

## Explosions in Clouds of Liquid Droplets in Air (Spray/Mist)

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### 3.1 Introduction

Sprays and mists of combustible liquids, e.g. hydrocarbons, in air at atmospheric pressure and normal temperature, with a droplet size of  $< 100 \mu\text{m}$  and a droplet mass concentration in the range  $100\text{-}500 \text{ g/m}^3$  are explosive. This is so regardless of whether the liquid is of a low or a high boiling point. In the case of a low boiling point liquid, the droplets will evaporate readily and the cloud will very soon become a mixture of combustible vapor and air. If the boiling point is high, i.e. the vapor pressure at normal ambient conditions is low, the droplets will, with regard to the combustion process, behave similarly to solid particles of an organic material, which are also known to be able to cause explosions when dispersed as clouds in air (see Chapter 5).

The phenomenon of spray/mist explosions is complex. Similarly to a gas or a dust explosion it is the result of two main consecutive processes, viz. generation and combustion of an explosive cloud. Ignition may be regarded as the coupling between the two main processes. Because of the partly unstable two-phase nature of a spray/mist, the cloud generation process is in itself very complex.

The terms spray and mist are used somewhat interchangeably in this text, although one can argue that there is a clear difference between the two. *Spray* then means a cloud of liquid droplets extending from one or more nozzles (e.g. accidental leaks from high-pressure process equipment), whereas *mist* denotes a cloud generated by condensation from a super-saturated fuel vapor. This implies that droplets in mists are generally smaller than typical spray droplets. With regard to accidental explosions, both spray and mist may be relevant depending on the actual accidental situation.

Spray/mist combustion research may be motivated by two different needs. The first is to prevent and control accidental explosions, whereas the second is to improve diesel engines, gas turbines, furnaces, rockets etc. in which liquid fuel sprays are burned deliberately. Published research on accidental spray/mist explosions is scarce, and it is therefore useful to consider literature related to deliberate generation, ignition and combustion of sprays. The basic phenomena are the same, whether the research is conducted to prevent explosions or to improve combustion engine performance, and work related to the latter is therefore also to a large extent relevant for resolving the explosion problem. Zehr (1965) pointed out that a spray/mist and a cloud of solid particles (dust) have common features in that both consist of a finely divided dense fuel phase suspended in an oxidizer gas. However, explosive mist clouds are less stable than explosive dust clouds because collisions between droplets give rise to coalescence and transformation to fewer and larger droplets. When the droplet size gets sufficiently large, the droplet sedimentation velocity in the gas becomes significant and the droplets settle out of the cloud.

In his instructive book on combustion of liquid fuel sprays, Williams (1990) has covered a wide range of topics relevant to spray and mist explosions. This includes various properties of liquid fuels, characteristics of sprays in terms of drop size and drop velocity distributions, processes for atomization of liquid fuels and combustion of single droplets and droplet clouds. Both experimental work and theoretical modeling is discussed. Förster (2000) also gives useful information on generation, ignition and combustion of sprays/mists.

## 3.2 Generation of Clouds Liquid Droplets in Air (Spray/Mist)

### 3.2.1 General

The production of mists is discussed by Green and Lane (1964) in their classical reference book on particulate clouds. As mentioned above, mists are produced by condensation, following sudden expansion or cooling of high-concentration vapor clouds. A classical theory describing this kind of condensation processes is discussed by Green and Lane. Sometimes small solid particles act as condensation nuclei. Mists can also be generated by slow condensation on solid nuclei.

### 3.2.2 Mechanisms of Spray Generation

Valuable insight in the mechanisms of accidental spray generation can be obtained by studying the methods used for producing sprays for research purposes in the laboratory. Williams (1990) reviewed various methods for spray formation by “atomization” of liquids. When a liquid is atomized, energy is expended mainly in three ways, viz. in forming new surface, in overcoming viscous forces in changing the shape of the liquid, and in losses due to inefficient application of the energy to the liquid. Atomizing devices commonly used in generating liquid sprays may be classified in three main types:

- *Air-blast or aero-dynamical atomizers*, in which compressed air or other gas at high velocity is used to break up liquid emerging from a nozzle, and to produce a fine degree of atomization. This kind of break-up is adopted in conventional paint spray guns, in Venturi atomizers and in many atomizers that generate aerosols for insecticidal, disinfectant and therapeutic purposes. It is characteristic of atomizers of this type that they give a very wide range of droplet sizes, though in some cases the range is narrowed by trapping the larger droplets within the atomizer.
- *Generators depending on centrifugal action*. In this case the liquid is fed on to the centre of a rotating disc, cone or top and centrifuged off the edge. The spray is characterized by uniformity of the main droplet size, in marked contrast to the heterogeneity of sprays produced by other methods.
- *Hydraulic or hydro-dynamical spray generators*, in which liquid is forced through a nozzle and breaks up into droplets. Here the disintegration depends more upon the physical properties of the liquid and the conditions of ejection from the nozzle than upon interaction between the liquid and the surrounding gas. Probably the most successful hydraulic atomizer, and indeed the only one which has application for fine atomization, is the swirl chamber atomizer used in agricultural spraying equipment, oil-fired furnaces, internal combustion engines and gas turbines. The swirl is produced by leading the liquid tangentially into the chamber and forcing it to spray out through a central orifice of small diameter.
- *Special atomizers*. These include the electrostatic atomizer which breaks up liquid by the action of electrostatic forces and the acoustic atomizer which utilizes high intensity sonic or ultrasonic vibrations.

Lefebvre (1989) summarized the challenges in spray generation as follows:

The subject of atomization and sprays is one that has attracted the attention of many research workers and has been the focus of numerous theoretical and experimental studies. However, our knowledge of the atomization process is far from complete. The physics is not well understood, the available data and correlations for drop size distributions are sometimes of questionable validity, and there is little agreement between the various investigators as to the exact relationships between liquid properties, nozzle dimensions, and mean drop size. These comments are especially true for pressure-swirl atomizers. Many factors contribute to this unsatisfactory situation. They include the great complexity of the atomization process, differences in the design, size, and operating conditions of the nozzles tested, and the difficulties involved in accurate drop size measurement. These difficulties include the very large number of drops in a spray, the high and varying velocity of the drops, the wide range of drop sizes encountered in most practical sprays, and the changes in drop size with time due to evaporation and coalescence.

### 3.2.3 Coalescence of Drops in Sprays/Mists

A comprehensive review of the state of the art more than forty years ago was given by Green and Lane (1964). Much of this information is still valid. The same applies to the comprehensive review by Zebel (1966), who considered three main categories of coalescence mechanisms. The first was thermal coalescence, driven by Brownian movement of the droplets, the second coalescence influenced by inter-droplet forces (van der Waals and electrical/magnetic forces). The third category was coalescence under the influence of external force fields (electrical and magnetic, gravitational and centrifugal, sonic, and laminar and turbulent flow fields).

