



Ignition behaviour of hybrid mixtures of coal dust, methane, and air

by G.V.R. Landman*

Synopsis

Changes in the explosion behaviour of mixtures of coal dust, methane, and air when exposed to different energy sources are discussed. Changes to the lower explosive limits, minimum ignition energies, and rates of pressure rise when the same hybrid mixture of coal dust, methane, and air is exposed to ignition sources which are either spatially extended or spatially concentrated, are examined. A diagram is presented from which coal-dust loadings and methane presence can be determined which are below the lower explosive limits, and stated as a safety factor.

Introduction

Despite two centuries of intense scientific attention, coal-mine explosions continue to be the cause of numerous colliery fatalities worldwide. During the 18th and 19th centuries, all explosions in mines were attributed to a gas that was ultimately identified as methane. The well known English researcher Faraday was the first scientist to recognise the danger of coal-dust explosions, but at the time little attention was paid to his opinion by the mining industry¹.

After the Courrières colliery explosion in 1906 in France, in which 1099 miners lost their lives, there was no longer any doubt concerning the explosibility of coal dust, since methane was known to be absent in the Courrières mine. Attempts were then made in the major coal-producing countries to express the hazard potential of dust in terms of hazard indices, such as the explosion constant K_{ex} , which was developed in Germany by Helwig² in the 1960s. The K_{ex} index is the average of the mean and maximum pressure rises over time at a dust concentration which delivers the maximum pressure rise in a closed explosion vessel.

Since the early 1960s, more attention has been paid to the explosion behaviour of hybrid mixtures of coal dust, methane, and air. The mechanization of collieries increased the risk of the simultaneous presence of methane and coal dust around cutting drums, or of situations where deposited coal dust could be easily entrained into air. The explosion behaviour of hybrid mixtures was then studied intensively, but most experiments were conducted using a single source of ignition, with the ignition energy of the source maintained at a constant level. However, a variety of ignition sources can be present in collieries. These vary from small hot spots such as a frictional metal smear behind cutting picks to large hot gas clouds occupying a large volume, such as a blown-out shot during blasting. At the same time, ignition sources represent different energy concentrations. Situations can thus be found where two sources are dimensionally equal, but are at different temperatures, resulting in dissimilar behaviour.

This paper describes changes in the explosion behaviour of explosive mixtures when exposed to different energy sources. Hybrid mixtures of coal dust, methane, and air were exposed to an ignition source that was spatially extended. The same mixtures were then exposed to a source that was spatially concentrated. The minimum ignition energies and the lower explosive limits for mixtures of methane and coal dust were determined, while the pressure rise over time was measured.

Thermal explosion theory

Semenov, as reported by Gray and Lee³, developed an elementary model for thermal explosions which elegantly illustrates the principal features of the explosion phenomenon. In his model, heat distribution throughout the reactant is assumed to be constant, a situation that can arise if the explosive gas is much more conductive than the walls surrounding it. The temperature is constant over the whole volume, but differs from that of the walls of the container. The source of ignition fills the whole volume, and any element of the volume of explosive mixture starts to ignite at the same time. The explosive mixture loses heat through the walls of the container, and a race between heat generation from the exothermic reaction and heat dissipation takes place.

According to Gray and Lee³, the Semenov theory gives a good estimate, not much altered by more sophisticated theories, of the critical temperature rise in an explosive system, while ignoring the effect of reaction consumption. Since the theory provides such a clear understanding of the ignition and explosion phenomena, it is summarized below.

Heat generation

Due to the zero-order exothermic reaction with an Arrhenius-type reaction rate expression, it is assumed the reaction self-heats uniformly to a temperature T_r , which is higher than the temperature of the surroundings at T_0 . The rate of heat generation is given by:

$$\frac{dq_g}{dt} = QV\rho Ae^{\left(\frac{-E}{RT_r}\right)}, \quad [1]$$

* Department of Mining Engineering, University of the Witwatersrand, Johannesburg.
© The South African Institute of Mining and Metallurgy, 1995. SA ISSN 0038-223X/3.00 + 0.00. Paper received, Aug. 1994; revised paper received Dec. 1994.

Ignition behaviour of hybrid mixtures of coal dust, methane, and air

where Q is the exothermicity of the reaction in joules per unit mass of a reactant of density ρ and volume V , A is the pre-exponential factor (s^{-1} for a zero-order process), E is the activation energy in joules per unit mass, and R the universal gas constant in joules per unit mass per degree temperature.

