times \exp(-60{,}600/RT) \qquad T>623K \tag{17}$$

In air, it can be

$$r = 3.4 \times 10^{7} \times \exp(-26{,}500/RT) \qquad T>573K \tag{18}$$

These results are summarized in Table 1.

(b) Other Data.

The current thermochemical model uses rather a small number of input variables, which are thought essential properties of material. Other than the kinetic parameters directly deduced from the TGA experiments, all the properties used in the model are obtained from the literature. These are shown in Table 2.

4. SPECIFIC TASKS IN THE INTERAGENCY AGREEMENT.

There were six tasks to be performed by JPL, specified in the Interagency Agreement between FAA and NASA. In this section, the results predicted by the thermochemical model is discussed per each of the six tasks. The first two tasks, however, are discussed under the same head. The computer programs for calculation of the burning rate, heat fluxes required and provided by the flame, and Spalding B number with variable flame standoff distance and ambient pressure are shown in Appendix A for the seat cushion and Appendix B for the carpet.

(a) Burning Rates Under Flaming and Non-flaming Conditions.

The first task is to predict the burning rates under the non-flaming condition, with incident radiant heat flux varying between 1 and 14 $Btu/ft^2.sec$. The reradiation from the surface is included in the calculation as a source of energy loss. The char layer of the material is assumed to be a diffuse-gray body having the emittance of 0.9.

(1) Carpet. Figure 7 shows the surface regression rates of wool carpet under steady-state non-flaming condition. The rate changes in three distinct segments as the incident radiant heat flux increases. The reason for this distinctiveness is, of course, the change of the activation energy and the pre-exponential factor as discussed in the previous section. It shows that the increasing heat flux does not result in a monotonic increase of the burning rate, but in a sequence of increase-decrease-increase modes. The higher

TABLE 1. ARRHENIUS CONSTANTS OBTAINED FROM TGA EXPERIMENTS

Experimental Condition			B Pre-Exponential Factor 1/sec	E Activation Energy cal/g mole
CARPET	N_2	1st Step, T<641K	7.2	9,270
		2nd Step, T>641K	3.8×10^{-8}	-15,000
	Air	1st Step, T<641K	7.2	9,270
		3rd Step, T>748K	3.3×10^{3}	22,000
	1% O_2 + 99% N_2	1st Step, T<641K	7.2	9,270
		3rd Step, T>823K	3.1×10^{2}	22,000
SEAT CUSHION	N_2	1st Step, T<548K	9.5×10^{4}	19,400
		3rd Step, T>623K	1.9×10^{18}	60,600
	Air	1st Step, T<548K	9.5×10^{4}	19,400
		3rd Step, T>573K	3.4×10^{7}	26,500

TABLE 2. BASIC DATA USED IN THE CALCULATIONS

		CARPET	CUSHION	GAS PHASE
ρ	(g/cm3), net/overall	1.32/0.22	1.05/0.04	ideal gas law
c	(cal/g °C)	0.3	0.35	0.3
k	(cal/cm °C sec)	0.0001[a]	0.00034	$0.0001 \times \sqrt{T/600}$ [b]
M	(monomer Molecular Weight)	138.4[c]	76[d]	
D	(cal/g)	300	300	
T_b	(K)			Carpet: 1400 Cushion:1400
To	(k)	300	300	
ϵ		0.9	0.4	
L	(cm)	0.8	10.2	

a. Thermal conductivity of carpet char is taken as 2×10^{-5} cal/cm °C Sec
b. Calculated according to Sutherland's law
c. Weight-averaged molecular weight of 17 different amino acids extracted from wool, Ref. 8.
d. For lack of the information on the specific chemical formulation, the base monomer is assumed to be

```
   H H  H
   ' '  '
H-C-C- C-OH
   ' '  '
   H OH H
```

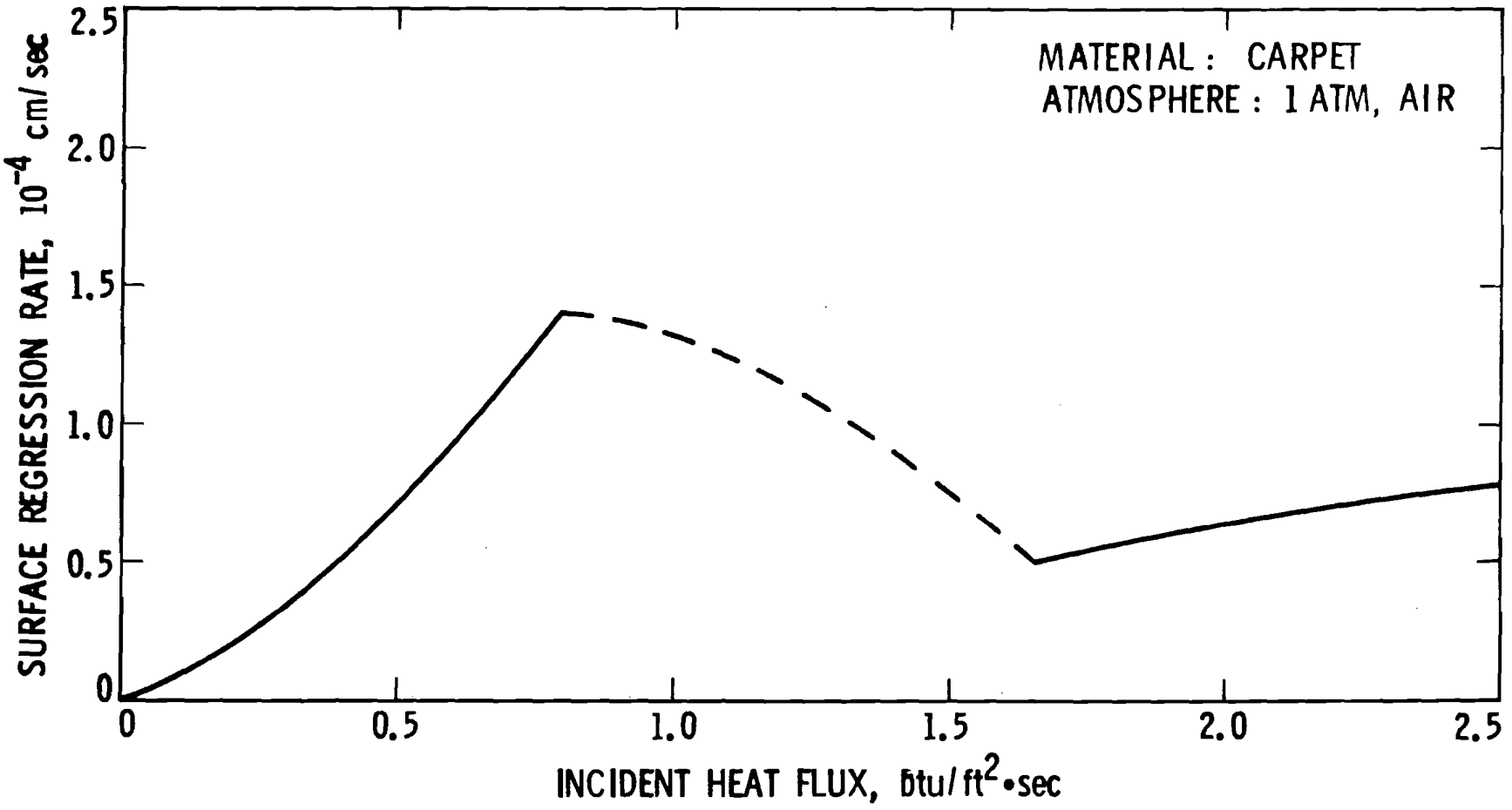


FIGURE 7. THE PREDICTED BURNING RATE OF CARPET WITH INCIDENT HEAT FLUX.

reradiation at the high heat flux region (due to the high surface temperature) reduces the burning rate compared to the rate in the low heat flux region.

The highest temperature region of Figure 7 is studied for the burning rates with self-sustaining flame. The calculation procedure for the burning rate when surface temperature is higher than charring temperature is different from that described earlier. The formation of a char layer causes a substantial reduction of thermal conductivity and hence reduces heat flux through this layer. The temperature profile will be discontinuous at the charring temperature, T_c (816K for carpet when the atmosphere is a mixture of 1 percent oxygen and 99 percent nitrogen), and a matching condition at this point c becomes

$$q_{c+} = q_{c-} \tag{19}$$

or

$$k_\ell \left(\frac{\partial T}{\partial x}\right)_{c-} = k_h \left(\frac{\partial T}{\partial x}\right)_{c+} \tag{20}$$

Mass continuity requires that the burning rate at the char free surface be equal to the burning rate at the point c under steady-state condition, that is

$$r \text{ at } T_s = r \text{ at } T_c \tag{21}$$

where

$$r \text{ at } T_c = \sqrt{\frac{(k_h/\rho c)\, B \exp(-E/RT_c)}{\left(\frac{E}{RT_c}\right)\left(\frac{T_c-T_o}{T_c}\right)\left[\left\{1 + \frac{D}{c(T_c-T_o)}\right\} \ln\left(\frac{FSC}{FSC-1}\right) - \frac{D}{c(T_c-T_o)FSC}\right]}} \tag{22}$$

and

$$r \text{ at } T_s = \sqrt{\frac{(k_\ell/\rho c)\, B \exp(-E/RT_s)}{\lambda\left(\frac{E}{RT_s}\right)\left(\frac{T_s-T_o}{T_s}\right)}} \tag{23}$$

for λ and details of derivation for Eq. (23), the readers are referred to Reference 9. (Note: Eq. (23) is not reduced from Eq. (8). These are solutions to two different problems.)

Thus the burning rate of wool carpet with a char layer on it is determined. Then the heat flux required to maintain this regression rate can be determined by use of Eq. (7), while the heat flux reaching the surface from the flame zone can be obtained by use of Eqs. (10) and (12). These two kinds of heat fluxes are plotted as functions of regression rate in Figure 8.

Figure 8 shows that there exists a special condition under which the carpet is able to sustain its own burning. For steady-state combustion, the heat flux required to produce fuel vapor at the surface must be exactly equal

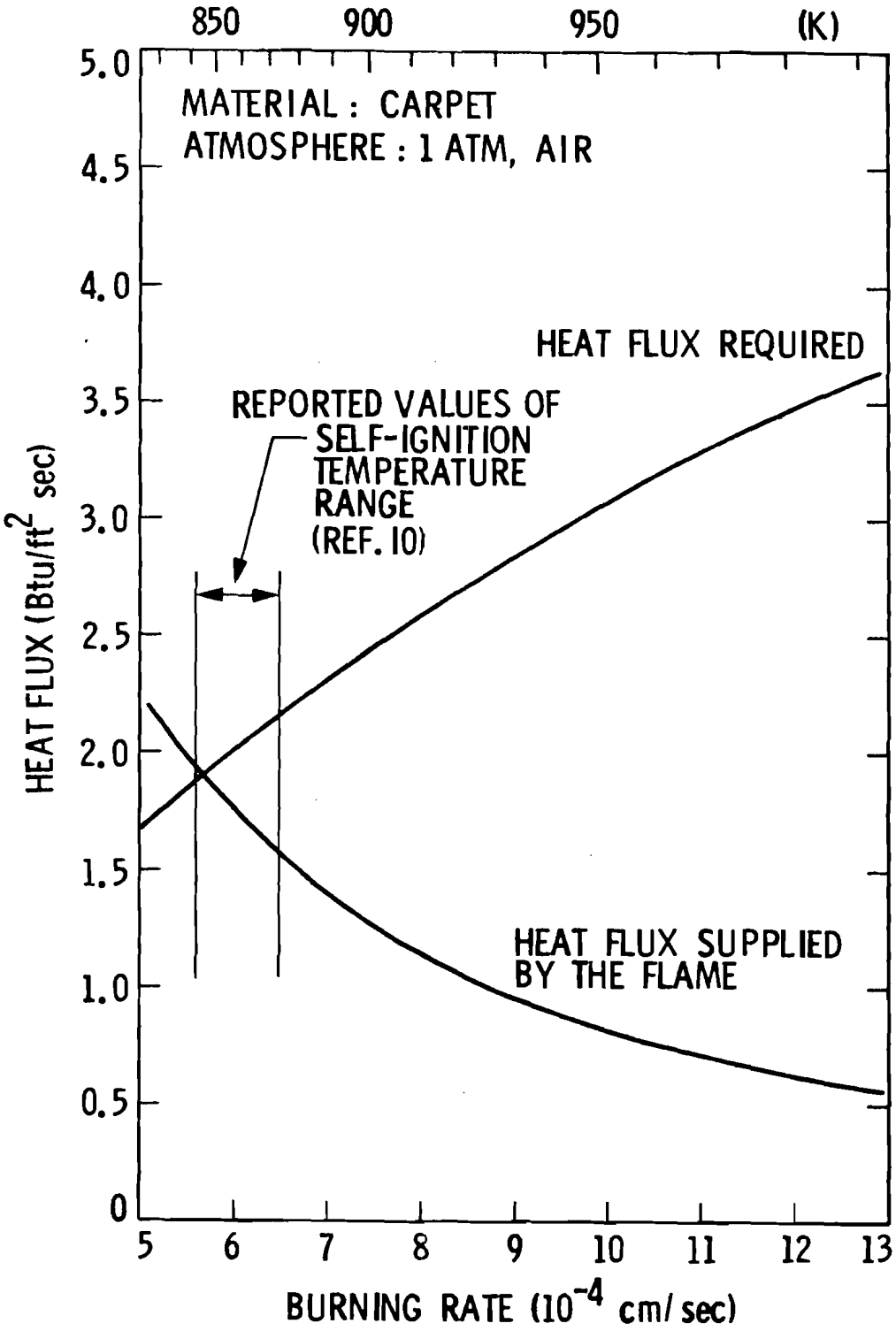


FIGURE 8. THE PREDICTED BURNING RATE OF CARPET.

to the heat flux from the flame generated by combustion of the fuel vapor. The crosspoint of two curves satisfies this condition. So, once this point is reached, the steady-state burning under self-sustaining flame commences. For higher burning rates, however, externally augmented heat flux is needed.

Regarding the actual observations of wool carpet burning, there are two points to be discussed here. The first is that the wool carpet does not get inflamed when a match or even a propane torch is used as an ignition source. The problem with the match fire is that it does not provide enough heat flux to raise the surface temperature for self-ignition. In the case of propane torch, the torch flame covers the surface preventing oxygen in air from mixing with the fuel vapor. The self-sustaining flame was actually observed, however, as shown in Figure 9 when the carpet was heated with the sunlight concentrated by a Fresnel lens (other radiation concentration devices may also be employed). This method has the advantage of providing high heat flux without hindering oxygen diffusion. But the flame disappears, i.e., extinguishes, when the incident radiation beam is blocked or moved away. In other words, the augmenting heat flux is necessary for the wool carpet to burn under a flame. This may seem contradictory to the above description about the self-sustaining flame at the crosspoint of two curves in Figure 8. The reason is the high ignition temperature of wool (reported data: 600°C from reference 10), at which additional 0.6 Btu/ft^2 sec is required from the external radiation heat source. Another reason for the difficulty and hence the sensitivity associated with the existence of flame of wool is due to the high LOI (limiting oxygen index), of which the reported value is 0.252 (reference 11). The LOI is believed to decrease with increasing temperature, so that the flame from wool could be finally observed in air at elevated temperatures, where the oxygen index is 0.21. Such decrease of LOI with temperature was observed for other polymers (reference 12) like polytetrafluoro ethylene, polyvinyl chloride, polymethyl methacrylate, etc.

(2) Seat Cushion. The procedure used for the carpet is applied to the seat cushion material as well. The underlying Arrhenius type reaction rates used in the calculation are those obtained in air, assuming that diffusion of oxygen takes place as in air through the open cell structure of the foam material.

Figure 10 shows the burning rates of seat cushions under flaming conditions. As in the case of the carpet, Figure 10 shows that there exists a condition under which the seat cushion is able to sustain its own burning. The condition is satisfied at the crosspoint of two curves.

(b) Effects of Chemical Fire Retarding Agents on Burning Rate

The burning of most polymeric materials proceeds in steps. The first step is the endothermic pyrolysis reaction taking place mostly in condensed phase, and the second step is the exothermic reaction in gas phase. A part of the heat liberated in the second step is transferred to the polymer surface for further cyclic processes.

Chemical fire retardants are those which operate in the condensed phase or in the gas phase to inhibit any of the above reaction steps. The effect of the fire retardant is manifested via physical actions, such as coating on the surface, evolution of non-combustible gases, and absorption of

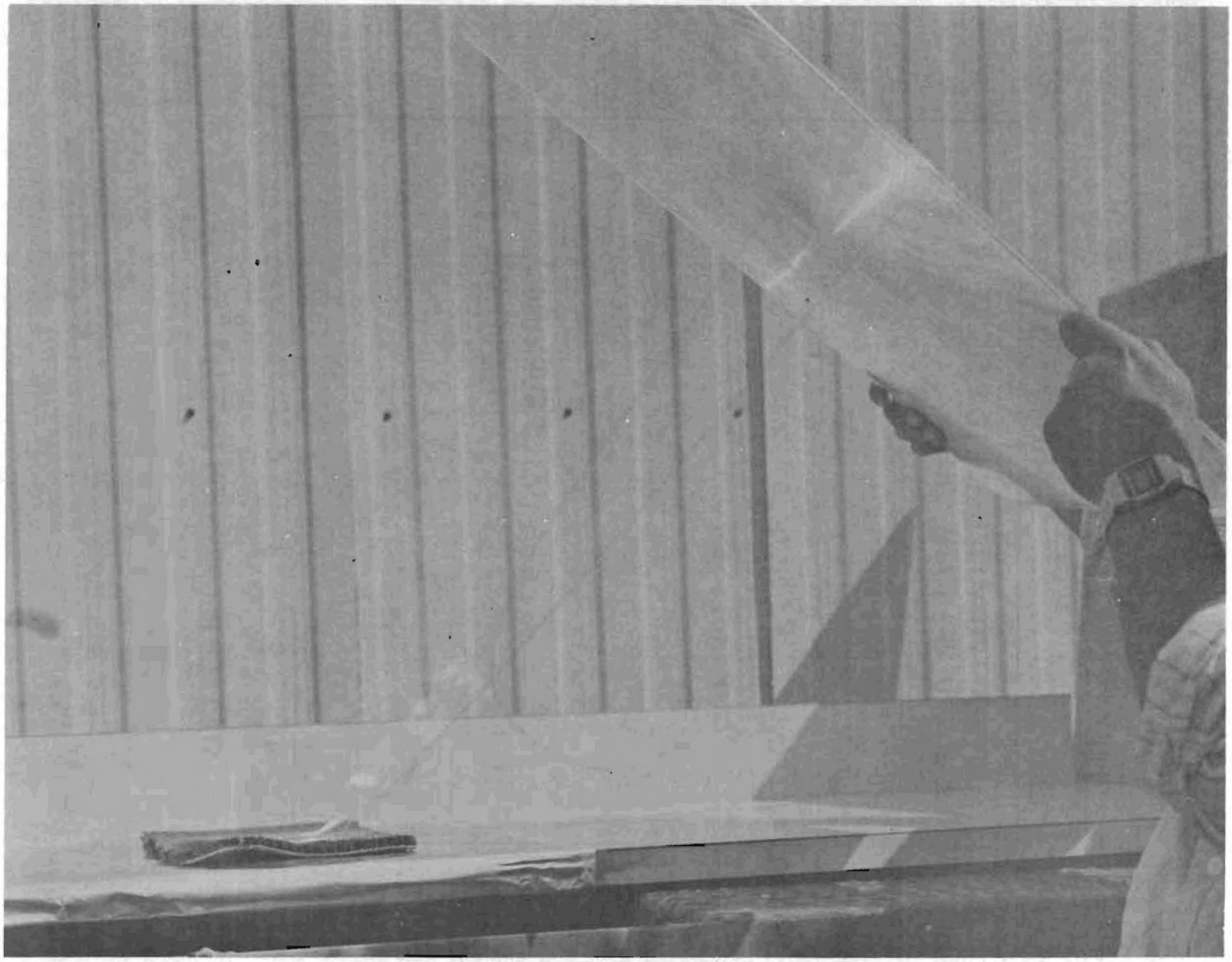


FIGURE 9. THE CARPET UNDER SELF-SUSTAINING FLAME WITH THE SUNLIGHT CONCENTRATION BY A FRESNEL LENS

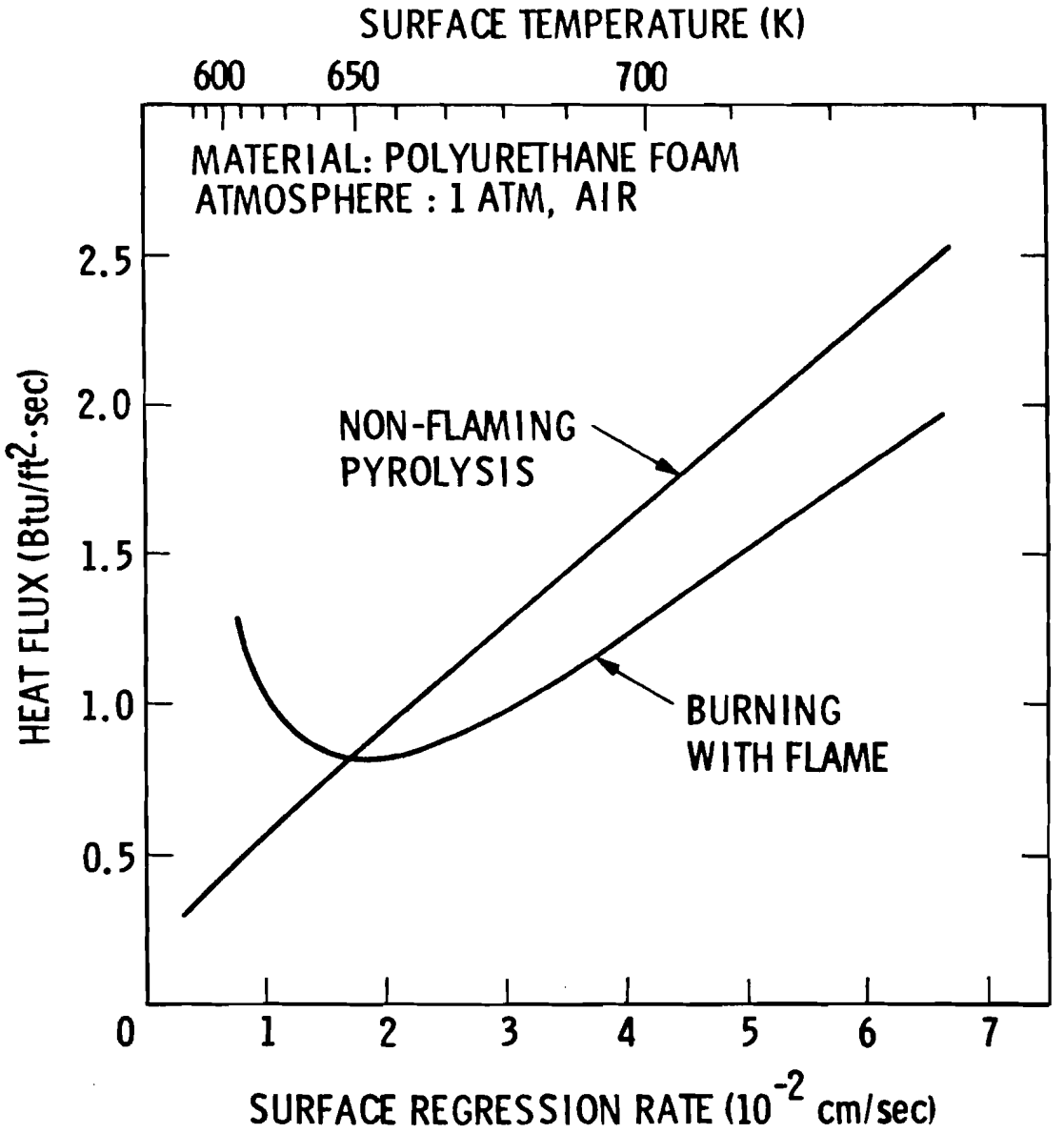


FIGURE 10. THE PREDICTED BURNING RATE OF SEAT CUSHION.

heat, or chemical actions, such as the modification of decomposition reactions, reducing the production of combustible gases, and increasing char formation.