Förster (1990) argued that accidental generation of large, explosive clouds of sprays/mists of organic liquids of high boiling points is not very likely. The reason is that the mean droplet-droplet distance in the explosive range is of the order of only 10 droplet diameters, which in a turbulent cloud makes fast coalescence of the small droplets to larger ones highly probable. The larger droplets will then “rain out” and the fuel concentration in the cloud will fall below the explosive range. Förster confirmed experimentally that with a high boiling point liquid (octanol) it was indeed very difficult to generate an explosive spray in a  $1 \text{ m}^3$  explosion chamber unless a highly sophisticated spray nozzle system was adopted.

### 3.3 Combustion of Clouds of Liquid Droplets in Air (Spray/Mist)

#### 3.3.1 General

Zehr (1965), emphasized that a spray/mist and a dust cloud have common features in the sense that both consist of a finely divided dense phase suspended in a gas (see Eckhoff, 2003). However, spray/mist clouds of high mass densities are less stable than high-density dust clouds because collisions between small drops inevitably give rise to coalescence and transformation of the cloud into one of fewer and larger drops. When the drop size gets sufficiently large, the drop sedimentation velocity in the gas becomes significant and the drops settle out of the cloud.

The ignition and combustion of droplets of organic liquids, and of particles of solid organic materials, is similar. The thermal energy from an ignition source, or from nearby burning droplets/particles, first causes the liquid of the droplet/particle to evaporate partly or fully (via pyrolysis for liquids of high boiling points, and solids). Further heating causes the vapor to ignite and burn, either as individual diffusion flames around each droplet/particle, or as a more or less homogeneous premixed vapor/air flame. Faeth (1987) discussed the theoretical description of mixing, transport, and combustion in sprays and mists. In particular, the description of drop/turbulence interactions was considered.

In his instructive book, Williams (1990) covered a wide range of topics relevant to spray explosions. This includes various properties of liquid fuels, characteristics of sprays in terms of drop size and drop velocity distributions, processes for atomization of liquid fuels, and combustion of single droplets and droplet clouds. Both experimental work and theoretical modeling are discussed.

Understanding the details of the ignition and combustion of individual liquid droplets is a premise for in-depth understanding of the combustion of collectives of such droplets, i.e. spray and mist combustion.

### 3.3.2 Laminar or Close-to-Laminar Flame Propagation in Sprays/Mists

In their classical investigation, Burgoyne and Cohen (1954) developed a method whereby suspensions of controlled uniform drop size could be prepared from pure liquids. Using tetralin (see caption of Figure 3–1) as the fuel, it was possible, within limits, to study the effect of the drop size on the combustion properties of a suspension of liquid drops in air. Through a study of limits of flammability, nitrogen dilution limits, and burning velocities, it was shown that the mechanism of flame propagation was completely changed over the drop-size range from 7–40  $\mu\text{m}$ . Thus, below about 7  $\mu\text{m}$  the suspension behaved like a premixed gas, whereas above 40  $\mu\text{m}$  the drops burned individually, in their own air envelope, one burning drop igniting adjacent ones, thus spreading combustion. At intermediate sizes, behavior was transitional.

In a later study Burgoyne (1963) discussed the concept of “concentration” of the droplets in a spray or mist. The following conclusions were drawn:

- For suspensions formed by uncontrolled condensation of saturated vapor (mists), the drop size is small and the lower limit of flammability, measured as mass of liquid per unit volume of air, is essentially the same as that of the vapor. For saturated hydrocarbons this is of the order of 45  $\text{g}/\text{m}^3$ .
- For suspensions formed mechanically by liquid break-up, the drop size is considerably larger, and in specifying lower limit concentrations account must be taken of the distinction between “static” and “kinetic” concentrations, arising from the sedimentation of the drops.

Burgoyne (1963) also pointed out that in very coarse sprays, with drop diameters between 0.6 and 1.4 mm, normal flame propagation becomes impossible although burning drops may carry flame downwards. However, the presence of smaller droplets in such suspensions may, depending on their concentration, make upward flame propagation possible. Furthermore, the entry of a fast-moving explosion flame (e.g. from a pipe) into a chamber containing a droplet suspension that is normally non-inflammable due to large drop size, flame propagation may nevertheless occur, due to the shattering or break-up effect on the drops of the pressure waves preceding the explosion flame.

Published work on exact burning velocities of explosive sprays/mists is scarce. This may in part be due to the rather complex experiments required, where fuel concentration and droplet size have to be controlled independently. Also, with low-boiling-point liquids, droplet evaporation during droplet cloud generation introduces further complications. Figure 3–1 gives some results from two independent studies of close-to-laminar flame propagation of tetralin droplets in air.

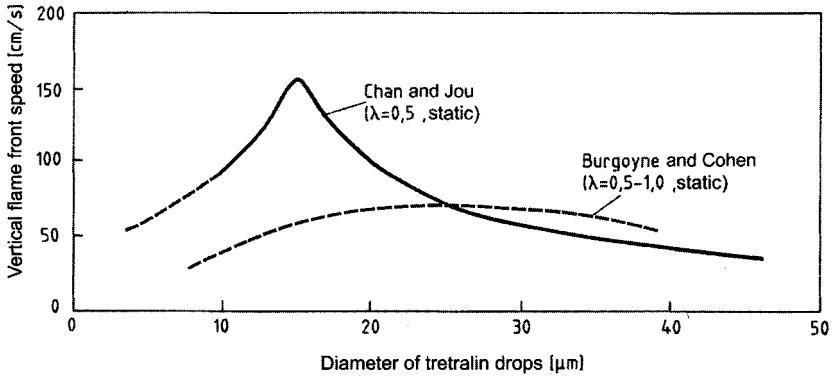
As Figure 3–1 shows, the two independent investigations gave somewhat diverging results for droplet diameters between 10 and 20  $\mu\text{m}$ . However, both studies conclude that there are two different combustion regimes of the tetralin droplets, depending on droplet size. For sizes  $<10 \mu\text{m}$  the droplets evaporate completely before combustion gets underway, and the flame propagation process resembles that of premixed gaseous fuel/air. For sizes  $> 50 \mu\text{m}$ , however, each droplet burns individually, and flame propagation is more discrete, from droplet to droplet. The distinct peak in vertical burning velocity in the data of Chan and Jou (1988) occurs in the region of drop sizes between these two regimes.

Flame propagation in sprays/mists is considerably more complex than in premixed gases. However, apart from the high values observed by Chan and Jou (1988) in the transition range, Figure 3–1 suggests that close-to-laminar burning velocities of sprays and mists of organic liquids in air are of the same order as laminar burning velocities of saturated gaseous hydrocarbon/air mixtures (alkanes).

