Origin and development of the Godbert-Greenwald furnace for measuring minimum ignition temperatures of dust clouds

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Key-words: *Dust clouds, dust explosions, hot surfaces, minimum ignition temperature, MIT, laboratory-scale test method, Godbert-Greenwald furnace, development history*

Abstract

Hot surfaces that can ignite explosible dust clouds can occur in various process situations in industry, e.g. inside furnaces, burners and dryers of various kinds. Hot surfaces can also be generated accidentally e.g. by frictional overheating of bearings and other mechanical parts, and electrically. To avoid accidental ignition of dust clouds by hot surfaces, it is essential to know the minimum temperature of any hot surface, at which a given explosible dust cloud that makes contact with that surface, will ignite. Currently the Godbert-Greenwald (G-G) furnace is the most commonly used apparatus for experimental laboratory-scale assessment of this minimum temperature for various dusts.

The G-G furnace was developed by Godbert and Greenwald in 1935. Two pioneering “forerunners” of this apparatus were described by M. J. Taffanel and A. Durr (1911) in France, and by R.V. Wheeler (1913) in UK. However, neither the two “forerunners” nor the G-G furnace itself were originally intended for assessing maximum permissible temperatures of hot surfaces in industrial plant for preventing accidental hot-surface ignition of dust clouds there. This new use of the G-G furnace was not introduced in UK and the USA until in the 1940ies.

The G-G furnace still appears to be the most widely used apparatus for assessing minimum hot-surface temperatures (MITs) for ignition of explosible dust clouds in air in industrial plant. However, not least in view of the history of the furnace, it is clear that the MITs that it produces do not apply to all possible hot-surface ignition scenarios that can be foreseen in industry. In most countries this problem is overcome by introducing a rather generous safety margin between the measured MIT for a given dust and the maximum permissible hot-surface temperature in industrial plants that produce and/or handle this dust.

1 Introduction

Experimental applied science makes use of a huge variety of different measurement methods within a very wide range of scientific fields, from medicine to metallurgy. Behind each measurement method there is a specific, unique history. How and when did the method come about in the first place? Why was it designed just like it was?

Industrial process safety is one of the numerous fields where a number of measurement methods are used. Prevention and mitigation of dust explosions is one of a wide range of subfields within process safety that utilizes a number of experimental measurement methods for assessing important safety-related parameters. One of these parameters is the minimum hot-surface ignition temperature of explosible dust clouds (MIT).

In the process industries hot surfaces capable of igniting dust clouds can exist in a wide spectrum of situations and locations. Examples include inside furnaces, burners, and dryers of various kinds, where the hot surface constitutes part of the process equipment itself. Hot surfaces can also be generated elsewhere in the plant by electrical heating and hot work, and by frictional overheating of bearings and other mechanical parts.

In areas in industry where explosible clouds in air of a given combustible dust can occur, it is clearly important to know the minimum temperatures of any hot surface in those areas, at which such clouds, when touching the surface, will ignite. As soon as an adequate estimate of this minimum temperature is known, precautions can be taken to ensure that temperatures of the hot surfaces of concern do not rise to this value.

The point of departure of the following historical account is a section of a more extensive review paper by Eckhoff (2019). The same paper also describes other apparatuses than the G-G furnace for MIT assessment for dust clouds, and compares results for given dusts provided by the different apparatuses. The same paper also briefly reviews some theoretical work on hot-surface ignition of dust clouds, and indicates possible future developments.

2 The “roots” of the Godbert-Greenwald furnace

Currently the Godbert-Greenwald (G-G) furnace is the most widely used apparatus worldwide for determining MITs of explosible dust clouds. The development history of the furnace started more than 100 years ago, and apparently the initiating event was a terrible coal dust explosion catastrophe in a coal mine in Courrieres Colliery near the Pas-de-Calais Mountains in France on March 10, 1906. Nearly 1100 miners lost their lives.

This catastrophe led to a very extensive research programme in France, in which the French researcher M. J. Taffanel played a central role. According to Brown and James (1962) Taffanel and his co-worker Durr (1911) were probably the first researchers to use a vertical tubular furnace for obtaining relative measures of minimum ignition temperatures of explosible dust clouds. The present writer was unable to obtain a copy of the original Taffanel/Durr report, but a drawing of their apparatus, reproduced in Fig. 1, had been included in a report by Frazer et al. (1913).

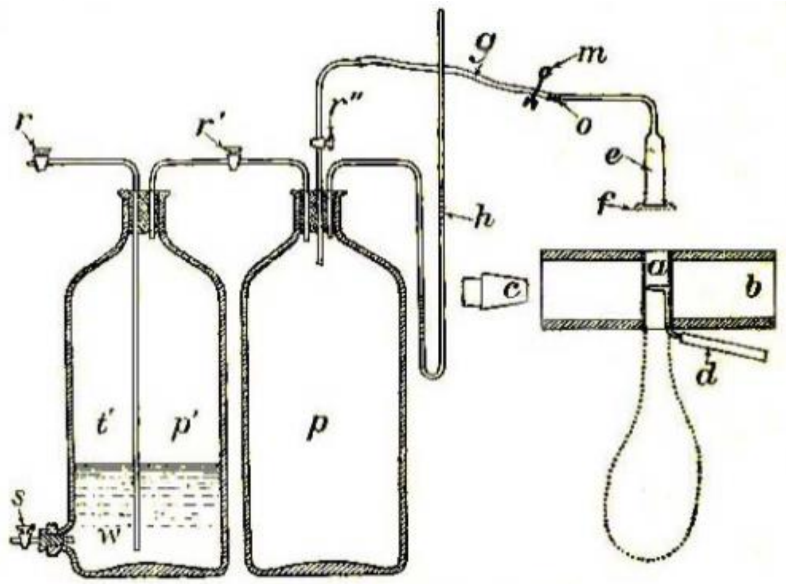

Figure 1. Drawing of the Taffanel and Durr (1911) apparatus for measuring the minimum ignition ignition temperatures of coal dust clouds in air. From Frazer at al. (1913)