Regarding the thermochemical model used in this work, the effect of the chemical fire retardant can be treated in two ways. If it operates in the condensed phase, the kinetic constants of pyrolysis (B and/or E in Arrhenius expression) will be affected. If it is operating in the gas phase, one or more parameters, such as flame temperature, gas velocity, flame standoff distance, and physical properties of the gas, will be changed.

In order to determine in which phase the fire retardant is effective, the aircraft carpet wool fibers and untreated wool fibers were tested with TGA under N_2 at the heating rate of 150°C/min. The resulting TGA curves show that there is virtually no difference between the flame retardant treated and the untreated wool fibers. In other words, the flame retardant does not affect the condensed phase decomposition reaction. With this particular flame retardant (of which the chemical composition is not known to us) applied to the aircraft carpet wool, it is reasoned that the flame retardancy takes place in the gas phase.

In the case of the seat cushion material, this type of TGA experiment to single out the effect of the flame retardant is not feasible, because of the difficulty in obtaining exactly the same material in a pair, i.e., one treated with a flame retardant and the other untreated.

Without having detailed information on the flame retardants actually used and their physical/chemical effect on gas phase reactions, the current model assumes a modified value (increased by 20 percent) of flame standoff distance as a surmised effect of the flame retardant. The flame temperature is another parameter that can be modified (lowered), but this change is equivalent to the change of the flame standoff distance for the present purpose.

The predicted results are shown in Figure 11 for the carpet and Figure 12 for the seat cushion. These are similar to the curves seen in Figures 8 and 10 except that the heat fluxes supplied from the flame are lowered because of the increased flame standoff distance. Hence for the case of wool carpet, the heat required from an external radiation source to start burning under flame is larger, making the ignition more difficult. This is the situation predicted using the same ignition temperature as that of untreated wool fibers. If the ignition temperature is increased due to the flame retardants, then the augmenting heat flux will be even larger. For the case of the seat cushion material, the same reasoning as for the wool carpet will hold. The ignition temperature of the urethane foam is not available in literature, and is not pursued in this work.

(c) Integration of the Nomenclature: "Thermal Thickness" and "Thermal Thinness".

The thermochemical model used in this work has been developed for and hence is applicable to a thermally thick material. The term "thermally thick" or "thermally thin" is used in comparison with the physical thickness L. So, when the physical thickness L is larger than the thermal thickness δ, it is

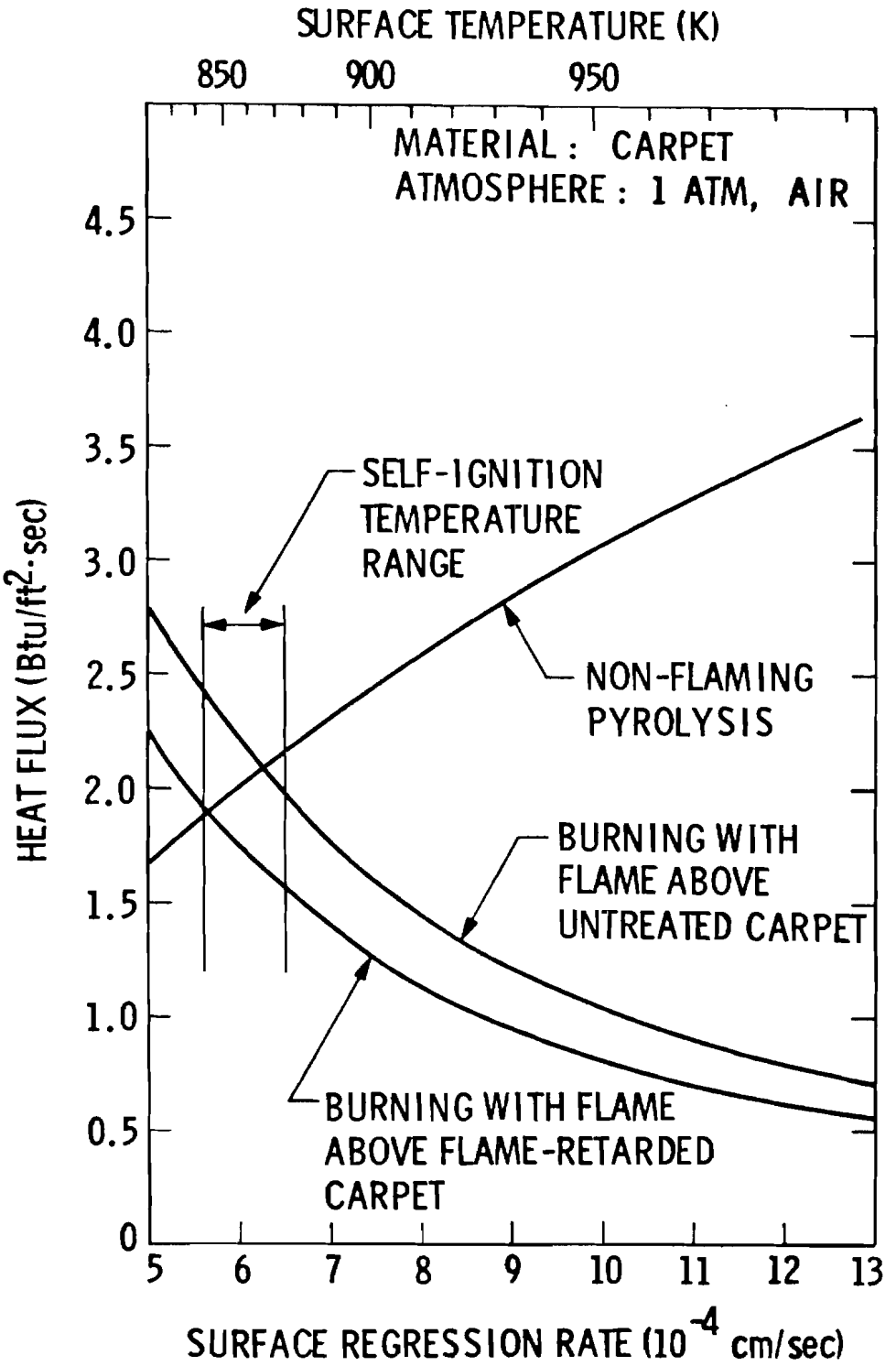


FIGURE 11. THE PREDICTED EFFECT OF FLAME-RETARDANT ON THE BURNING OF CARPET.

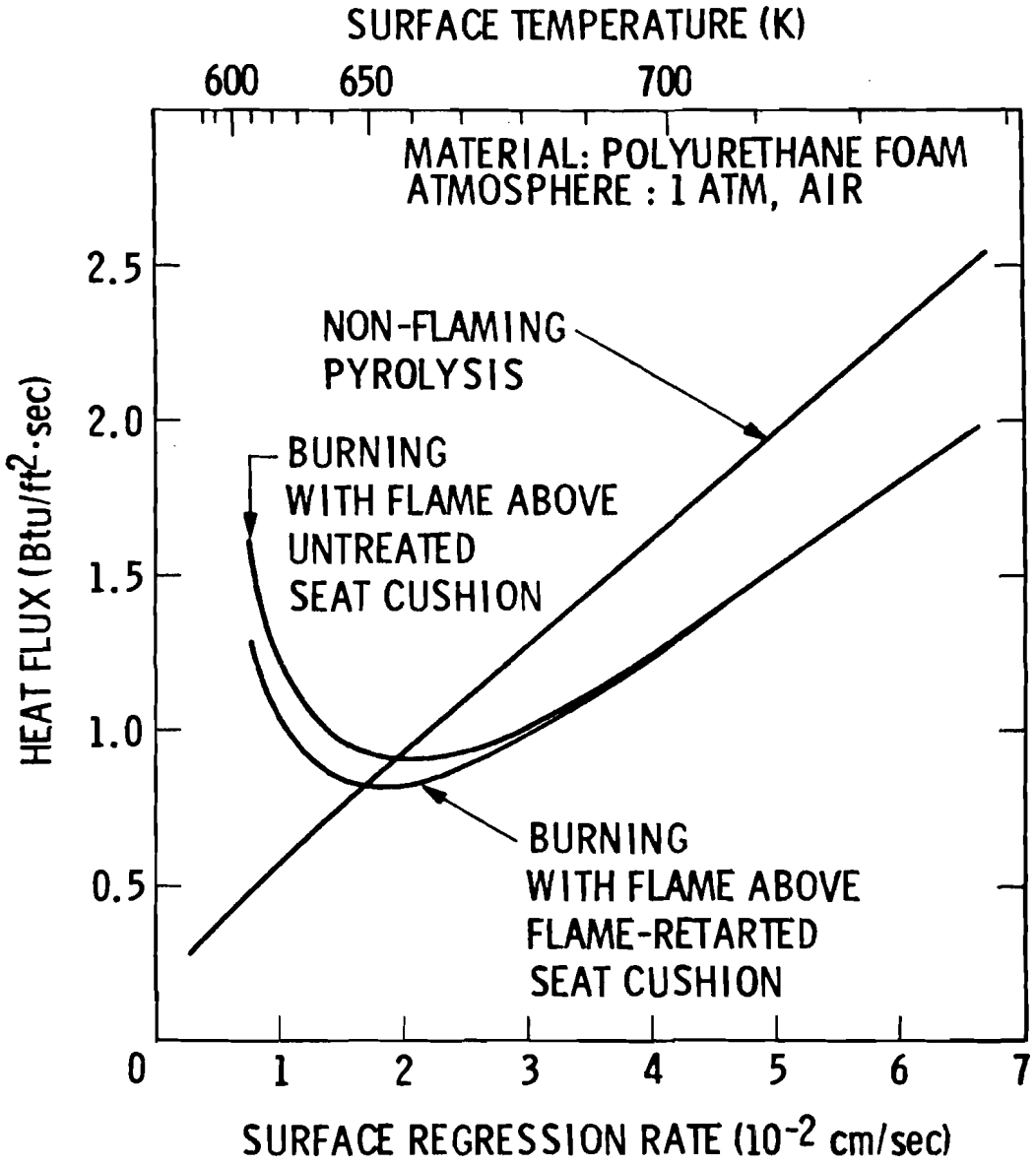


FIGURE 12. THE PREDICTED EFFECT OF FLAME-RETARDANT ON THE BURNING OF SEAT CUSHION.

called "thermally thick", otherwise "thermally thin", i.e.,

$\delta \ll L$ thermally thick
$\delta \gg L$ thermally thin

The δ can be deduced (reference 2) from the outer region (cold side) temperature profile of a slab whose other side is heated. That is,

$$\frac{T-T_o}{T_s-T_o} = \exp(-xr/\alpha) \tag{24}$$

where α is the thermal diffusivity.

Then $$x = -\frac{\alpha}{r} \ln \left(\frac{T-T_o}{T_s-T_o}\right) \tag{25}$$

The thermal thickness δ is defined as the depth from the surface where the dimensionless temperature $(T-T_o)/(T_s-T_o)$ is equal to $1/e$.

or $$\delta = \frac{\alpha}{r} = \frac{k}{\rho c r} \tag{26}$$

In the calculation of δ for the carpet, the data of the thermal conductivity, density, and heat capacity used are for the carpet char layer because this is where most of the temperature drop occurs and hence thermal resistance is provided. For seat cushion, the calculation is straight forward.

With the physical properties listed in Table I, it can be seen that

$\delta < L$ for carpet
$\delta \ll L$ for seat cushion

In other words, both materials can be regarded as thermally thick. If the physical thickness (L) is reduced and becomes smaller than thermal thickness (δ), the material is considered thermally thin. For a thermally thin material, the burning rate can be calculated directly from the Arrhenius rate equation,

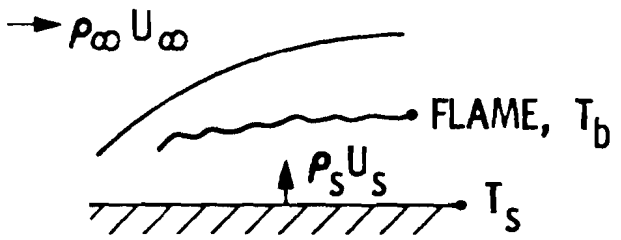
$$r = L\ B \exp(-E/RT_s) \tag{27}$$

It should be appropriate to note here that the thermal thickness (δ) of the carpet changes with the progress of thermal degradation, due to the change of k and r. Before the char layer is formed at the surface, the same calculation shows that the entire carpet is thermally thin. But after the charring, largely due to the change in k, the carpet has become a thermally thick material. A detailed study of this effect can be found in Reference 9.

(d) Relating the Vaporization Concept to the Spalding B Number.

This task is to study the effect of convective flow over the burning surface on the burning rate of the condensed phase. The geometry under consideration is depicted in Figure 13. At a distance away from the leading edge of burning surface, the heat flux to the condensed phase is

$$k \left.\frac{\partial T}{\partial x}\right]_{x=o} = (\rho U)_\infty\ c\ (T_b-T_s)\ C_H \tag{28}$$



DEFINITION:

$$B = \frac{(\rho U)_s}{(\rho U)_\infty C_H}$$

FIGURE 13. THE SCHEMATIC DIAGRAM FOR THE CONDENSED PHASE BURNING WITH CONVECTIVE FLOW.

where C_H is the Stanton number, and $(\rho U)_\infty$ is the mass flow rate at the outer edge of the boundary layer at that location. The mass transfer number B, (or Spalding B number) is defined by

$$B = \frac{(\rho U)_s}{(\rho U)_\infty C_H} \tag{29}$$

where $(\rho U)_s$ is the mass burning rate at the surface. Since C_H is the reduced heat transfer coefficient due to the burning mass injection, frequently it is assumed that Reynolds analogy holds and hence,

$$\frac{C_H}{C_{H_o}} = \frac{C_f}{C_{f_o}} \tag{30}$$

where C_f is the skin friction coefficient and C_{H_o} and C_{f_o} are, respectively, Stanton number and friction factor without mass injection to the flow.

Further analysis (reference 13) shows that the ratio of Stanton numbers can be approximated as

$$\frac{C_H}{C_{H_o}} = \frac{\ln(1+B)}{B} \qquad \text{for } B<5 \tag{31}$$

$$\frac{C_H}{C_{H_o}} = 1.2\, B^{-0.77} \qquad \text{for } 5<B<95 \tag{32}$$

and

$$C_{H_o} = \frac{C_{f_o}}{2} = 0.12\, Re^{-0.2} \tag{33}$$

where Re is the Reynolds number based on the distance from the leading edge of burning surface. The Spalding B number is calculated after rearranging Eqs. (29) and (31) or (32) to give

$$B = \exp\left\{\frac{(\rho U)_s}{(\rho U)_\infty C_{H_0}}\right\} - 1.0 \qquad \text{for } B < 5 \tag{34}$$

or

$$B = \left\{\frac{(\rho U)_s}{1.2\ (\rho U)_\infty C_{H_0}}\right\}^{1/0.23} \qquad \text{for } 5 < B < 95 \tag{35}$$

The Spalding B number calculated for carpet ranges from 0.17 to 0.18 at surface temperatures of 830 to 850K, at 2 feet downstream from the leading edge of the burning surface, and at 3.0 mile/hr blowing velocity of free stream. The value of B number is comparable to that of carbon (reference 14), i.e., 0.12, but easier to burn than the carbon. However, in order to make the carpet actually burn, more additional heat flux is needed from an outside source. In other words, the effect of the flow is such that there will be no burning with a self-sustaining flame but only smoldering.

Under the same condition, the Spalding B number for seat cushion is 1.13 at the surface temperature of 650K, where the burning can proceed with the self-sustaining flame. The relatively high value of B compared to that of carpet is because of the high reactivity of seat cushion as shown from the TGA experiments (see Table 1).

(e) Effect of Pressure on Burning Rates.

The effect of changing pressures were studied since the pressure affects the ignition/combustion process in several ways. The most obvious is the effect on vapor density (ρ= PM/RT) and the vapor phase chemical kinetic rates that are frequently approximated by P^n where n is the "index" of reaction rates.

In our particular thermochemical model the pressure affects two important characteristics. Firstly, under the basic hypothesis of heterogeneous condensed phase reactions by an autocatalytic species (probably the cure catalyst), the condensed phase pre-exponential factor B is directly proportional to the mean pressure. That is, B takes the form of BxP, where P is in atmospheres. Secondly, under the novel vapor pressure equilibrium criterion used here, pressure affects the mean molecular weight of the vaporizing species, namely the pyrolysis products. So, FSV is modified by a factor of $p^{-0.2615}$, as shown in Equation (5). These separate effects are believed here to be very essential for a complete understanding of the pressure effects. It is also thought that highly simplified approaches may ignore the main point of the negative effect of pressure that has sometimes been observed in fire phenomena.

The results show that the pressure increase does increase the burning rate in a monotonic way, as shown in Figure 14 for carpet and Figure 15 for seat cushion. The burning rates of these curves are those obtained under the steady-state self-sustaining flames. So, additional incident heat flux will increase the burning rates accordingly. As shown in these figures, the pressure dependence is far weaker than a direct (linear) dependence. The curves here do indicate the basic thoughts behind pressure scaling (modeling) of fires in experimental facilities.

5. CONCLUSIONS.

The present work on the prediction of thermochemical performance of carpet and seat cushion leads to the following conclusions.

1. The assumption of condensed-phase degradation as the rate-limiting step in the model leads to theoretical results which match qualitatively with experimental observations.

2. The application of vapor pressure equilibrium criteria appears to be a valid procedure in removing the arbitrariness in the description of the vaporization step at the surface.

3. Although it was satisfactory in the present work, a further understanding of the flame standoff distance and heat flux therefrom seems necessary, especially for the slow burning materials like the carpet.

4. As an overall summary, the specific objective of predicting the burning rates as a function of the material properties was accomplished with qualitative agreement with experiments.

Up to this point, the theoretical results have not been tested with quantitative experimental measurements. In order to appreciate the validity of the model, actual burning rate measurement is necessary after re-evaluating the fundamental physical and thermal properties of the material used in the calculation. In fact, some of the property values were taken from the literature and may not be correct for the specific material in consideration.

6. FUTURE WORK.

The extension of the present work is planned for a more practical case of multi-layered polymeric materials, namely a system consisting of polyurethane foam (cushion) - neoprene sheet (blocking layer) - nylon/wool fabric (cover). Also planned is the experimental measurement of thermochemical performance of the system using a modified NBS Smoke Chamber. A Mellen furnace is to provide radiant heat flux varying from 2 to 10 Btu/ft^2 sec and the resultant weight loss of and temperature profile in the material will be measured. The kinetic constants of the individual material deduced from TGA experiments along with other thermal data will be integrated into the model and its prediction compared with the observed results. This work is scheduled to commence shortly under the sponsorship of the FAA.

