

FIRE AND EXPLOSION HAZARDS IN SPRAY DRYERS

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An analysis of the fire and explosion risk in spray dryers is presented by consideration of the potential ignition sources and the flammability of materials (powders, dust clouds, vapours).

The means of achieving safe operation (e.g. avoidance of ignition sources, inert atmospheres, explosion venting, suppression and containment) are discussed, compared and applied to spray dryer systems using flammable and non-flammable liquors.

1. INTRODUCTION

Spray drying involves the injection of liquid droplets into a hot air stream (200-500°C). As the droplets pass through the dryer chamber the liquor evaporates and dry powder falls to the base of the chamber and passes through the downstream units. These consist of a combination of cyclones, blenders, hoppers, dust filtration systems and the final product package.

If either the powder or the liquor is flammable then consideration has to be given to the potential explosion and fire risk involved in the operation. Little detailed information has been published on incidents in spray dryers. This provides some indication that spray drying is a low risk operation. However, fires and explosions are known to have occurred during drying; in the majority incidents the consequence of ignition has been a fire, but explosions have been initiated both in the dryer chamber and in the down-stream units.

Section 31, Factories Act (1) requires that, in any plant handling dust of such a character as to be liable to explode on ignition all practicable steps should be taken to restrict the spread and effects of such an explosion. In any powder plant handling flammable or explosible dust therefore the risk of a dangerous explosion must be avoided by eliminating all ignition sources, by the use of a non flammable atmosphere or by the application of explosion protection techniques (e.g. venting, suppression, explosion containment).

2. ESTABLISHMENT OF THE CONDITIONS FOR THE SAFE OPERATION OF A SPRAY DRYER

In common with all powder processing equipment the assessment of risk in, and the definition of conditions for the safe operation of a spray dryer require consideration of the following in relation to the dryer chamber and downstream units: (1) the flammability or explosibility of the powder, (2) the identification of potential ignition sources and means of eliminating them, (3) the necessity for, and the means of making the atmosphere non flammable, (4) the necessity for explosion protection systems and the selection of the most appropriate type, and (5) the operating procedures that will minimise ignition risk.

Account must be taken of the following types of carrier liquor: (A) non flammable (aqueous) liquors, (B) liquors that are predominantly non flammable but contain small amounts of flammable liquid, and (C) liquors that are flammable under the operating conditions (e.g. solvents).

This analysis is concerned with cocurrent dryers but a similar one can be made for the counter-current type.

A. DRYING FROM NON FLAMMABLE (AQUEOUS) LIQUORS3. FLAMMABILITY/EXPLOSIBILITY OF THE POWDER

In the U.K. information for assessing the dust explosion risk associated with a powder is obtained from laboratory tests described by the Joint Fire Research Organisation (2). A material is classified as Group (a) - a dust whose ignition could produce a dust explosion or as Group (b) - a dust unlikely to cause an explosion in the presence of an ignition source - depending on whether or not ignition is obtained in the tests.

This classification has limited application in the drying of powders because it refers only to dust clouds dispersed in air at relatively low temperatures (i.e. less than 110°C). The temperatures in the dryer chamber are normally 140-500°C and the ignition of a Group (b) dust under these conditions may result in an explosion. In principle the explosibility of a powder may be determined by carrying out the J.F.R.O. tests at the maximum temperature in the dryer chamber. However account must also be taken of the possible presence and effect of ignition sources (e.g. burning material) whose temperature exceeds that of the dryer air. In practice, it is normally more convenient to use the Godbert Greenwald Furnace (3) (4) operating at a temperature of 1000°C as the means of establishing whether or not a material can produce a dust explosion. Ignition in this test (Class I and Class II dusts) indicates that, in a high temperature environment, a dust cloud formed from the material may be flammable. Non ignition (Class III dust) indicates that the development of a dust explosion will not occur under all conceivable drying conditions.

The flammability of a dust cloud depends not only on the chemical formulation of the powder but also its water content and the particle size distribution within the cloud. The sample tested to classify a powder must therefore be representative of the powder condition in the dryer. The particle size of the sample should not normally exceed 60-70 microns (4) (5).

If a material is classified as flammable or explosible then consideration must be given to prevention of a dangerous dust explosion.

4. IDENTIFICATION AND CONTROL OF IGNITION SOURCES IN THE DRYER CHAMBER

The sources of ignition in the drying chamber and means of controlling them may be summarised as follows.