Explanations of some of the letters in Fig. 1 were given by Frazer at al. (1913). With regard to the furnace itself (to the right in the figure) they stated as follows:
"A vertical porcelain tube (a) is heated from the outside to the desired temperature, as indicated by the thermocouple (d). The dust under investigation is placed at (o) and is ejected by the compressed air contained in the 1-litre bottle (p). Just previous to the injection of the dust by the current of air, the tube *(e) is pressed down tightly on (a), (f) making a tight joint between the two. During the passage of the dust laden air through (a), ignition occurs if (a) is sufficiently hot. In addition to determining the temperature of ignition, the investigator should study the size of the flame that issues from the lower end of (a). This study is facilitated by photographing the flames* (flame size indicated by the dotted pocket below the furnace exit). *The results recorded permit the classification of the dusts with reference to their inflammability. The dusts studied by Taffanel and Durr were classified into eight groups, designated A to H in the order of increasing inflammability."*

In a historical perspective it is interesting to observe that most of Fig. 1 is an illustration of how a controlled, reproducible air blast for dispersing the dust into the furnace was obtained from simple basic principles. At the first glance this method may appear "old fashioned" and outdated. However, the method is an excellent illustration of the practical use of e.g. the equation of state of ideal gases. At times one may feel that today this kind of basic, practical perception is sometimes under-communicated to young students.

A step-by-step explanation of the air blast generation in Fig. 1 may be as follows: As indicated above the purpose was to generate a suitable and reproducible blast of air for blowing the powder/dust sample (o) contained inside the rubber tube (g) as a dust cloud into the hot vertical-furnace core (a). The first step in obtaining this reproducible air blast was to feed water (w) into the glass bottle to the far left in Fig. 1 through the opened valve (s). With the valves (r) and (r') closed, this compressed the volume of the air trapped in that bottle and hence raise the air pressure and temperature there to (p') and (t') respectively. The desired pressure (p) of the air in the second glass bottle, used for dust dispersion, was obtained by opening valve (r') and admitting compressed air from the first bottle to the second one until the pressure there, as read by the manometer (h), had reached the desired value. The valve (r") was then opened, and the desired, reproducible air flow for dispersing the dust into the hot furnace core was finally obtained by releasing the clip (m) on the rubber hose (g).

In a review paper of laboratory methods for determining the flammability of coal dusts Godbert (1927) presented a detailed construction drawing of the Taffanel/Durr furnace, as shown in Fig. 2.

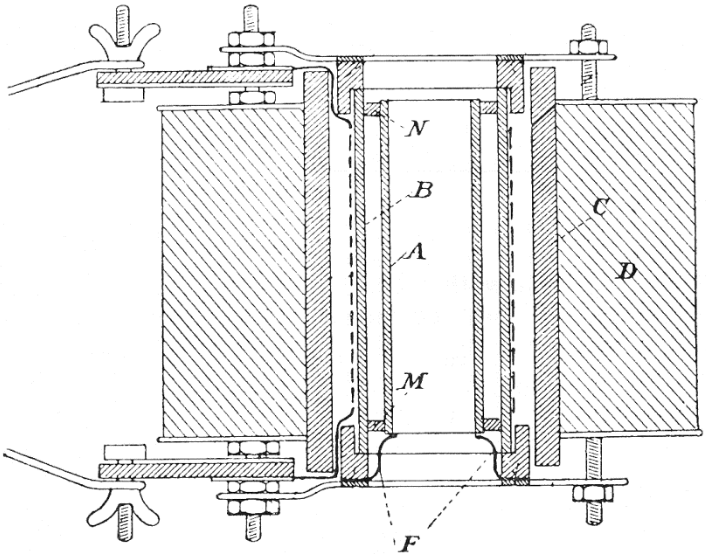

Figure 2. Cross section of the Taffanel/Durr furnace as presented by Godbert (1927)

Godbert described the various parts of the furnace, as shown in the figure, as follows:
The apparatus consisted of a porcelain tube A supported on metal arches F, within a furnace tube B, 11 cm in length and 4.1 cm in width. The furnace was heated electrically (indicated by the dotted lines on the outside of tube B). *An outer cylinder C of silica, and asbestos lagging D, minimized heat losses, and two asbestos rings M and N, prevented the passage of cooling air currents through the annular space between the tubes A and B. A cloud of dust was blown through the heated inner tube by means of compressed air, and the volume of the flame produced at the mouth of the tube was measured photographically.*

Brown and James (1962) provided the main dimension of the inner tube A as follows: "*The furnace consisted of a porcelain tube 10 cm long and 2 cm in diameter, heated electrically* (via the outer electrically heated tube B), *through which dust could be blown downwards by air. The criterion of ignition was the appearance of flame at the bottom of the tube, and the volume of the flame (obtained photographically) was taken as a measure of inflammability. …….. This apparatus is important as the forerunner of many subsequent forms of laboratory furnaces or hot-tube apparatus."*

In his recent review paper Eckhoff (2019) assumed that French researchers Taffanel and Durr were the genuine inventors of the type of dust dispersion system illustrated in Fig 1. More recently, however, it came to light that the air blast generation set-up in Fig. 1 is practically identical with that illustrated in an earlier paper by the German researchers Holtzwart and von Meyer (1891). It is not unreasonable to assume, therefore, that Taffanel and Durr somehow knew of the work by Holtzwart and von Meyer when they carried out their own research about 20 years later.