Heat loss

The rate of heat loss is as follows:

$$\frac{dq_l}{dt} = hS(T_r - T_o), \quad [2]$$

where h is the heat transfer coefficient in joules per unit area per second, and S is the surface area of the reactant in contact with the surroundings.

Steady state

A steady state is reached when heat generation and heat loss are in balance:

$$QV\rho Ae^{\left(-\frac{E}{RT}\right)} = hS(T_r - T_o). \quad [3]$$

A stationary state should exist for zero-order reactions where the reaction stays at T_o , but since reaction rates fall off as reactants are consumed, a steady state is never truly attainable, adding a time dimension to the process. A steady state will exist only for a limited time as the reaction rate reaches its maximum.

Relation between heat loss and heat generation

When the heat loss and heat release are plotted as functions of temperature, curves like those in Figure 1 are obtained. Three conditions can be distinguished. They are the stationary state condition, explosive state condition, and the critical state condition. Each state will be discussed separately.

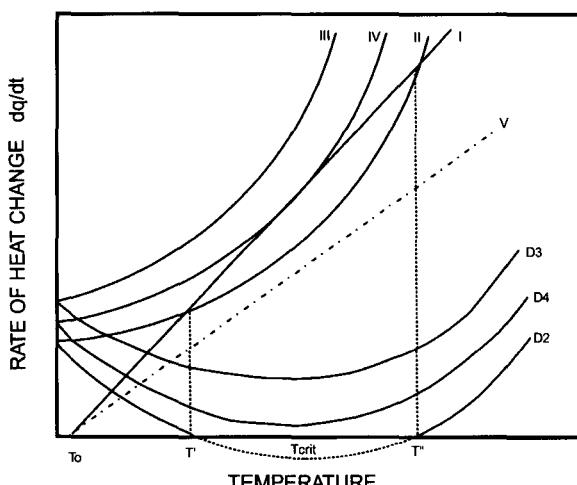


Figure 1—Heat generation (curves II, III and IV), heat loss (lines I and V), and the difference between them (curves D₂ to D₄), as functions of temperature (after Gray and Lee³)

Stationary states

The heat generation curves (II, III, and IV) should be S-shaped, but since heat released by the reaction alone is not enough to reach the upper part of the S-shaped curve, only the lower part is considered. The reaction self-heats when the heat generation exceeds the heat loss, but at temperature T' the situation becomes stationary. The criterion for stability is that the rate of change of temperature versus the rate of heat generation becomes less than the rate of change of temperature versus the rate of heat loss, i.e.

$$d\left(\frac{dq_g}{dt}\right)_{T'} < \frac{d\left(\frac{dq_l}{dt}\right)}{dT}. \quad [4]$$

The reaction will therefore not be able to self-heat to temperatures above T' , and cannot proceed along the dotted portion of curve D₂, since more heat is lost than is generated in this region. Should a temperature T'' be reached, the situation will be unstable, and an explosion will occur.

Explosive states

For this condition, curves I and III never touch or cross each other, and heat generation always exceeds heat loss. Reactions are always in the explosive states. A change in the vessel size will drop line I to form line V, forming explosive states for reaction heat-production curves II to IV.

Critical state

When the heat generation curve is tangential to the heat loss line, a critical condition is reached. This occurs when

$$\left(\frac{dq_g}{dt}\right)_{T_{crit}} = \left(\frac{dq_l}{dt}\right)_{T_{crit}}. \quad [5]$$

The critical condition is

$$d\left(\frac{dq_g}{dt}\right)_{T_{crit}} = \frac{d\left(\frac{dq_l}{dt}\right)}{dT}_{T_{crit}}. \quad [6]$$

At the critical temperature, T_{crit} , the behaviour of the reaction changes from a steady to an unstable state. In effect, T' and T'' become coincident.

The approach to the critical state should be as follows: the rate of self-heating falls to zero as T_{crit} is reached, but if a disturbance raises the temperature above T_{crit} , the rate of self heating will rise without limit if reaction consumption is not a limiting factor. The Semenov thermal explosion theory provides a good explanation of how an explosion initiates when an ignition source is spatially extended, such as a blown-out shot during blasting or a small methane pocket exploding in the presence of coal dust.

Thermal theory of ignition by hot spots

When ignition sources are spatially concentrated, such as an electric spark or a frictional hot spot while cutting coal, ignition is initiated from the hot spot, while heat generation is retarded by heat loss to the sphere of explosive mixture surrounding the hot spot. The heat transferred to the surrounding sphere ignites it, and the process is repeated. Explosion development is therefore limited by the rate of heat transfer in the gaseous medium.

