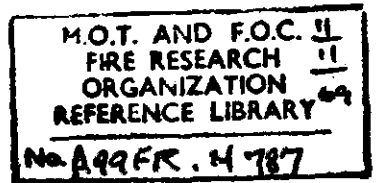


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Fire Research Note

No. 787

**FIRE PROTECTION ENGINEERING WITH
PARTICULAR REFERENCE TO CHEMICAL
ENGINEERING.**

by

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TO CHEMICAL ENGINEERING

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SUMMARY

This Fire Research Note provides a resume of four lectures to be given at the Chemical Engineering Department, University College, Swansea, November 6th-7th 1969. A brief statement of the principles underlying fire processes and protection against fire and explosions is outlined.

KEY WORDS: Fire, explosion, fire protection, chemical engineering.

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MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

FIRE PROTECTION ENGINEERING WITH PARTICULAR REFERENCE
TO CHEMICAL ENGINEERING

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Introduction

Fire is a problem which touches most of man's activities. A measure of its significance may be obtained from its effect on life and property. About one thousand people per annum die in this country because of fire, and the financial cost of the direct damage caused is about £100 M. However, the latter represents only a portion of the total cost of fire. Thus local authority and industrial fire brigades also cost about £80 to £100 M. The cost of providing fire precautions in buildings is another £70 M and the extra cost of designing plant and apparatus to take into account the phenomenon of fire, is also probably a similar amount. It is in these three latter fields that the need for an engineering discipline in fire protection arises, and these lectures will be concerned with a broad delineation of some of the scientific and engineering concepts on which this discipline is founded and their relationship with chemical engineering. It is important to see fire protection in perspective as part of the whole system associated with the fire problem. This system includes activities such as fire insurance, fire prevention and legislation. Fire insurance serves to distribute losses amongst the whole nation. The cost of this service to the country is about £60 M per annum. Fire prevention may be regarded perhaps as a branch of fire protection, the emphasis being on education and publicity. Fire legislation and the formulation of Standards and Codes of Practice, is a form of expression of fire prevention and fire protection requirements. All these activities are interlinked and it is important to bear in mind that the object of any of the activities should be reduction of the total burden which fire places on the community.

The subject matter to be covered in the four lectures will be as follows:-

- (1) A statement of the fire problem and description of the physical structure of fire.
- (2) Ignition and extinction processes.
- (3) Protection against fires.
- (4) Protection against explosions and economic aspects of fire and explosion protection.

Relationship between fire engineering and chemical engineering

Fire engineering touches chemical engineering in two important ways. Firstly, fire is a chemical reaction, and its prevention and control necessarily involves many concepts which have their parallel in chemical engineering. Fluid mechanics, heat and mass transfer and chemical kinetics are basic sciences of both disciplines, although perhaps in chemical engineering transfer processes are generally of forced convection, with fire engineering, radiation and natural convection form the main basis of the transfer of heat and materials. The other main point of contact, of course, is that chemical engineering involves the use of a wide range of flammable materials, and as a consequence fire protection is a very important consideration in the design and use of chemical plant.

The range of fire hazards

An idea of the very wide range over which fire hazards come into human affairs may be conveyed by the statistics of fire incidents.

Tables 1, 2 and 3 give respectively information on the number of fires that take place per annum in different occupancies; the different sources of ignition (often loosely described as the cause of the fire) and the different materials that were first ignited. Nearly all organic matter is capable of sustaining a fire, and under some conditions, very small sources of energy are capable of starting one. The use of combustible material and energy in one form or another increases with increasing application of technology. This may account for the fact that the number of fire incidents per million population have almost doubled between the years 1950 and 1967.

Structure of fire

The discipline of fire protection must rest in the first instance on an understanding what fire is, and the laws by which fires may be ignited and continue to burn and are extinguished. Fire in this context is an uncontrolled chemical change, usually accompanied by flame, that gives out heat. The most important reason for the lack of control is that much more of the material concerned is exposed than is actually taking part in the chemical change at any moment. Usually as a result of a heat transfer process, some of the heat from the reaction enters the exposed material, and as a result changes it to a condition where it can take part. In the vast majority of cases the reaction concerned is the oxidation of organic materials by atmospheric air or oxygen. However, there are exceptions to this which include the oxidation of hydrogen and metals, the decomposition of individual substances such as schedules explosives, organic peroxides, hydrazine acetylene, etc.