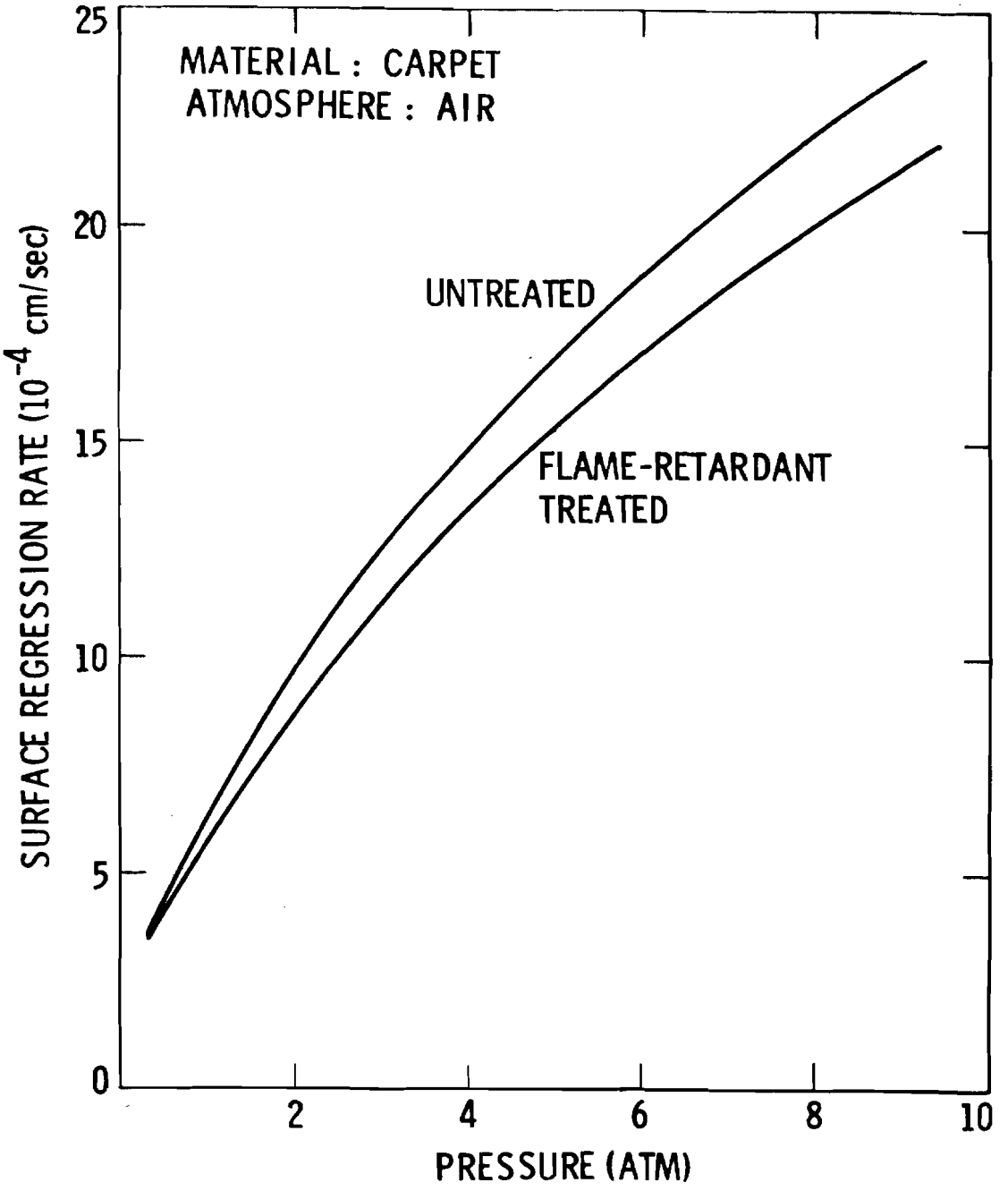


FIGURE 14. THE PRESSURE DEPENDENCE OF BURNING RATE OF CARPET.

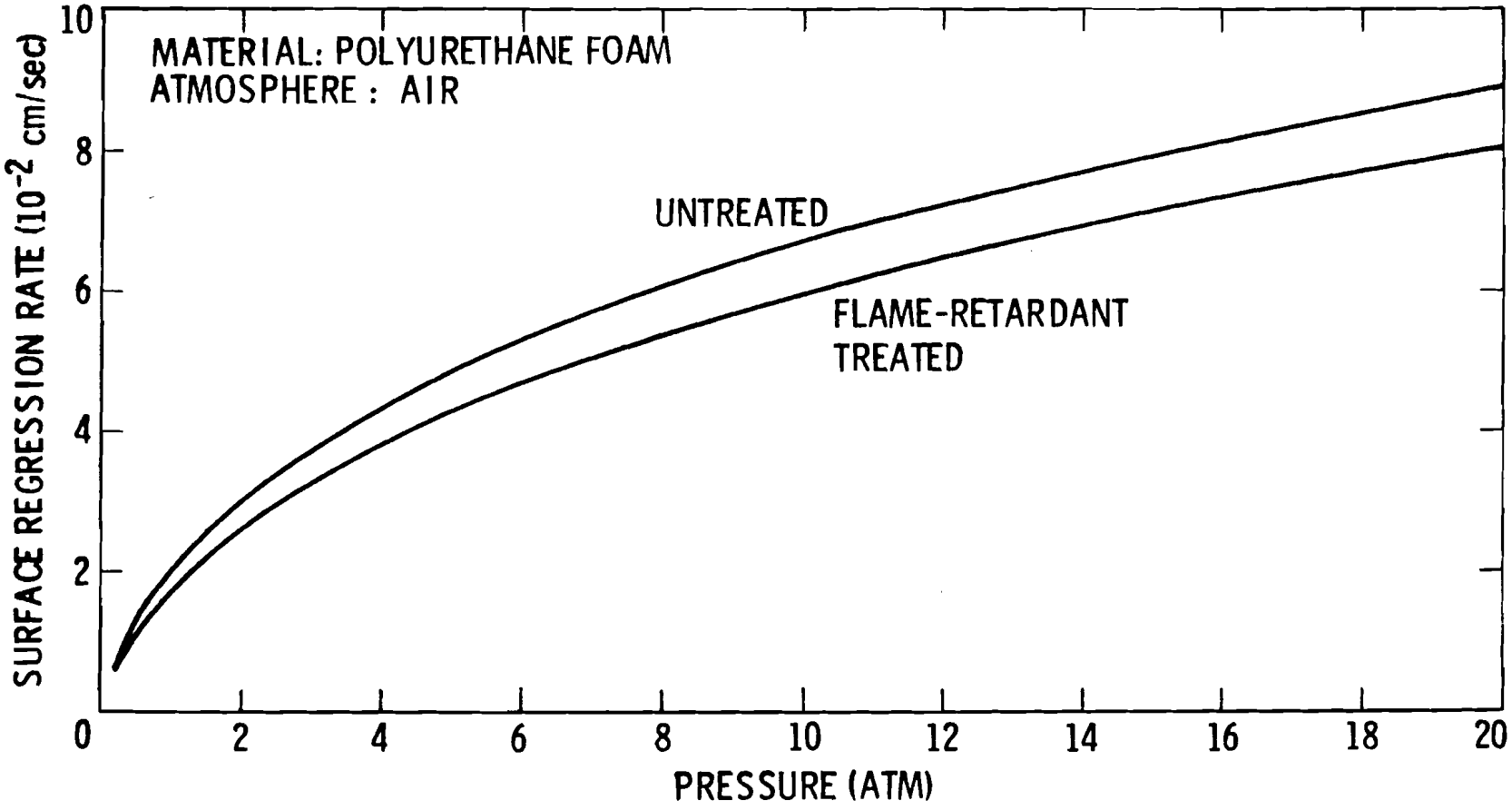


FIGURE 15. THE PRESSURE DEPENDENCE OF BURNING RATE OF SEAT CUSHION.

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APPENDIX A

COMPUTER PROGRAM FOR CALCULATIONS FOR SEAT CUSHION

Computer program for calculation of the burning rate, heat fluxes required and provided by the flame, and Spalding B number with variable flame stand-off distances and ambient pressure for seat cushion.

```
C     THIS PROGRAM IS FOR THE FAA SEAT CUSHION MATERIAL ONLY
C     THE KINETIC CONSTANTS WERE OBTAINED  IN AIR
C     AT THE HEATING RATE OF 30 C/MIN.
   10 READ (5,800,END=99) P, XRATIO, TB
  800 FORMAT (3F10.3)
      WRITE (6,910) P, XRATIO, TB
  910 FORMAT (1H1,3X, 'THERMOCHEMICAL PERFORMACE OF AIRCRAFT SEAT '
     - 'CUSHION' /, 15X, 'PRESSURE =  ', F6.1, ' ATM',/,
     - 15X,'XSTAR REDUCED BY ',F6.1,' (1.0 MEANS FLAME RETARDED, '
     - 'OTHERWISE UNTREATED)',/
     - 15X, 'FLAME TEMPERATURE = ', F7.1, 'K', //)
      DN = 0.04
      CP= 0.35
      CPGAS=0.3
      RTH = 0.00034
      EPSLON = 0.4
      SIGMA=1.355E-12
      D= 300.0
      R= 1.98717
      RM = 82.06
      TO=300.
      WRITE (6,911)
  911 FORMAT ( 10X, 'TS', 11X, 'RH', 14X, 'FLUX', 10X, 'FLMFLX', 12X,
     - 'DSUP', 11X, 'SPALDR',/
     - 10X, '(K)', 7X, '(CM/SEC)', 6X, '(BTU/FT2.SEC)',
     - 3X, '(BTU/FT2.SEC)', 8X, '(CM)',/)
      DO 97 I=450,750,10
      TS= FLOAT(I)
      IF (TS.GE.573.) GO TO 652
      B = 95000.
      E =  19400.
      GO TO 655
  652 CONTINUE
      B = 3.4E7
      E =  26500.
  655 CONTINUE
      B = B*P
      FSV= 32.8*EXP(0.00367*TS)
      FSV = FSV * ( P **-0.2615)
C     MONOMER MOLECULAR WEIGHT OF FOAM MATERIAL IS ASSUMED TO BE 76.
      FSV = FSV / 76.
      IF (FSV.LE.1.0)  GO TO 97
      W = ((RTH/(DN*CP))*B*EXP(-E/(R*TS)))
      U = (E/(R*TS))*((TS-TO)/TS)
      Y=((1.0+(D/(CP*(TS-TO))))*ALOG(FSV/(FSV-1.0)))
      Q =  D/(CP*(TS-TO) *FSV)
      S = (W/(U*(Y-Q)))
      IF (S.LE.0.0)  S=-S
```

```
      RH = (S)**0.5
      FLUX=(DN*RH*((CP*(TS-TO))+(D/FSV)))+(EPSLON*SIGMA*(TS**4.))
C     HERE WE CONVERT FROM CALORIES PER SQUARE CENTIMETERS TO BTU PER SQ.FT
      FLUX=FLUX*3.686
C     THIS IS THE FLAME TEMPERATURE IN AIR
C     TB (FLAME TEMP.) IS IN KELVIN.
      RHOGAS=0.0012*(TO/TB)
      RHOGAS = RHOGAS * P
      THCOND=0.0001*SQRT(TB/600.)
C     THERMAL CONDUCTIVITY OF THE GAS IS CALCULATED HERE WITH SUTHERLANDS LAW
      THDIFF=THCOND/(RHOGAS*CPGAS)
      UGAS=(DN/RHOGAS)*RH
C     THE FLAME STANDOFF DISTANCE IS COMPUTED BASED ON THE EXPERIMENTS OF JACK
C     WE FOUND IN SIMPLE BURNING OF A PIECE OF CARPET THAT THE FLAME STANDOFF
C     DISTANCE WAS NEARLY THREE (3) MILLIMETERS MAXIMUM AND TWO (2) ON AVERAGE
C     THE MEASURED AVERAGE VALUE OF 2 MM IS AT A VERY LOW FLOW VELOCITY
      XSTAR = UGAS / 3.0
      XSTAR = XSTAR * XRATIO
C     HERE WE CALCULATE THE HEAT FLUX TO THE SURFACE FROM THE FLAME ZONE ONLY
      TEXP = EXP(UGAS*XSTAR/THDIFF)
      FLMFLX = -RHOGAS*UGAS*CPGAS*(TB-TS)*TEXP/(1.-TEXP)
C     HERE WE CONVERT FLMFLX TO BTU PR SQ.FT.SEC  FROM CAL.PER.SQ.CM.SEC.
      FLMFLX=FLMFLX*3.686
C     WE CALCULATE SPALDING NUMBER B
      RHOO = P/(RM*TB)*28.84
      UOO = 134.06
      X = 61.08
      VISCOS = (1.764/1100.)*(TB-600.) + 2.028
      VISCOS = VISCOS * 14.882 * 0.00001
      RHOUOO = RHOO * UOO
      REYNOL = RHOUOO * X / VISCOS
      CHO = 0.12 * REYNOL**-0.2
      SPALDB = ((DN*RH)/(1.2*RHOUOO*CHO))**(1./0.23)
      IF (SPALDB.LE.5.0) GO TO 71
      CHCHO = 1.2 * (SPALDB**-0.77)
      GO TO  72
   71 CONTINUE
      SPALDB = EXP(DN*RH/(RHOUOO*CHO)) - 1.0
      CHCHO = ALOG(1.0+SPALDB) / SPALDB
   72 CONTINUE
      CH = CHCHO * CHO
      QSUP = CPGAS*RHOUOO*(TB-TS)*CH
C     HEAT SUPPLIED IS CONVERTED TO BTU/FT2.SEC FROM CAL/CM2.SEC
      QSUP = QSUP * 3.686
      WRITE (6,950) TS,RH,FLUX,FLMFLX,QSUP,SPALDB
  950 FORMAT (8X,F6.1, 6X, F7.4,4(8X,F8.3))
   97 CONTINUE
      GO TO 10
   99 STOP
      END
```

THERMOCHEMICAL PERFORMACE OF AIRCRAFT SEAT CUSHION
PRESSURE = 1.0 ATM
XSTAR REDUCED BY .8 (1.0 MEANS FLAME RETARDED, OTHERWISE UNTREATED)
FLAME TEMPERATURE = 1400.0K

TS (K)	RH (CM/SEC)	FLUX (BTU/FT2.SEC)	FLMFLX (BTU/FT2.SEC)	QSUP (CM)	SPALOB
450.0	.0003	.090	44.006	.795	.015
460.0	.0004	.100	32.903	.784	.021
470.0	.0005	.111	24.881	.774	.027
480.0	.0007	.124	19.017	.762	.035
490.0	.0008	.138	14.682	.750	.045
500.0	.0011	.153	11.444	.738	.058
510.0	.0013	.171	9.002	.724	.073
520.0	.0017	.191	7.143	.710	.092
530.0	.0021	.213	5.717	.694	.115
540.0	.0026	.238	4.614	.678	.144
550.0	.0031	.266	3.756	.660	.178
560.0	.0038	.297	3.084	.640	.220
570.0	.0046	.332	2.555	.619	.270
580.0	.0041	.334	2.814	.620	.238
590.0	.0051	.378	2.249	.596	.307
600.0	.0064	.429	1.824	.568	.396
610.0	.0079	.488	1.506	.538	.511
620.0	.0097	.557	1.270	.505	.661
630.0	.0118	.636	1.101	.469	.859
640.0	.0144	.728	.986	.429	1.125
650.0	.0174	.834	.921	.387	1.486
660.0	.0209	.957	.901	.343	1.989
670.0	.0250	1.098	.928	.298	2.706
680.0	.0297	1.261	1.003	.252	3.757
690.0	.0352	1.449	1.126	.169	6.538
700.0	.0416	1.664	1.292	.096	13.422
710.0	.0488	1.911	1.491	.055	27.057
720.0	.0572	2.193	1.719	.032	53.598
730.0	.0666	2.514	1.974	.019	104.414
740.0	.0774	2.881	2.259	.011	200.177
750.0	.0896	3.297	2.575	.007	377.921

THERMOCHEMICAL PERFORMACE OF AIRCRAFT SEAT CUSHION
PRESSURE = 1.0 ATM
XSTAR REDUCED BY 1.0 (1.0 MEANS FLAME RETARDED, OTHERWISE UNTREATED)
FLAME TEMPERATURE = 1400.0K

TS (K)	RH (CM/SEC)	FLUX (BTU/FT2.SEC)	FLMFLX (BTU/FT2.SEC)	QSUP (CM)	SPALDB
450.0	.0003	.090	35.206	.795	.015
460.0	.0004	.100	26.323	.784	.021
470.0	.0005	.111	19.906	.774	.027
480.0	.0007	.124	15.216	.762	.035
490.0	.0008	.138	11.749	.750	.045
500.0	.0011	.153	9.159	.738	.058
510.0	.0013	.171	7.207	.724	.075
520.0	.0017	.191	5.721	.710	.092
530.0	.0021	.213	4.582	.694	.115
540.0	.0026	.238	3.701	.678	.144
550.0	.0031	.266	3.016	.660	.178
560.0	.0038	.297	2.481	.640	.220
570.0	.0046	.332	2.061	.619	.270
580.0	.0041	.334	2.266	.620	.238
590.0	.0051	.378	1.818	.596	.307
600.0	.0064	.429	1.483	.568	.396
610.0	.0079	.488	1.234	.538	.511
620.0	.0097	.557	1.053	.505	.661
630.0	.0118	.636	.928	.469	.859
640.0	.0144	.728	.849	.429	1.125
650.0	.0174	.834	.815	.387	1.486
660.0	.0209	.957	.823	.343	1.989
670.0	.0250	1.098	.875	.298	2.706
680.0	.0297	1.261	.973	.252	3.757
690.0	.0352	1.449	1.113	.169	6.538
700.0	.0416	1.664	1.288	.096	13.422
710.0	.0488	1.911	1.491	.055	27.057
720.0	.0572	2.193	1.719	.032	53.598
730.0	.0666	2.514	1.974	.019	104.414
740.0	.0774	2.881	2.259	.011	200.177
750.0	.0896	3.297	2.575	.007	377.921

APPENDIX B

COMPURER PROGRAM FOR CALCULATIONS FOR CARPET

Computer program for calculation of the burning rate, heat fluxes required and provided by the flame, and Spalding B number with variable flame stand-off distances and ambient pressure for carpet.

```
C       THIS PROGRAM IS FOR THE FAA CARPET MATERIAL ONLY
C       THE KINETIC CONSTANTS WERE OBTAINED FROM FAA CARPET BLUE PORTION
C       UNDER (99 PERCENT NITROGEN + 1 PERCENT OXYGEN)
C       AT THE HEATING RATE OF 30 C/MIN.
   10 READ (5,800,END=99) P, XRATIO, TR
  800 FORMAT (3F10.3)
      WRITE (6,910) P, XRATIO, TR
  910 FORMAT (1H1,3X, 'THERMOCHEMICAL PERFORMACE OF AIRCRAFT '
     - 'CARPET'  /, 15X, 'PRESSURE =  ', F6.1, ' ATM',/,
     - 15X,'XSTAR REDUCED BY ',F6.1,' (1.0 MEANS FLAME RETARDED, '
     - 'OTHERWISE UNTREATED)',/
     - 15X, 'FLAME TEMPERATURE = ', F7.1, 'K', //
     - 7X, 'TS', 9X, 'FSC', 10X, 'RH', 11X, 'RL', 9X, 'Q-REQ', 7X,
     - 'Q-XSTAR', 5X, 'Q-FLOW', 4X, 'SPALDING B'/
     - 7X, '(K)', 25X, '(CM/SEC)', 16X, '(  BTU  /  FT2 . SEC  )',//)
      R= 1.98717
      RM = 62.06
      DN=0.22
      CP= 0.3
      CPGAS = 0.3
      D= 300.0
      QCOMB = 4900.
      RTH=0.0001
C     THIS VALUE OF THE CHAR CONDUCTIVITY IS A GUESS ONLY AT THIS TIME
      RTL=0.00002
      EPSLON = 0.7
      SIGMA = 1.355E-12
      TD=300.
      TC = 816.
      DO 97 I=820,950,10
      TS= FLOAT(I)
      FSV= 32.8*EXP(0.00367*TS)
      FSV = FSV * (P**-0.2615)
      FSV=FSV/138.42
      IF (TS.GE.816.)  GO TO 652
      IF (TS.LE.816..AND.TS.GE.641.)  GO TO 654
      B = 7.21
      E = 9265.
      GO TO 655
  652 CONTINUE
      B = 177.6
      E = 21100.
      GO TO 655
  654 CONTINUE
      B = 3.84E-8
      E = -15000.
  655 CONTINUE
      B = B*P
      DO 95 N=1,2000
      FSC=FSV+ 0.1*FLOAT(N)
```

```
      IF (FSC.EQ.1.0) GO TO 85
      W = ((RTH/(DN*CP))*B*EXP(-E/(R*TC)))
      U = (E/(R*TC))*((TC-TD)/TC)
      Y=((1.0+(D/(CP*(TC-TD))))*ALOG(FSC/(FSC-1.0)))
      Q =  D/(CP*(TC-TD) *FSC)
      S = (W/(U*(Y-Q)))
      IF (S.LE.0.0) GO TO 85
      RH = (S)**0.5
      VH = D/(CP*(TS-TD))
      VTHETA = E/(R*TS)
      VKSI = (TS-TD)/TS
      VZETAS= -VH/FSV
      VZETAC= -VH/FSC
      VTAW= (TC-TD)/(TS-TD)
      VZETAC=VTHETA*VKSI*(1.0-VTAW)
      HEC = VH + VZETAC
      HES = VH + VZETAS
      IF (HEC.EQ.0.0) GO TO 85
      IF (HES.EQ.0.0) GO TO 85
      ENC = EXP(-VZETAC)
      VK = (-VZETAC+(1+VH)*ALOG(HEC)-(1+VH)*ENC*ALOG(HES)+VZETAS*ENC)
     $ /(1.0-ENC)
      VLAMDA = (VZETAS-(VH*ALOG(VZETAS+VH)))-(ALOG(VH+VZETAS))+VK
      TT=(((RTL/DN/CP)*B*EXP(-VTHETA))/(VLAMDA*VTHETA*VKSI))
      IF (TT.LE.0.0) GO TO 85
      RL = (TT)**0.5
      FLUX=(DN*RL*((CP*(TS-TD))+(D/FSV)))+(EPSLDN*SIGMA*(TS**4.))
C     HERE WE CONVERT FROM CALORIES PER SQUARE CENTIMETERS TO BTU PER SQ.FT
      FLUX=FLUX*3.686
C     TB (FLAME TEMP.) IS IN KELVIN.
      RHOGAS=0.0012*(TD/TB)
      RHOGAS = RHOGAS * P
      THCOND=0.0001*SQRT(TB/600.)
C     THERMAL CONDUCTIVITY OF THE GAS IS CALCULATED HERE WITH SUTHERLANDS LAW
      THDIFF=THCOND/(RHOGAS*CPGAS)
      UGAS=(DN/RHOGAS)*RL
C     THE FLAME STANDOFF DISTANCE IS COMPUTED BASED ON THE EXPERIMENTS OF JACK
C     HE FOUND IN SIMPLE BURNING OF A PIECE OF CARPET THAT THE FLAME STANDOFF
C     DISTANCE WAS NEARLY THREE (3) MILLIMETERS MAXIMUM AND TWO (2) ON AVERAGE
C     THE MEASURED AVERAGE VALUE OF 2 MM IS AT A VERY LOW FLOW VELOCITY
      XSTAR=UGAS/3.
      XSTAR = XSTAR* XRATIO
C     HERE WE CALCULATE THE HEAT FLUX TO THE SURFACE FROM THE FLAME ZONE ONLY
      FLMFLX=-(RHOGAS*UGAS)*CPGAS*(TB-TS)/(1.-EXP(UGAS*XSTAR/THDIFF))
C     HERE WE CONVERT FLMFLX TO BTU PR SQ.FT.SEC  FROM CAL.PER.SQ.CM.SEC.
      FLMFLX=FLMFLX*3.686
C     WE CALCULATE SPALDING NUMBER B
      RHOD = P/(RM*TB)*28.84
      UDO = 134.08
      X = 61.08
```

```
      VISCOS = (1.764/1100.)*(TB-600.) + 2.028
      VISCOS = VISCOS * 14.882 * 0.00001
      RHOUDU = RHOU * UOU
      REYNOL = RHOUDU * X / VISCOS
      CHO = 0.12 * REYNOL**-0.2
      SPALDB = [(DN*RH)/(1.2*RHOUDU*CHO)]**(1./0.23)
      IF (SPALDB.LE.5.0) GO TO 71
      CHCHO = 1.2 * (SPALDB**-0.77)
      GO TO  72
   71 CONTINUE
      SPALDB = EXP(DN*RH/(RHOUDU*CHO)) - 1.0
      CHCHO = ALOG(1.0+SPALDB) / SPALDB
   72 CONTINUE
      CH = CHCHO * CHO
      QSUP = CPGAS*RHOUDU*(TB-TS)*CH
C     HEAT SUPPLIED IS CONVERTED TO BTU/FT2.SEC FROM CAL/CM2.SEC
      QSUP = QSUP * 3.686
   65 WRITE (6,90) TS,FSC,RH,RL,FLUX,FLMFLX,QSUP,SPALDB
   90 FORMAT (F10.1,3X, F9.3,2(3X,F10.5),4(3X,F9.3))
      IF (RH.GE.RL)  GO TO 97
   95 CONTINUE
   97 CONTINUE
      GO TO 10
   99 STOP
      END
```