4.1 Air Heater

The drying air may be indirectly heated using steam, electricity, oil or gas as the source of heat or may be directly heated by oil or gas burners. Safe operation of the heater unit should be ensured by the application of the safety measures prescribed for the particular type of unit employed (6) (7) (8).

A potential ignition source not covered by these recommendations are the hot particles that may be entrained with the inlet air when a direct fired dryer has been in use for some time. The ignition risk from these particles depends on the sensitivity of the dust cloud to ignition by small heat sources, the maximum size of the hot particle and its maximum temperature. The precise relationship between these parameters is not known. Figure 1 indicates the ignition temperature of organic dust clouds determined in the Number 1 Wheeler test in which the ignition source is a hot wire of length 32 cm, thickness 0.027 cm coiled on 0.25 cm diameter glass tube covering length 1.78 cm. This histogram indicates that with this ignition source few powders are ignited at temperatures below 600°C. Thoenes (9) has shown that to ignite oil mists (auto ignition temperature 400-500°C) with metallic or glowing oil particles requires a temperature of at least 1500°C when the particle diameter is approximately 1 mm. and a temperature of 1000°C when the particle diameter is 10 mm.

These data indicate that incandescent particles (temperature 600-800°C) will not ignite dust clouds if the diameter of the particle is less than 3-5 mm. This ignition source can be eliminated by siting a fine mesh (less than 5 mm. apertures) over the air inlet and keeping it free of contamination by appropriate cleaning.

4.2 Static Electricity

Static electricity can be generated during the spraying of the liquid droplets and by the subsequent movement of the powder. The major hazard, a discharge from an insulated conductor, can be eliminated by the normal precaution of earthing all metal plant. With materials extremely sensitive to static electricity it may also be necessary to restrict the use of non conducting materials and to prevent the build-up of large amounts of electro-statically charged powder in the base of the dryer (10).

4.3 Mechanical Friction

Although certain injector systems contain moving parts dangerous frictional heating will not occur if these are operated and maintained correctly.

4.4 Spontaneous Ignition of the Dust Cloud

If a dust cloud is exposed to a sufficiently high temperature it will ignite spontaneously. The ignition temperature obtained in the Godbert Greenwald Furnace test indicates the hazardous temperature level. The histogram (Fig.1) obtained from tests on 2000 organic powders indicates that the ignition temperature of the majority of powders is greater than the maximum air inlet temperature (500°C) in normal use. However in the operation of disc and rotary jet spray dryers the circulatory air flow pattern can result in dry dust clouds existing in the region of the hot air inlet. Extensive dust clouds can also be produced if mal-operation occurs and dust is dispersed from the bottom of the chamber. This ignition source can be eliminated by prescribing that the air inlet temperature should be less than the Godbert Greenwald Furnace temperature. In practice, to allow a satisfactory safety margin, an air inlet temperature 50°C below this value is normally prescribed.

4.5 Exothermic Decomposition/Oxidation of Powder Layer Deposits

In the ideal situation the change from liquid droplets to powder particles should occur as the material moves down through the dryer chamber and dry powder should only be exposed to the relatively low temperatures in the lower regions of the chamber. With the nozzle type of dryer in which a uniform downward air flow is established before the injection of the liquid droplets this situation exists. However with the disc and rotary nozzle dryers, the localised eddies of air lead to the deposition of powder near or on the top surface of the chamber. These deposits are swept with a plentiful supply of air at or near the temperature of the air entering the chamber from the heater. Their temperature can be further increased by the oxidative decomposition and/or thermally induced exothermic decomposition of the material. If this decomposition/oxidation progresses to red heat then the burning powder presents a potential source of ignition particularly if the layer breaks away from the chamber surface and passes through it into the downstream units.

Bowes and Townshend (11) have shown that, by exposing powder layers of different thickness to increasing temperatures, a relationship between layer thickness and ignition temperature can be established that can be used to predict the exothermic behaviour of deposits of a specific material. The ignition temperature so determined applies only to the powder tested. Relatively minor changes in formulation or inadvertent contamination of the powder deposit can significantly modify the thermal stability characteristics of a material. For example the basic cause of one dust explosion in a dryer was the reduction in the ignition temperature of a powder from 385°C to 220°C caused by a faulty injector system that permitted the powder layer on the upper surface of the chamber to become contaminated with the lubrication oil.