Flame

Fires of organic material in air are often characterised by flame which accompanies the process of oxidation of fuel gas or vapour. For flame to occur in the presence of an igniting source the concentration must be within the limits of flammability.

Flames can be divided into two kinds:-

Premixed flames - If a large volume of mixture within the limits is present the rate of burning depends on the rate at which flame propagates through the mixture. The usual effect of such flames is to produce a rise in pressure and explosions.

Diffusion flames - If fuel and air are fed separately to a zone where they mix to within the flammable limits and burn, then the general effect is to have a continuing fire. Under free burning conditions the rate of burning depends on the rate of supply of fuel but under "air starved" conditions on the rate of supply of air.

The speed of flame propagation of a premixed flame depends on the nature of the fuel, and the temperature, composition, pressure and state of quiescence of the mixture. Behind the flame the burned gases expand according to the temperature reached in the combustion process, and if there is no way for the gases to escape, this results in the flame being pushed forward at a correspondingly faster rate and the gas mixture in front of the flame also being moved forward. This results in the development of turbulence ahead of the flame, which increases the speed at which the flame travels. Turbulence produced by other factors such as the presence of obstacles, or the existence of movement in the gas prior to ignition, can also cause the flame to accelerate. The turbulence has this effect because it produces mixing of hot combustion products which would normally flow away behind the combustion front, with unburned gas ahead of the combustion front. The rate of flame movement in a turbulent gas can be several orders greater than the rate of flame movement in a quiescent gas. In both laminar and turbulent flame propagation, the energy which brings the unburned material into a state of reaction is handed over by a heat transfer process. These combustion processes are called deflagration. However, it is also possible to establish a detonation which is a shock wave that has sufficient strength to heat the reacting mixture to a temperature at which the reaction rate is sufficiently high to drive the shock wave. Flame speeds

in gaseous detonation is of the order of 1,000 metres per second. As a rule, however, detonation does not develop unless the explosive gases are confined by a long duct.

Apart from pressure effects, the movement of flame over large distances may also result in a widespread initiation of fire. This is perhaps more important in the phenomenon of dust explosion, in which the fuel distributed in the air is in the form of dust particles rather than as vapour or gaseous molecules. The range of materials which can give gas and dust explosions is very wide and are of course of particular importance to chemical and process engineers.

In diffusion flames the size of the flame is the size necessary for at least sufficient air to feed into the flame by natural convection processes associated with flame buoyancy to burn the vapours emitted from the fuel. The rate of burning is controlled fundamentally by heat transfer between the flames and the fuel. For large flames this is predominantly by radiation. However, for small flames and also for small solid surface elements with a large flame, convective heat transfer is important. The upward velocity and flame temperatures are controlled by the flame buoyancy. The rate of spread of fire along the fuel surface which is not burning depends on the rate at which heat may be transferred to the surface to raise it to such a temperature that it produces sufficient flammable vapours to burn. In general the lower this temperature the more rapid will be the spread of fire across the surface. However, the heat transfer processes by which neighbouring fuel is heated can be quite complicated. It includes not only heat transfer from the flame, but also in flammable liquids heat loss due to convection processes set up within the fuel. For cellulosic solid fuels, flame spread occurs when the fuel has been heated to a temperature of 300°C . For beds of fuel such as cribs, layers of vegetation, etc., radiation through the matrix of fuel is the main mechanism of heat transfer. Flame spreads upwards in cellulosic fuels at metres/minute but horizontally at centimetres per minute.

Ignition

A flammable material exposed to air, is not in thermodynamic equilibrium and will react at a very slow rate. This rate is governed by the ambient temperature according to a law such as the Arrhenius exponential law. The form of the relationship is shown in curve AA in figure 1.⁽¹⁾ However, from each point of the reacting system heat would be lost according to the local heat transfer rate. This again predominantly depends on the temperature at the point concerned, and would have a straight line relationship with temperature difference as shown by the lines B. of figure 1.

Under normal conditions a stable condition is set-up as at point P on the graph close to ambient temperature. However, if any point of the system is caused to be heated to above a certain critical temperature, then heat is produced faster than it can be dissipated and ignition is obtained. Under these conditions, the rate of heat production will usually become dependent on some factor other than that predicted by the Arrhenius reaction rate (usually by limitation of fuel or air).