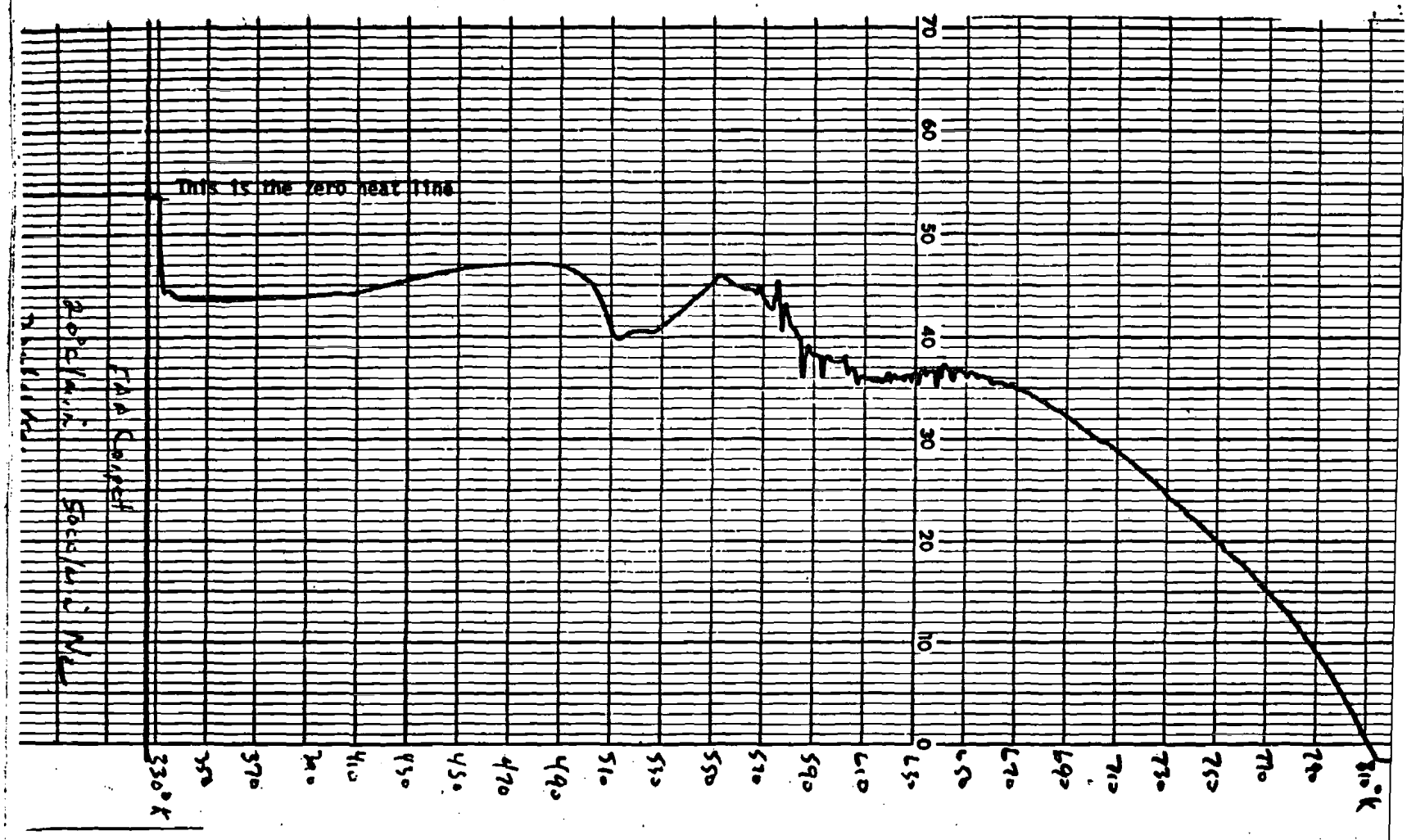
THERMOCHEMICAL PERFORMACE OF AIRCRAFT CARPET
PRESSURE = 1.0 ATM
XSTAR REDUCED BY 1.0 (1.0 MEANS FLAME RETARDED, OTHERWISE UNTREATED)
FLAME TEMPERATURE = 1400.0K

TS (K)	FSC	HM	RL (CM/SEC)	Q-REQ	Q-XSTAR	Q-FLOW	SPALDING B
				(BTU / FT2 , SEC)			
820.0	4.904	.00052	.00036	1.644	3.177	.454	.160
830.0	5.084	.00053	.00072	1.788	1.503	.445	.164
830.0	5.184	.00053	.00052	1.751	2.134	.444	.167
840.0	5.270	.00054	.00103	1.924	1.007	.436	.169
840.0	5.370	.00055	.00074	1.872	1.454	.436	.171
840.0	5.470	.00055	.00061	1.849	1.779	.435	.173
840.0	5.570	.00056	.00053	1.836	2.042	.435	.175
850.0	5.464	.00055	.00133	2.063	.733	.428	.173
850.0	5.564	.00056	.00095	1.995	1.083	.427	.175
850.0	5.664	.00057	.00078	1.965	1.335	.427	.177
850.0	5.764	.00057	.00069	1.948	1.539	.427	.179
850.0	5.664	.00058	.00062	1.936	1.712	.426	.181
850.0	5.964	.00058	.00057	1.927	1.863	.426	.183
860.0	5.664	.00057	.00164	2.207	.550	.419	.177
860.0	5.764	.00057	.00117	2.123	.837	.419	.179
860.0	5.864	.00058	.00096	2.086	1.043	.418	.181
860.0	5.964	.00058	.00084	2.064	1.208	.418	.183
860.0	6.064	.00059	.00076	2.050	1.348	.418	.186
860.0	6.164	.00060	.00070	2.039	1.471	.417	.188
860.0	6.264	.00060	.00066	2.031	1.579	.417	.190
860.0	6.364	.00061	.00062	2.024	1.677	.417	.192
860.0	6.464	.00061	.00059	2.019	1.766	.416	.194
870.0	5.872	.00058	.00196	2.358	.416	.411	.182
870.0	5.972	.00058	.00140	2.257	.659	.410	.184
870.0	6.072	.00059	.00116	2.212	.831	.410	.186
870.0	6.172	.00060	.00101	2.186	.969	.410	.188
870.0	6.272	.00060	.00091	2.168	1.086	.409	.190
870.0	6.372	.00061	.00084	2.155	1.188	.409	.192
870.0	6.472	.00061	.00079	2.145	1.278	.408	.194
870.0	6.572	.00062	.00074	2.137	1.360	.408	.196
870.0	6.672	.00063	.00071	2.131	1.434	.408	.198
870.0	6.772	.00063	.00068	2.125	1.502	.407	.200
870.0	6.872	.00064	.00065	2.121	1.565	.407	.202
870.0	6.972	.00064	.00063	2.117	1.624	.407	.204
880.0	6.088	.00059	.00232	2.518	.312	.402	.186
880.0	6.188	.00060	.00166	2.398	.521	.402	.188
880.0	6.288	.00060	.00137	2.345	.669	.401	.190
880.0	6.388	.00061	.00119	2.314	.787	.401	.192
880.0	6.488	.00061	.00108	2.292	.886	.401	.194
880.0	6.588	.00062	.00099	2.277	.973	.400	.196
880.0	6.688	.00063	.00093	2.265	1.049	.400	.198
880.0	6.788	.00063	.00088	2.256	1.119	.400	.200
880.0	6.888	.00064	.00083	2.248	1.182	.399	.202
880.0	6.988	.00064	.00080	2.241	1.239	.399	.204
880.0	7.088	.00065	.00077	2.236	1.293	.399	.206
880.0	7.188	.00065	.00074	2.231	1.343	.398	.208
880.0	7.288	.00066	.00072	2.227	1.389	.398	.210
880.0	7.388	.00067	.00070	2.223	1.433	.398	.212

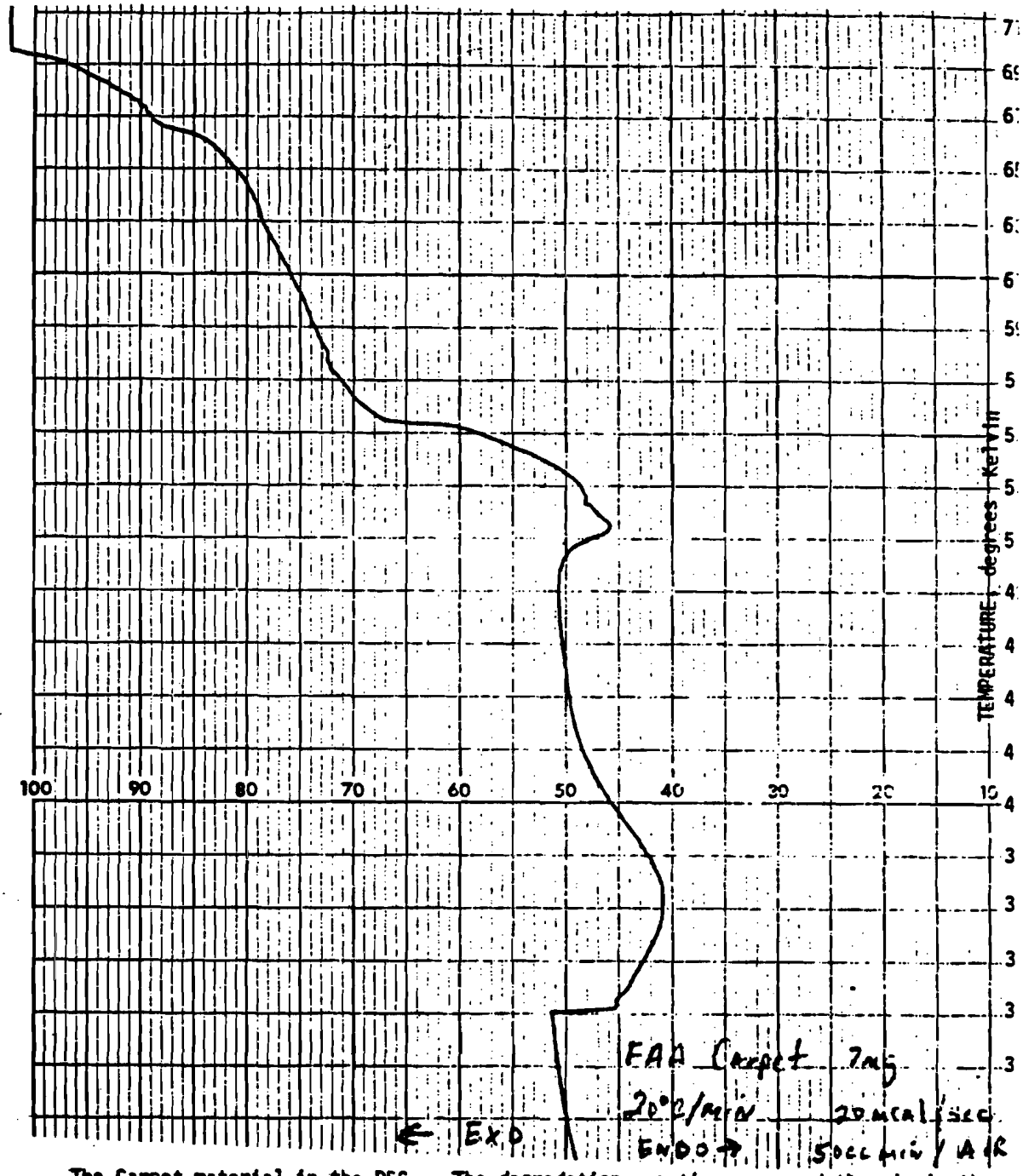
880.0	7.488	.00067	.00068	2.220	1.474	.397	.213
880.0	7.588	.00068	.00066	2.217	1.512	.397	.215
890.0	6.312	.00060	.00270	2.688	.230	.394	.191
890.0	6.412	.00061	.00193	2.546	.411	.393	.193
890.0	6.512	.00062	.00159	2.484	.540	.393	.195
890.0	6.612	.00062	.00139	2.448	.642	.393	.197
890.0	6.712	.00063	.00125	2.423	.727	.392	.199
890.0	6.812	.00063	.00116	2.405	.802	.392	.201
890.0	6.912	.00064	.00108	2.391	.868	.392	.202
890.0	7.012	.00064	.00102	2.379	.928	.391	.204
890.0	7.112	.00065	.00097	2.370	.982	.391	.206
890.0	7.212	.00066	.00093	2.363	1.032	.391	.208
890.0	7.312	.00066	.00089	2.356	1.078	.390	.210
890.0	7.412	.00067	.00086	2.350	1.121	.390	.212
890.0	7.512	.00067	.00083	2.345	1.161	.390	.214
890.0	7.612	.00068	.00081	2.341	1.198	.389	.216
890.0	7.712	.00068	.00079	2.337	1.233	.389	.218
890.0	7.812	.00069	.00077	2.334	1.267	.389	.220
890.0	7.912	.00069	.00075	2.330	1.298	.388	.221
890.0	8.012	.00070	.00073	2.328	1.328	.388	.223
890.0	8.112	.00070	.00072	2.325	1.356	.388	.225
890.0	8.212	.00071	.00071	2.322	1.364	.388	.227
900.0	6.544	.00062	.00312	2.868	.163	.385	.195
900.0	6.644	.00062	.00223	2.703	.321	.385	.197
900.0	6.744	.00063	.00184	2.631	.434	.384	.199
900.0	6.844	.00064	.00160	2.588	.523	.384	.201
900.0	6.944	.00064	.00145	2.560	.598	.384	.203
900.0	7.044	.00065	.00133	2.538	.663	.383	.205
900.0	7.144	.00065	.00124	2.522	.721	.383	.207
900.0	7.244	.00066	.00117	2.509	.773	.383	.209
900.0	7.344	.00066	.00111	2.499	.820	.383	.211
900.0	7.444	.00067	.00107	2.490	.863	.382	.213
900.0	7.544	.00067	.00102	2.482	.903	.382	.215
900.0	7.644	.00068	.00099	2.475	.941	.382	.216
900.0	7.744	.00068	.00096	2.470	.975	.381	.218
900.0	7.844	.00069	.00093	2.464	1.008	.381	.220
900.0	7.944	.00069	.00090	2.460	1.039	.381	.222
900.0	8.044	.00070	.00088	2.456	1.068	.380	.224
900.0	8.144	.00070	.00086	2.452	1.095	.380	.226
900.0	8.244	.00071	.00084	2.449	1.121	.380	.227
900.0	8.344	.00072	.00083	2.446	1.146	.380	.229
900.0	8.444	.00072	.00081	2.443	1.170	.379	.231
900.0	8.544	.00073	.00080	2.440	1.192	.379	.233
900.0	8.644	.00073	.00078	2.438	1.214	.379	.234
900.0	8.744	.00073	.00077	2.435	1.234	.378	.236
900.0	8.844	.00074	.00076	2.433	1.254	.378	.238
900.0	8.944	.00074	.00075	2.431	1.273	.378	.240
900.0	9.044	.00075	.00074	2.430	1.291	.378	.241
910.0	6.785	.00063	.00358	3.059	.111	.377	.200
910.0	6.885	.00064	.00255	2.869	.247	.376	.202
910.0	6.985	.00064	.00210	2.786	.346	.376	.204
910.0	7.085	.00065	.00184	2.737	.425	.376	.206
910.0	7.185	.00065	.00166	2.703	.491	.375	.208
910.0	7.285	.00066	.00152	2.679	.548	.375	.210
910.0	7.385	.00067	.00142	2.660	.599	.375	.212
910.0	7.485	.00067	.00134	2.645	.645	.374	.213
910.0	7.585	.00068	.00127	2.633	.686	.374	.215

APPENDIX C

EXPERIMENTAL DSC DATA



The carpet material tested in the DSC. The degradation reactions are solely endothermic in this inert(N_2) atmosphere as can be seen in the trace above. The heating rate is 20°C/min. Such data are useful in the analyses treating the subsurface reactions where the access to atmospheric oxygen is limited.



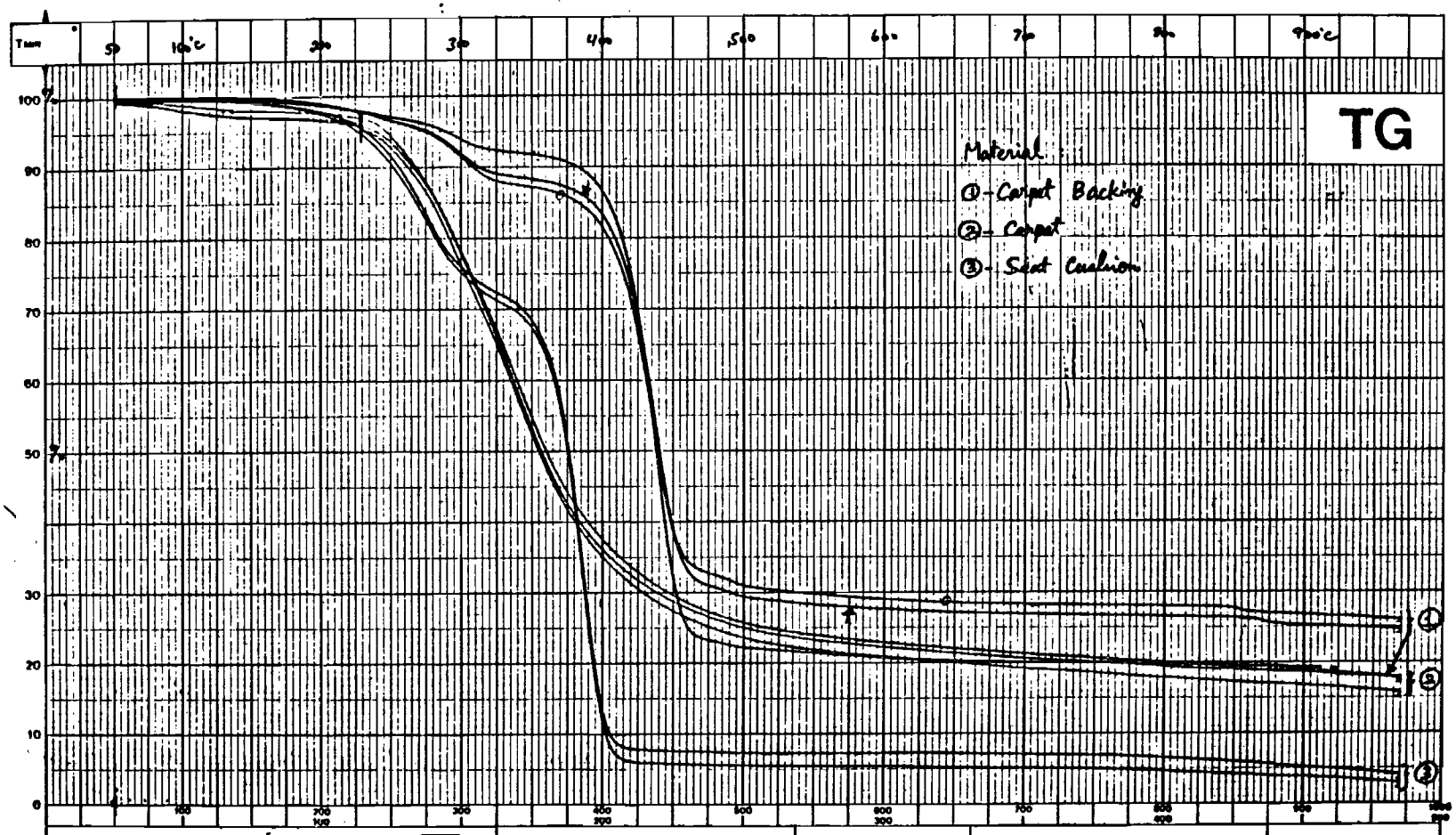
The Carpet material in the DSC. The degradation reactions are endothermic in the beginning but become exothermic as the temperature increases. The atmosphere is air. In contrast to the trace in figure 4a, strong effects of oxidative degradatio are indicated. Such data are useful in treating surface reactions in an actual carpet in a fire situation. (the heating rate is 20°C/min.)

