MAJOR FACTORS INFLUENCING FIRE GROWTH

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Abstract

The main factors that influence the likelikood and speed with which full room involvement occurs are type of materials and their distribution so called fuel load, interior finish of the room, air supply, and size, shape, and construction of the room. Fires develop through several stages or realms. These are preburning, initial burning, vigorous burning, interactive burning, and remote burning. These realms are presented with quantitative descriptions.

1. MAIN FACTORS IN FIRES AND HEAT TRANSFER

The combustion characteristics are considered as the basis for a fire growth hazard analysis. The main factors that influence the probability and rate with which full room involvement occurs are as follows:

- Fuel load (type of materials and their distribution),
- Interior finish and surface roughness,
- Air supply,
- Size, shape, construction, and insulation of the room.

Heat transfer which is effective in "preburning, initial burning, vigorous burning, interactive burning, and remote burning" stages (called realms) occurs according to three different mechanisms: Conduction, convection, and radiation.

From the point of view of heat transfer the major physical properties of a material are the thermal conductivity, k [J/msK], the density, ρ [kg/m^3], and heat capacity, c [J/kgK]. In fact, the product ρc [J/m^{3}K] that is of interest in the field of conduction, is a measure of the amount of heat necessary to raise the unit volume of material by unit temperature.

If the surface of a material is suddenly exposed to a temperature rise, then the temperature at a depth of L[m] within the material will begin to change substantially at a certain time. This delay is called the characteristic time of the material:

$$t_k = L^2 \rho c / k$$

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As it is seen, the increase of this characteristic time indicating the thermal inertia of the material shows the decrease in heat transfer.

The convective heat transfer can be expressed as follows

$$\dot{Q} = hA(T - T_o)$$

where h [J/m²sK] : convective heat transfer coefficient,
A [m²] : surface area
(T-T₀) : temperature difference between the fluid and the surface of the material, [1].

The radiant emission per unit area from a black surface is proportional to the fourth power of its absolute temperature. The heat

$$\dot{Q} = \varepsilon\sigma AT^4$$

where ε: surface emissivity correction factor,
$\sigma=5.67\times10^{-8}$ [W/m²K⁴]: Stefan-Boltzmann constant,
T [K] : surface temperature.

The surface emissivity correction factor is 1.0 for an ideal black body. This value is close to 1.0 for most non-metallic materials in the infrared wavelength region. Radiation is a form of energy travelling across a space or through materials as electromagnetic waves, such as light, radio waves, or X-rays. Radiant energy is absorbed, reflected, or transmitted on arrival at a body.

Symmetrical diatomic molecules such as H_2, O_2, N_2 transmit freely radiative heat. Unsymmetrical molecules such as CO, CO_2, H_2O, SO_2 in narrow wavelength bands, and also suspended liquid or solid particles in air or smoke absorb the radiant heat.

CO_2 and H_2O molecules in air prevent solar radiation in the range of 2.8×10^{-6} [m] and $4,4\times10^{-6}$ [m] from reaching the surface of the earth. Visible light consists of wavelengths between 0.4×10^{-6} [m] to $0,7\times10^{-6}$ [m]; violet to red, respectively.

Emission from combustion phenomena occurs mainly in the infrared region, i.e. wavelengths are longer than the red wavelength. Therefore only a small fraction of the emitted electromagnetic waves can be seen by eyes. Flame detectors operating in infrared wavelengths, i.e. responding only in the range of 2.8×10^{-6} [m] to 4.4×10^{-6} [m], are blind to solar radiation. The hot H_2O and CO_2 molecules in combustion phenomena emit the infrared wavelengths. Since H_2O and CO_2 molecules in the atmosphere absorb the infrared solar radiation, the emission at the same wavelength of the hot H_2O and CO_2 molecules in the flame regions can be sensed by the flame detectors.

Large scale forest fires, LPG or LNG fires are less hazardous when humidity of surrounding atmosphere is high. This is due to the existence of H_2O molecules. Although water droplets, fog, mists or water sprays help to absorb almost all of the incident infrared radiation, at the same time they atlenuate the radiation due to the latent heat effect and the decrease of the temperature.

2. FIRE REALMS

Fire development in a room can be divided into several realms. The most identified and sequentially occured realms are as follows, Figure 1.

(i) Preburning,
(ii) Initial burning,
(iii) Vigorous burning,
(iv) Interactive burning,
(v) Remote burning.