The vertical-furnace apparatus developed by the English researcher Wheeler (1913) has sometimes been regarded as the main "root" of the modern G-G furnace. However, because of the very similar lengths and diameters of the French and English furnaces, it may seem as if the work of Taffanel and Durr (1911) was somehow known to Wheeler.

The following introductory note in Wheeler's (1913) report provides the background of his work:
"In consequence of the two serious dust explosions, which occurred in November, 1911, at a provender mill in Glasgow and an oil cake factory in Liverpool, a series of experiments has been carried out at the Home Office Experimental Station at Eskmeals by Dr. Wheeler, the chemist attached to the Explosions in Coal Mines Committee, with samples of all kinds of carbonaceous dust, so far as known to the Inspectors, which are liable to be generated on premises under the Factory and Workshop Acts, with a view to determine their degree of inflammability and capacity to transmit explosions ……. Experiments were made with 66 samples in all. The samples were not specially selected, but were in all cases ordinary samples taken by Factory Inspectors from beams, ledges or other projections in the course of their inspections. The Report deserves the careful consideration of all occupiers of factories and workshops in which carbonaceous dusts are generated."

Wheeler defined 3 different "inflammability" classes of dusts (= dust clouds in air) as follows:

Class I*: Dusts which ignite and propagate flame readily, the source of heat required for ignition being comparatively small; such, for example, as a lighted match.*

Class II*: Dusts which are readily ignited, but for which the propagation of flame require a source of heat of large size and high temperature (such as an electric arc), or of long duration (such as the flame of a Bunsen burner).*

Class III*: Dusts which do not appear to be capable of propagating flame under any conditions likely to obtain in a factory; either (a) because they do not readily form a cloud in air,* *or (b) because they are contaminated with a large quantity of incombustible matter, or (c) because the material of which they are composed does not burn rapidly enough.*

Wheeler (1913) described two different test methods that he used for determining the class to which a given dust should be assigned. The method of concern in the present context is Wheeler's *"Test no. 2. Determination of the lowest temperatures at which ignition can be effected"*. The apparatus is illustrated in Fig. 3.

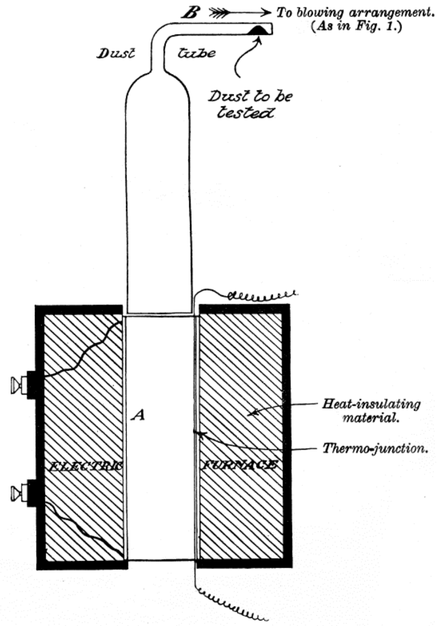

Figure 3. Wheeler's "second method", used for assessing "the lowest temperatures at which ignition can be effected" with dust clouds igniting in Wheeler's first method. From Wheeler (1913)

It is clear from the Wheeler (1913) report that his intention with *Test No. 2* was *not* to estimate minimum hot-surface temperatures at which dust clouds would be expected to ignite in contact with hot surfaces in industry, i.e. to estimate MITs in the current meaning of the term. He described his *Test No. 2* as follows:

"The igniting surface in this test is a loosely rolled spiral of copper gauze contained in a porcelain tube (A), of 25 mm internal diameter and 10 cm long. This tube is placed vertically as shown in Fig. 2. The sieved and dried dust is introduced into the horizontal dust-tube (B), its weight being 0.2 grams. The wide portion of this dust-tube is then placed vertically over the porcelain tube which is heated by a small electric furnace. A tap which connects with the apparatus for giving a constant puff of air, previously described (Fig. 2) is now quickly opened. All the dust in the dust-tube is thus projected downwards through the furnace. If the temperature is high enough it ignites there and a flame appears underneath.

Before making the series of determinations with the different dusts, a series of experiments was made using dust of the same composition and varying the time of passage of the cloud through the tube. This was done by varying the time of fall of the piston in the apparatus for giving a constant puff of air. It was found, as anticipated, that, up to a certain point, the slower the rate of passage of the dust-cloud through the porcelain tube the lower need the temperature of the latter be to cause ignition."

It is interesting to note that Wheeler considered the *"loosely rolled spiral of copper gauze"*, inserted into the heated porcelain tube as the real ignition source, rather than the internal surface of the porcelain tube.

After having conducted careful experiments with all the 66 carbonaceous dusts in both apparatuses, he arrived at the following conclusion:

"*With a few exceptions the dusts could be grouped in the defined inflammability classes on the principle that Class II contained those dusts which were incapable of propagating a flame when exposed to Test No. 1 (small ignition source of short duration), but which inflamed readily in Test No. 2. The Class I dusts included all the dusts that propagated flame readily even in Test No. 1."*

It is worth mentioning that also Price and Brown (1922), Beyersdorfer (1925), and Brown (1951) described Wheeler's second test method in detail, with reference to Fig. 3. Portraits of the two pioneers M.J. Taffanel and R.V. Wheeler are shown in Fig. 4.

Figure 4. Portraits of the French researcher M.J. Taffanel (1875-1946) and the English researcher R.V. Wheeler (1883-1939). From Cybulski (1975)

As already pointed out, Wheeler *did not* develop his furnace apparatus (*Test No. 2)* for determining MITs of dust clouds in the present meaning of this term. Wheeler did measure the minimum furnace temperatures at which the various dusts ignited, but he did not relate these measurements to the issue of predicting the minimum hot-surface temperatures at which the dusts would ignite in contact with various kinds of hot surfaces in industry. His objective was to assign the various dusts to one of the three flammability classes that he had defined.