Ignition in fires covers three main types of system. The most important is perhaps the ignition of flammable gases and vapours with air. This requires a source of energy to raise a kernel of the mixture to a temperature at which heat produced by the rate of reaction exceeds the rate of heat loss, according to the above concept*. Flame then propagates away from this kernel to encompass the whole flammable mixture present. Small flames, electric sparks, frictional sparks, hot surfaces, could all act as a local source of energy. The total amount of energy needed depends on the size and shape of the source as well as the nature of the flammable mixture.

The second system concerns the ignition of packed solids. In this case the reaction concerned is the solid reaction with air present in the packing. The above concepts of thermal ignition apply particularly to this system. The crucial factors are the ambient temperature on the surface of the stack and the size of the stack, since these factors control the heat loss, and therefore whether the material inside the stack will rise to a critical temperature at which it will ignite. Thus, any stack of flammable materials will ignite if it is large enough, provided it is not sealed to ingress from extraneous air. The third system is a variant of the first and concerns the heating of a solid or liquid fuel to produce a sufficient quantity of flammable vapours to become ignited. This is what happens when a match is dropped on paper. Cellulosic materials need to be heated to a temperature of about 300°C before they produce sufficient vapours to be ignited. At a temperature of 500°C the vapours ignite spontaneously.

N.B. *Where a chain branching mechanism of ignition is dominant chain branching must exceed chain terminations.

Extinction

In extinction the progress of a fire is stopped, usually by the removal of the fuel vapour that burns. Thus the predominant action of water against ordinary fires is to cool the burning material below a temperature of 300°C at which point insufficient vapour enters the flames to burn. Below a critical rate which depends upon the heat transfer conditions between the flames and the fuel on the one hand, and the fuel and applied water on the other, the water is incapable of removing heat fast enough and the fire continues. Fires in flammable liquids with high flash-points can also be extinguished by water spray in this way. However, fires in flammable liquids are usually extinguished with water foam. The foam forms a blanket over the surface which prevents the flammable vapour reaching the air, where it can burn. Here again there is a critical rate of foam application to counter the breakdown of foam caused by vaporization due to heat transfer from the fire and drainage caused both by heating and the action of the flammable liquid.

Flames may also be extinguished by changing the fuel/air mixture to a condition under which flame will not propagate. A useful concept here is that of the adiabatic flame temperature. This is the temperature of the combustion products which would ensue if all the fuel and oxygen in the mixture had reacted to the maximum extent possible and without heat loss. As stated above, there is a lower limit below which flame will not propagate through a mixture. This lower limit is associated with a certain adiabatic flame temperature, which for many flammable vapours is about 1500°K . If a heat absorbing additive is uniformly dispersed in the flammable gas/air mixture such that the adiabatic flame temperature is reduced to the value of the lower limit, then it has generally been found that the mixture ceases to propagate flame. Such additives are inert gases such as carbon dioxide, nitrogen, as well as inert powders like limestone, talc, etc. However, there are certain materials which can extinguish flame even though there is insufficient present, to reduce the adiabatic flame temperature to that at the lower flammability limit. These are called inhibitors, and vaporizing liquids containing bromine, and dry powders containing alkali metals fall in this category.

Flame may also be extinguished by passage through a matrix of cold surfaces or through a narrow gap. This is the basis for the design of flameproof equipment and flame arresters in industrial plant. This process concerned can be accounted for by heat transfer.

Protection against fire

The major forms of protection against fire may be listed as follows:-

- (1) Fire limitation by space separation and compartmentation.
- (2) The fire services and the industrial fire brigades.
- (3) Automatic fire detection systems and watch systems.
- (4) Automatic fire extinguishing and control systems.
- (5) Hand fire extinguishers and hosereels.

A basic tenet of fire protection is that it should be considered at the design stage of a process or a building. At this stage the flammability of the materials being used and the possible ignition sources should be assessed, and with this the extent to which protection is necessary. The steps needed to limit the damage caused by a fire by space separation or compartmentation should also be planned. Space separation is the distance that is needed to prevent a large fire starting another in a separate building or plant by radiation. Its value can be calculated from estimates of the exposure and the size of flames that are possible. Compartmentation is introduced by structural items within a building such as walls or floors in buildings, through which fire will not pass and which will continue to bear their design load during a fire. These items are specified on the basis of fire resistance tests, the thermal diffusivity of the materials used being an important factor in imparting fire resistance to the element concerned.