In a multi product unit the time and effort required to establish the ignition temperature/layer thickness relationship for each formulation presents practical difficulty. However an indication of the ignition temperature can be obtained by using a test that exposes a layer of the material to hot air under similar conditions to those found in the dryer chamber. The histogram in Figure 2 summarises the data obtained for 80 organic powders in a test in which hot air is passed over a 5mm thick layer of powder at a velocity of 4 metres per minute. Initially the temperature of the air is raised by 50°C every 15 minutes but the final minimum ignition temperature is only defined after two samples have been exposed to it for two hours. These data indicate that many organic powders may exotherm and progress to burning when exposed to temperatures of $200\text{--}300^{\circ}\text{C}$. Operation of a spray dryer in a manner that precludes ignition of this type of deposit would require that the air inlet temperature be below this value. With this restriction and the use of the typical air outlet temperature $100\text{--}140^{\circ}\text{C}$, a drying operation tends not to be efficient. Experience has shown that the use of air inlet temperatures above the ignition temperature to produce more efficient drying does not lead to a high risk situation. Relative freedom from incident occurs because of a combination of the following, (a) ignitions do not occur because of the physical nature and thickness of the layer, (b) ignitions occur, but the deposit does not become detached and enter zones where flammable dust clouds exist or (c) the glowing deposits become detached but do not possess a heat capacity sufficient to ignite the dust cloud. When operating with an air inlet temperature above the powder layer ignition temperature it is important to limit the temperature below the level at which significant product degradation occurs or a frequency of fires and/or explosions is produced that is unacceptable.

The difficulty of precisely defining the ignition temperature and the need to operate above this temperature to produce an efficient drying system prevents this potential ignition risk from being eliminated by control of the air inlet temperature in many types of spray drying operations. The only feasible basis for eliminating this source of ignition is to operate the dryer in such a manner that powder layers are not formed within the dryer; if this cannot be guaranteed then in

many situations the possibility of ignition from this source cannot be completely eliminated.

4.6 Exothermic Decomposition/Oxidation of Bulk Material

In normal operation the powder should pass freely through the dryer chamber and should not bulk above the powder outlet (see Section 8). Bulking does occur however in downstream units (e.g. storage hoppers, product packages) and, although availability of air is limited in these units, spontaneous ignition can occur as a result of thermally induced exothermic reactions. To assess this source of risk the ignition temperature of bulk material must be determined.

The extent to which self heating due to thermal instability occurs in a product is dependent on the surface area/volume ratio and increases as this ratio decreases. The amount of powder stored immediately downstream of the dryer chamber may range from kilograms to tons.

Grewer (12) has shown that the instability characteristics obtained from laboratory scale tests depend on the detailed experimental procedures. Bowes (13) has shown that using cubes of material of increasing size it is possible to establish a relationship between the ignition temperature and the volume of bulk material. However the problems arising from the effort involved in this type of testing and the effect of changes in formulation and of contamination described for powder layers also apply to bulk material characterisation.

At present the temperature at which thermal instability will be induced is initially determined using small scale tests (4) (5) (12) in which the exothermic activity of the powder contained in a glass tube or wire basket (to simulate conditions of limited air availability) is monitored as the sample temperature is increased.

Materials exhibiting thermal instability at relatively low temperatures (e.g. less than 150°C) are normally re-tested on a larger scale (e.g. 0.5-2 kg) to establish the effect of increasing volume on the temperature at which exothermic decomposition is detected and the temperature rise produced by it. A relatively new development in this field is the determination of the exothermic decomposition characteristics in containers with extremely low heat loss (e.g. Dewar flask). The increase in temperature measured in this type of container is the maximum likely to be obtained irrespective of the package size provided the packing conditions in the test flask and the large scale container are similar.

The ignition risk from this source can be eliminated by ensuring that the powder leaves the dryer chamber below the temperature at which bulked material will exotherm to red heat if necessary by the provision of product cooling before the material bulks.

4.5 Control of Ignition Sources as the Basis for Safe Operation

With one exception all the ignition sources considered above can be readily eliminated without practical difficulty during the operation of a spray dryer. The exception is the ignition risk that can arise from the exothermic decomposition to red heat of powder layers formed in the high temperature regions of the dryer chamber. If deposits cannot be avoided then it is necessary to base safety on some means other than the avoidance of ignition sources.

5. CONTROL OF THE FLAMMABILITY OF THE ATMOSPHERE IN THE DRYER CHAMBER

The conditions necessary for the initiation of a propagating explosion are (a) the dust concentration must be above the Lower Explosive Limit for the material (2), and (b) the oxygen concentration must be sufficient to support combustion.