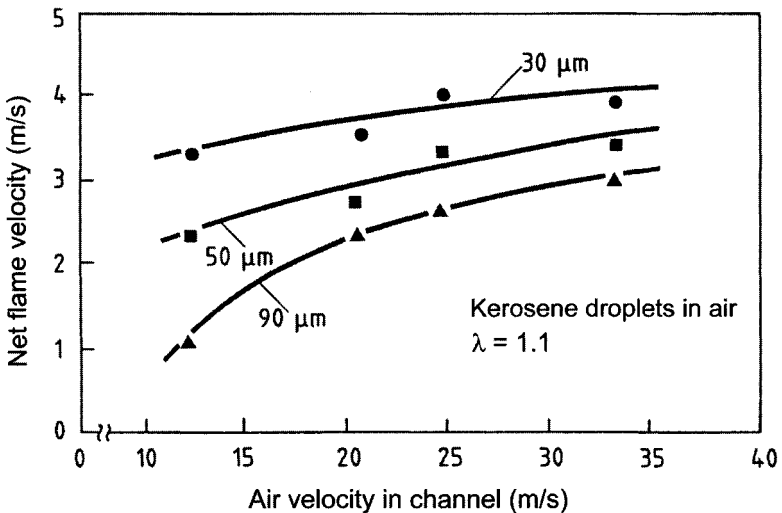
### 3.3.3 Turbulent Flame Propagation in Sprays/Mists

Figure 3–2 shows some results from flame propagation experiments in turbulent clouds of kerosene droplets in air. The Reynolds numbers were of the order of  $\text{Re} \approx 10^5$ . By increasing the flow velocity in the channel ( $\text{Re}$  is proportional to the flow velocity) by a factor of 3, the turbulent burning velocity (net velocity in relation to unburned cloud ahead of flame front) with 90  $\mu\text{m}$  droplets increased by about the same factor. Also when the droplet size was reduced to 50  $\mu\text{m}$  and further to 30  $\mu\text{m}$ , the turbulent burning velocity increased systematically with flow velocity, but the relative increase got smaller with decreasing droplet size.

Figure 3–3 shows the variation of the turbulent burning velocity with the kerosene/air ratio, for three different droplet sizes. For the smallest droplets the maximum burning velocity occur red at about stoichiometric

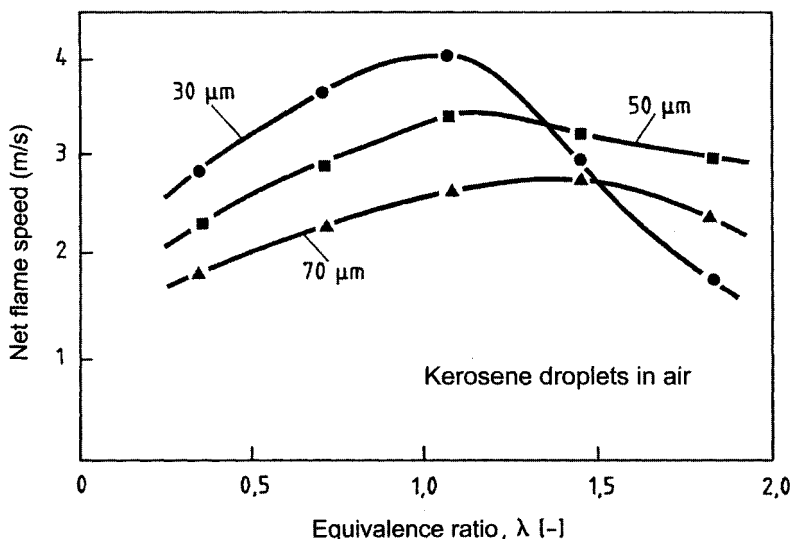


**Figure 3-1** Experimental flame speeds (vertical upwards flame propagation) in suspensions of mono-sized tetraline droplets in air, as a function of droplet size. Tetralin is a cyclic organic compound of molecular weight 132, boiling point 207°C, and flash point 71°C. From Burgoyne and Cohen (1954), and Chan and Jou (1988).



**Figure 3-2** Influence of flow generated turbulence on the burning velocity of suspensions of kerosene droplets in air, for various mean droplet sizes. Kerosene is a petroleum distillate with boiling point range 180–300°C, and flash point range 38–66°C. Slightly over-stoichiometric fuel concentration (equivalence ratio  $\lambda = 1.1$ ). Horizontal flow of droplet suspension in a channel of rectangular cross-section (width 30 cm, height 10 cm). From Richards and Lefebvre (1989).





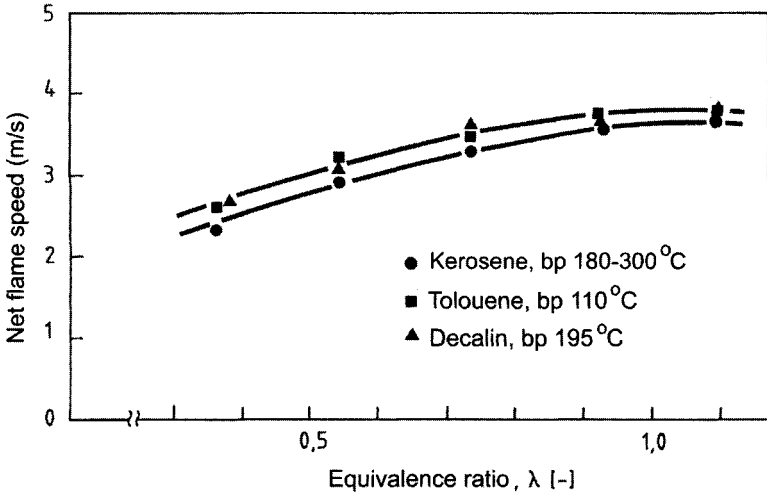
**Figure 3-3** Influence of fuel/air ratio and droplet size on burning velocity of suspensions of kerosene droplets in air, flowing at 25 m/s in a horizontal channel of rectangular cross-section (width 30 cm, height 10 cm). Kerosene is a petroleum distillate with boiling point range 180–300°C, and flash point range 38–66°C. From Richards and Lefebvre (1989).

composition ( $\lambda = 1.0$ ), whereas the peak was shifted systematically towards higher kerosene/air ratios ( $\lambda > 1.0$ ) as the droplet size increased.

Figure 3-4 shows that with the prevailing flow conditions and range of  $\lambda$  values studied, the turbulent burning velocities for 30  $\mu\text{m}$  droplets were nearly identical for the three different fuels kerosene, toluene and dekalin. However, other data obtained by Richards and Lefebvre (1989) indicate that for larger droplet sizes the burning velocity tends to decrease with increasing boiling point of the liquid. The complete relationships between burning velocity on the one hand, and degree of turbulence, droplet size, fuel/air ratio etc. on the other, are very complex.

Hansen and Wilkins (2004) conducted a series of interesting spray explosion experiments in a straight horizontal vented laboratory-scale channel of length 2.5 m and 0.3 m x 0.3 m square cross section. They found that:

- Sprays of hexane droplets (high volatility) exploded at least as violently as premixed propane/air.



**Figure 3-4** Influence of fuel/air ratio on burning velocity of suspensions of 30  $\mu\text{m}$  diameter droplets in air of three different liquid fuels, flowing at 20 m/s in a horizontal channel of rectangular cross-section (width 30 cm, height 10 cm).  
From Richards and Lefebvre (1989).