16 years after the Wheeler (1913) report, Godbert and Wheeler (1929) adapted Wheeler's *"dust flammability"* concept to the more restricted, but indeed very important, area of preventing coal dust explosions in coal mines. More specifically, the idea was to develop a laboratory-scale method by which one could determine *"the amount of inert dust required in a mixture with coal dust to suppress the ignition of the dust"*. For that purpose they developed and used modified versions of both of the two Wheeler (1913) tests.

In both modified test methods the dust was blown into the furnace by a blast of *oxygen*, rather than *air*. In the case of *test No. 2* the temperature of the interior of the furnace was kept constant at 700 ^{o}C in all tests. Godbert and Wheeler (1929) did not mention any *"loosely rolled spiral of copper gauze"* inserted into the heated porcelain tube, as pointed out in the Wheeler (1913) report. It may appear therefore, that there was no copper gauze spiral in the 1929 version of the furnace. A photograph of the 1929 furnace is shown in Figure 5. From the 1929 report it appears that the length of the heated tube was 11 cm and its internal diameter 2 cm, as opposed to the 10 cm and 2,5 cm of the Wheeler (1913) furnace. So perhaps a new, slightly different furnace was built for the purpose of the 1929 investigation.

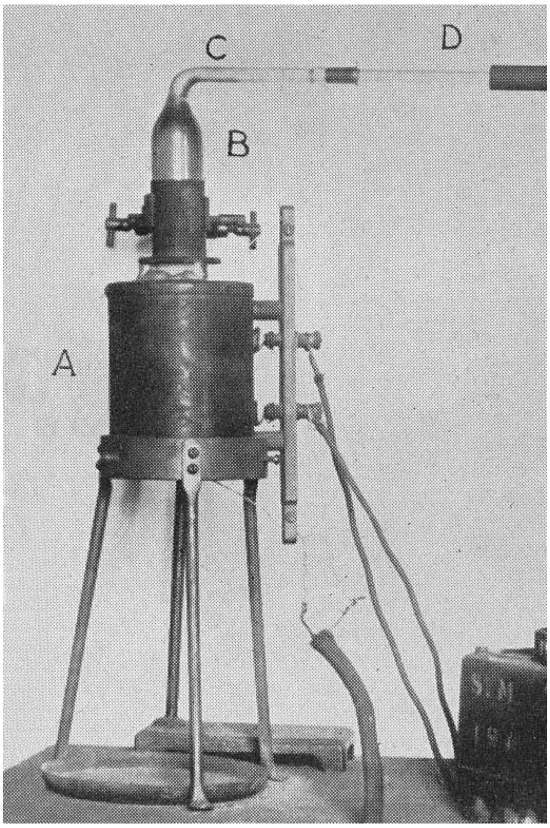

Figure 5. Original photograph of the Wheeler "Test No. 2 apparatus".
From Godbert and Wheeler (1929)

3 Development of the Godbert-Greenwald (G-G) furnace

3.1 Background

The very first description of the G-G furnace, having a prolonged heating section of about 20 cm, is that by Godbert and Greenwald (1935). Their report was the end result of a quite long story starting more than one decade earlier.

The materialization the Godbert/Greenwald cooperation was probably a direct consequence of the work done by Godbert and Wheeler (1929). The ultimate objective of Godbert and Greenwald was to develop a laboratory-scale test method that, in a better way than Godbert and Wheeler's 1929 method, could predict whether or not a given coal dust, or a mixture of a coal dust and inert dust, could give dust explosions in large scale mine galleries.

In his historical review the American pioneer in the field, George S. Rice (1925) described how this special cooperation between Great Britain and USA actually came about:

"*Following informal conferences in the summer of 1923 at the Eskmeals Station* (on the North-Western coast of England)*, with Dr. R.V. Wheeler, in charge of the research work under the Safety in Mines Research Board* (in Great Britain), ------*, a proposal was made by the Secretary for Mines* (in Great Britain) *to the Director of the Bureau of Mines* (in USA), *through the Secretaries of State and Interior, for a cooperation on research relating to safety in mining."*

It is clear that this original formulation of the objective of the cooperation was rather wide and general. The agreement was formally put into force in 1924.

Quite a few years should pass before the agreement materialized in the specific cooperation between Godbert and Greenwald that resulted in the G-G- furnace. US Bureau of Mines

(USBM) had themselves already been working for some time to develop a laboratory-scale method that could predict whether or not a given dust cloud could propagate a dust flame in large-scale coal mine galleries. As "benchmarks" they could use unique data from tests conducted in their own full-scale experimental mine gallery. However, up to 1931 the efforts in the USA to develop a suitable laboratory-scale prediction method had not given satisfactory results. Apparently, therefore, the Americans were interested in learning from the work conducted by Godbert and Wheeler (1929), whose laboratory-scale data had correlated fairly well with data from intermediate-scale-gallery coal dust explosion experiments conducted at Buxton in UK.

In his foreword to the Godbert and Greenwald (1935) report, George S. Rise emphasized that the unique large-scale mine gallery experiments conducted by USBM were of particular significance in the cooperation across the Atlantic Ocean. These experiments had produced invaluable data for the fractions of inert dust that had to be mixed with coal dusts of various categories, to suppress flame propagation on the scale of a real coal mine gallery. The results from these investigations therefore constituted a unique basis for seeking a correlation between large-scale and data from a possible new laboratory-scale test method.

3.2 Godbert-Greenwald cooperation finally realized

It was eventually agreed that Godbert, who worked at the Safety in Mines Research Board (SMRB) in Great Britain under the supervision of professor Wheeler, was to visit US Bureau of Mines (USBM) for the two years 1931-32 to work together with the American researcher Greenwald to investigate whether the "*second*" Wheeler apparatus (Figs. 3 and 5), with some modifications, could be made to meet even the American needs. Clearly, Godbert, when joining Greenwald in USA, brought with him the extensive experience he had gained from working with Wheeler on the problem at hand.