APPENDIX D

EXPERIMENTAL TGA DATA

SAMPLE TEMPERATURE °C

073080-N



MULTI-STEP PROGRAMS	P1	P2	P3	P4
TEMP (°C)	50	1000		
TIME (min)				
RATE (°C/min)	20°C			

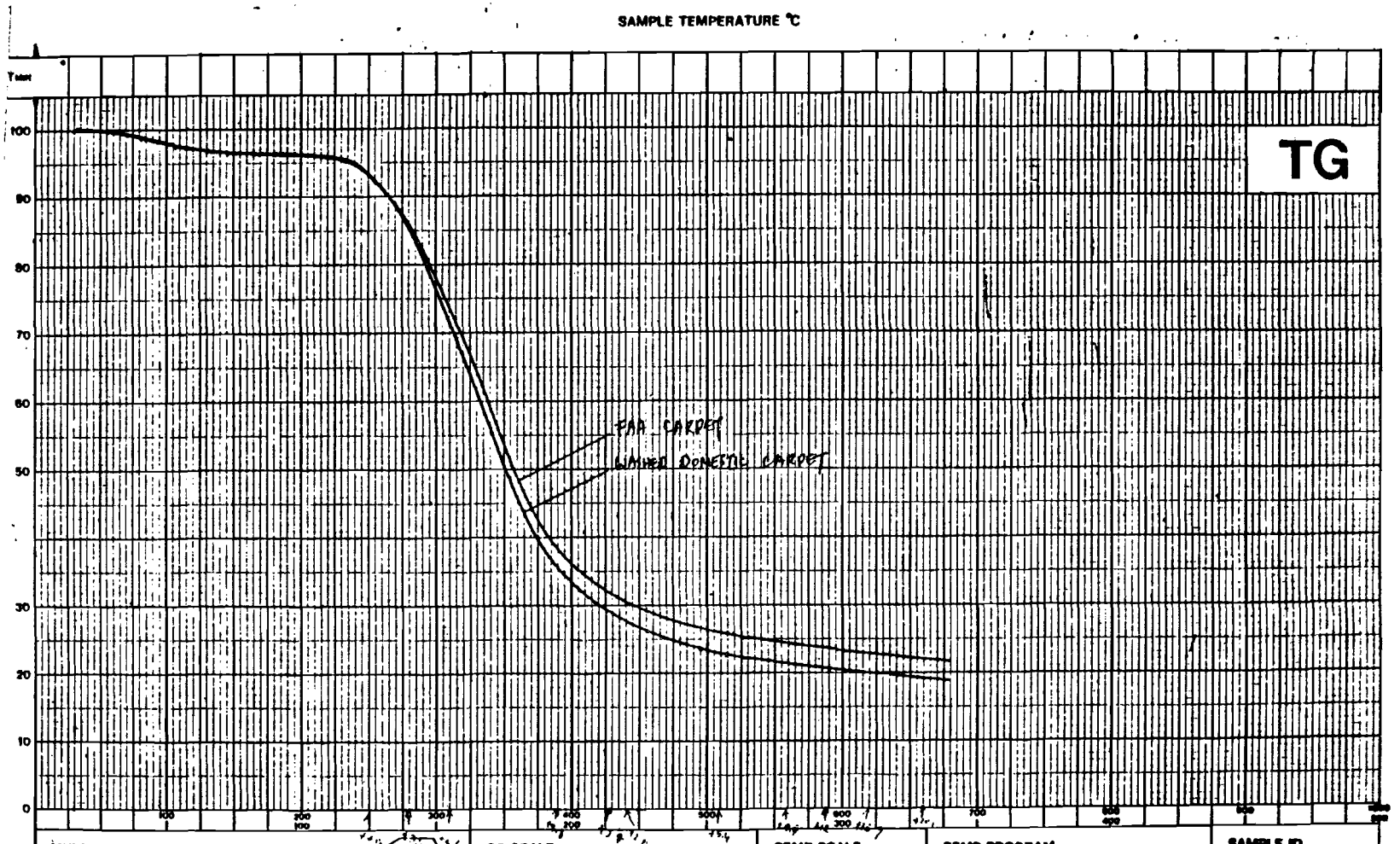
TG SCALE
RECORDER RANGE (Wt) 2.0 mg
Wt SUPPRESSED ____ mg
100 % SAMPLE Wt = 100 DIVISIONS
FDC RANGE (DTG) ____ mg/min

TEMP SCALE
T_{MIN} ____ °C
T_{SPAN} ____ °C

ATMOSPHERE
N_2 @ 50 cc/min

TEMP PROGRAM
LOWER TEMP (T_{MIN}) 50 °C
UPPER TEMP (T_{MAX}) 1000 °C
HEATING RATE 20 °C/min
COOLING RATE MAX °C/min

SAMPLE ID
MATERIAL ____
WEIGHT ~2.0 mg
DATE ____
OPERATOR FNT



MULTI-STEP PROGRAMS

	P1	P2	P3	P4
TEMP (°C)				
TIME (min)				
RATE (°C/min)				

TG SCALE

RECORDER RANGE (Wt) _____ mg

Wt SUPPRESSED _____ mg

___ % SAMPLE Wt = 100 DIVISIONS

FDC RANGE (DTG) _____ mg/min

TEMP SCALE

T_{MIN} _____ °C

T_{SPAN} _____ °C

ATMOSPHERE

N_2 50 cc/min

TEMP PROGRAM

LOWER TEMP (T_{MIN}) 30 °C

UPPER TEMP (T_{MAX}) 800 °C

HEATING RATE 30 °C/min

COOLING RATE _____ °C/min

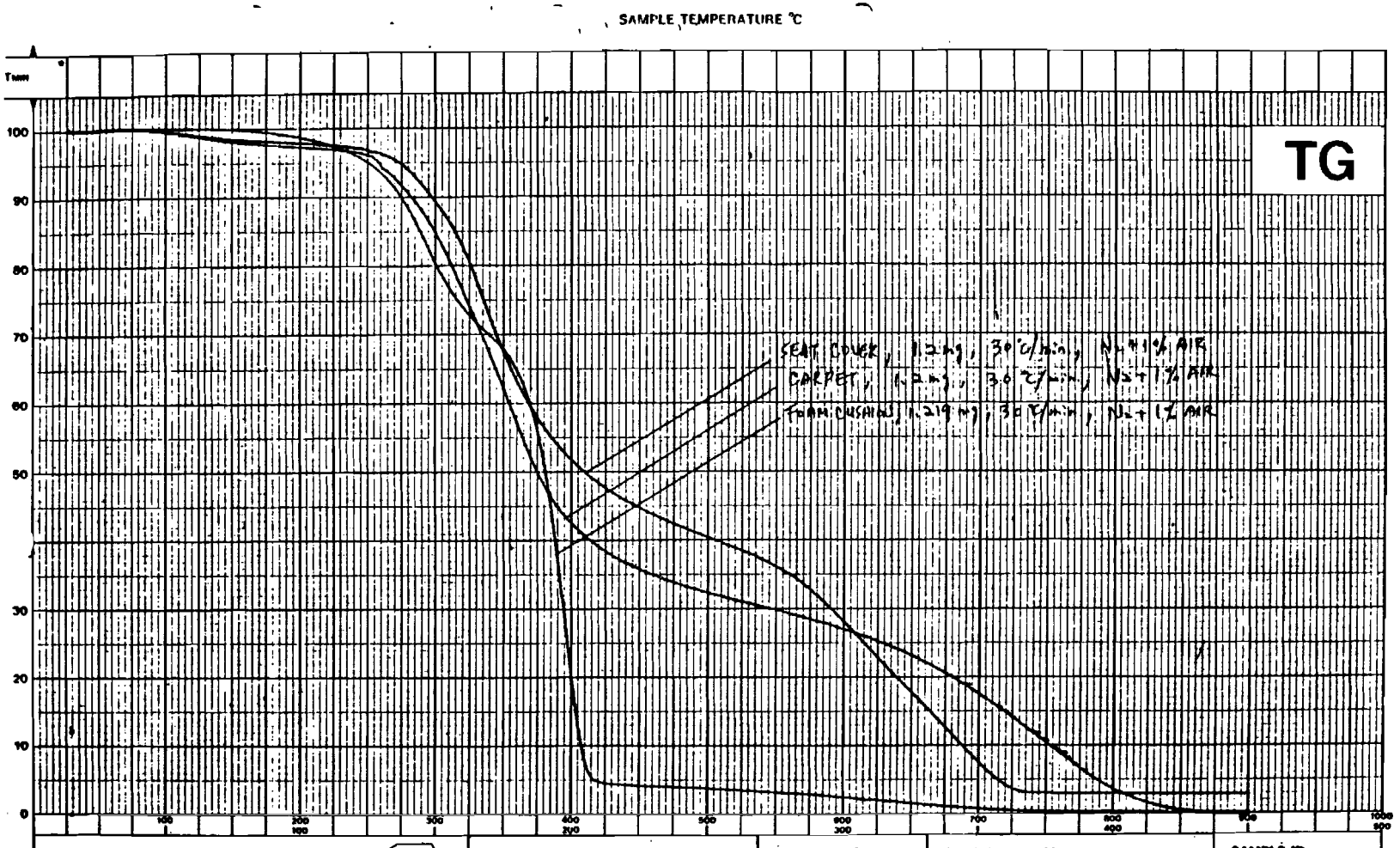
SAMPLE ID

MATERIAL _____

WEIGHT _____ mg

DATE 10/16/80

OPERATOR [illegible]



MULTI-STEP PROGRAMS	P1	P2	P3	P4
TEMP (°C)				
TIME (min)				
RATE (°C/min)				

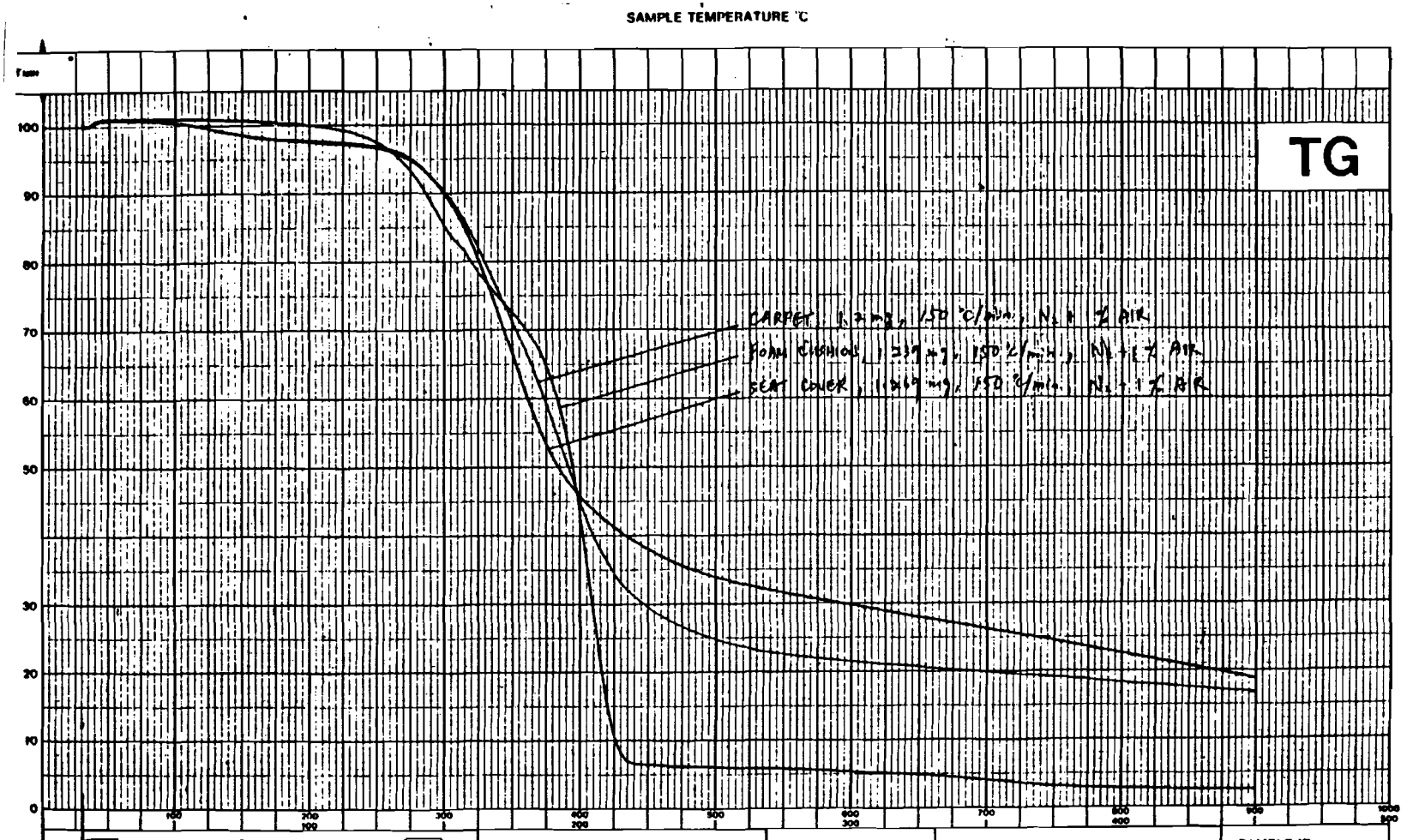
TG SCALE
RECORDER RANGE (Wt) _____ mg
Wt SUPPRESSED _____ mg
_ % SAMPLE Wt = 100 DIVISIONS
FDC RANGE (DTG) _____ mg/min

TEMP SCALE
T_{MIN} _____ °C
T_{SPAN} _____ °C

ATMOSPHERE
___ @ ___ cc/min

TEMP PROGRAM
LOWER TEMP (T_{MIN}) _____ °C
UPPER TEMP (T_{MAX}) _____ °C
HEATING RATE _____ °C/min
COOLING RATE _____ °C/min

SAMPLE ID
MATERIAL _____
WEIGHT _____ mg
DATE 1-16-81
OPERATOR _____



MULTI-STEP PROGRAMS	P1	P2	P3	P4
TEMP (°C)				
TIME (min)				
RATE (°C/min)				

TG SCALE
RECORDER RANGE (Wt) ____ mg
Wt SUPPRESSED ____ mg
____ % SAMPLE Wt = 100 DIVISIONS
FDC RANGE (DTG) ____ mg/min

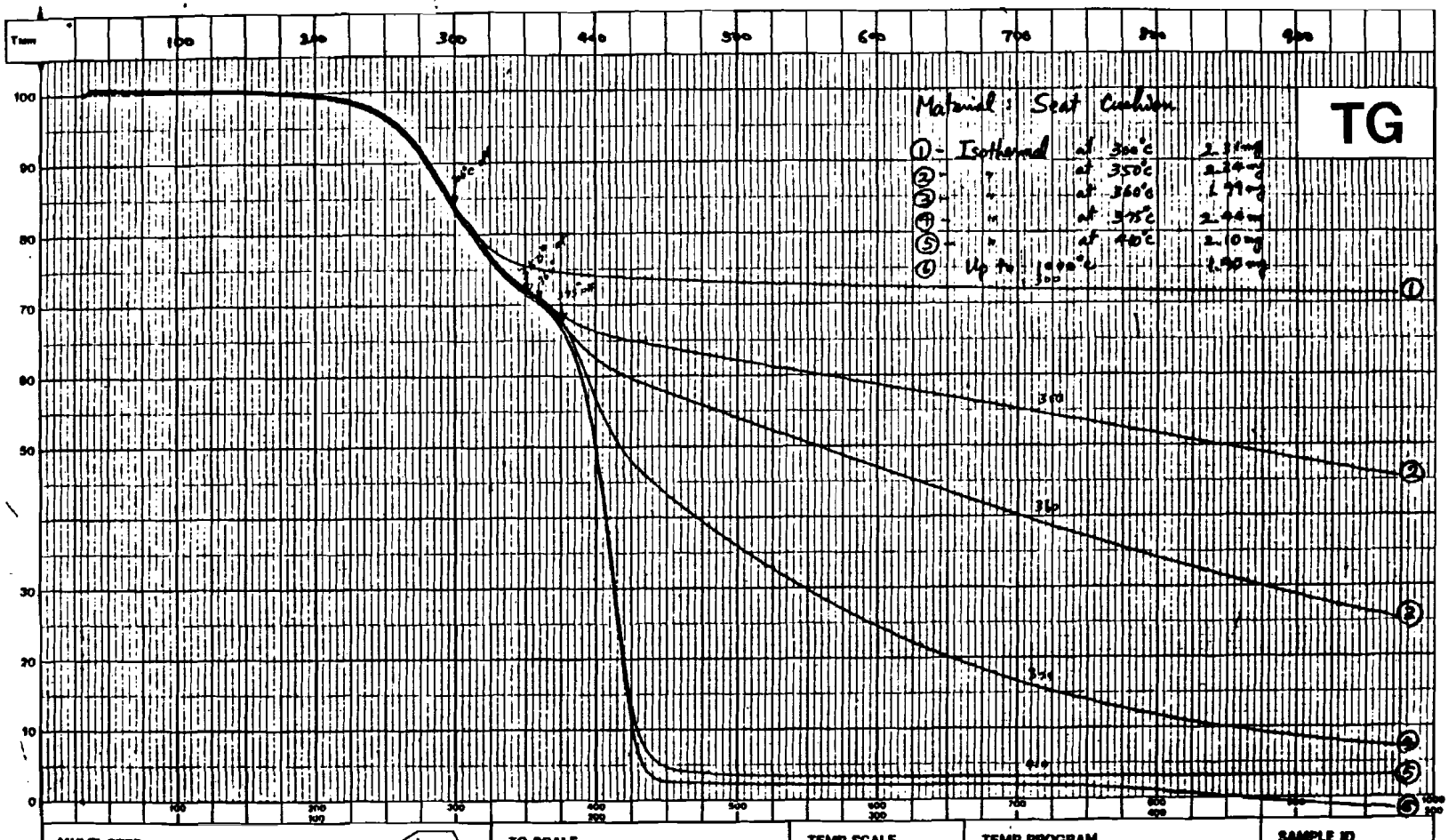
TEMP SCALE
T_{MIN} ____ °C
T_{SPAN} ____ °C

ATMOSPHERE
____ @ ____ cc/min

TEMP PROGRAM
LOWER TEMP (T_{MIN}) ____ °C
UPPER TEMP (T_{MAX}) ____ °C
HEATING RATE ____ °C/min
COOLING RATE ____ °C/min

SAMPLE ID
MATERIAL ____
WEIGHT ____ mg
DATE 1-16-81
OPERATOR ____

SAMPLE TEMPERATURE °C



MULTI-STEP PROGRAMS	P1	P2	P3	P4
TEMP (°C)				
TIME (min)				
RATE (°C/min)				