- The violence of spray explosions remained high also for over-stoichiometric spray concentrations.
- Mounting of a baffle in the channel raised the maximum explosion pressure by a factor of 8, probably due to droplet break-up by intense flow-induced turbulence.
- Under conditions causing droplet break-up, even sprays of high-flash-point oils exploded violently.
- Worst-case spray concentrations increased with decreasing volatility and increasing droplet size.

### 3.3.4 Maximum Constant-Volume Adiabatic Explosion Pressures in Sprays/Mists

Experimental data presented by Förster (2000) indicate that the maximum pressures generated in constant-volume adiabatic combustion of clouds of droplets of some organic liquids in air is of the order of 5 bar.

### 3.3.5 Detonation in Sprays/Mists

Sprays and mists of combustible liquids in air can detonate, depending on fuel chemistry, droplet size and liquid mass concentration. This is not surprising in view of the fact that both homogeneous mixtures of combustible gases and air and clouds of some organic dusts in air can propagate detonation waves. Bull et al. (1979) performed experiments to determine the marginal conditions for spherical detonation in unconfined sprays in air. The sprays were generated in a 5 m<sup>3</sup> plastic foil tent by sonic air-blast atomizers producing measured droplet sizes in the range 5–30 μm. Detonation of the spray cloud was initiated by detonating plastic high explosive charges positioned inside the cloud. Particular attention was paid to studying the influence of fuel volatility on the detonability of the spray. N-hexane and n-dodecane were used to represent extremes of very high and very low vapor pressure fuels. Fuels having intermediate volatilities were synthesized by mixing the two fuels in appropriate proportions.

It was found that n-hexane sprays detonated within fuel/air mass concentration limits similar to those for gaseous detonations, although the measured detonation front velocities were somewhat lower than the calculated Chapman-Jouquet (CJ) values, even with droplet diameters smaller than 50 μm. However, sprays of n-dodecane and n-decane did not detonate, even when using 0.5 kg initiator charges. It was concluded that this was because with these fuels the minimum effective equivalence ratio necessary for detonation propagation was not being attained behind the shock wave within the limiting induction period available. It was further concluded that propagation of self-sustained detonations in n-alkane sprays in the spherical mode, with droplet sizes larger than 10 μm, may require the presence of a certain quantity of fuel vapor prior to ignition.

Smeets (1985) performed experimental spray detonation studies in a 50 cm diameter vertical shock tube. The sprays were stoichiometric clouds of droplets in air of methanol, ethanol, propanol, hexanol, decanol, or decane. The droplets had a defined narrow size distribution with a mean diameter of 350 μm. It was found that even in sprays of low vapor pressure fuels, like n-decane and hexanol, self-sustained detonations can exist. However, a minimum concentration of fuel vapor is required, in addition to the droplets, as also indicated by Bull et al. (1979) and discussed above. By measuring several physical quantities within the reaction zone, using laser Doppler techniques, the processes of liquid fuel fragmentation, evaporation, turbulent mixing, and combustion could be observed in

detail. From the data recorded it was concluded that for sprays of 350  $\mu\text{m}$  diameter droplets, the controlling mechanism for the reaction is turbulent mixing of the vapor originating from the droplets, with air.

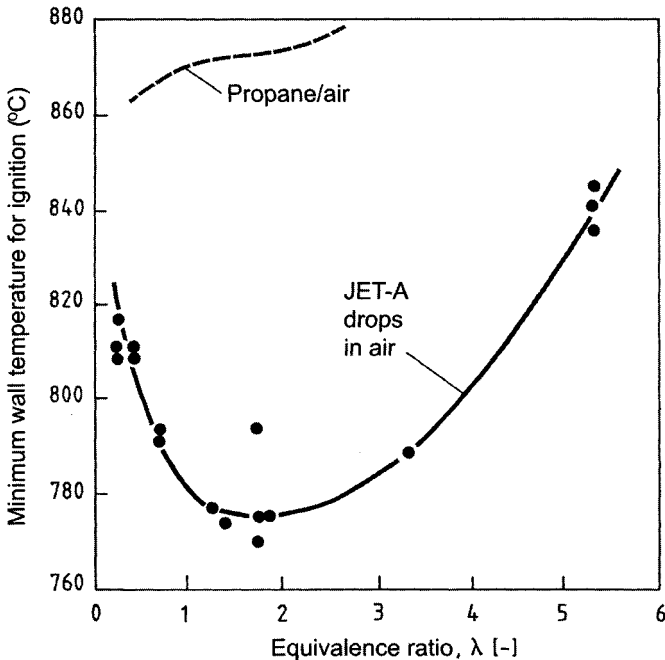
Tang et al. (1986) wanted to explain the difference between the theoretically predicted and the experimentally observed detonation velocities in clouds of droplets of low-vapor-pressure liquids in air or oxygen. Monosized n-decane droplets of diameter 400  $\mu\text{m}$  were allowed to settle vertically in air or oxygen at ambient pressure and temperature in a vertical shock tube. A shock wave was emitted vertically downwards into the droplet suspension, initiating a self-sustained detonation wave in the cloud. The propagation of this wave was monitored using pressure switches and pressure transducers. Measured detonation velocities were compared with theoretical predictions. Quite satisfactory agreement between experiment and theory was obtained for lean mixtures, but there were quite substantial differences for very rich mixtures. In the latter case, the experimental velocities reached a peak somewhat on the rich side and then decreased very little for richer mixtures.

Förster (2000) gives some references to published work on detonation of sprays and mists, confirming that clouds of combustible liquid droplets in air can detonate in the same way as premixed clouds of gaseous fuels and air. Typical measured detonation velocities are in the range 1,300–1,600 m/s, i.e. somewhat lower than typical values for saturated hydrocarbon gas/air mixtures.

## 3.4 Ignition of Clouds of Liquid Droplets in Air (Spray/Mist)

### 3.4.1 Ignition by Hot Surfaces

The problem is of the same nature as discussed in Chapter 2 with hot-surface ignition of gases and vapors. However, it has not been possible to trace any standardized test methods for measuring minimum ignition temperatures of sprays/mists. Figure 3–5 gives some results from hot-surface ignition of suspensions of JET-A fuel droplets flowing through a vertical furnace. Note that the vertical axis in Figure 3–5 covers only 120°C. This figure also gives corresponding data for premixed propane/air, and it is

