A Method for the Quantitative Evaluation
of Flammability in Polymers

Despite the considerable effort which has been expended in reducing the fire hazards in various plastics applications, the plastics engineer must still rely on some sort of qualitative prediction of the hazards based on a myriad of small-scale tests. Unfortunately, there is often little correlation among different types of flammability tests and between tests and field performance.[1] The experiments reported here are the first part of a program to develop general quantitative methods for the prediction of polymer flammability in various applications and to develop test procedures for the designing of safe materials.

A model of the rate of flame spread over a polymer surface has been developed by McAlevy and co-workers[2] based upon mass and energy balances over the gas and solid phases. The flame spread velocity V is obtained by solving these equations using the boundary condition that the heat flux from the gas phase to the solid–gas interface is absorbed by the solid phase. The resulting equations are

$$V = \frac{2k_g \Delta H Y_{ox} F(P, Y_{ox}) U_g^{1/2}}{p_s c_s c_g \tau (T_s - T_0)}$$

for thermally-thin beds, and

$$V = \frac{2[k_g \Delta H Y_{ox} F(P, Y_{ox})]^2 U_g^{1/2}}{k_s p_s c_s^2 c_g \tau (T_s - T_0)^2}$$

for thermally-thick beds, where V = burn rate, k_s, k_g = thermal conductivities of solid and gas phases, c_s, c_g = heat capacities of solid and gas phases, p_s = density of solid, τ = sheet thickness, P = pressure, Y_{ox} = mole fraction oxidant in bulk gas phase, U_g = gas velocity, T_0 = ambient temperature, T_s = surface volatilization temperature, and ΔH = heat of combustion. The surface temperature T_s and the heat of combustion ΔH are characteristic parameters which describe the flammability of the material.

The key assumption in this model for the vertically downward-burning of polymer sheets and films, the same configuration as the Oxygen Index Test,[5] is that the rate of burning of the bulk polymer is controlled by the rate of flame spread over the film surfaces. For very thick films, or for other geometries, this assumption would not be justified. However, the two flammability parameters T_s and ΔH should be important in describing other types of burning, although the specific equation describing the process would be different because of the change in the geometry.

This particular model has been tested experimentally on samples of polystyrene film, polystyrene foam, flame-retarded polystyrene film, and polycarbonate film. Tests of the model for polyimide films and various other polymers are also planned. Typical results from the application of the model to vertically downward-burning of films are shown in Figure 1, where the experimentally measured burn rate is compared to the predicted burn rate of a polycarbonate film. All of the parameters in the equation are known independently, except for T_s, which is measured directly by a thermocouple implanted in the film surface, and ΔH, which is treated as a fitting parameter at the present time. The molar oxygen concentration Y_{ox} was varied in the polycarbonate tests from 30% to 70%, using both nitrogen and helium as diluents. Film thicknesses were varied from 3 to 35 mils, and the ambient temperature was varied from 23°C to 180°C. As assumed in the model, the measured surface volatilization temperature, after correction for thermocouple error, was constant at 580°C for polycarbonate, independent of the operating conditions. The heat of combustion varied with diluent, but was independent of ambient temperature and oxygen concentration. A summary of the results for all of the materials tested are given in Table I. These data represent the results of several hundred burning tests on the various materials.

TABLE I
Flammability Parameters

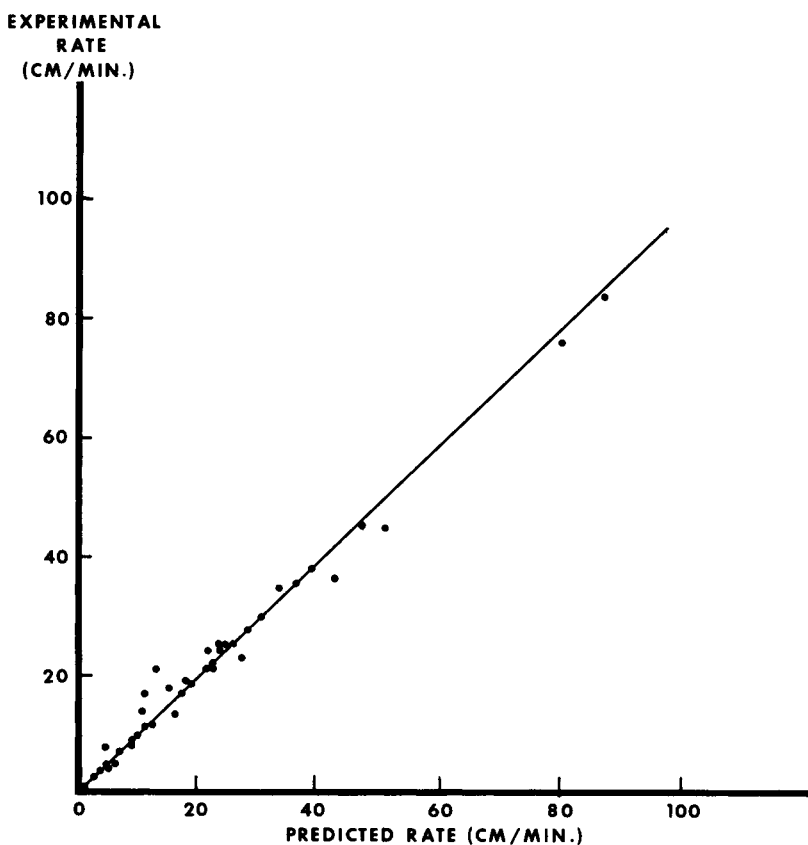| Polymer	T_0, °C	Diluent	T_s, °C	H, cal/g
Polystyrene film	23	N_2	390	2.1×10^4
	60	N_2	390	1.7×10^4
	23	He	390	3.0×10^3
Polystyrene foam	23	N_2	390	4.4×10^4
	23	He	390	4.4×10^3
Flame-retarded PS	23	N_2	560	1.7×10^4
Polycarbonate	23	N_2	580	1.6×10^3
	23	He	580	2.5×10^3
	180	N_2	580	1.3×10^3

Fig. 1. Evaluation of the flame-spread-model polycarbonate film.

These experiments confirm the applicability of the flame spread model to this particular burning test, despite the approximations made in its development. The next step will be to develop models of other burning tests to verify the hypothesis that T_s and ΔH will suitably serve for the characterization of polymer flammability and then to develop general procedures for the utilization of this information.

References

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