Within any realm a fire may continue to grow, or it may be unable to sustain continued development and die down.

Fire realms will be explained in the following subsections

2.1. Preburning Realm

It is the realm where overheat to ignition takes ploce. Entering and leaving heat fluxes to or from the ignitable material (q_G, $q_Ç$); surface areas expased to these heat fluxes (A_G, $A_Ç$), and almount and duration of heat flux influence the preburning realm.

If a body given in Figure 2 has a mass of m, specific heat of c, and temperature of T, then the energy equation of the body will be as follows:

için aşırı ısınmanın olduğu dönemdir. Tutuşabilir malzemeye gelen ve çıkan ısı akıları (q_G,$q_Ç$) malzemenin bu ısılara maruz yüzey alanları (A_G, $A_Ç$) ve ısı geçişinin süresi önyanma dönemini etkilemektedir. Şekil 2'de verilen cismin kütlesi m, özgül ısısı c, sıcaklığı T olduğuna göre yanma öncesi cisme ait enerji denklemi:

Accumulation of energy = Entering heat - Leaving heat

$$mc\frac{dT}{dt} = A_G q_G - A_Ç q_Ç$$

Here, a generalized formula covering conduction, convection and radiation may be used. Entering and leaving heat fluxes can be written in terms of the overall heat transfer coefficients and temperature differences:

$$q_G = h_G (T_G - T),$$

$$q_Ç = h_Ç (T - T_A)$$

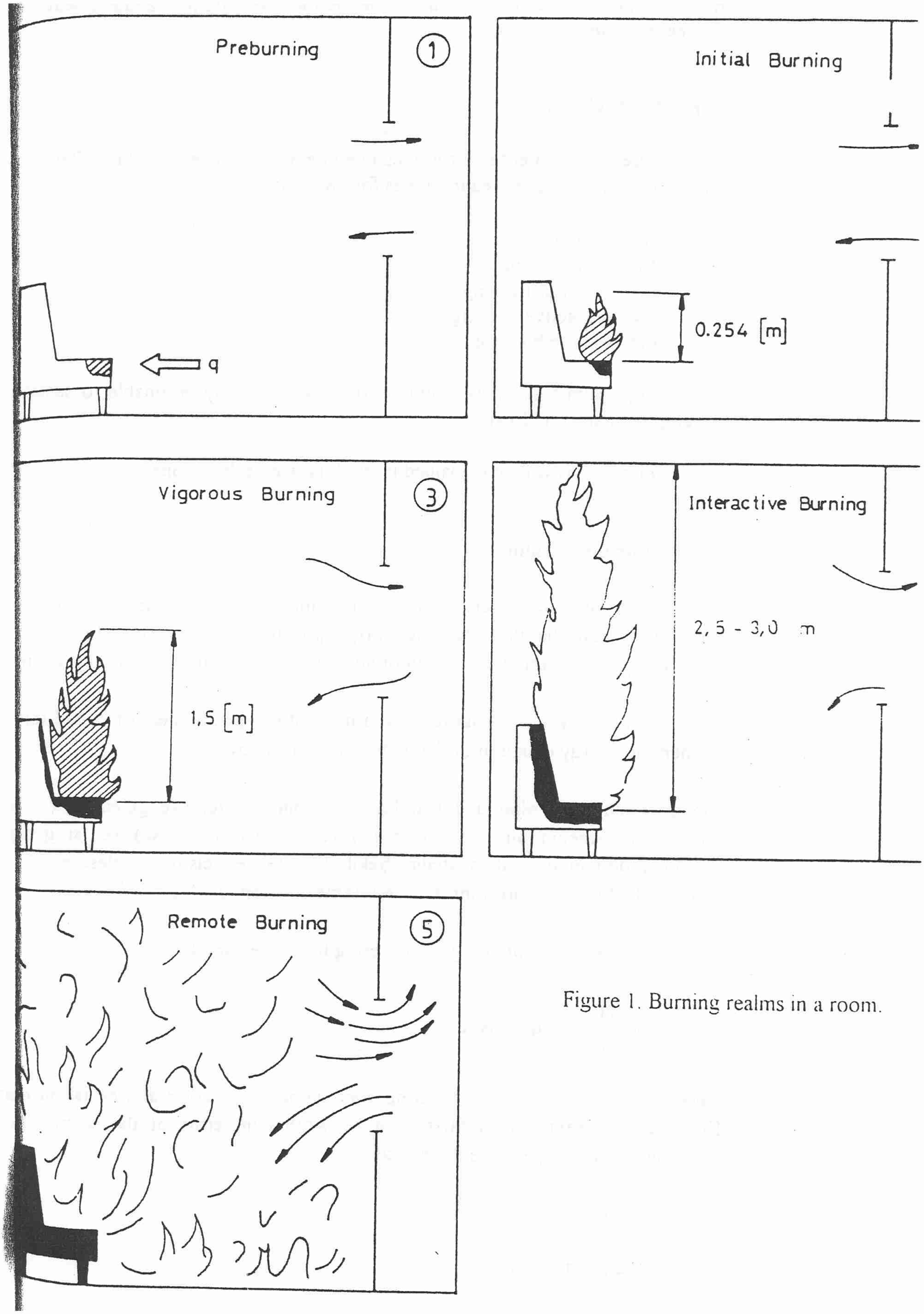

Figure 1. Burning realms in a room.

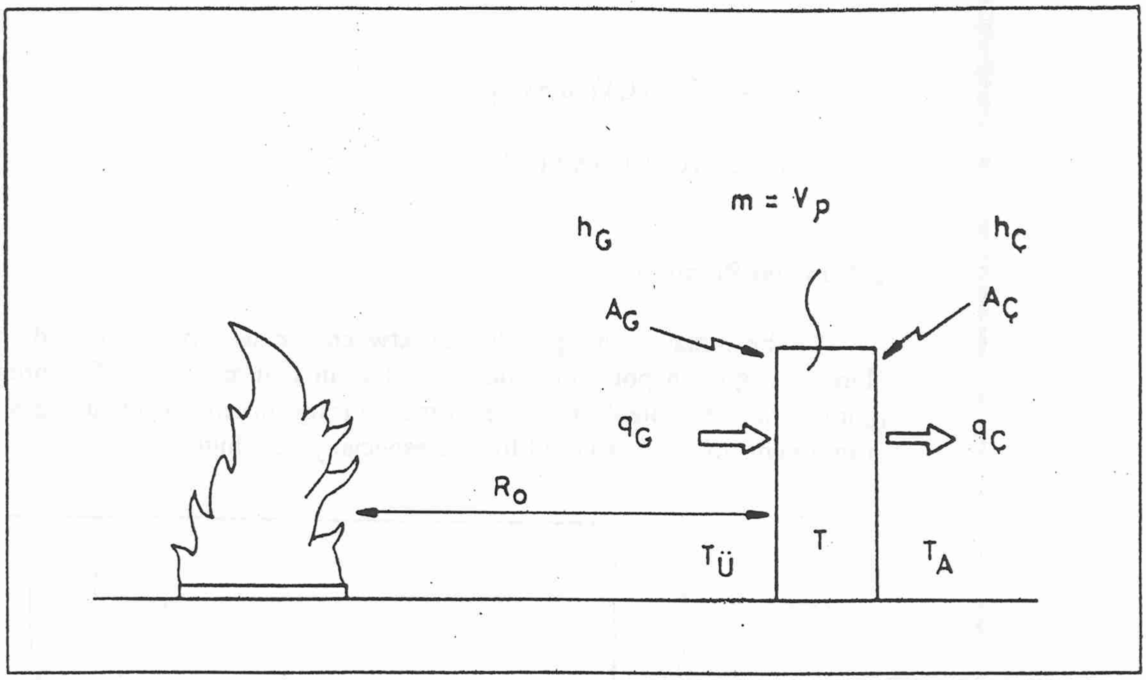

Figure 2. A body with a mass m having 1D heat transfer, and its environment.

As dimensionless quantities

$u = T/T_A,\ \ u_Ü = T_Ü/T_A,\ \ u_o = T_o / T_A$

$C_A = A_G/A_Ç,\ \ C_h = h_G / h_Ç$

$C_1 = C_A C_h + 1,\ \ C_2 = C_A C_h u_Ü + 1$

$C = C_2 / C_1$;

characteristic time

$\tau = mc/A_Ç h_Ç C_1$,

and dimensionless time

$z = t / \tau$

can be defined. The energy equation after substitution the dimensionless values will be in the following simple form:

$$dz = du / (-u+C).$$

If this differential equation is solved in the range of $u=u_o$ for $z=0$; $u=u$ for $z=z$, then one obtains

$$z = -\ln[(-u+C)/(-u_0+C)]$$

$$u = C - (C-u_0) \cdot \exp(-z)$$

2.2. Initial Burning

The initial burning realm is between the ignition point and the radiation point. Here, the ignition point may be defined as in Figure 3. [2]. The preparation change to ignition of the ignitable mixture formed during mixing of air and gasified or vaporized components of solid or liquid fuels is especially very high.