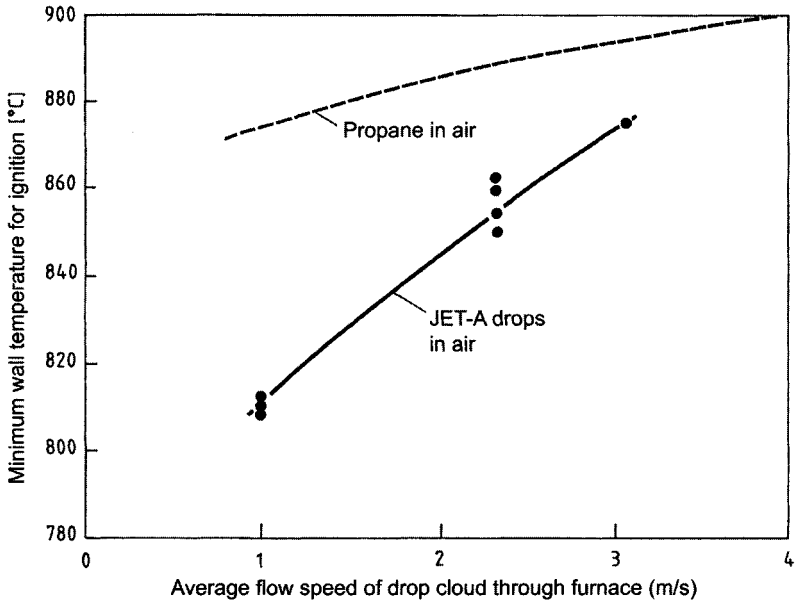


**Figure 3-5** Influence of fuel/air ratio on the minimum temperature of a hot wall in a vertical furnace required for igniting a suspension in air of JET-A fuel droplets flowing at 1 m/s. JET-A is a petroleum distillate similar to kerosene (see caption of Figure 3-2). Droplet diameters < 50  $\mu\text{m}$ . Comparison with ignition of propane/air in same apparatus and at same mean flow velocity. From Graves et al. (1986).

seen that the JET-A droplet cloud ignites at significantly lower furnace wall temperatures than the propane/air under the prevailing conditions.

A comparison of the  $T_{\min}$  values for propane/air in Figure 3-5 with those in Figure 2-17 gives further support to the view that  $T_{\min}$  for gases and vapors determined by standard flask tests, which are sometimes also applied to sprays/mists, are highly conservative for many practical situations.

Figure 3-6 shows that  $T_{\min}$  for a cloud of JET-A fuel droplets increases systematically with the velocity of the cloud across the hot surface. As expected, the trend was the same for propane/air, although less pronounced.

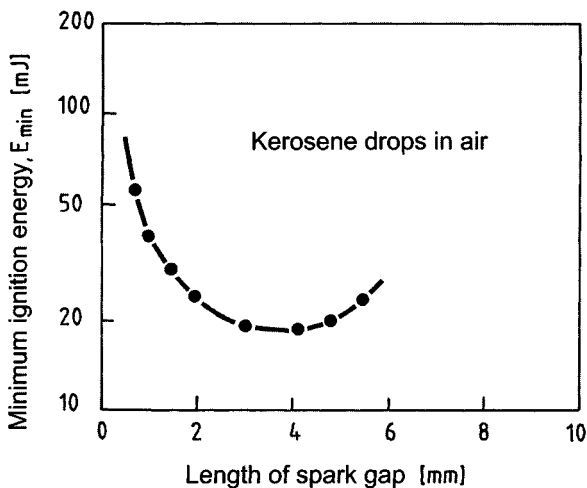


**Figure 3-6** Influence of mean flow velocity on the minimum temperature of a hot wall in a vertical furnace required for igniting a suspension in air of JET-A fuel droplets. JET-A is a petroleum distillate similar to kerosene (see caption of Figure 3-2). Droplet diameters  $<50 \mu\text{m}$ . Stoichiometric fuel/air ratio. Comparison with ignition of propane/air in same apparatus. From Graves et al. (1986).

### 3.4.2 Ignition by Electric/Electrostatic Sparks/Discharges

Explosive sprays/mist can be ignited by electric spark discharges in the same way as premixed gaseous fuel/air mixtures can. In principle, therefore, the concepts of Minimum Ignition Energy (MIE) and Quenching Distance (QD) are equally valid for sprays/mists as for premixed gases. However, in the case of spray/mists the experimental determination is considerably more difficult.

Figure 3-7 gives a set of data showing the influence of spark gap length on minimum ignition energy of a suspension of kerosene droplets in air (see caption of Figure 3-2). The data indicate that the minimum ignition energy in this particular case, with the droplet suspension flowing at a fairly high velocity past the spark gap, was about 20 mJ and the quenching distance 3–4 mm.

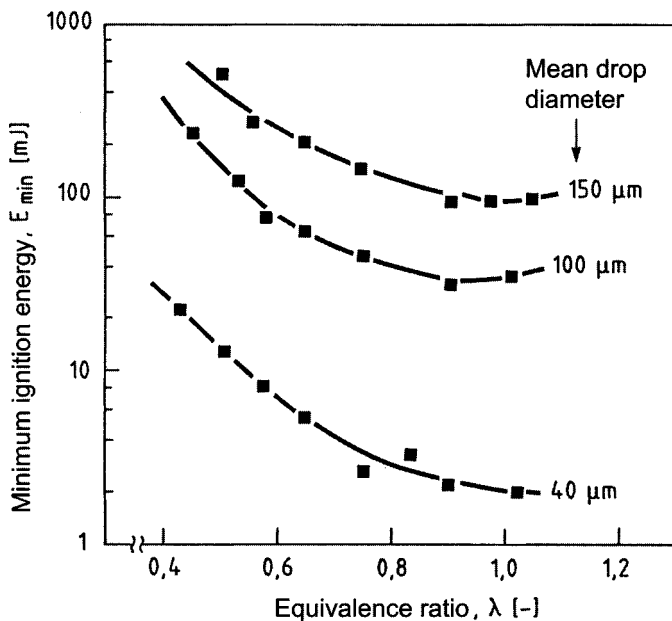


**Figure 3-7** Influence of spark gap length on minimum ignition energy of a suspension of kerosene droplets in air at atmospheric pressure and normal temperature. Flow velocity of suspension past spark gap 3 m/s, and equivalence ratio  $\lambda = 0.65$  ( $\lambda = 1$  for stoichiometric mixtures). From Rao and Lefebvre (1976).

Ballal (1976) performed detailed measurements of the ignition characteristics of kerosene sprays injected into a flowing air stream. Measurements of spark discharge parameters (breakdown voltage, optimum spark duration, energy released in the gap) and ignition characteristics (optimum spark gap, minimum ignition energy, lean ignition limit) were performed. Three different spray generators (atomizers) were used at air velocities up to 38 m/s, producing fuel droplet diameters in the range 20 to 110  $\mu\text{m}$ . The initial pressure was varied between 0.2 and 0.9 bar (absolute), the initial temperatures between 228 and 350 K, and the equivalence ratios between 0.3 and 0.9. The results showed that optimum spark duration for ignition increased with decreasing initial pressure and spray cloud velocity, and with increasing droplet size. Minimum ignition energy decreased markedly with decreasing fuel droplet size.

Figure 3-8, from the subsequent work by Ballal and Lefebvre (1978), shows the variation of MIE for clouds of heavy-oil droplets in air, with the equivalence ratio  $\lambda$  in the range of  $\lambda < 1$ , and the mean droplet diameter in the range 40–150  $\mu\text{m}$ . As Figure 3-8 shows, MIE for 40  $\mu\text{m}$  droplets of heavy oil was only 2 mJ.