The Lower Explosive Limit for many dusts lies in the range 10-60 mg/l. In many drying situations the total quantity of dry powder is sufficient to produce a concentration within the flammable range. Although, for cocurrent dryers, the powder should be predominantly in the lower regions of the chamber, the air flow pattern in many chambers is not uniform and dry powder moves into the upper regions. The possibility of a flammable dust cloud is increased if any mal-operation causes the powder layers on the sides of the dryer to be dispersed into the system. The dryer chamber will contain for some, if not all of, the operating cycle a dust cloud that is flammable and control of the dust concentration so that it does not enter the flammable region is impracticable.

The minimum amount of oxygen required to support combustion varies from powder to powder. It is also dependent on temperature, the value increasing from about 5-7% (v/v) at 1000°C to 12-14% (v/v) at 20°C. Methods of determining this parameter have been described by Raftery (2). In a typical spray dryer situation the oxygen content must be below about 8-10% (v/v) for the atmosphere to be incapable of supporting combustion.

In dryers using direct fired heaters the process of combustion reduces the oxygen content, the actual value depending on the relative amounts of air passing through the burner and entering the

chamber directly. This is a function of the burner design and the air inlet temperature. During the drying process the water vapour also decreases the oxygen content but this may not be present in significant amounts at the start-up and/or shut-down of a dryer. In any particular installation the effect of these factors on the oxygen content can be calculated. Our experience indicates that the combined effect of both is unlikely to reduce the oxygen content to below 12% (v/v). This assumes uniform distribution of water vapour throughout the chamber, an assumption that is not valid in all dryers.

With few exceptions, safety can only be based on the avoidance of a flammable atmosphere by the provision of inert gas to ensure that the oxygen content is below that required to support combustion (e.g. 8% (v/v)).

This system offers the advantage that no restrictions on drying temperature is required other than that imposed by product quality and the maximum possible throughput can therefore be obtained. The decision whether or not to use inert gas will generally be based primarily on economic considerations.

6. SYSTEMS OF EXPLOSION PROTECTION FOR THE DRYER CHAMBER

In spray dryers processing flammable materials explosion protection must be provided where the elimination of all ignition sources cannot be guaranteed. The most appropriate form of protection (e.g. venting, explosion suppression, containment of the explosion) depends upon the explosibility characteristics of the powder, the design and size of the dryer, and the compatibility of the protective system with the efficient, economic operation of the plant (14).

6.1 Explosion Venting

Although vents are in common use to protect powder processing equipment the technology of explosion venting is still only partially developed and the methods recommended for the calculation of the vent area that will prevent the explosion pressure exceeding the rupture strength of the vessel contain some degree of approximation (15).

In the U.K. (1), the vent area calculation is based on the Vent Ratio (area of vent/volume of vessel). However, with dryers of large volume (greater than 3-4 metre³) this procedure can require areas that are impracticably large and that cannot be sensibly incorporated into the dryer chamber surface.

Recent work (15) (16) (17) has shown that the small vent areas obtained using calculations based on the K Factor (cross sectional area of the vessel/area of the vent equals a constant) and the Cube Root Law (area of the vent proportional to the cube root of the vessel volume) can be used to maintain the explosion pressure below the vessel rupture strength.

Some uncertainty still remains because no data have been obtained with volumes equal to those of the larger drier chambers (e.g. 150 metre³). However the rapid propagation of flame and development of pressure throughout the chamber is inhibited by the non uniform distribution of powder in the chamber and by the reduced oxygen level caused by the combustion process in a direct fired drier and by the evaporated water vapour. The relatively high temperature of the environment has the converse effect in that it tends to increase the rate of flame propagation and pressure development.

The area of vent required to prevent the maximum explosion pressure exceeding the rupture strength of the chamber depends upon the pressure time characteristics of the dust, the strength of the chamber and the pressure at which the vent closure opens. With few exceptions (e.g. metal dusts) the area of the vent can be calculated using the K Factor relationship based on a 3% mol (v/v) pentane data (14) (15) and the Cube Root Law relationship based on dust classified as St.2 by Bartnekt (17). Using these calculation techniques and taking account of the conditions discussed above that exist in the dryer chamber the following is a typical vent specification:

Area of vent: 50% of the cross sectional area of the vessel.

Strength of the drier chamber: 21 kN m⁻².

Pressure required to open explosion vent: less than 4 kN m⁻².

The combustion products and gases should discharge directly from the chamber to a safe area (1).