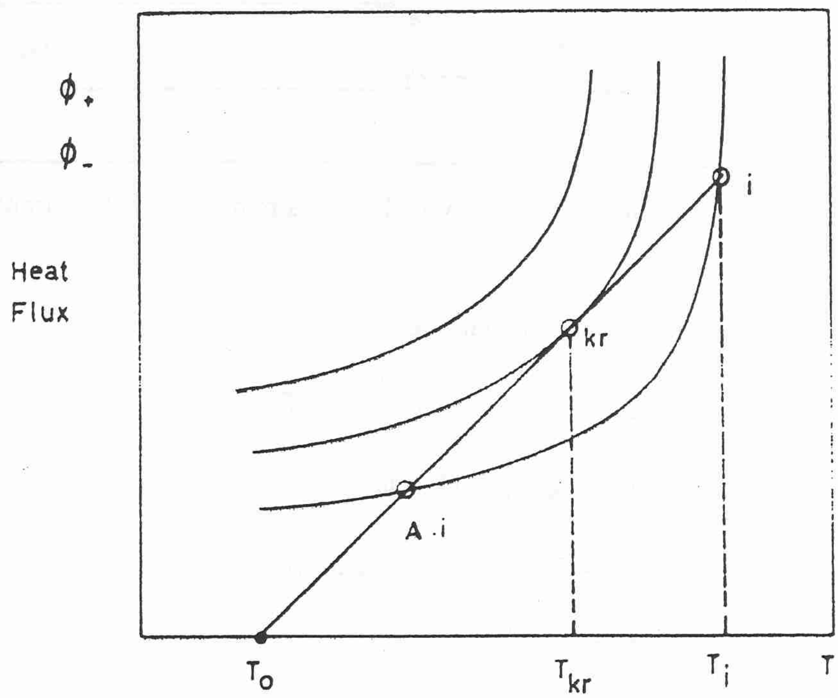

Figure 3. Definition of ignition point, [2].

Ignition Point

Heat flux generated per unit volume by chemical reactions in gaseous phase over the surfae of a material can be expressed in terms of the specifict reaction rate and the lower calorific heating value of the material behaving as a fuel:

$$\phi_{-} = \frac{d[\text{Fuel}]}{dt} \cdot H_u = f(\text{temperature, concentration})$$

Sözkonusu tutuşma bölgesinden T_0 sıcaklığındaki çevreye kaçan ısı akısı [J/m^{3}s]

$$\phi = hS(T - T_0) / V$$

Here, h [J/m^{2}sK] the overall heat transfer coefficient.

S $[m^2]$: the surface area of the ignition volume.
V $[m^3]$: the volume where the ignition is expected.

Ignition volume is the volume where the ignitable species concentration is available. It can be described as the zone where air, gas, vapor, etc. are mixed.

The critical ignition temperature can be determined solving the following two equations

$$\phi_+ = \phi_- \quad \text{and} \quad \frac{d\phi_+}{dt} = \frac{d\phi_-}{dt}$$

denklemleri çözülerek

$$T_{Kr} \cong T_o + \frac{E}{RT_o^2}$$

where E [J/kmol] : Activation energy,
R = 8314.3 [J/kmolK] : Universal gas constant.

<u>Radiation Point</u>

The radiation point is the instant when the flame height reaches the value of 0.254 [m] (10 inch).

The initial burning realm depends on fuel continuity, material ignitability, thickness of the material, surface roughness, and thermal inertia of the fuel. These parameters can be seen in the ignition equations.

2.3. Vigorous Burning

Effective burning between the ignition point and the enclosure point is called as the vigorous burning. The flame height is between 0.254 [m] and 1.5 [m]. Interior finish in a room, fuel continuity, feedback, material ignitability, thermal inertia of the fuel, proximity of flames to walls are the major factors that influence fire growth.