There is a close relationship between the second and third of the above factors since the effectiveness of any firefighting action depends on the rapidity of detection of the fire. Thus, fires which are discovered in the small hours of the night are about five times more likely to become large fires than fires discovered during the day because of the delay in detecting the fires. A fire which has not extended beyond a few hundred square feet area can be quickly brought under control and extinguished by the skilled application of some tens of gallons of water. Thus, a fire in a room of 200 ft² in area and completely involved may be controlled with the use of ten gallons of water. Such fires are well within the scope of a water carrying fire appliance. However, as fires become substantially bigger, the amount of water needed increases much more than proportionately. For large fires, then experience both in this country and Japan indicates that one large jet delivering 100 to 150 gallons/min is used for every 30 ft of fire perimeter. It is thus very important that the fire brigade should arrive on the scene before the fire has grown to a size greater than the order 100 - 1000 ft².

Fire detection systems generally can detect fires which are of the order of one square foot in size. Smoke detectors used at present are several times more sensitive than heat detectors but are more expensive. Within most urban areas of this country fire brigades can attend within five minutes. For most ordinary risks, therefore, an automatic fire detection system with a direct line to the brigade is a powerful form of defence. However, in a situation where a fire may spread rapidly, e.g. where there is a large vertical dimension of thin cellulosic materials, an automatic extinguishing system is required. The most important type of system is water sprinklers. Other systems employ agents such as tonnage carbon dioxide, vaporizing liquids, dry powder, foam, and high expansion foam; these are used in general only in special cases.

Extinguishers are generally useful before the fire is of the order of size ten to twenty square feet. Beyond this size one would not normally expect an individual, who has not been specially trained, to approach a fire. The most important properties of an extinguisher are that it should not be affected by long exposure to ambient conditions and it should operate when required completely reliably and safely.

Protection against explosion

Explosions in gases, vapours and dusts are a major industrial risk. Here again it is vital to assess the hazards and plan for them in the design stage. The major defence against gas and vapour explosions is ventilation which acts by preventing large pockets of explosive mixtures developing. This can be checked by monitoring for the flammable gas. If a possibility exists of the formation of dangerous explosive mixtures then it is important to eliminate or protect against ignition sources, particularly in electrical apparatus. Flame arresters which prevent flames travelling from one part of a plant to another and explosion relief which mitigates the damage caused by an explosion which also are important factors in design.

Protection against dust explosions is more difficult to deal with than gas explosions because as a rule it is impossible to prevent the build-up of dust concentrations within a plant. The fundamental precaution is good housekeeping, particularly in removing loose dust from outside a plant; otherwise this dust can cause a disastrous secondary explosion to develop from a less serious primary explosion. Apart from this, the major protection is to put sensitive items of plant in the open air, or in a specially built chamber with a light roof. Other precautions are to put the plant near an outside wall so that explosion relief from the plant may be used, and to separate items of plant with butterfly valves and screw worms.

Dust explosions, and in some cases gas explosions, are sufficiently slow to allow automatic protection to be used.

Economic aspects

All forms of fire protection are costly, and as indicated earlier, the total cost of fire protection is probably substantially greater than the total financial cost of fire damage. It is therefore important in designing fire protection to obtain a balanced approach rather than an indiscriminate use of every measure that could have some effect. Where many personnel are continuously present, the balance should be towards extinguishers and education of personnel in their use, and education in fire prevention. Where plant or buildings may be left for long periods unattended and there is a good local authority fire service, the balance should be towards rapid automatic detectors. Where there is a possibility of particularly rapid spread of flame, then the balance should veer towards automatic extinguishing installations.

Unfortunately, it is not possible to attach hard cost effectiveness figures on to various methods of protection at this stage. A straightforward approach would be to leave these aspects to the accountant working on the premium reductions allowed by insurance and investment, grants and taxation reductions by Government departments. However, not all aspects of fire that affect a firm can be covered by insurance, and the availability of premium reductions and grants is only a blunt guide to the effective emphasis that might be placed on different fire protection methods.

A particularly difficult problem arises when there is a very remote chance of a catastrophic event occurring. Thus, although local explosions take place in chemical plant from time to time, occasionally explosions extending to the whole plant may occur, because of propagation of detonation through long lengths of pipelines. Another possibility of catastrophe could follow the large-scale spillage of flammable vapour in the open in a complex of plants; the turbulent explosion which results from an ignition of this vapour could itself result in explosion damage and fire over a wide area. This would present the fire-fighters with a very difficult task at the inception of the incident. Again, where there is large-scale storage or transport of liquefied flammable gases or liquefied oxygen, a very extensive and difficult fire over a wide area could follow an accidental breach of a tank in an unfavourable location.