6.2 Explosion Suppression

This technique maintains the explosion pressure below about 21 kNm⁻² by the rapid injection of a large amount of inerting material that suppresses flame propagation throughout the chamber. The

initiation of an explosion is detected in its early stages by a pressure device activated to operate at a pressure rise of about 4 kNm^{-2} . Its efficiency depends on the rapid distribution of the suppressant throughout the chamber volume. In the larger dryers considerable suppressant is required to achieve this and to offset the diluting effect of the air entering the dryer chamber from the heater system. This technique can be employed with the small volume dryers (1 m^3) but as the volume of the chamber increases the siting of multiple suppressant injection points can present practical difficulty and can make it economically less attractive.

6.3 Containment of the Explosion

Safety can be based on strengthening the dryer to withstand the internal pressure rise produced in the explosion. The maximum pressure rise produced by organic dust clouds is 700 kNm^{-2} (4) and in the dryer chamber it can be expected to be below this value due to the low oxygen content and non uniform dust dispersion. However if containment is to be used as the basis for safety then it is better to design the chamber to withstand the maximum possible pressure in order to cover mal-operation conditions where the two inhibiting factors may not be fully effective.

Application of this technique is limited to the laboratory scale dryers. In addition to the chamber it is necessary to ensure that all equipment directly connected to it can withstand an explosion pressure rise of 700 kNm^{-2} .

7. FIRE PROTECTION

Experience indicates that the most likely consequence of ignition is a fire in the dryer chamber rather than an explosion. In themselves these rarely present a rapidly developing dangerous situation because the powder in the dryer chamber is limited in amount and the burning tends to take the form of smouldering rather than the rapid spread of flame. Extinguishing the fire within the enclosed unit can however present practical difficulties unless provision is made during the design of the equipment. This difficulty can be overcome by siting a permanent fire extinguishing system (e.g. water sprays) into the chamber design.

8. OPERATING PROCEDURES TO MINIMISE IGNITION RISK

The above safety measures have been concerned with the avoidance of a dangerous dust explosion and the rapid control of a fire should ignition occur. Whatever the basis of safety it is desirable that the risk of ignition should be minimised. The detailed control and detector systems to achieve this fall outside the scope of this paper but application of the following general conditions will form the basis for a safe operating procedure:-

- (a) The powder flow through the dryer should be monitored and the drier should be stopped if powder begins to accumulate at the base of the chamber. This limits the amount of powder in the chamber that can become involved in an explosion and also minimises the risk of the temperature profile within the dryer changing and producing higher temperatures than normal in regions where powder deposits or bulk powder may be present.
- (b) Maintaining a constant heat load and temperature profile within the dryer. This can be achieved by establishing the dryer on water before switching to product feed and returning to water before switching off the feed. If the product feed stops due to mal-operation then the hot air should be switched off to prevent abnormally high temperatures being produced in regions where powder deposits may be formed that could exotherm to red heat when exposed to abnormally high temperatures.
- (c) The use of a temperature detector at the base of the dryer not only indicates any abnormality in temperature profile but can also indicate the occurrence of a blockage of the dryer outlet due to the accumulation of powder.
- (d) When inert gas is used to maintain the atmosphere non flammable an in-line oxygen monitor will ensure that the system is non flammable before the heaters are started or the liquor injected into the chamber.
- (e) A prescribed start-up procedure should be defined that takes account of the liquor flow properties etc. in order to avoid the deposition of undried material on the upper, high-temperature surfaces in the upper regions of the chamber.
- (f) The exposure of material to temperatures from which it will exotherm to red heat is a common cause of ignition in spray dryers. This risk can be minimised by the appropriate maintenance and cleaning procedures.

9. ANCILLIARY EQUIPMENT

An ignition risk may be present in all downstream units that are directly connected to the dryer chamber. In general, units such as a cyclone, blender, dust filtration equipment and product package will contain a flammable dust cloud. Furthermore, the effect of the reduction in oxygen by combustion and the presence of water vapour will diminish as the units become more remote from the dryer chamber.

Three possible sources of ignition in the ancilliary equipment are an electrostatic discharge, mechanical friction, and burning powder carried forward from the preceding section.

If safety in the dryer chamber has been based on the avoidance of ignition sources then the drying operation as such cannot introduce ignition sources into the downstream units. However these units may themselves contain sources of ignition (e.g. mechanical friction in a mal-operating screw feed) and in this case some form of explosion protection will be required (1).

If safety in the dryer chamber is based on the use of an inert gas then, with appropriate design, this can be used to prevent the propagation of burning from the dryer chamber into downstream units and these only require further consideration if their operation causes potential ignition risk.