Figure 3-9 gives experimentally determined MIEs for clouds in air of 100  $\mu\text{m}$  droplets of a range of different liquid fuels, as a function of the



**Figure 3-8 Influence of the equivalence ratio  $\lambda$  (fuel/air ratio) and mean droplet diameter on the MIE of close-to-quietest suspensions of heavy oil droplets in air at atmospheric pressure and normal temperature ( $\lambda = 1$  for stoichiometric mixtures). From Ballal and Lefebvre (1978).**

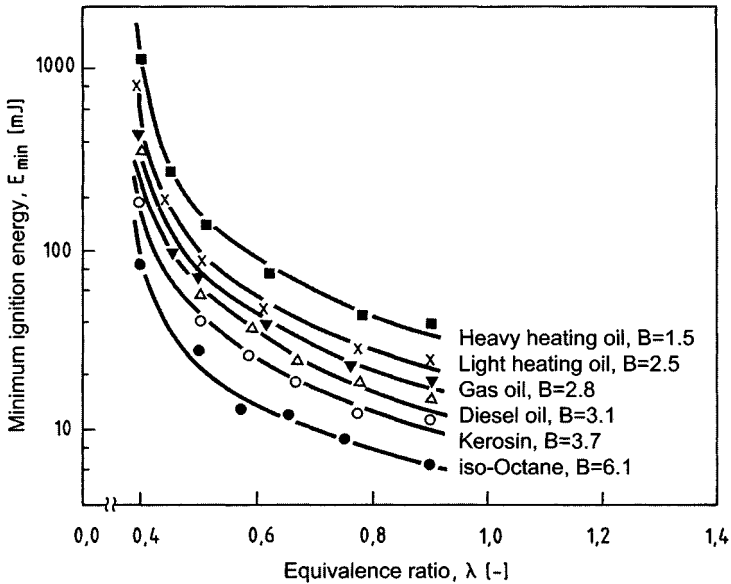
equivalence ratio  $\lambda$ . Spalding's mass transfer number  $B$ , as defined in the figure caption, is used as parameter.  $B$  is an amplified function of vapor pressure  $P_A$  of the liquid, and Figure 3-9 shows quite clearly that MIE decreases systematically with increasing  $B$ , or  $P_A$ .

Later Ballal and Lefebvre (1979) extended their studies to measurement of MIE over wide ranges of initial pressures, velocities, turbulence intensities, equivalence ratios, mean droplet sizes, and fuel volatilities. Model predictions showed satisfactory agreement with the experimental data.

### 3.4.3 Other Ignition Sources

Explosive clouds of liquid droplets in air can also be ignited by fast (adiabatic) compression (diesel engines). Baev et al. (1984) determined induction times for liquid fuel sprays at high temperatures and pressures. The apparatus was a closed cylindrical chamber of 150 mm diameter and





**Figure 3-9 Influence of the equivalence ratio  $\lambda$  ( $\lambda = 1$  for stoichiometric mixtures) on MIE of close-to-quietest suspensions of  $100 \mu\text{m}$  droplets of various combustible liquids in air at atmospheric pressure and normal temperature.  $B$  is Spalding's dimensionless 'mass transfer number' defined as  $B = P_A / (P_{\text{tot}} - P_A)$ , where  $P_A$  is the vapor pressure of the combustible liquid, and  $P_{\text{tot}}$  the total pressure. From Ballal and Lefebvre (1978).**

length, filled with air at the desired temperature and pressure. The end plates were fitted with thick quartz windows. The fuel was injected into the chamber during 3–4 ms via a special nozzle system. They also measured the induction time defined as the time interval from onset of fuel injection to onset of the sharp rise in pressure due to combustion in the chamber.

It may also be expected that explosive clouds of liquid fuel droplets in air can be ignited by certain types of metal sparks and thermite reactions from single impacts. However, it has not been possible to trace any experimental data illustrating this.

#### 3.4.4 Standard Test Methods for Ignitability and Explosivity of Sprays/Mists

It has not been possible to trace any standardized methods for assessing ignitability and explosivity of clouds of combustible-liquid droplets in air.

### 3.5 Case Histories of Spray/Mist Explosions

The main source of this chapter is the review by Eckhoff (1991). Open reports of case histories of accidental spray/mist explosions in the process industries are scarce. Therefore, some spray/mist explosions that have occurred in other contexts have been included in the present section.

#### 3.5.1 Spray/Mist May Have Been Involved in Some Reported “Vapor Cloud” Explosions

Eichhorn (1973) refers, without giving any details or references, to a report, probably from the 1950s, of a mist explosion in the chemical industry, which had prompted an experimental and literature study of mist combustion. The experimental work undertaken suggested that mists of flammable liquids in air can propagate flames, and that the vapor pressure of the liquid is a poor index for judging mist flammability. Spray/mists of chlorinated liquid compounds, however, can be self-quenching.

Quite often the clouds that gave rise to reported vapor cloud explosions were generated by rapid release of combustible liquids from pressurized process equipment. However, such a process may, in addition to producing genuine vapor, also generate sprays of fine liquid droplets that may have played a significant part in the explosion development. The Flixborough disaster in UK in 1974 may be one example (see Section 2.3.4). An investigation conducted by ICI and presented by Kletz (Anonym, 1975) suggested that of all the cyclo-hexane that exploded only one-eighth appeared as true vapor, whereas most of the rest formed a liquid spray. It was pointed out that the spray should be regarded as being just as dangerous (explosive) as the genuine premixed vapor.

#### 3.5.2 Oil Mist Explosion in a Compressor Test Loop

This explosion, discussed by Schmitt (1973), occurred in 1959 in a compressor test facility at Ingersoll-Rand Co.’s plant in Phillipsburg, N.J., USA. The test of a centrifugal compressor was being conducted in accordance with standard procedure, which involved the use of a closed loop for containment and re-circulation of the gas used during the test. The test was nearly completed when, after approximately six hours of test opera-

tion, an explosion occurred. The inlet side of the loop pipe ruptured with great violence, claiming the lives of six men, severely injuring six others, and imposing minor injuries on twenty-four additional men.

The explosion was described as a heavy flash fire accompanied by shock waves. Small localized fires and smoke followed. The floor plates of the platform immediately over the test loop were ripped loose. Heavy brick walls in the immediate vicinity were blown out. The roof of the building immediately over the blast was damaged and moved approximately 30 cm. The lightweight side walls of the building were torn off. Many windows were broken, some of these being located as far as 150 m away from the explosion center. The test loop, the seal oil system, and most of the equipment on the lower level were destroyed or damaged beyond repair. The coupling spacer between the gear and the compressor was shattered, and the coupling end of the gear pinion was twisted off and thrown away to outside the building.

The centrifugal compressor involved was the high-pressure unit of a system employed for compressing natural gas in oil field re-pressuring service. Floating-ring-type oil seals were used to contain the gas within the test loop where the shaft passed through the casing. This design combined the seal with the radial bearings. The sealing medium was oil supplied at a pressure of 3–3.5 bar above the gas pressure in the loop. A small quantity of oil was permitted to pass through the seal for lubrication.