It is desirable that once the possibility of this type of incident is recognised, then those responsible for fire protection should collect sufficient information at least to indicate its probability. There may be no precedent for a major incident of the type envisaged. Nevertheless, from information on the occurrence of component factors, it might be possible to arrive at some estimate of the probability of a major catastrophe, which should at least provide some guide at the level of expenditure that is reasonable in adapting the plans to mitigate the major hazard.

Reference

- (1) BOWES, P. C. Spontaneous heating. Encyclopedic Dictionary of Physics. Pergamon Press.

TABLE 1 - HAZARD IN WHICH FIRES STARTED - 1966

Hazard in which fire started	Number of fires
	1966
FIRES IN BUILDINGS	
Agriculture, forestry, fishing	3 306
Industry (including construction)	12 543
Gas, electricity and water	353
Transport and communication	1 359
Distributive trades	5 062
Financial, professional and miscellaneous services	5 200
Places of public entertainment	740
Clubs, hotels, restaurants, public houses	3 635
Public administration and defence	1 487
Private dwellings	34 251
Private occupancies (other than dwellings), derelict and unknown occupancies	20 226 (1)
Total	88 162
FIRES NOT IN BUILDINGS	
Crops, standing or stooked, ricks, stacks, etc.	1 514
Grassland, heathland, railway embankments	22 546
Woods, forests, plantations, orchards	244
Aircraft	50
Railway rolling stock and structures	620
Road vehicles	13 193
Ships, river craft and marine structures	688
Refuse	26 214
Outdoor storage	2 026
Other fires	9 796
Total	76 891
TOTAL	165 053

(1) Includes 1 841 chimney fires which did not spread beyond the hearth

TABLE 2A

SOURCE OF IGNITION OF FIRES IN BUILDINGS 1966

Source of ignition of fire	Number of fires
	1966
Ashes and soot	1 440
Chimney, stove pipe, flue (not confined to)	3 999
Explosives, fireworks	296
Intentional burning of grassland, gorse etc.	19
Locomotives	66
Malicious or intentional ignition ¹	2 055
Matches	901
Children with fire, e.g. matches ²	15 219
Mechanical heat and sparks	1 017
Naked light (no further information given) ³	892
Natural occurrences	257
Rubbish burning	4 168
Smoking materials	8 026
Spontaneous combustion	423
Taper, lighted paper, sticks ²	232
Total	39 010
ELECTRIC APPLIANCES AND INSTALLATIONS	
Cooking appliances	5 545
Space heating	2 158
Wire and cable	4 846
Wireless and television	1 224
Blanket and bedwarmer	1 480 (4)
Refrigerator	327
Lighting ⁵	1 067
Supply apparatus	205
Other	2 350
Total	19 202
GAS (TOWN) APPLIANCES AND INSTALLATIONS	
Cooking appliances	3 873
Space heating	379
Other	833
Total	5 085
SOLID FUEL APPLIANCES AND INSTALLATIONS	
Fire in grate	3 125
Slow combustion stove	748
Other	565
Total	4 438

TABLE 2A (cont'd)

SOURCE OF IGNITION OF FIRES IN BUILDINGS 1966

Source of ignition of fire	Number of fires
	1966
OIL APPLIANCES AND INSTALLATIONS	
Space heating	3 177
Engine	257
Welding or cutting equipment, paint stripper	839
Lamp	175
Other	869
Total	5 317
LIQUEFIED PETROLEUM GAS APPLIANCES AND INSTALLATIONS	748
ACETYLENE APPLIANCES AND INSTALLATIONS	913
OTHER AND UNSPECIFIED FUEL APPLIANCES AND INSTALLATIONS	
Cooking appliances	1 241
Space heating	124
Other	932
Total	2 297
MISCELLANEOUS	926
UNKNOWN	10 226
TOTAL	88 162