In their report Godbert and Greenwald (1935) described the laboratory-scale method that they finally arrived at, as follows:

"The furnace is mounted on a tripod. The heated central (vertical) *tube is cylindrical, of refractory material, and 1 1/4 inches* (32 mm) *in inside diameter and 8 inches* (203 mm) *long. Heat is supplied through a nichrome winding placed in a groove on the outside of the tube. The temperature gradient along the tube is reduced by concentrating the winding towards the ends." …."The furnace temperature is measured by a base-metal thermocouple, inserted in the bottom of the tube. The thermojunction is against the tube wall at its midpoint vertically and is kept in that position by a clamp attached to one of the tripod legs."*

It is interesting to note that the length of the vertical heated ceramic tube was now about 20 cm, not 10-11 cm as in the previous two Wheeler/Godbert furnaces. Furthermore, no mention was made of the "*loosely rolled spiral of copper gauze"* inserted into the heated porcelain tube in Wheeler's (1913) original *test no. 2*. As already mentioned, it appears that this insert was removed even by Godbert and Wheeler (1929).

In their report Godbert and Greenwald (1935) concluded that the best agreement between the large-scale mine gallery data and the data from their modified laboratory-scale test method was obtained when all the laboratory-scale tests were conducted with a constant hot-surface temperature in the furnace of 720 ^{o}C.

As would be expected, the correlation finally obtained between large and small scale tests was not perfect. Therefore, the ultimate question asked, was if it was good enough. At the end of their report Godbert and Greenwald (1935) arrived at the following conclusion:

"*The results of the tests made in the laboratory apparatus and in the experimental coal mine agree as well as can be expected until experimental mine tests agree better among themselves*."

A lot can be learnt from this conclusion even today. Large scale experiments do not always provide an ultimate precise answer!

4 Adoption of G-G furnace for MIT determination of dust clouds at large

Today the G-G furnace is the most widely used apparatus for standardized experimental estimation of MITs of dust clouds, i.e. the minimum temperature of a hot surface in industry that will ignite a cloud in air of a given combustible dust that makes contact with that surface. When and where was the G-G furnace first adopted for this purpose?

4.1 UK

According to Brown (1951) the exact year of adopting the about 22 cm long G-G furnace for this purpose in UK, by both the Safety in Mines Research Board and the Fire Research Station), was 1949. In this new application of the furnace the automatically controlled temperature of the internal wall of the ceramic furnace core tube was varied systematically in steps of 10^{o}C and the experiment repeated until a minimum furnace temperature for ignition of clouds in air of the dust tested had been identified.

Tonkin and Raftery (1961), in their FRS report on ignitability and explosibility of dusts, refer to their version of the G-G furnace for MIT measurements as "*Wheeler's Test No.2 modified*". The most significant modification was probably the doubling of the length of the heated vertical section of the furnace from about 10 cm to about 20 cm, as performed by Godbert and Greenwald (1935). The method was also described by Raftery (1968). Palmer (1973) confirmed that the G-G furnace was in use in UK even before 1970 for measuring MITs of dust clouds. He provided a short description of the construction of the furnace and the MIT test procedure used in UK at that time.

4.2 USA

The earliest mention that has been traced of the use of the G-G furnace in the USA (USBM) for measuring MITs of dust clouds is in a report on inflammability and explosibility of metal powders by Hartmann *et al.* (1943). In a later USBM report describing various laboratory-scale methods for evaluating ignitability and explosibility of dust clouds at large, Dorsett *et al.* (1960) incorporated the MIT method as described by Hartmann et al. (1943).

5 Standardization of the G-G furnace in IEC, Europe and USA

5.1 The IEC test method

In 1970 the IEC (International Electrotechnical Commission) decided to establish a working group for development of a series of experimental laboratory-scale test methods for determining ignitability and explosibility data of dusts layers and dust clouds. The exact name of the group was IEC Technical Committee 31, Sub Committee 31H, Working Group 2. Its first meeting was held at Bundesanstalt für Materialprüfung (BAM) in Berlin, Germany, on February 28-March 2 in 1973. The 2nd meeting took place on September 12-14 of the same year at Fire Research Station (FRS), Borehamwood (London), UK. The outstanding secretary/chairman of the group was Ken N. Palmer from FRS.

Round about 1970 the present writer had just started the building-up of a dust ignitability/explosibility test laboratory at Chr. Michelsen Institute (CMI) in Bergen, Norway. It was therefore a most timely privilege and opportunity for him to be allowed to join the IEC working group as the Norwegian delegate at its 3rd meeting in 1974, at US Bureau of Mines (USBM) in Pittsburgh, PA, USA. This made it possible also for Norway to take part in all the subsequent "round robin" tests through the following years, of both the G-G furnace, and other test apparatuses/methods developed and standardized by this working group.

During the Pittsburgh meeting standardization of the G-G furnace for MIT measurements was a main topic. USBM offered to send each of the participating laboratories 3 tailor-made

Alundum core tubes (one for use and two spares) for the new G-G furnaces to be built by all the participating laboratories. The special spiral groove on the outer tube surface for guiding the electric-heating wire on the outer tube surface was an important feature of these tubes. The distance between windings at the tube ends were smaller than at the central parts of the tube, in accordance with the design of Godbert and Greenwald (1935).

At the same Pittsburgh meeting FRS, England, offered to send three of their silica core tubes to those of the participating laboratories wanting to consider this option, which included our laboratory in Norway. Even these tubes had the Godbert-Greenwald-type winding grooves on the outside.