TG SCALE
RECORDER RANGE (Wt) ____ mg
Wt SUPPRESSED ____ mg
100 % SAMPLE Wt = 100 DIVISIONS
FDC RANGE (DTG) ____ mg/min

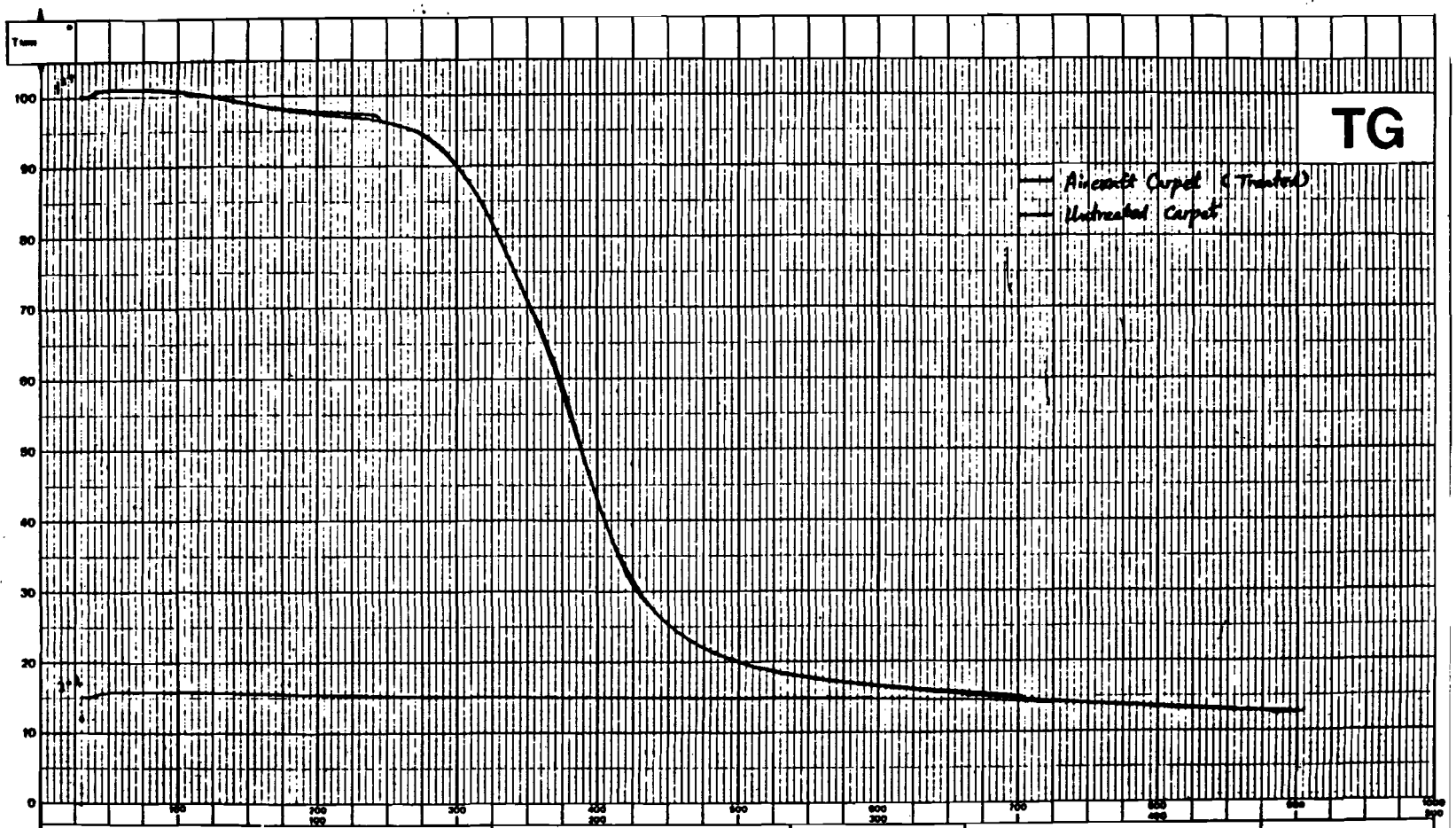
TEMP SCALE
T_{MIN} ____ °C
T_{SPAN} ____ °C

ATMOSPHERE
N_2 @ 50 cc/min

TEMP PROGRAM
LOWER TEMP (T_{MIN}) 20 °C
UPPER TEMP (T_{MAX}) 1000 °C
HEATING RATE 150 °C/min
COOLING RATE MAX °C/min

SAMPLE ID
MATERIAL ____
WEIGHT ~1.0 mg
DATE ____
OPERATOR WD

SAMPLE TEMPERATURE °C



MULTI-STEP PROGRAMS

P1 P2 P3 P4

TEMP (°C)

TIME (min)

RATE (°C/min)

TG SCALE

RECORDER RANGE (WT) ____ mg

WT SUPPRESSED ____ mg

____ % SAMPLE WT = 100 DIVISIONS

FDC RANGE (DTG) ____ mg/min

TEMP SCALE

T_{MIN} ____ °C

T_{SPAN} ____ °C

ATMOSPHERE

N_2 @ 50 cc/min

TEMP PROGRAM

LOWER TEMP (T_{MIN}) 30 °C

UPPER TEMP (T_{MAX}) 900 °C

HEATING RATE 150 °C/min

COOLING RATE MAX. °C/min

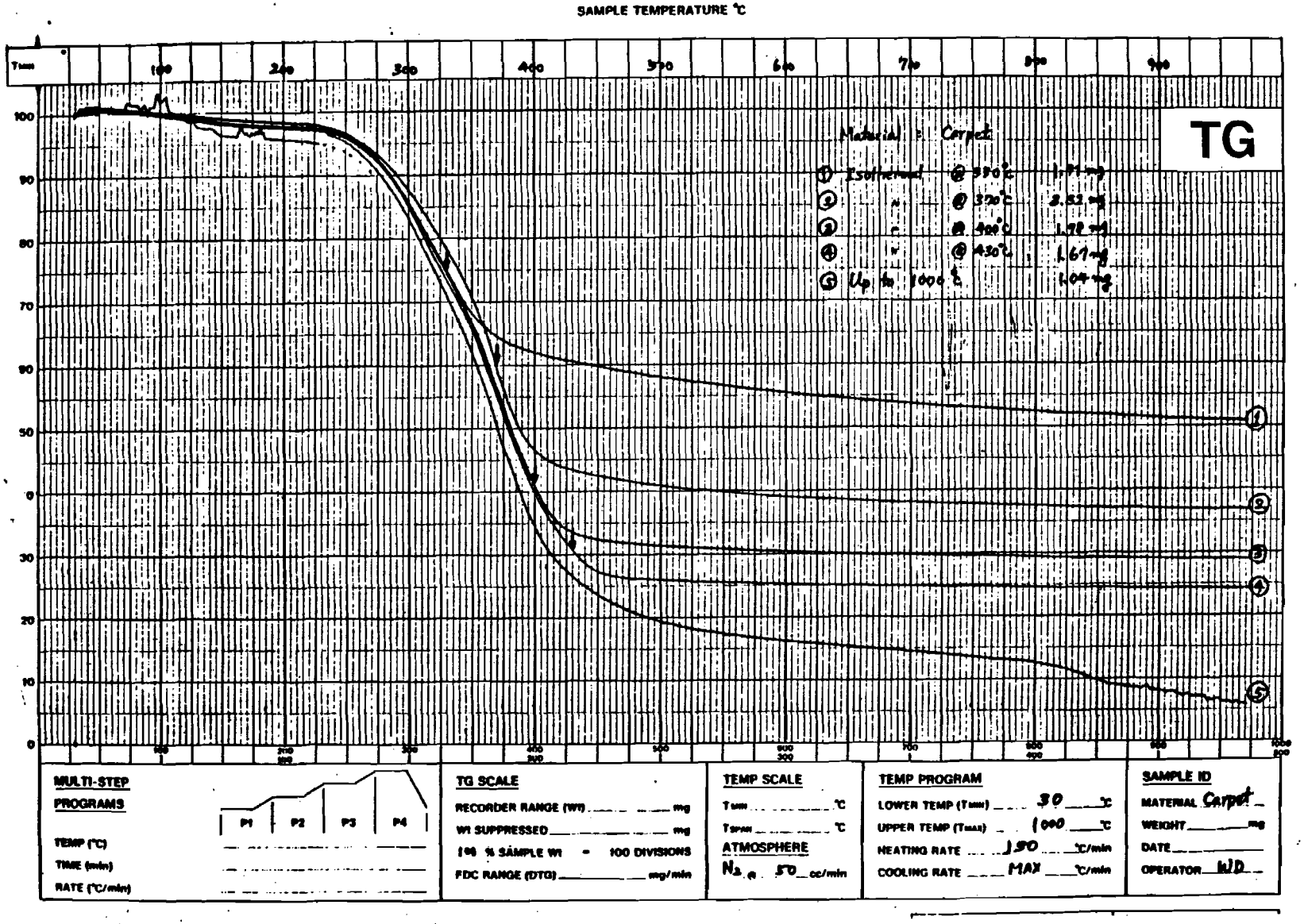
SAMPLE ID

MATERIAL Carpet Fiber

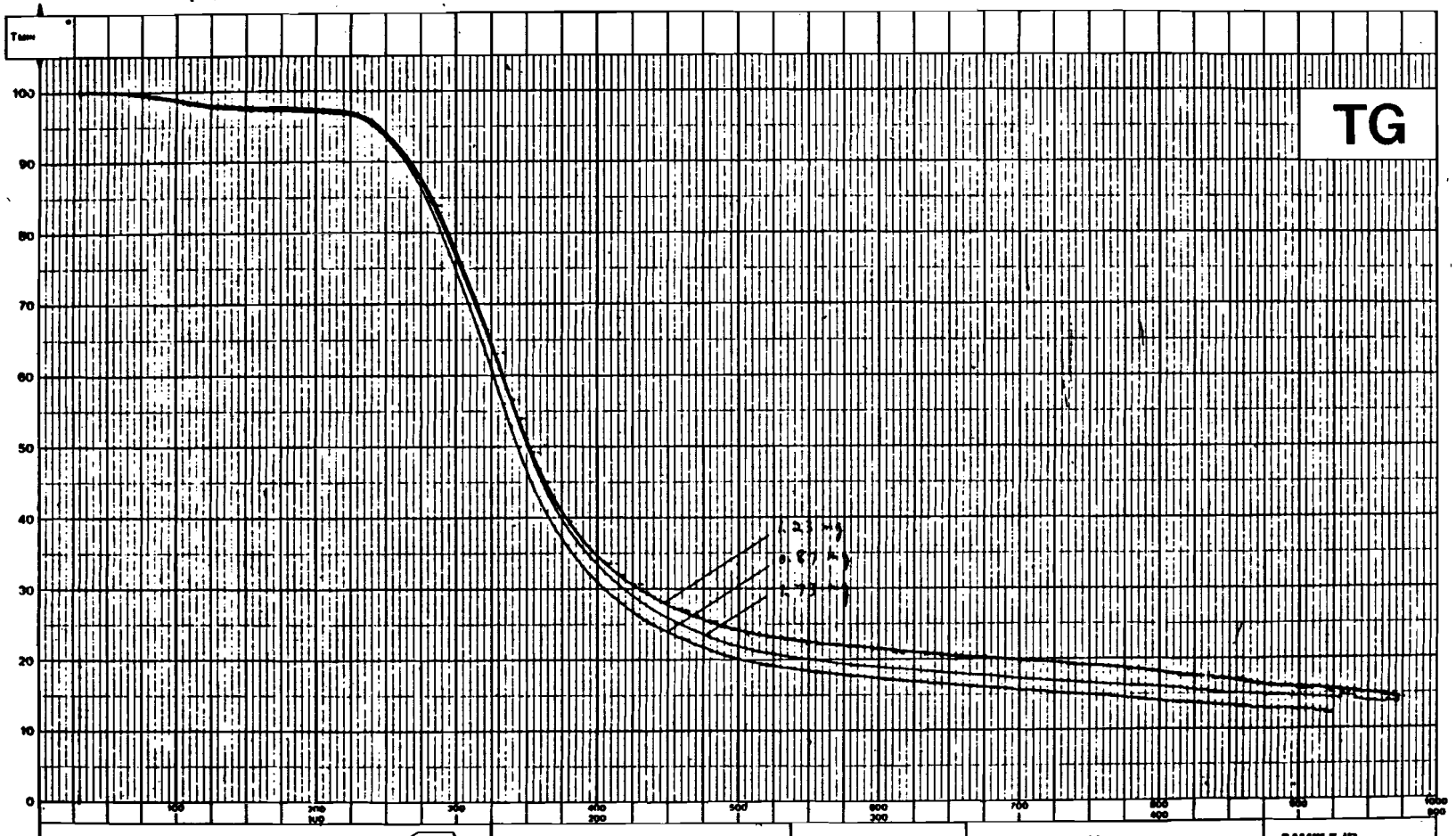
WEIGHT 1.21 mg

DATE 12-1-90

OPERATOR JEF


SAMPLE TEMPERATURE °C
TG
Material: Carpet
① Isothermal @ 330°C 1.71 mg
② " @ 370°C 3.53 mg
③ " @ 400°C 1.98 mg
④ " @ 430°C 1.61 mg
⑤ Up to 1000°C 1.04 mg
MULTI-STEP PROGRAMS
P1
P2
P3
P4
TEMP (°C)
TIME (min)
RATE (°C/min)
TG SCALE
RECORDER RANGE (Wt) mg
Wt SUPPRESSED mg
100 % SAMPLE Wt = 100 DIVISIONS
FDC RANGE (DTG) mg/min
TEMP SCALE
°C
°C
ATMOSPHERE
N2 @ 50 cc/min
TEMP PROGRAM
LOWER TEMP 30 °C
UPPER TEMP 1000 °C
HEATING RATE 190 °C/min
COOLING RATE MAX °C/min
SAMPLE ID
MATERIAL Carpet
WEIGHT mg
DATE
OPERATOR WD

SAMPLE TEMPERATURE °C



MULTI-STEP PROGRAMS	P1	P2	P3	P4
TEMP (°C)				
TIME (min)				
RATE (°C/min)				

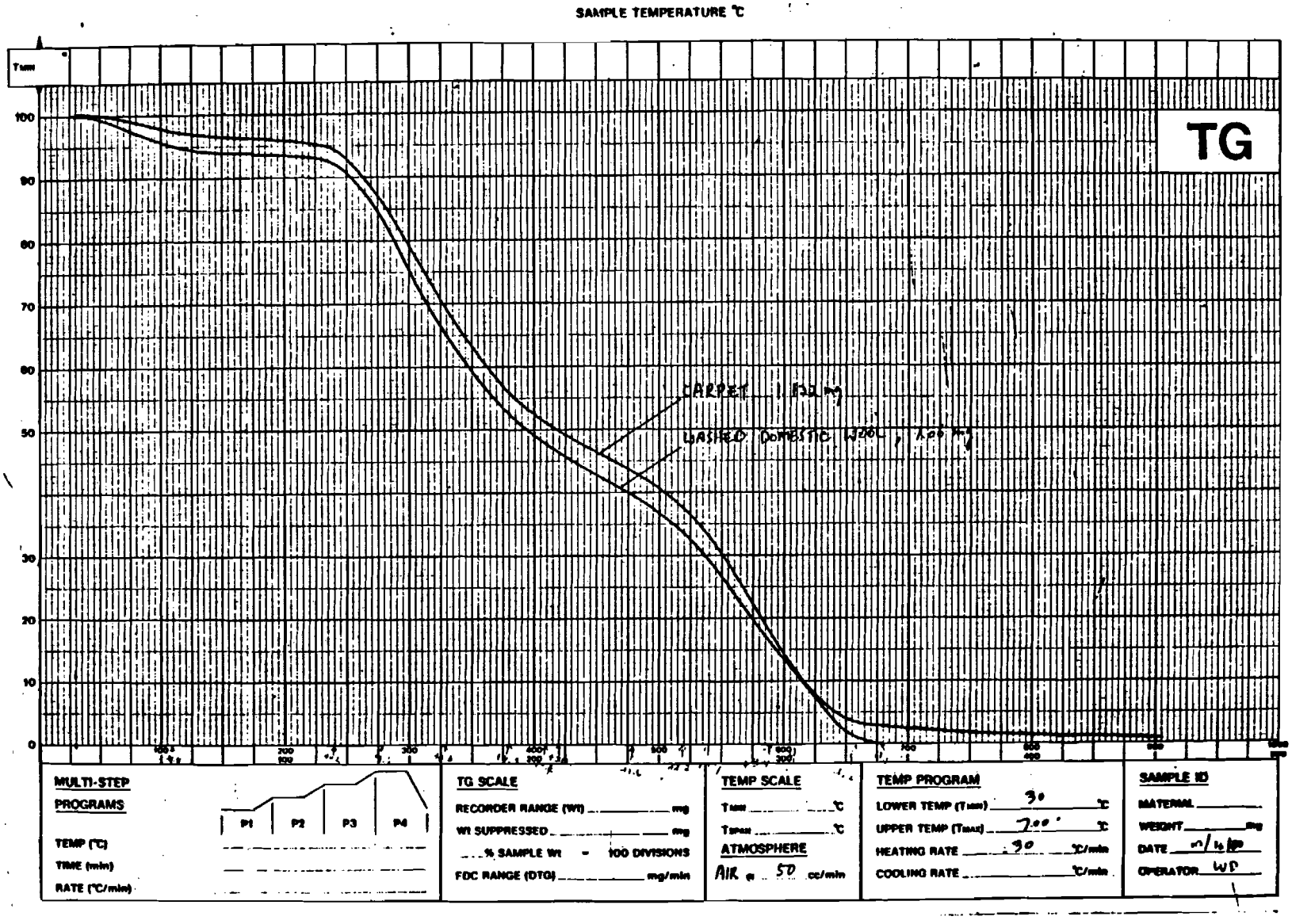
TG SCALE
RECORDER RANGE (Wt) ____ mg
Wt SUPPRESSED ____ mg
____ % SAMPLE Wt = 100 DIVISIONS
FDC RANGE (DTG) ____ mg/min

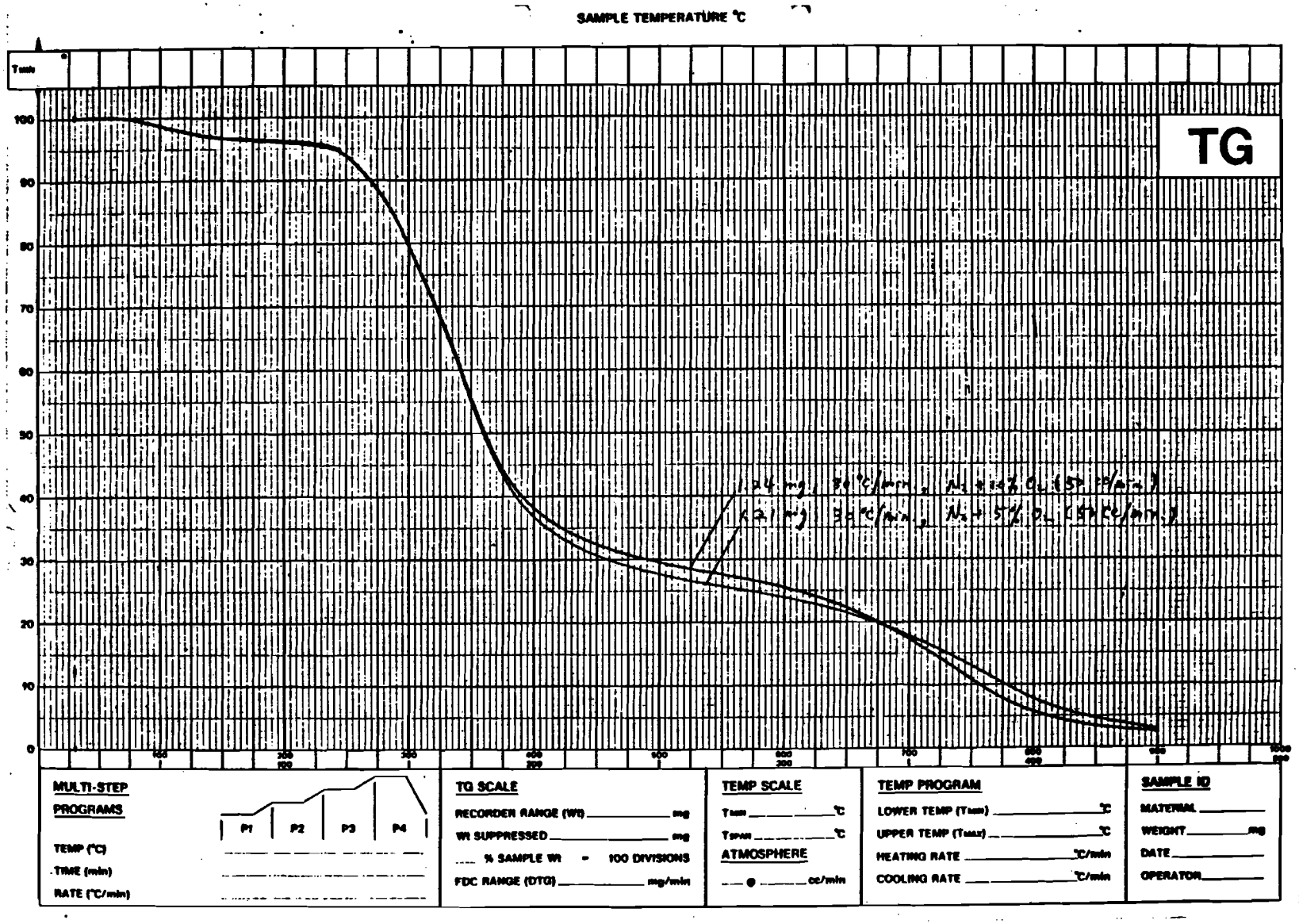
TEMP SCALE
T_{MIN} ____ °C
T_{SPAN} ____ °C