1. From 1960 onward in

Table 3

Materials which ignited first in fires 1966

Gases	Town gas	1320	Dust powder	490
	LPG	327	flour	
	Acetylene	109	Food	9353
	Other	66	Lagging	528
Liquids	Petrol, lighter fuel	979	Rubber	380
	Paraffin	2095	Packaging	1137
	Diesel oil	571	Paper, cardboard	3766
	Paint domestic	257	Insulation	4365
	Other oils	984	Wood dust and shaving	695
	Other liquids	459	Unspecified waste	5500
Carbonaceous minerals etc.	Coal, Coke	151	Furniture and fittings	10,094
	Bitumen Tar	239	Structural fittings	7579
	Soot	95		
	Other	7		
	Agricultural and forestry produce	1927		
	Textiles	5079		

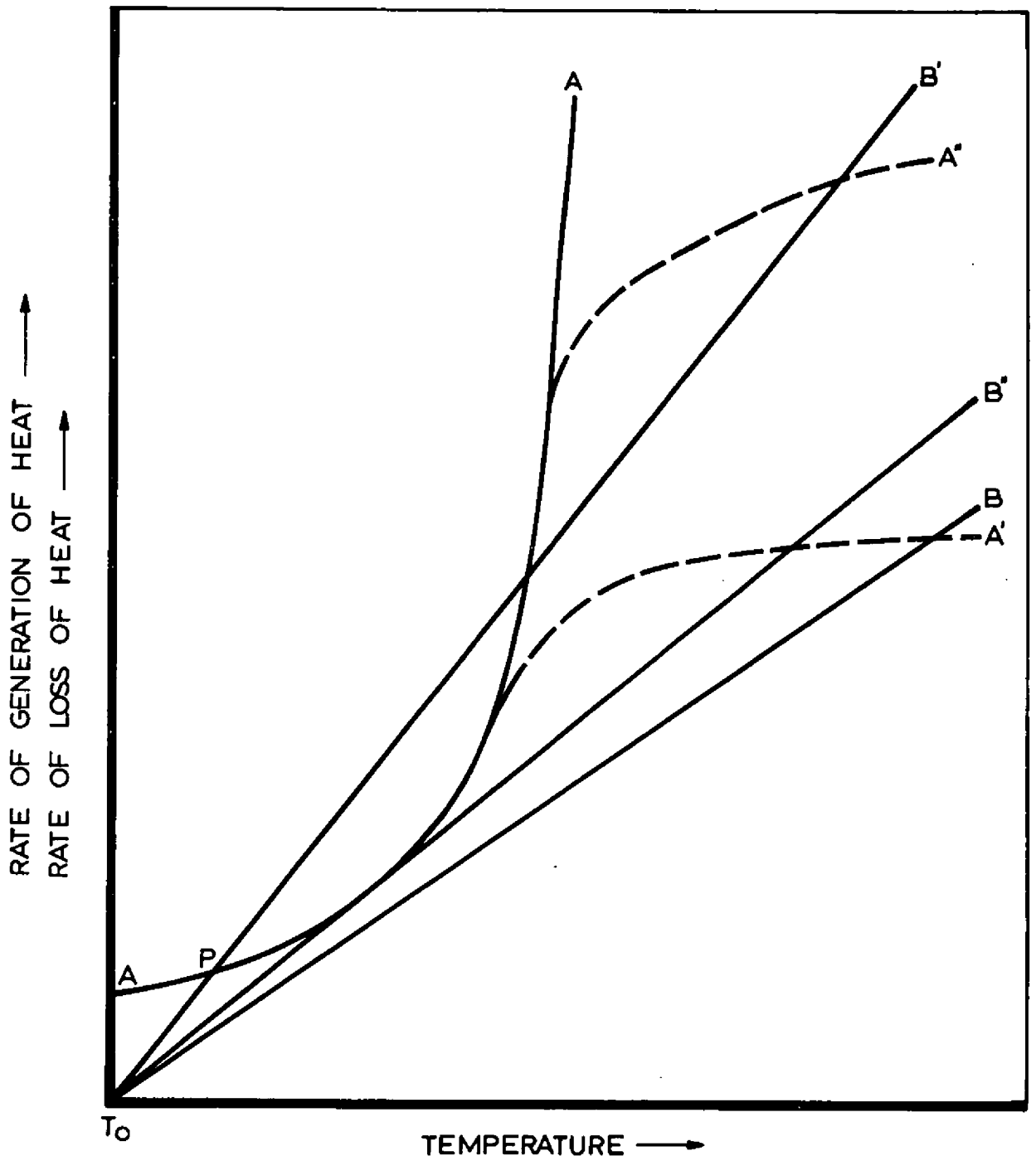


FIG.1. THERMAL BALANCE IN SPONTANEOUS HEATING