If however protection is based on explosion venting or explosion suppression then burning material may be passed from the dryer chamber into the downstream units because a fire will not activate either the vent or the suppression equipment. Some form of explosion protection will therefore be required in these units.

The most appropriate protection method for the ancilliary equipment will depend on the units in use and their detailed design. It is important however that the method chosen be compatible with the system used for the protection of the dryer chamber (e.g. a dryer chamber whose safety is based on the containment of an explosion should not be directly connected to a much weaker unit fitted with explosion vents).

B. DRYING FROM NON FLAMMABLE LIQUORS CONTAINING MINOR FLAMMABLE COMPONENTS

In certain industries (e.g. dye manufacture) the spray drying liquor contains a number of components in addition to the powder (e.g. dedusting agents). In certain cases these minor components are flammable solvents.

In the dryer chamber, the throughput of air is sufficient to maintain the vapour concentration of these minor components below their lower flammable limit. However, if the material leaving the dryer contains only a few percent of a volatile solvent then it is important to ensure that the temperature at which the powder accumulates in downstream units after disentrainment from the main air stream is below that at which this flammable component can produce a flammable vapour concentration in still air.

With this exception the hazard associated with drying this type of material is similar to that discussed for the drying of non flammable liquors. It is necessary to establish the temperature at which the bulk material could produce a flammable vapour concentration in still air by the use of a test similar to that used to determine the Flash Point of a liquid. A hazard from this source can be avoided by ensuring that the outlet air temperature or product cooling system reduce the temperature to below the measured value before it accumulates in still air. In common with the use of Flash Point temperatures a safety margin of 5°C is applied.

C. DRYING FROM FLAMMABLE LIQUORS

The general analysis given above can also be applied with certain modifications to the drying of powders in flammable liquors. The essential and important difference is that a flammable vapour atmosphere can, and will probably be present throughout the dryer chamber and in certain of the downstream units. If an ignition source such as burning material is produced in the chamber therefore the risk of a propagating explosion is greater than with non flammable liquors.

In principle the safety measures described for non flammable liquors can be utilised in the protection of solvent spray dryers. There is however a major difference in the explosion venting considerations. Explosion venting of the dryer chamber in the case of non flammable liquors could be satisfactorily implemented because of the relatively low dust concentration in the chamber and its non uniformity. If however the liquor characteristics and drying procedure produce a flammable vapour throughout the dryer chamber then, although in principle explosion vents can be designed to protect the unit, the area will be greater than that for the non uniform dust cloud and the strength of the chamber will have to be significantly greater than is normally considered practicable in spray dryers. In certain systems the flammable vapour may exist in the downstream units and control of this is complicated due to the variations in temperature that exist throughout

a spray dryer system. Vapour condensing out at one stage of a process may re-evaporate to form a flammable vapour-air mixture at a later stage.

It is generally recognised that, because of complications such as these, safety of a spray dryer operating with flammable liquors can only be ensured by the use of an inert gas system.

10. CONCLUSIONS

Although spray drying is a low risk operation precautions against fires and explosions are required unless it can be established that the liquor and dry powder are not flammable. The procedure described above and summarised schematically in Figure 3, can be used to assess the fire and explosion hazard in a system and to select the most appropriate means of achieving safe operation.

REFERENCES

1. Anon., 1970, "Dust Explosions in Factories", Health and Safety at Work Booklet 22, Dept. of Employment. H.M.S.O.
2. Raftery M.M., 1968, "Explosibility Tests for Industrial Dusts", Fire Research Technical Paper No.21, H.M.S.O.
3. Dorsett H.G. et alia, 1960, "Laboratory Equipment and Test Procedures for Evaluating Explosibility of Dusts" U.S. Bureau of Mines Report No. 5624. Pittsburgh, U.S.A.
4. Gibson N, 1972, "Characteristics of Powders Processed in the Chemical Industry" 1st Intern. Symp. on Prevention of Occupational Risks in the Chemical Industry, Karlovy Vary, C.S.S.R.
5. Lutolf, J., 1971, Staub Reinhaltung der Luft, 31, No.3, 1
6. Anon, 1973, "Electrical Installations in Flammable Atmospheres" I.C.I. Engineering Codes and Regulations Group C (Electrical) Vol. 1.5, Royal Soc. Prevention Accidents, London.
7. Anon, 1971, "Evaporating and Other Ovens". Health and Safety at Work Booklet 46, Dept. of Employment, H.M.S.O.
8. Anon. "Handbook on Industrial Gas Controls" and "Standards for Automatic Gas Burners, Forced and Induced Draught", Gas Council, London.
9. Thoenes, H.W., 1964, Technische Überwachung, 5 12 and 59.
10. Gibson, N. 1974 "Safety Problems Associated with Electrostatically Charged Solids" 2nd Intern. Conf. on Static Electricity. DECHEMA. Monograph 1370-1409 Frankfurt, Germany.
11. Bowes P.C., Townshend S.E., 1962, Br.J.Applied Physics 13, 105.
12. Grewer, T. 1971, Staub Reinhaltung der Luft 31, No.3, 7.
13. Bowes, P.C., 1972, Combustion and Flame 19, 55.
14. Gibson N., 1973, "Explosion Protection of Powder Processing Plant" 2nd Intern. Symp. on Prevention of Occupational Risks in the Chemical Industry, Frankfurt, Germany.
15. Gibson N., Harris G.F.P., 1976, "Calculation of Dust Explosion Vents", 10th Annual Loss Prevention Symp., Amer.Inst. Chem. Eng., Kansas City, U.S.A.
16. Donat, C., 1971, Staub Reinhaltung der Luft, 31, No.4, 17
17. Bartknecht, W. 1974, Staub Reinhaltung der Luft 34, No.11, 381 and No.12, 456