After a couple of years a proposal for a new IEC standard method for experimental laboratory-scale determination of MITs of dust clouds could be submitted to IEC's Central Office in Geneva. The final IEC (1975) standard described both the test apparatus and the experimental procedure in considerable detail. Specifications of the way of generating the air blast for dispersing the dust were also included. Figure 6 illustrates a G-G furnace that is essentially in agreement with the first IEC standard. Figure 7 shows a photograph of a test with fine aluminium dust in the G-G furnace built and used in Norway.

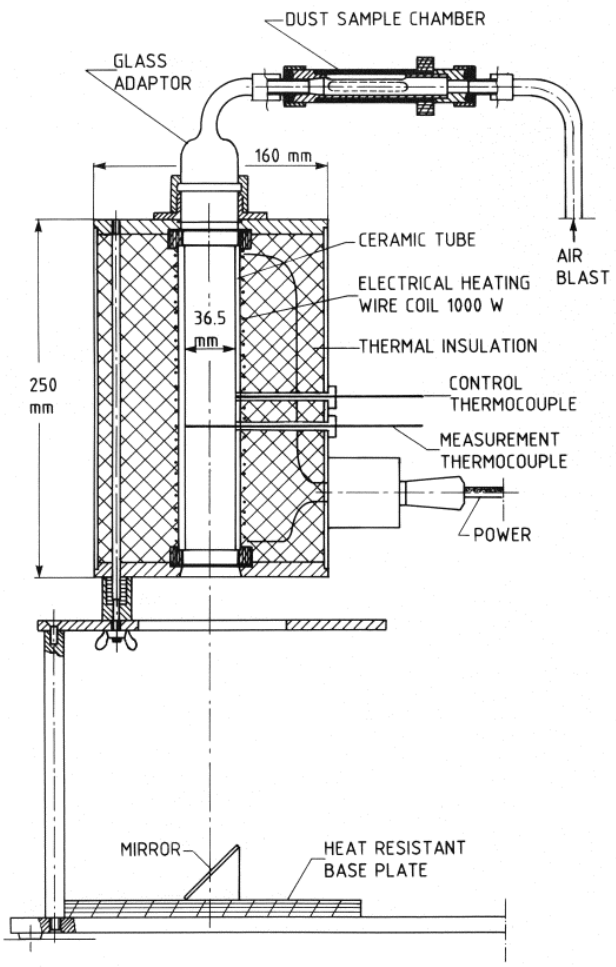

Figure 6. IEC version of Godbert-Greenwald (G-G) furnace for determination of MITs of dust clouds. From Eckhoff (2016)

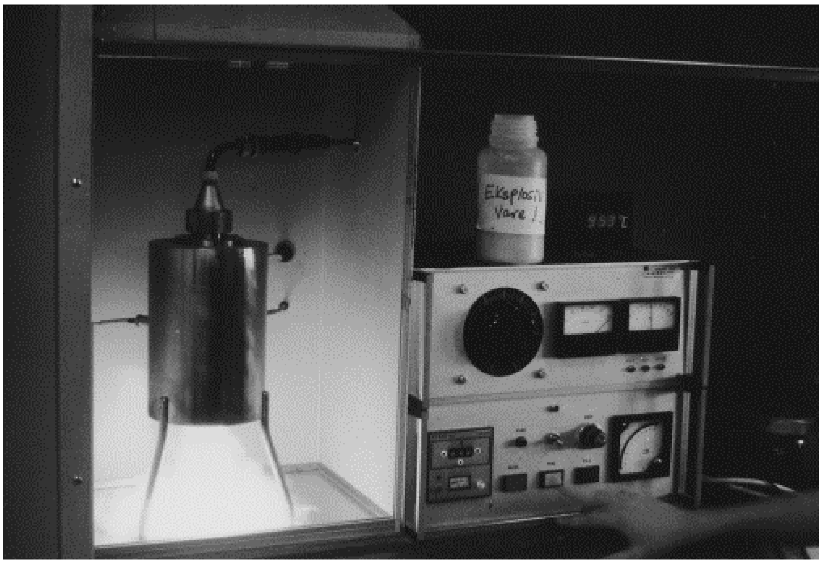

Figure 7. Ignition of an aluminium dust/air cloud in the Godbert-Greenwald (G-G) furnace. From Eckhoff (2003)

5.2 Current situation in some countries

USA

The standard issued by ASTM (2015) in USA for measuring MITs (or minimum auto-ignition temperatures, MAITs) of dust clouds in air describes 4 different recommended test apparatus-es, viz. the G-G furnace, the German BAM furnace, the USBM 1.2 litre furnace, and the USBM 6.8 litre furnace. As discussed by Eckhoff (2019) the MITs obtained with the various apparatuses for a given dust vary somewhat.

Germany and the BAM furnace

It is interesting to note that Bundesanstalt für Materialprüfung in Berlin (BAM), where the BAM furnace was originally developed, is no longer using this apparatus for MIT measure-ments of dust clouds. Apparently they are presently using the G-G furnace only.

European Union countries at large and EU-associated countries

Apparently most EU and EU-associated countries have adopted the G-G furnace test method as their main method for determining MITs of dust clouds. In the EU context the G-G furnace method is described in a rather short section of the multi-method standard ISO/IEC (2016). Very few details on apparatus and procedures are specified in the standard.

In view of the history of the G-G furnace it is clear that MITs produced by this apparatus are not generally applicable to all possible hot-surface ignition scenarios that can be foreseen in industry. In regulations and standards in current use the simple and pragmatic answer to this challenge is as follows: Maximum temperatures of any hot surface in industry, with which an explosible dust cloud may make contact, shall not exceed 2/3 of the MIT in ^{o}C of that dust cloud, as measured by one of the current standard test methods.