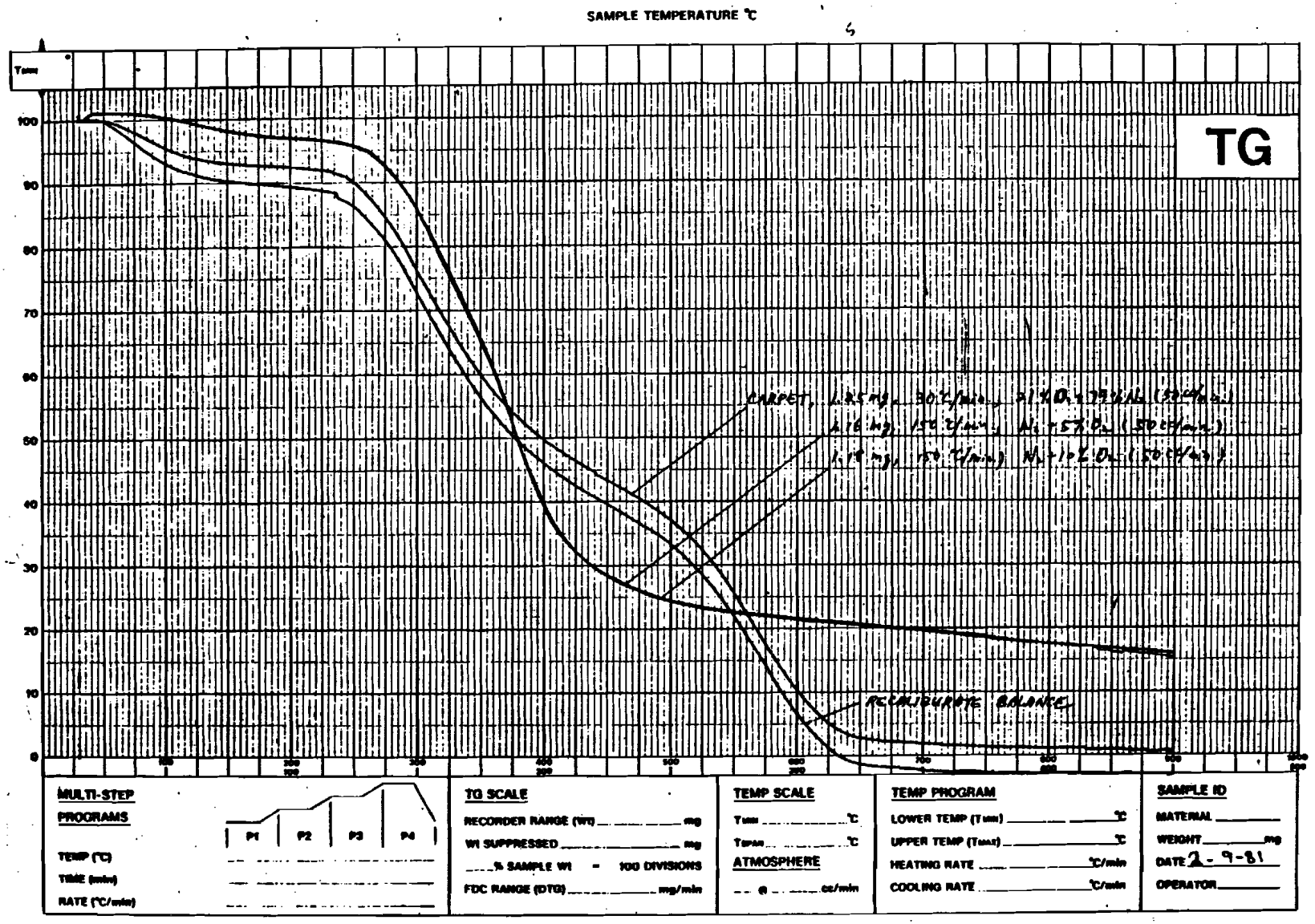
ATMOSPHERE
N_2 @ 50 cc/min

TEMP PROGRAM
LOWER TEMP (T_{MIN}) 30 °C
UPPER TEMP (T_{MAX}) ____ °C
HEATING RATE 20 °C/min
COOLING RATE ____ °C/min

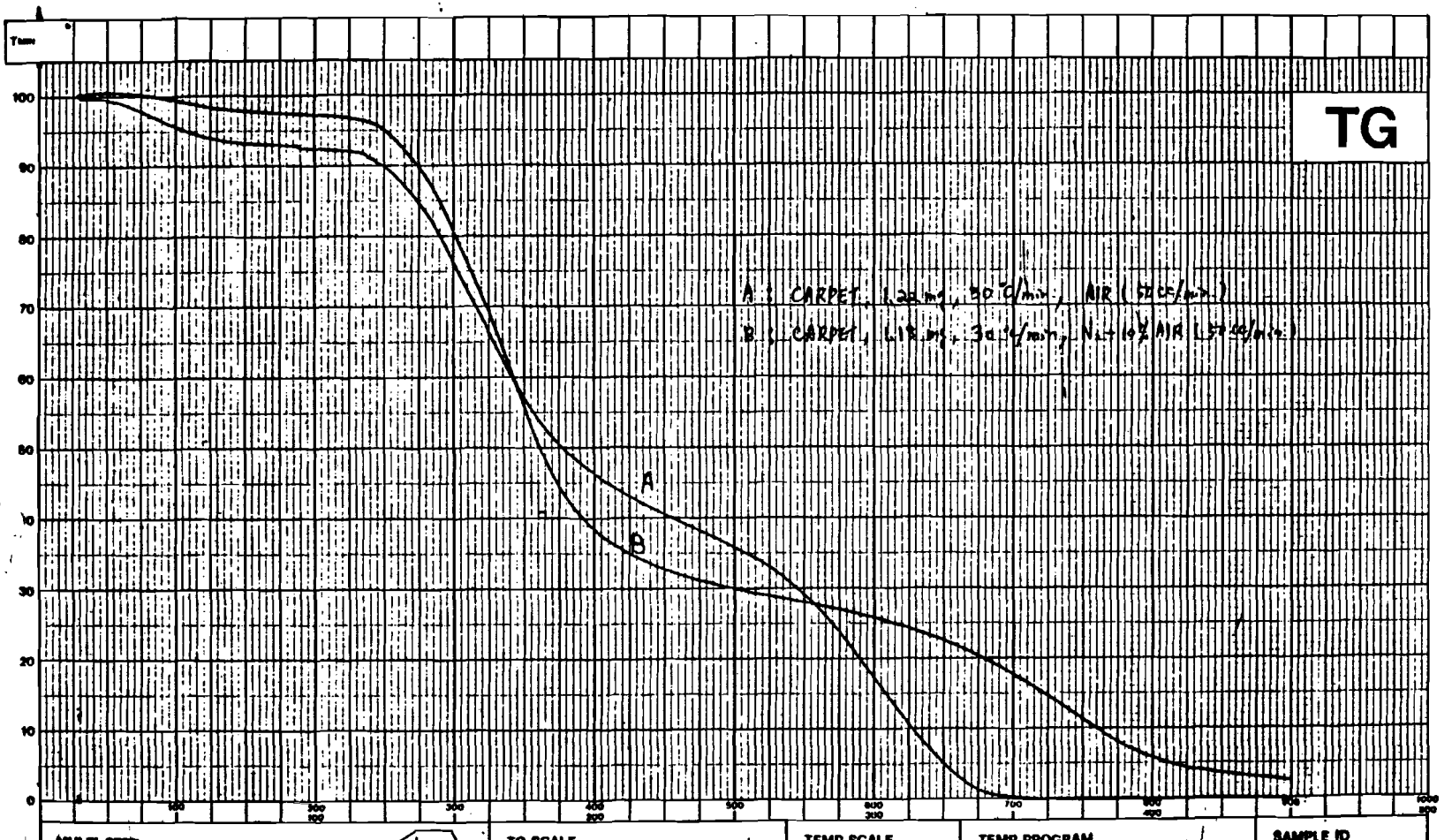
SAMPLE ID
MATERIAL Domestic CARPET
WEIGHT ____ mg
DATE 8/11/87
OPERATOR WD


SAMPLE TEMPERATURE °C
TG
100
90
80
70
60
50
30
20
10
0
CARPET
WASHED DOMESTIC WOOL
MULTI-STEP PROGRAMS
P1
P2
P3
P4
TEMP (°C)
TIME (min)
RATE (°C/min)
TG SCALE
RECORDER RANGE (Wt) mg
Wt SUPPRESSED mg
% SAMPLE Wt = 100 DIVISIONS
FDC RANGE (DTG) mg/min
TEMP SCALE
°C
°C
ATMOSPHERE
AIR @ 50 cc/min
TEMP PROGRAM
LOWER TEMP (Tmin) 30 °C
UPPER TEMP (Tmax) 700 °C
HEATING RATE 30 °C/min
COOLING RATE °C/min
SAMPLE ID
MATERIAL
WEIGHT mg
DATE
OPERATOR WP


SAMPLE TEMPERATURE °C
TG
100
90
80
70
60
50
40
30
20
10
0
MULTI-STEP PROGRAMS
P1
P2
P3
P4
TEMP (°C)
TIME (min)
RATE (°C/min)
TG SCALE
RECORDER RANGE (Wt) mg
Wt SUPPRESSED mg
% SAMPLE Wt = 100 DIVISIONS
FDC RANGE (DTG) mg/min
TEMP SCALE
°C
°C
ATMOSPHERE
@ cc/min
TEMP PROGRAM
LOWER TEMP °C
UPPER TEMP °C
HEATING RATE °C/min
COOLING RATE °C/min
SAMPLE ID
MATERIAL
WEIGHT mg
DATE
OPERATOR


SAMPLE TEMPERATURE °C
TG
CARPET, 1.85 mg, 30°C/min, 21% O2, 79% N2 (50 cc/min)
1.16 mg, 15°C/min, N2 + 5% O2 (50 cc/min)
1.18 mg, 15°C/min, N2 + 10% O2 (50 cc/min)
RECALIBRATE BALANCE
MULTI-STEP PROGRAMS
P1
P2
P3
P4
TEMP (°C)
TIME (min)
RATE (°C/min)
TG SCALE
RECORDER RANGE (Wt) mg
Wt SUPPRESSED mg
% SAMPLE Wt = 100 DIVISIONS
FDC RANGE (DTG) mg/min
TEMP SCALE
°C
°C
ATMOSPHERE
@ cc/min
TEMP PROGRAM
LOWER TEMP (Tmin) °C
UPPER TEMP (Tmax) °C
HEATING RATE °C/min
COOLING RATE °C/min
SAMPLE ID
MATERIAL
WEIGHT mg
DATE 2-9-81
OPERATOR

SAMPLE TEMPERATURE °C



MULTI-STEP PROGRAMS	P1	P2	P3	P4
TEMP (°C)				
TIME (min)				
RATE (°C/min)				

TG SCALE
RECORDER RANGE (Wt) ____ mg
Wt SUPPRESSED ____ mg
____ % SAMPLE Wt = 100 DIVISIONS
FDC RANGE (DTG) ____ mg/min

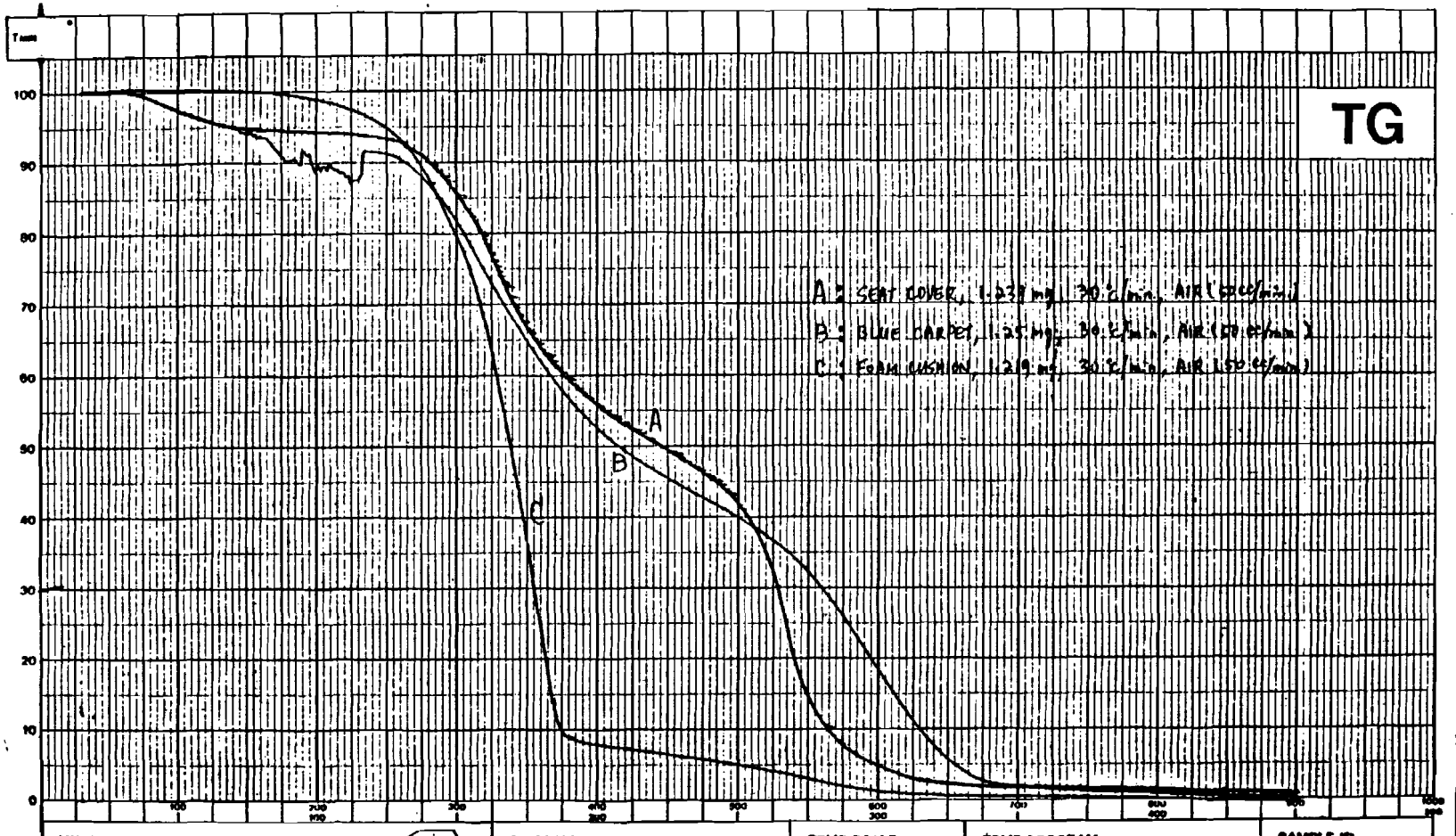
TEMP SCALE
T_{MIN} ____ °C
T_{SPAN} ____ °C

ATMOSPHERE
____ @ ____ cc/min

TEMP PROGRAM
LOWER TEMP (T_{MIN}) ____ °C
UPPER TEMP (T_{MAX}) ____ °C
HEATING RATE ____ °C/min
COOLING RATE ____ °C/min

SAMPLE ID
MATERIAL ____
WEIGHT ____ mg
DATE 3-4-81
OPERATOR ____

SAMPLE TEMPERATURE °C



MULTI-STEP PROGRAMS	P1	P2	P3	P4
TEMP (°C)				
TIME (min)				
RATE (°C/min)				

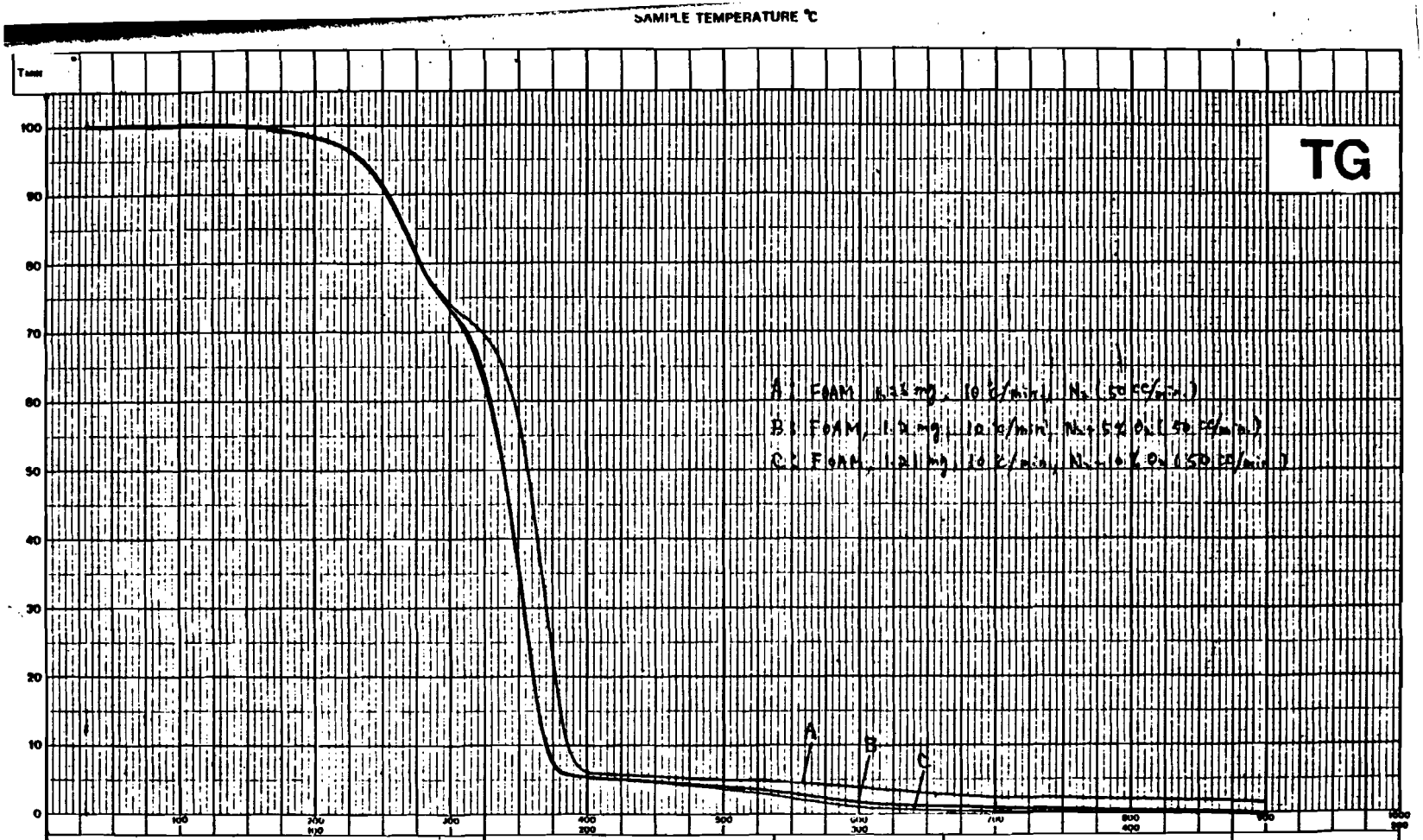
TG SCALE
RECORDER RANGE (Wt) _____ mg
Wt SUPPRESSED _____ mg
____ % SAMPLE Wt = 100 DIVISIONS
FDC RANGE (DTG) _____ mg/min

TEMP SCALE
T_{min} _____ °C
T_{SPAN} _____ °C

ATMOSPHERE
____ @ ____ cc/min

TEMP PROGRAM
LOWER TEMP (T_{min}) _____ °C
UPPER TEMP (T_{max}) _____ °C
HEATING RATE _____ °C/min
COOLING RATE _____ °C/min

SAMPLE ID
MATERIAL _____
WEIGHT _____ mg
DATE 1-16-81
OPERATOR _____



MULTI-STEP PROGRAMS	P1	P2	P3	P4
TEMP (°C)				
TIME (min)				
RATE (°C/min)				

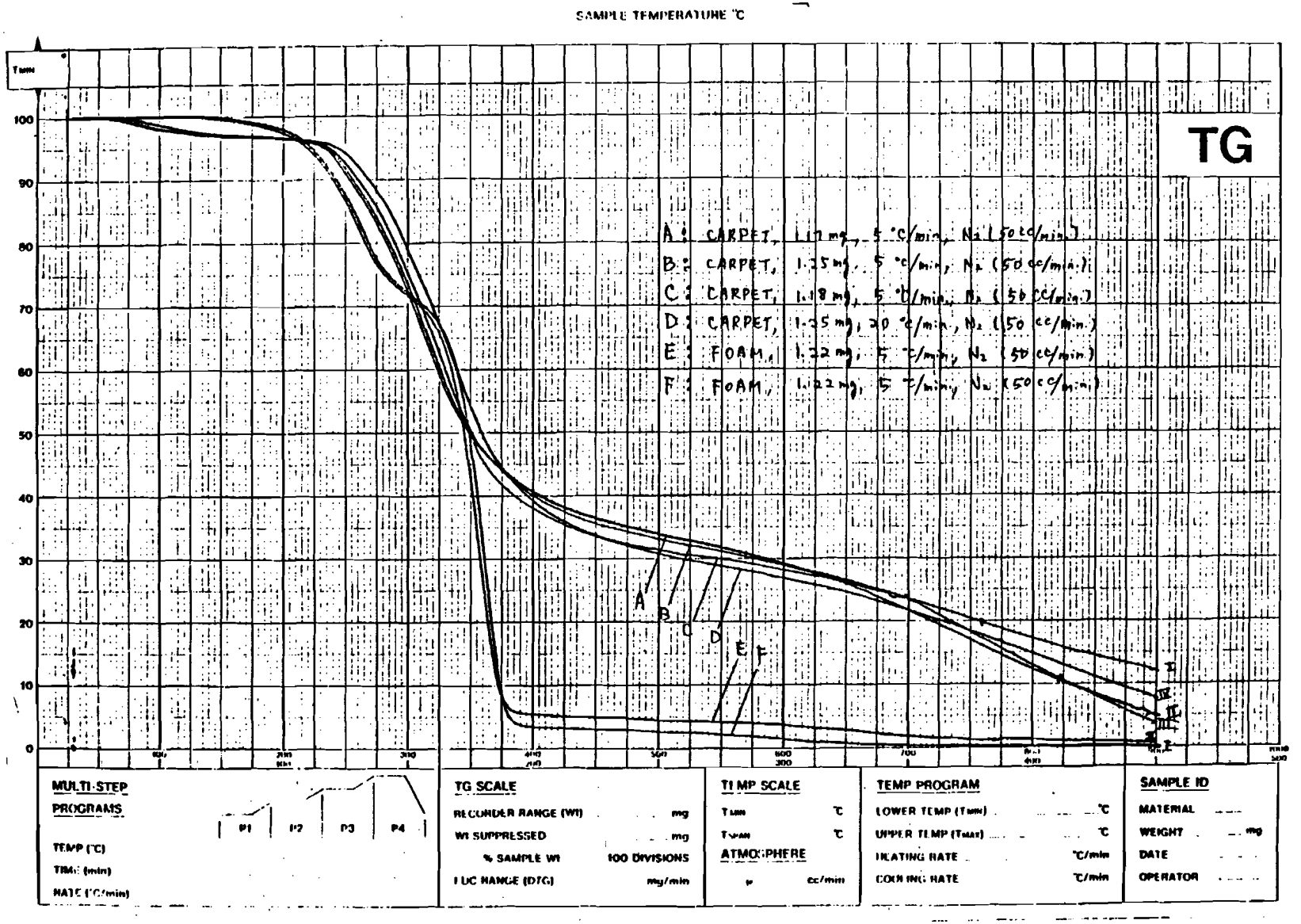
TG SCALE
RECORDER RANGE (Wt) ____ mg
Wt SUPPRESSED ____ mg
% SAMPLE Wt = 100 DIVISIONS
FDC RANGE (DTG) ____ mg/min