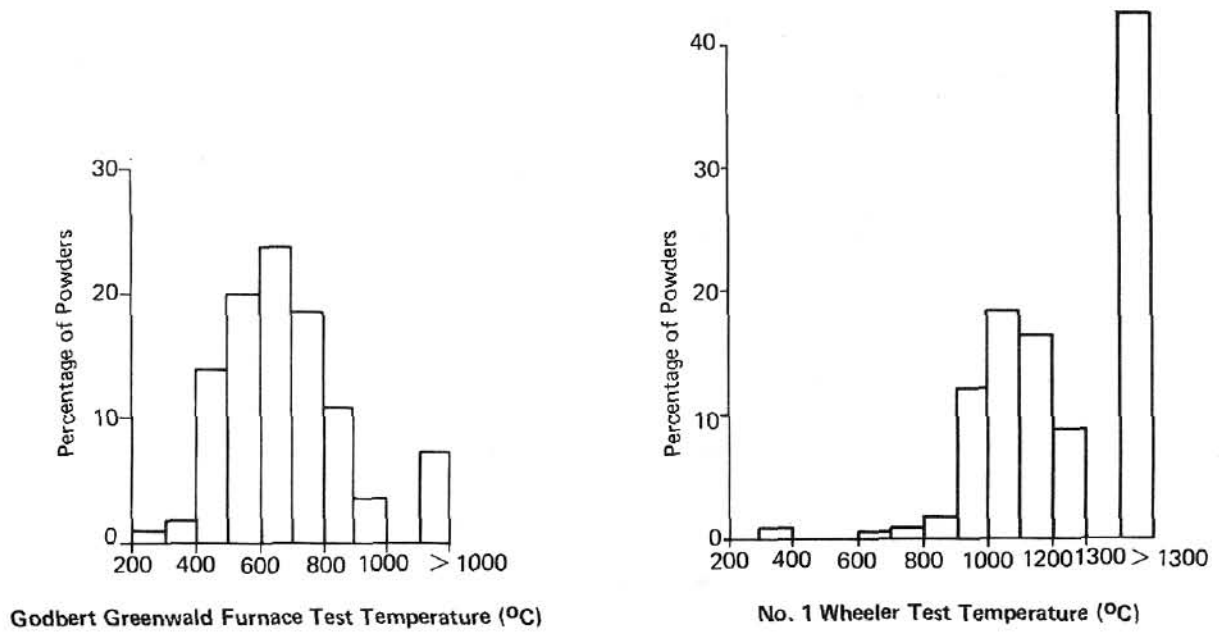


FIG. 1 IGNITION TEMPERATURE OF DUST CLOUDS

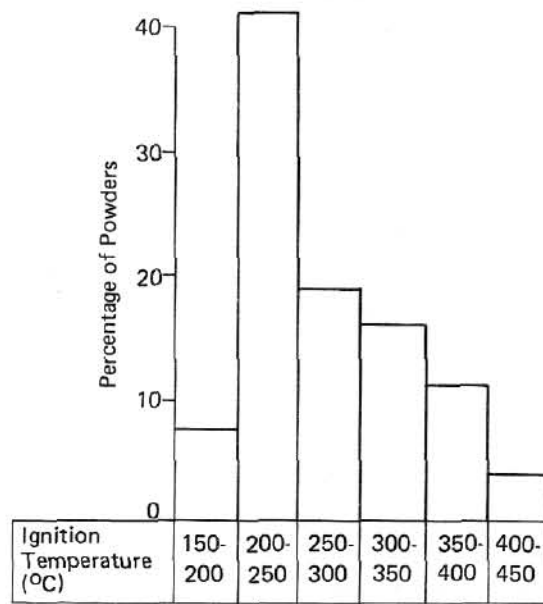