The investigating committee concluded that regardless of the details of the design of this type seal, extremely small leakages of oil into the gas stream are unavoidable. As a result of the high air velocities, which tend to atomize and mix the oil droplets with the gas flow in such a manner that they cannot be effectively drained, the concentration of oil spray in the air tends to increase with time. The definite evidence of a combustion-type explosion confirmed that there must have been enough hydrocarbon oil present within the loop system to produce an explosive oil/air mixture throughout the loop system. Oil had been found to be present when blowing out low points in the piping between test runs. The destructive pressures were produced by heat liberated by the combustion of fine oil spray being circulated by the compressor. The pressure produced by an explosion is approximately proportional to the initial absolute pressure of the explosive mixture. For mixtures of common hydrocarbon compounds in air, the ratio of explosion pressure to initial pressure can be as high as eight.

### 3.5.3 Spray/Mist Explosions in Crank Cases in Large Diesel Engines

Crank case explosions, their origin and nature, and means of prevention and mitigation were discussed in detail by Minkhorst (1957) in a comprehensive literature survey. Engines fitted with cranks are normally equipped with a lubrication system by which oil is supplied to the bearings by pressurization. In order to protect the environment from oil spray and to prevent loss of oil, the crank system is usually fully enclosed by a case. Explosive spray clouds may be generated within the case by oil being flung into the air from rotating parts. In addition, mists of finer droplets may be generated by evaporation of oil in the hotter parts of the crank case and subsequent circulation to and condensation in the colder parts. If ignition occurs, the ignition source would normally be a hot surface, generated e.g. by a faulty bearing or a cylinder liner where the clearance between piston and liner is too narrow. In the early stages, before the mist concentration has reached explosive levels, the hot surface may act as a mist generator by enhancing evaporation of oil that is subsequently condensed to mist in the colder parts of the system. If the temperature of the hot surface is very high, the oil may be subject to chemical cracking, and highly explosive vapors may also be formed.

A severe crank case explosion, discussed by Minkhorst (1957), occurred in September 1947 in all the four engines of the ship *Reina del Pacifico*. The first warning of a potential hazard was given by some maintenance people who had noticed that a cylinder liner of one of the engines was overheated. Somewhat later a strong explosion occurred in the same engine, which subsequently propagated into the other three engines of the ship. Four distinct explosions were heard at very short intervals. The engines blew up, and twenty-eight men were killed and twenty-three were injured. Minkhorst also discussed a number of experimental investigations related to initiation and propagation of crank case explosions, and to various possible means of preventing and mitigating such explosions.

According to Nordahl (1991), crank case explosions in ship engines have also occurred more recently. In fact, the frequency of such explosions seems to have increased rather than decreased since the time when Minkhorst conducted his investigation. The chain of events leading to the explosions seems to be the same as in the past, the ignition source being

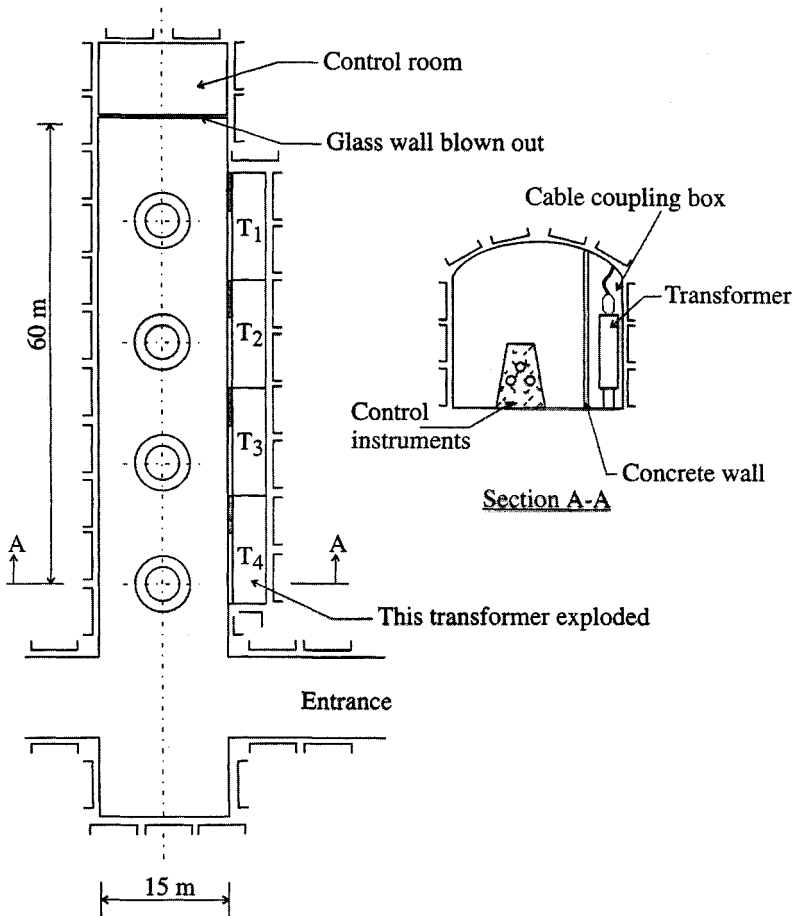
unintentionally heated surfaces. Large 12-cylinder ship engines of up to 60,000 Hp have crank cases of 18–20 m length and 150 m<sup>3</sup> volume. It seems that crank case explosions occur more frequently with 4-stroke engines than with 2-stroke ones.

#### 3.5.4 Major Oil Spray/Mist Explosion in a Transformer Room of a Hydroelectric Power Station

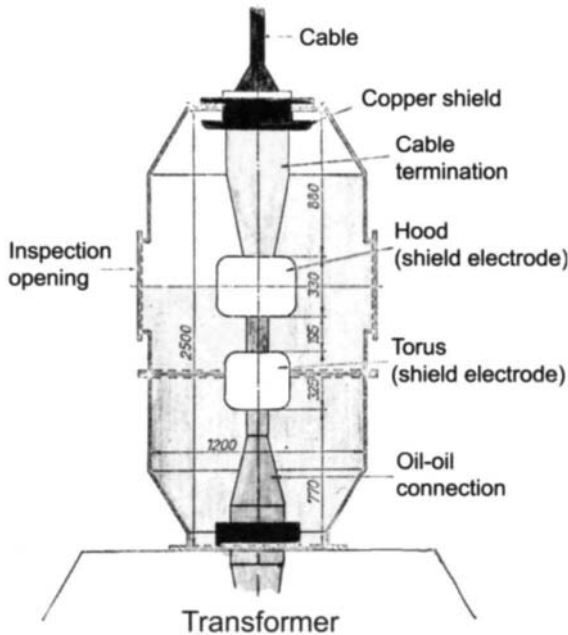
This accident, in which three men were killed and several others injured, was described by Johnsen and Holte (1973). Further details were given by Schjelderup (1990). The accident occurred in 1973 in the hydroelectric power station at Tonstad, Sirdal in Norway. The entire station is located underground. Figure 3–10 gives a top view of the entire underground installation.