2.4. Interactive Burning

The interactive burning realm is between the enclosure point and the ceiling point. In other words, the flame height during the interactive burning is between 1.5 [m] and flame touching ceiling. Fire growth is influenced from interior finish of the room, fuel arrangement, feedback, tallness of fuels, proximity of flames to walls, ceiling heigth, room insulation, size and location of openings, heating-ventilation-air conditioning operation.

2.5. Remote Burning

The remote burning realm is between the ceiling point and the full room involvement. The major factor that influence the fire growth are fuel arrangement, ceiling height, length/width ratio, room insulation, size and location of openings, heating-ventilation-air conditioning operation.

3. NUMERICAL APPLICATIONS

The simplified mathematical model for the preburning prepared in the previous section is applied for a material made from flexible polyurethane. Some properties of this substance are given in Table 1.

Table 1. Some Properties of Flexible Polyurethane.

Properties	**Numerical Values (Applied)**
Density, ρ $[kg/m^3]$	29-47 (40)
Minimum Radiant Heat Flux for Ignition, q_{Rmin} $[kW/m^2]$	16-30 (20)
Minimum Mass Loss Rate for Ignition, $\dot{m}/A$ $[g/m^2s]$	5.3-7.2
Energy Required for Ignition, e_i $[g\,m^{-2}s]$	150-770
Ignition Temperature, T_i [K]	729-852 (750)
Effective Heat of Gasification, e_g [MJ/kg]	1.2-2.7
Lower Calorific Heating Value, H_u [MJ/kg]	23.2-28
Minimum O_2, m_{O_2}/m_F [kg/kg] Minimum Air, m_A/m_F [kg/kg] for theoretical complete combustion	1.725 (for polyurethane) 7.435 (for polyurethane)
Specific heat, c_p [kJ/kg K]	1.75-1.84 (for polyurethane)

Using the minimum radiant heat flux for ignition

$$q_G - q_Ç = q_{Rmin}$$

$$h_G\,(T_Ü - T) - h_Ç\,(T - T_A) = q_{Rmin}$$

assuming

$$h_G \cong h_Ç = h$$

and lower surface temperature T_A=300 [K], temperature of the heat source $T_Ü=T_i$=750 [K], minimum radiant heat flux q_{Rmin} =20000 [W/m^2] in the equation

$$h\,(T_Ü - T_A) = q_{Rmin}$$

the heat transfer coefficient can be calculated as $h=20$ [W/m^2K].

Using the surrounding temperature To = 300 [K], the dimensions of the flexible polyurethane material V = 1x1x1 [cm^3], $A_G=A_C=1$ [cm^2], the specific heat c_p = 1750 [J/kgK], and as a parameter $u_G=T_G/T_A$, then the result of computation is as follows:

$$m = 40 \times 10^{-6} \text{ [kg]}, \quad u_o=1, \quad \tau=17{,}5 \text{ [s]}$$

$$C=C_2/C_1=(u_G+1)/2$$

hence

$$z=-\ln \{[-u+(u_G+1)/2]/[-1+(u_G+1)/2]\}.$$

The equation is represented in Figure 4 for the range of u_G=2.3-3.0 and u=1-2, and in Figure 5 for the range of ü=2-3 and u=1-1.4.

4. RESULTS and DISCUSSIONS

The study of major parameters influencing the fire growth is based on the concept of burning realms. For this purpose fire burning stages, pre-burning, initial burning, vigorous burning, interactive burning, and remode burning, are described. Furthermore, preburning and initial burning realms are investigated by mathematical models, and the relations between major parameter and fire growth are represented.

The importance of heat transfer and preparation period for ignition in the preburning realm is studied numerically. As a results of this investigation, it is determined quantitatively that the increase in the temperature of the heat source and the body decrease the ignition time. It is shown numerically that sharp decrease in the dimensionless temperature after ignition was due to the change of the direciton of the heat flux vector. The proposed mathematical models help to recognize the major parameters of the fire realms.