FIG. 2 IGNITION TEMPERATURES OF POWDER LAYERS

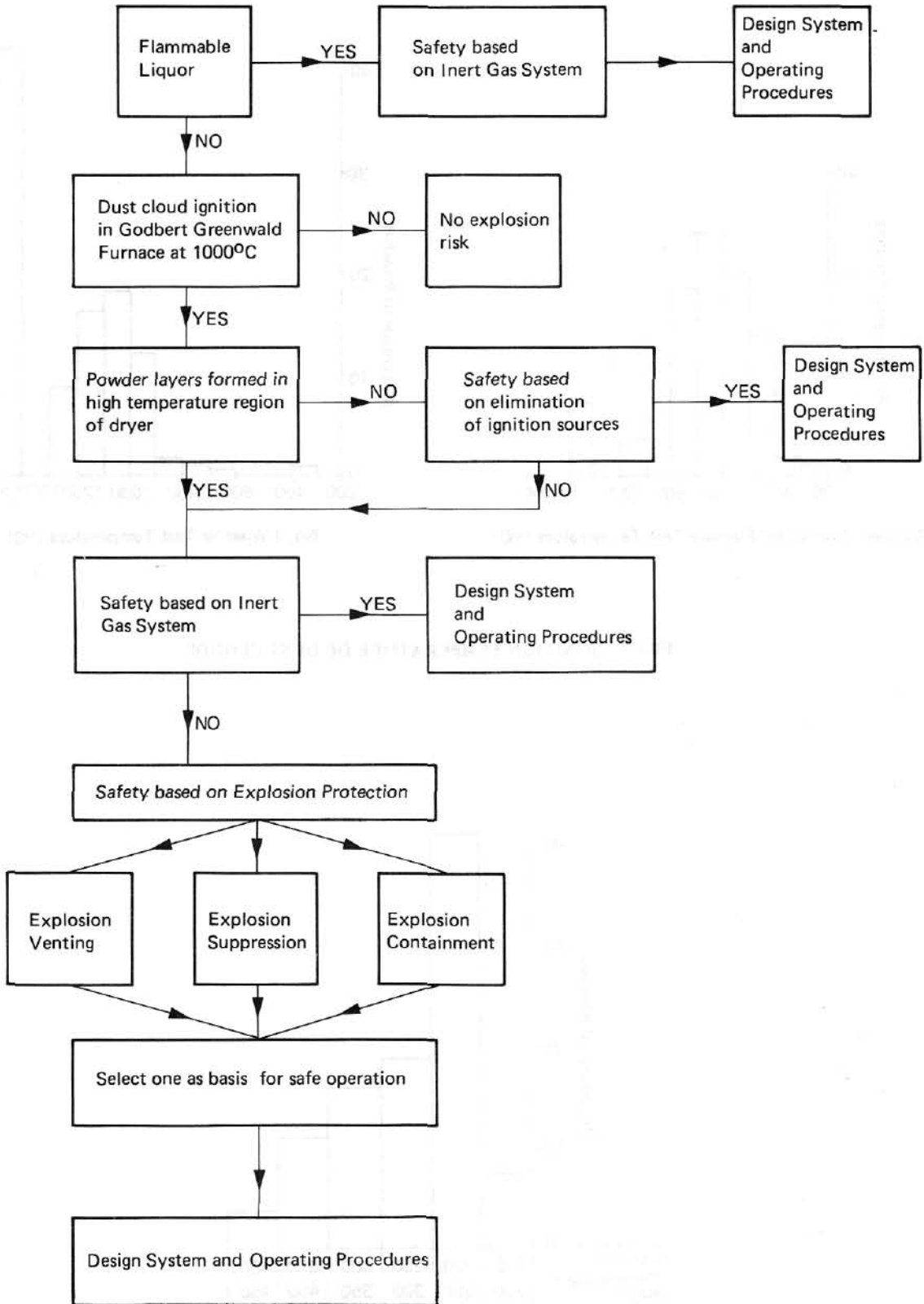


FIG. 3 SUMMARY OF ANALYSIS PROCEDURE