Figure 3–11 gives a cross-section of the oil-filled cable junction box, and Figure 3–12 a cross-section of the main underground hall with the control rooms and a transformer with junction box on top in a separate room.

The origin of the event was a flash-over inside a 2 m<sup>3</sup> oil-filled cable junction box of one of the transformers (see Figure 3–11). The probable reason for the flash-over was the presence of significant dissolved quantities of a sulphur-containing cement in the oil, which, in combination with moisture, reduced the flash-over resistance of the oil and gave rise to electrical breakdown. The substantial thermal power of the flash-over arc caused a sudden and substantial rise of the internal pressure in the junction box. This caused the box to rupture and the oil to be expelled as a fine spray throughout the un-vented concrete cell of volume 800 m<sup>3</sup>, in which the high-voltage transformers were located. The quantity of oil in the 2 m<sup>3</sup> junction box was more than sufficient to supply the entire 800 m<sup>3</sup> volume of the transformer cell with an oil mist cloud of the most explosive concentration. The mist cloud exploded immediately (see Figure 3–13 and Figure 3–14), ignited by the arc in the junction box, and the wall of the transformer cell was blown out. A strong blast wave swept through the large engine hall and blew in the windows of the central control room. Dense smoke penetrated the entire system including the road tunnels to the open, rendering the rescue operation very difficult.



**Figure 3-10** Top view, with side view of one section, of the underground hydroelectric power plant at Tonstad, Sirdal, Norway, with vertical section through the main hall, the control instruments above the dynamos, and the transformer in a separate room on the side of the main hall. From Schjelderup (1990).

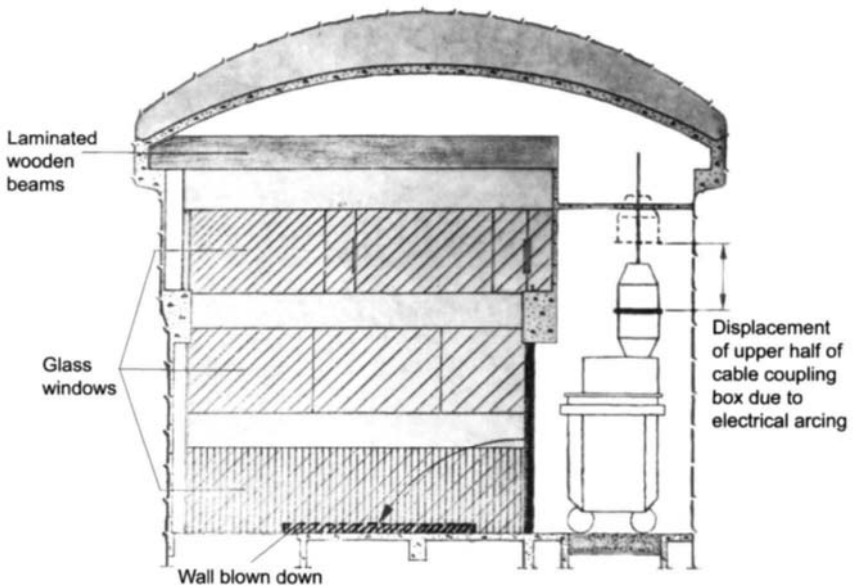


**Figure 3-11** Cross-section of the oil-filled cable junction box that exploded in the underground hydroelectric power plant at Tonstad, Sirdal, Norway.

## 3.6 Means of Preventing and Mitigating Spray/Mist Explosions in the Process Industries

### 3.6.1 Preventing and Limiting Size of Explosive Clouds

Although the physics, not least the fluid dynamics, of mists and sprays differs appreciably from the physics of homogeneous gases, it is customary to apply the principles developed for gases even to mists/sprays. These are described in Section 2.4.2. This may be a reasonable approach in the case of liquids of low boiling points, in the case of which the droplets will evaporate quickly once released into the open air. But, in the case of liquids of high boiling points, the approach of adopting the gas principles may not always seem reasonable. However, published specific guidance for sprays/mists does not seem to exist.

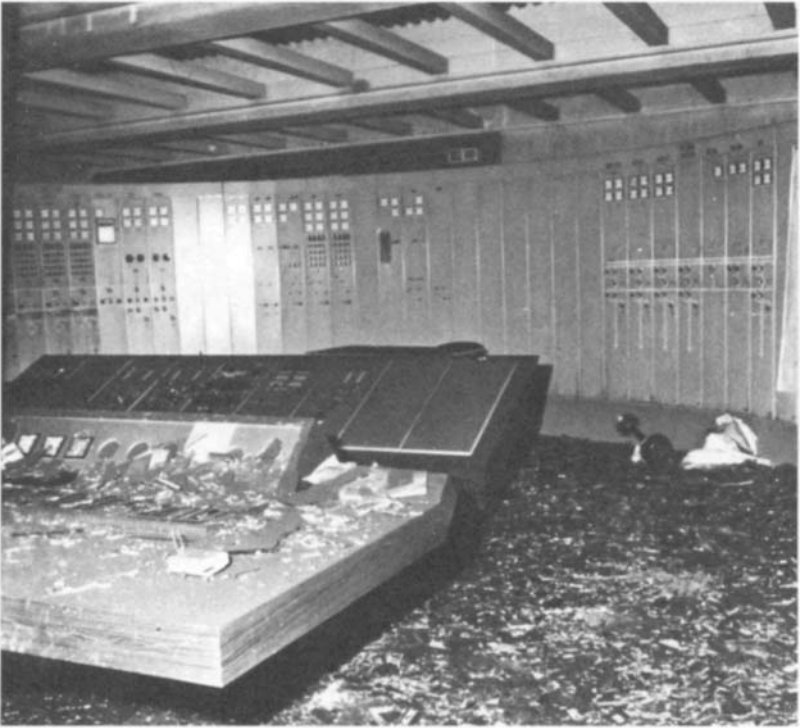


**Figure 3-12** Cross-section of the main hall of the underground hydroelectric power plant at Tonstad, Sirdal, Norway, with the separate transformer concrete cell to the right.



**Figure 3-13** Photo of debris after the oil spray/mist explosion in the main hall of the underground hydroelectric power station at Tonstad, Sirdal, Norway, illustrated in Figure 3-10. The conical cabinets of the control instruments are seen clearly.





**Figure 3-14** Photo of debris and damage in the control room after the oil spray/mist explosion in the underground hydroelectric power station at Tonstad, Sirdal, Norway.

### 3.6.2 Preventing and Controlling Ignition Sources

The same overall comment as in Section 3.6.1 applies. Guidance for explosive gases is given in Section 2.4.3 and Section 2.4.4.

### 3.6.3 Mitigatory Measures

The same overall comment as in Section 3.6.1 applies. Guidance for explosive gases is given in Section 2.4.5.