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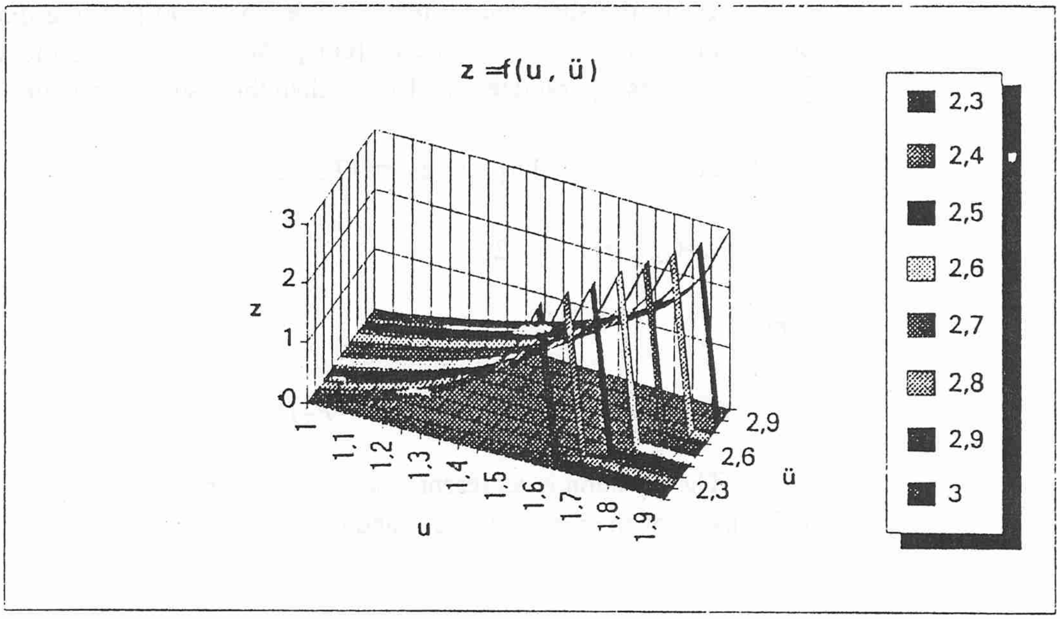

Figure 4. z = f(u,uü) for flexible polyurethane during preburning and ignition.

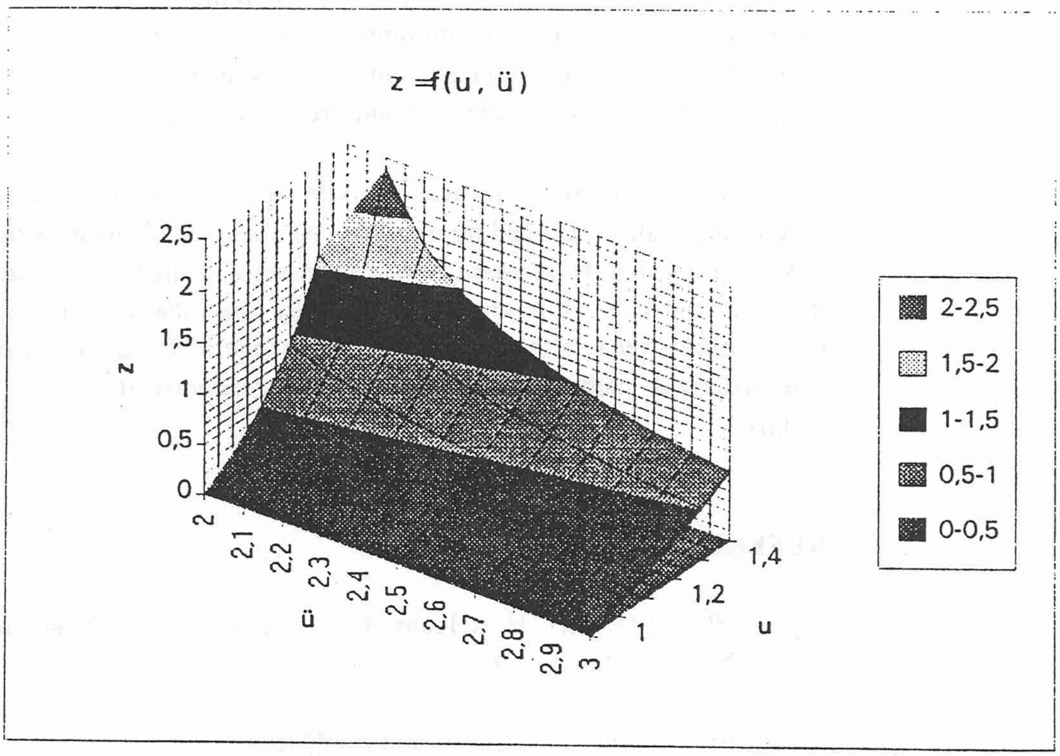

Figure 5. Characteristic surface z = f (u, uü) for flexible polyurethane during preburning.