6 Tyler's theory of ignition of explosible dust clouds in hot-surface furnaces

6.1 Background

In industry it may sometimes be difficult to comply with the quite large safety factor of 1/3 of the measured MIT in ^{o}C of the dust clouds of concern. Most probably for this reason Tyler

(1987) addressed the problem of scaling of MITs obtained by the G-G furnace apparatus to industrial scale.

6.2 Basis of the Tyler theory

Tyler pointed out that there is no single physical/chemical process, irrespective of dust type, that determines whether a given dust cloud (in air) will ignite. For example, with dusts of sulphur and polyethylene, the minimum ignition temperatures are sufficiently high to allow complete evaporation or pyrolysis of the dust particles to form gaseous fuels, before ignition gets under way. At the other extreme, particles of metals of high boiling points will not vaporize fully before ignition takes place.

A basic assumption in the Tyler theory is that the ignition process is of the Semenov-type. This means that the temperature across the dust cloud in the furnace is uniform, whereas the main temperature drop from the dust cloud to the furnace wall occurs at the boundary between the cloud and the wall (Biot number equal to zero). However, Tyler found it difficult to validate his model, but useful parametric studies could be performed. For example, the model predicted a significant decrease of the minimum ignition temperature with increasing furnace diameter. The modern G-G furnace has a diameter of 37 mm. For a much larger furnace diameter of 300 mm, and a dust with a G-G furnace MIT of about 700 °C, the MIT predicted by the model was at least 150 °C lower than the G-G value.

Eckhoff (2019) described two more recent USBM laboratory-scale furnaces of larger internal diameters than the G-G furnace. Tyler's theoretical prediction agrees qualitatively with the decrease of experimental AITs when moving from the G-G furnace to the USBM 1.2 litre furnace (furnace diameter ca. 100 mm). However, the further increase of the furnace volume to 6.8 litre (furnace diameter ca. 200 mm) gave a less pronounced reduction of the AITs/MITs of the dust clouds tested. One reason for this could be as follows: If the dust is blown into the furnace by means of a blast of air at ambient temperature, the temperature distribution in the dust cloud across the furnace diameter at the moment of ignition may deviate significantly from uniformity, i.e. the Semenov assumption of zero Biot number does not apply.

6.3 Tyler's suggestions for further work

Tyler concluded that he had not been able develop a mathematical model by which data from G-G furnace tests could be transformed to minimum ignition temperatures in more complex practical situations in industry. He suggested that perhaps stirred reactor ignition experiments, as performed successfully for combustible gas mixtures, might provide a more fundamental understanding of dust cloud ignition processes. Such experiments could yield appropriate activation energies for the ignition processes, which may be used to scale minimum ignition temperatures more reliably.

7 Conclusions

1. Two, almost identical, forerunners of the modern Godbert-Greenwald (G-G) furnace were described by Taffanel and Durr (1911) and Wheeler (1913). Both furnaces had vertical electrically heated ceramic tubes of lengths about 10 cm and internal diameters of about 2 cm into which the dust was blown by means of a blast of air. However, neither furnace was developed for measuring MITs of dust clouds in the current meaning of this concept.
2. Godbert and Wheeler (1929) described an almost identical vertical furnace, also of length about 10 cm and internal diameter of about 2 cm, used for laboratory-scale prediction of whether or not given mixtures of coal dust and inert dust would be able to propagate dust flames in full-scale coal mines. In this new test the dust was blown into the furnace by means of a blast of *oxygen*, rather than by a blast of air.

3. The specific G-G furnace currently used for MIT measurements of dust clouds was first developed by Godbert and Greenwald (1935) as a result of a joint British/American research cooperation effort. However, their aim was not at all to develop a laboratory-scale method for MIT determination of dust clouds in air. Their goal was to develop an apparatus that could predict whether or not given mixtures of coal dust and inert (stone) dust would be able to propagate dust flames in full-scale coal mines.
4. The new use of the G-G furnace for measuring MITs of explosible dust clouds in air was introduced by UK in 1949 and by the USA about the same time. After several years of international cooperation IEC (1975) issued their first standard for assessing MITs of combustible dust clouds in air in industrial environments at large, using their new version of the G-G furnace.
5. All current standards known to the present writer recommend that the G-G furnace be the first option for experimental assessment of MITs of explosible dust clouds in air at large. However, the MITs resulting from this method produces are not generally applicable to all possible hot-surface ignition scenarios foreseen in industry. In most standards this problem is overcome by imposing a quite generous safety margin between the MIT determined by the G-G furnace for a given dust, and the maximum permissible temperature of hot surfaces occurring in industrial plants (see pt. 8 below).
6. It is not straightforward at all to develop a numerical model that can predict whether a given hot surface in industry can ignite an explosible cloud of a given dust. In addition it can be difficult to define the detailed worst-case scenario to which such a model should be applied.
7. Cost/benefit analyses may rule out mathematical modelling as a realistic short-term option in most cases. It seems unlikely therefore, that numerical modelling will be widely used in the near future for specifying maximum permissible surface temperatures in the dust industry.
8. For the foreseeable future, therefore, it seems sensible, as a main rule, to stick to the traditional requirement that maximum temperatures of hot surfaces in industrial plant that may make contact with explosible dust clouds, shall not exceed 2/3 of the MIT in ^{o}C, as measured by an accepted standard method.

Acknowledgements

As a professor emeritus at the Department of physics and technology at the University of Bergen, the author wishes to express his indebtedness to this Department for so generously allowing him to keep an office there and for providing him with the infrastructure that makes it possible for him to carry on with his writing.

The author also wishes to express his sincere thankfulness to his outstanding previous student at the University of Bergen, Trygve Skjold, who is now also his good friend and colleague at the same university, for having brought to his attention several of the older literature sources on which the present paper is based.