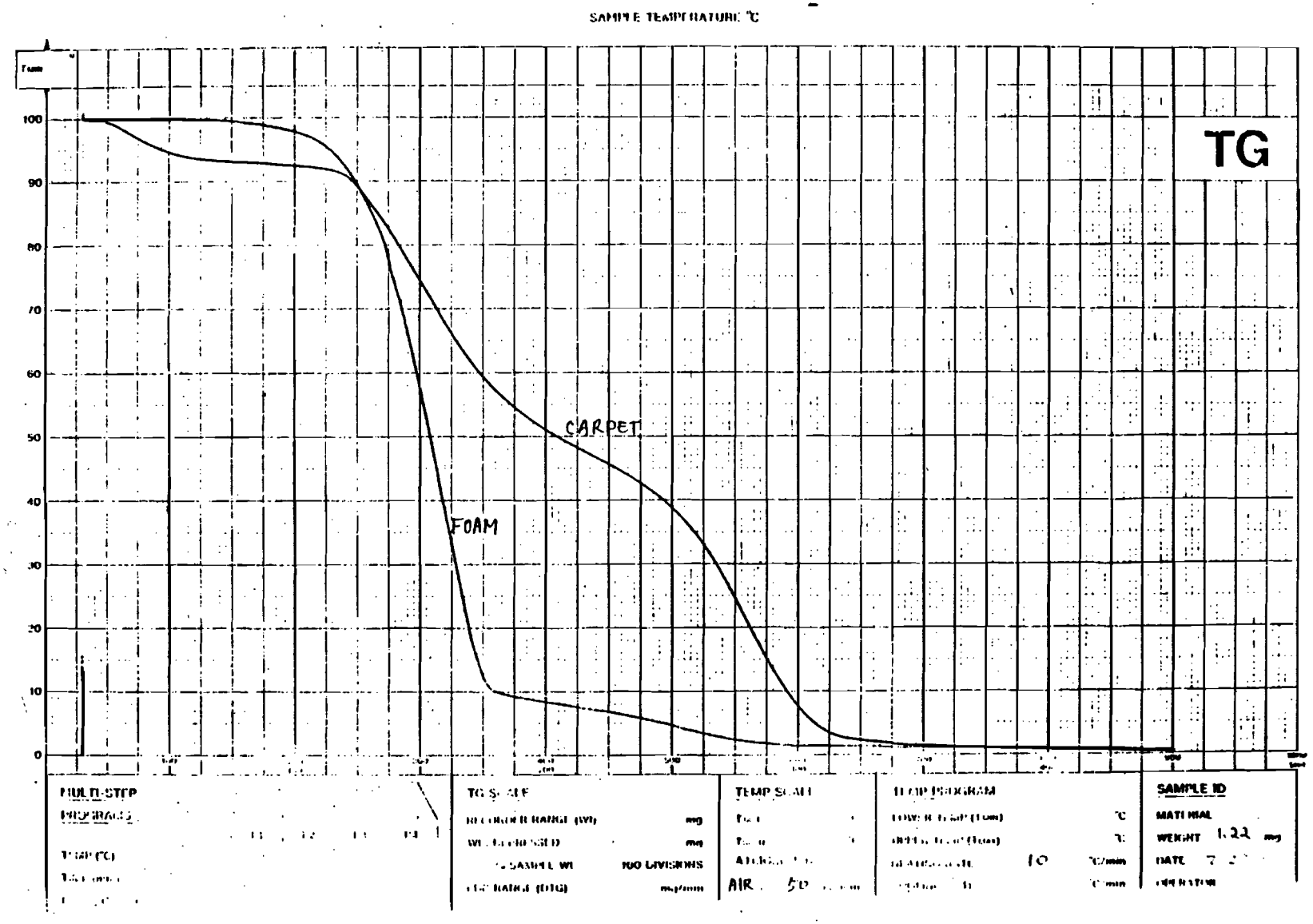
TEMP SCALE
T_{MIN} ____ °C
T_{SPAN} ____ °C

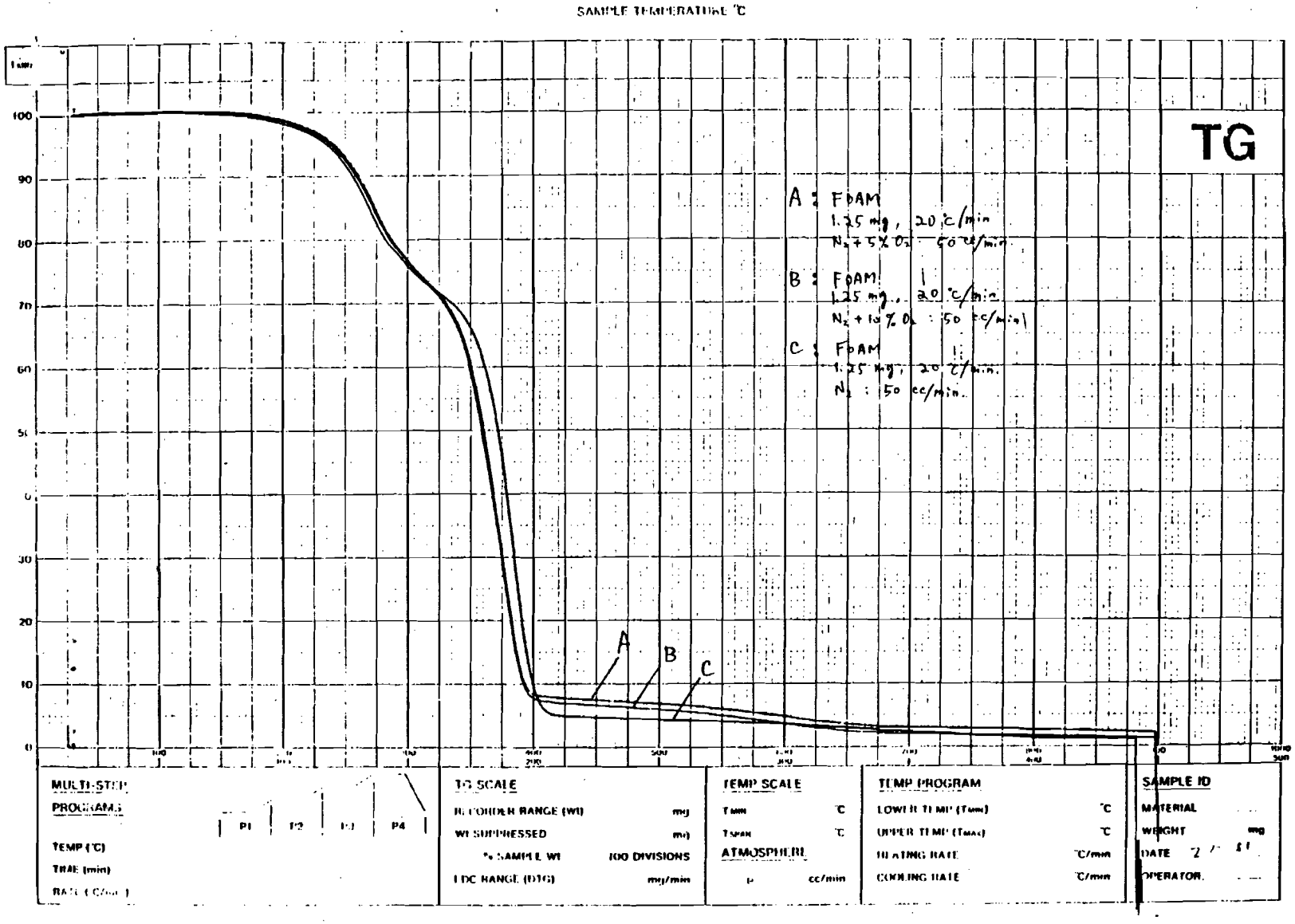
ATMOSPHERE
____ cc/min

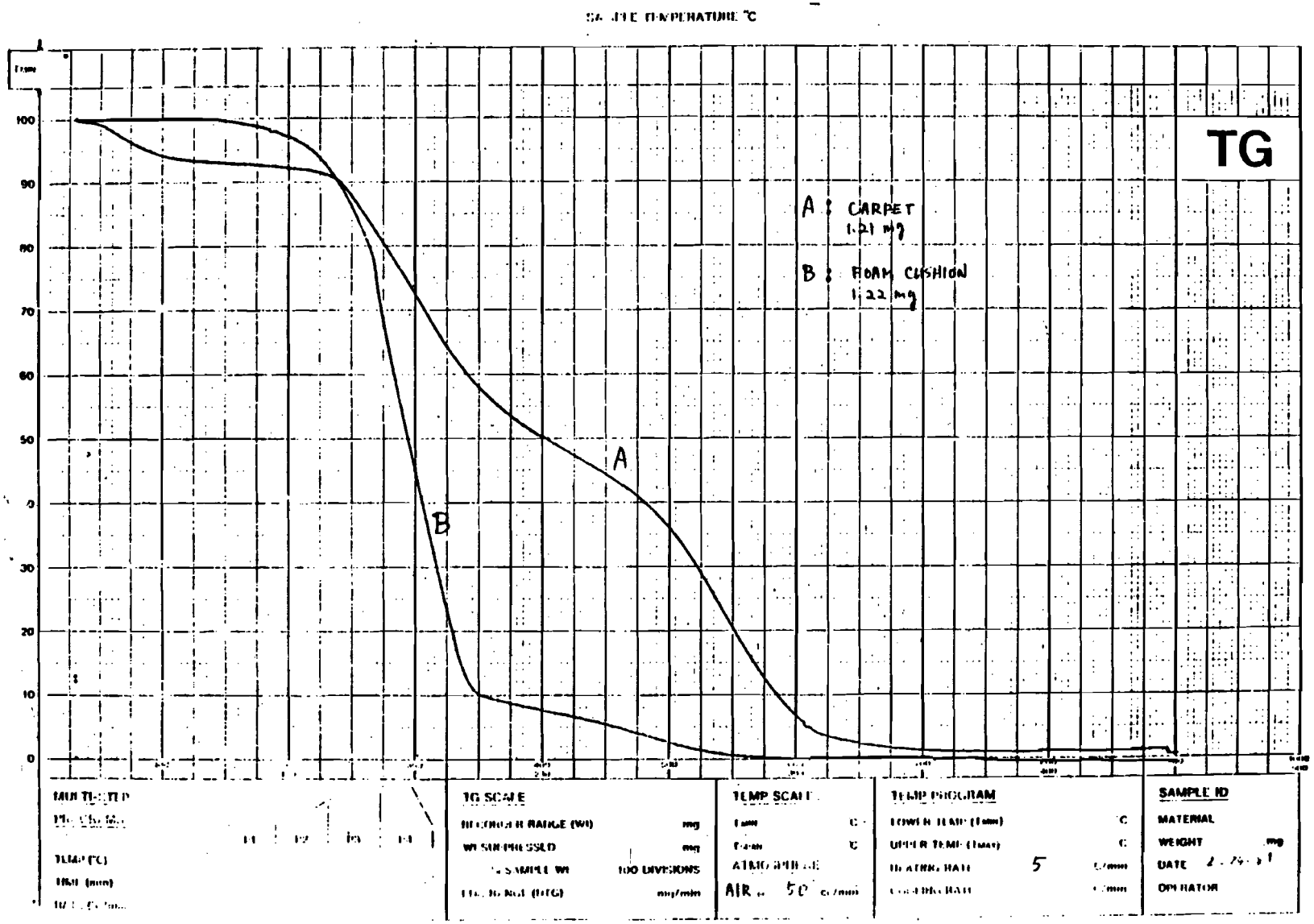
TEMP PROGRAM
LOWER TEMP (T_{MIN}) ____ °C
UPPER TEMP (T_{MAX}) ____ °C
HEATING RATE ____ °C/min
COOLING RATE ____ °C/min

SAMPLE ID
MATERIAL ____
WEIGHT ____ mg
DATE 3-1-81
OPERATOR ____

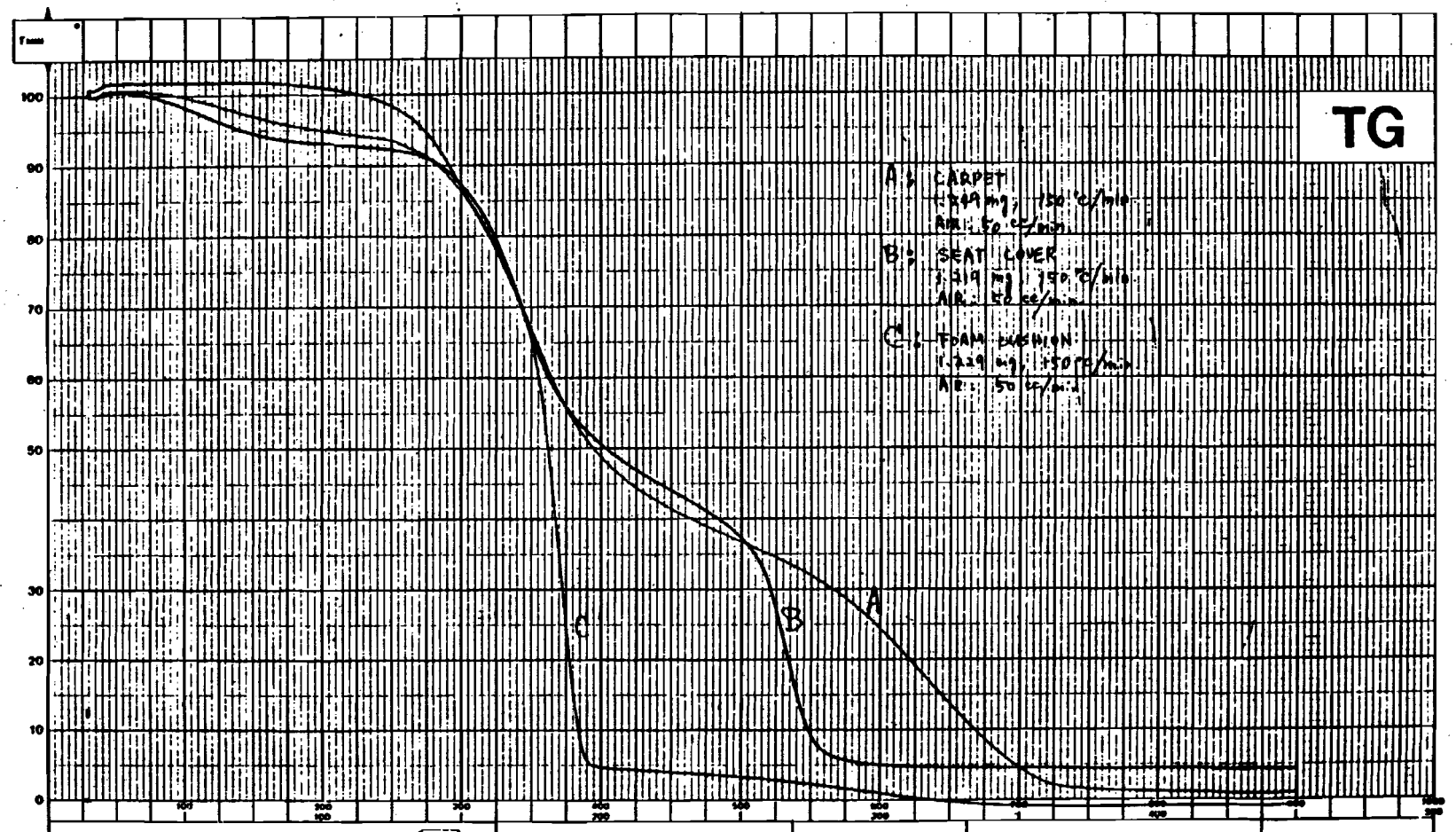

SAMPLE TEMPERATURE °C
TG
A: CARPET, 1.17 mg, 5 °C/min, N2 (50 cc/min)
B: CARPET, 1.25 mg, 5 °C/min, N2 (50 cc/min)
C: CARPET, 1.18 mg, 5 °C/min, N2 (50 cc/min)
D: CARPET, 1.25 mg, 20 °C/min, N2 (50 cc/min)
E: FOAM, 1.22 mg, 5 °C/min, N2 (50 cc/min)
F: FOAM, 1.22 mg, 5 °C/min, N2 (50 cc/min)
100
90
80
70
60
50
40
30
20
10
0
A
B
C
D
E
F
MULTI-STEP PROGRAMS
P1
P2
P3
P4
TEMP (°C)
TIME (min)
RATE (°C/min)
TG SCALE
RECORDER RANGE (WT) mg
WT SUPPRESSED mg
% SAMPLE WT 100 DIVISIONS
DTG RANGE (DTG) mg/min
TEMP SCALE
TMIN °C
TMAX °C
ATMOSPHERE
cc/min
TEMP PROGRAM
LOWER TEMP (TMIN) °C
UPPER TEMP (TMAX) °C
HEATING RATE °C/min
COOLING RATE °C/min
SAMPLE ID
MATERIAL
WEIGHT mg
DATE
OPERATOR


SAMPLE TEMPERATURE °C
TG
100
90
80
70
60
50
40
30
20
10
0
CARPET
FOAM
MULTI-STEP
TG SCALE
TEMP SCALE
TEMP PROGRAM
SAMPLE ID
MATERIAL
WEIGHT 1.22 mg
DATE
AIR
10 °C/min
100 DIVISIONS


SAMPLE TEMPERATURE °C
TG
A : FOAM
1.25 mg, 20 °C/min
N₂ + 5% O₂ : 50 cc/min
B : FOAM
1.25 mg, 20 °C/min
N₂ + 10% O₂ : 50 cc/min
C : FOAM
1.25 mg, 20 °C/min
N₂ : 50 cc/min
A
B
C
100
90
80
70
60
50
0
30
20
10
0
MULTI-STEP PROGRAMS
P1
P2
P3
P4
TEMP (°C)
TIME (min)
RATE (°C/min)
TG SCALE
RECORDER RANGE (WT) mg
WT SUPPRESSED mg
% SAMPLE WT 100 DIVISIONS
DDC RANGE (DTG) mg/min
TEMP SCALE
TMIN °C
TSPAN °C
ATMOSPHERE
P cc/min
TEMP PROGRAM
LOWER TEMP (TMIN) °C
UPPER TEMP (TMAX) °C
HEATING RATE °C/min
COOLING RATE °C/min
SAMPLE ID
MATERIAL
WEIGHT mg
DATE
OPERATOR


SAMPLE TEMPERATURE °C
TG
A : CARPET
1.21 mg
B : FOAM CUSHION
1.22 mg
A
B
100
90
80
70
60
50
40
30
20
10
0
MULTI-STEP
TEMP (°C)
TG SCALE
RECORDER RANGE (WT)
mg
WT SUBTRACTED
mg
SAMPLE WT
100 DIVISIONS
mg/min
TEMP SCALE
°C
°C
ATMOSPHERE
AIR
50
cc/min
TEMP PROGRAM
LOWER TEMP (Tmin)
°C
UPPER TEMP (Tmax)
°C
HEATING RATE
5
°C/min
COOLING RATE
°C/min
SAMPLE ID
MATERIAL
WEIGHT
mg
DATE
OPERATOR

SAMPLE TEMPERATURE °C



MULTI-STEP PROGRAMS	TG SCALE	TEMP SCALE	TEMP PROGRAM	SAMPLE ID
P1 P2 P3 P4	RECORDER RANGE (Wt) ____ mg	T_{MIN} ____ °C	LOWER TEMP (T_{MIN}) ____ °C	MATERIAL ____
TEMP (°C)	Wt SUPPRESSED ____ mg	T_{SPAN} ____ °C	UPPER TEMP (T_{MAX}) ____ °C	WEIGHT ____ mg
TIME (min)	____ % SAMPLE Wt = 100 DIVISIONS	ATMOSPHERE	HEATING RATE 150 °C/min	DATE 1-16-91
RATE (°C/min)	FDC RANGE (DTG) ____ mg/min	AIR @ 50 cc/min	COOLING RATE ____ °C/min	OPERATOR ____