References

ASTM (2015a): American Society for Testing and Materials, Standard E 1491 for Testing of Minimum Auto-ignition Temperature of Dust Clouds. *Annual book of ASTM Standards,* Vol. 14.02, ASTM, Philadelphia, USA

Beyersdorfer, P. (1925): *Staub-Explosionen*, Dresden und Leipzig Verlag von Theodor Steinkopff

Brown, K.C. (1951): *A review of the present methods of testing industrial dusts for inflammability*, SEMRE Research Report No. 21, April 1951, Safety in Mines Research Establishment, UK

Brown, K.C. and James G.J. (1962): *Dust explosions in factories: A review of the literature*, Safety in Mines Research Establishment, Research Report No. 201, H.M. Factory Inspectorate, Ministry of Labour, June 1962

Cybulski, W. (1975): *Coal dust explosions and their suppression*, English translation of the original book in Polish (1973), published for the US Bureau of Mines, USA, by the Foreign Scientific Publications Department of the National Center for Scientific, Technical and Economic Information, USA.

Dorsett, H. G., Jacobson, M., Nagy, J., Williams, R.P. (1960): *Laboratory Equipment and Test Procedures for Evaluating Explosibility of Dusts.* Rep. Inv. 5424, US Bureau of Mines

Eckhoff, R.K. (2003): *Dust explosions in the process industries*, 3rd edition, 720 pages, Gulf Professional Publishing (an imprint of Elsevier), Boston, USA, ISBN 0-7506-7602-7

Eckhoff, R.K. (2016): *Explosion hazards in the process industries*, Chapter 2, 2nd edition Gulf Publishing Company (an imprint of Elsevier), ISBN 978-0-12-803273-2

Eckhoff, R.K. (2019): Measuring hot-surface minimum ignition temperatures of dust clouds – History, present, future, *Journal of Loss Prevention in the Process Industries* Vol. 59 (2019) pp. XX-XX

EN 1127-1 (2007): *European Standard EN 1127-1: Explosive Atmospheres – Explosion Prevention and Protection. Part 1: Basic Concepts and Methodology*, European Committee for Standardization, Management Centre: Rue de Stassart 36, B-1050 Brussels

Frazer, J.C.W., Hoffman, E.J., Scholl, L.A. (1913): *Laboratory Study of the Inflammability of Coal Dust*, Bulletin 50, Dept. of the Interior, Bureau of Mines, Governmental Printing Office, Washington DC

Godbert, A.L. (1927): Laboratory methods for determining the flammability of coal dusts, *Publications of the Safety in Mines Research Board*, Volume III, Paper No. 31, His Majesty's Stationery Office, London

Godbert, A.L. and Wheeler, R.V. (1929): *The relative Inflammability of Coal Dusts. A Laboratory Study*, Safety in Mines Research Board, Paper No. 26

Godbert, A.L. and Greenwald, H.P. (1935): *Laboratory Studies of the Inflammability of Coal Dusts. Effect of Fineness of Coal and Inert Dust on the Inflammability of Coal Dusts*. Bulletin 389, United States Department of the Interior, Bureau of Mines. Published by US Government Printing Office, Washington DC.

Hartmann, I., Nagy, J., Brown, H.R. (1943): *Inflammability and Explosibility of Metal Powders*, US Bureau of Mines Report of Investigations No. 3722, US Department of the Interior

Holtzwart, R. and Meyer, E. von (1891): Ursachen von Explosionen in Braunkohlenfabriken, Teil III: Über das Zustandekommen von Explosionen mit Braunkohlenstaub. *Polytechnische Journal*, Band 280, Heft 10, pp. 237-240 . In: Dingler-online, Vol. 280, pp. 185-190, http://dingler.culture.hu-berlin.de/article/pj280/ar280088

IEC (1975): Electrical apparatus for explosive gas atmospheres. Part 4: Method of test for ignition temperature. Second edition. IEC publication 74-4, Central Office of the International Electrotechnical Commission, Geneva, Switzerland

ISO/IEC (2016): International Standard ISO/IEC 80079-20-2/Ed1, *Explosive atmospheres, Part 20-2: Material characteristics, Combustible dusts test methods, pt. 8.1,* International Electrotechnical Commission, Geneva, Switzerland

Palmer, K.N. (1973): *Dust Explosions and Fires,* book in Powder Technology Series, published by Chapman & Hall Ltd., London, UK. SBN 412 09430-4

Price, D.J. and Brown, H.H. (1922): *Dust Explosions: Theory, Nature, Phenomena, Causes, Methods of Prevention,* National Fire Protection Association, Boston, USA.

Raftery, M. M. (1968): *Explosibility Tests for Industrial Dusts.* Fire Research Technical Paper No. 21, Her Majesty's Stationery Office, London

Rice, G.S. (1925): Review of coal-dust Investigations, *Trans. American Institute of Mining and metallurgical engineers,* No. 1435-F. Issued with *Mining and Metallurgy,* March 1925

Taffanel, J. and Durr, A. (1911): *Fifth series of experiments on the inflammation of dusts: tests of inflammability*. Comité Central des Houilleres de France, Station d'Essais de Lievin, Paris, August 1911

Tonkin, P.S. and Raftery, M.M. (1961): *Testing of Industrial Dusts For Explosibility,* Fire Research Note No. 464, Fire Research Station, Boreham Wood, Herts., UK, (unpublished draft report dated June 1961)

Tyler, B. J. (1987): *Scaling the Ignition Temperatures of Dust Clouds.* Report No. F3/2/347, (June) Fire Research Station, UK.

Wheeler, R.V. (1913): *Report on the inflammability and capacity for transmitting explosions of carbonaceous dusts liable to be generated on the premises under the Factory and Workshops Act.* Command Paper 6662, Factory Department, UK