To cater for this situation, the Semenov theory can be developed further. The theory aims at predicting the size and temperature of the smallest hot spot that will ignite a self-sustaining reaction which will spread and involve the whole mass. The development of the hot spot theory is omitted here, and only the heat generation and heat loss equations are given.

Rideal and Robertson⁴ attempted in 1948 to make a theoretical calculation of the critical size of the hot spot at different temperatures. The heat generation term is simply the product of the volume of the hot spot and the exothermicity of the reaction:

$$q_{gen} = \left(\frac{4}{3} \pi r_0^3 \right) \rho t Q A e^{-\frac{E}{RT}} \quad [7]$$

and heat loss:

$$q_{loss} = \int_{r_0}^{\infty} 4\pi r^2 \theta C_v \rho dr, \quad [8]$$

where r_0 is the radius of the hot spot, t an arbitrary time interval, θ a dimensionless temperature term, and C_v the specific heat of the explosive mixture. The model is applicable only for a spherical hot spot.

From the theory it is evident that the behaviour of the two extreme situations, namely a volumetric and a hot spot ignition, are different. These differences were investigated in the experimental programme, and are discussed in the following sections.

The experimental programme

The explosibility experiments were conducted using a 40-litre explosion vessel normally used for determining the inherent explosibility of different coals, as expressed by the K_{ex} index⁵. The 40-litre chamber was modified to allow the introduction of methane and coal dust, and to accept a spark generator in addition to the original pyrotechnic igniter. The pyrotechnic igniter was used to simulate volumetric ignitions, and the spark generator to represent ignitions from hot spots. A more comprehensive description of the equipment used can be obtained from Phillips and Landman⁶.

Two coals, each milled to a mean particle size of 20 μm , were mixed with methane and air before being exposed to the sources of ignition. The coals represent a high and low volatile content, 32 and 22 per cent by volume respectively. A specific mixture of coal dust, methane and air was introduced to the explosion chamber and exposed to the volumetric igniter. The energy level of the igniter was reduced until no explosion was generated. The point was defined as the lower explosive limit for that mixture. The mixture was then exposed to the hot spot or point source igniter, and a minimum ignition energy was also determined. By testing a variety of different combinations of coal dust, methane, and air, the explosive limits could be determined.

Hybrid mixtures were formed by coal dust concentrations not exceeding 600 g/m^3 and methane contents not exceeding 10 per cent by volume. Greater emphasis was given to lower concentrations, since these are the hybrid mixtures more likely to be found in collieries.

Pressure-time histories of volumetric and point ignition sources

The propagation of a coal-dust explosion depends on the rapidity of expansion of gases during combustion in order to create a movement of air ahead of the combustion zone that is strong enough to ensure the dispersion of dust. The dust must also be sensitive enough so that the radiation from particles in the flame front can ignite the dust cloud sufficiently quickly to sustain the expansion of gases.

Ignition behaviour of hybrid mixtures of coal dust, methane, and air

Pressure-time histories of a hybrid mixture exposed to the two different ignition sources (Figure 2) show that the explosion initiated by the volumetric source behaves totally differently from that generated by the point sources igniter. The maximum pressure in both cases is 0,7 MPa, but it is reached in 76 ms for the pyrotechnic igniter, and only after 447 ms for the electric spark igniter. Since heat is lost to the immediate environment in the case of point ignition, the reaction takes place at a lower temperature than that of volumetric ignition, and the reaction rate is much slower. The arbitrary time t included in Equation [7] is determined by the rates of radiation, convection, and conduction, which are slower than the reaction rate of the chemical

reaction when ignited volumetrically. Explosions of the same mixture ignited from a point source, are much slower and weaker than those initiated from a volumetric source. The latter is then also much more likely to initiate a pure coal-dust explosion.

Ignition zones

At lower concentrations of methane and dust, mixtures which were ignitable with the pyrotechnic igniter were not ignitable by the spark igniter. Three ignition zones are distinguishable, separated by the lower explosive limits of the mixture if exposed to either the volumetric or point source of ignition. The initiation zones are shown in Figure 3. The first is a non-ignitable zone, where the rate of heat generation from the exothermic reaction is less than the heat lost from the system, and thus no explosion is possible. Above this zone, an ignition zone exists where the rate of heat generation from the volumetric igniter exceeds the heat loss from the system, making the mixtures explosive. The same mixtures are not explosive from a point source, since heat transfer from the hot spot to the sphere surrounding it is not rapid enough to exceed heat loss from the system over the same time. In the third zone, explosions can be generated from both volumetric and point sources, but the rate of pressure rise of the volumetric sources is far in excess of that of point initiation.

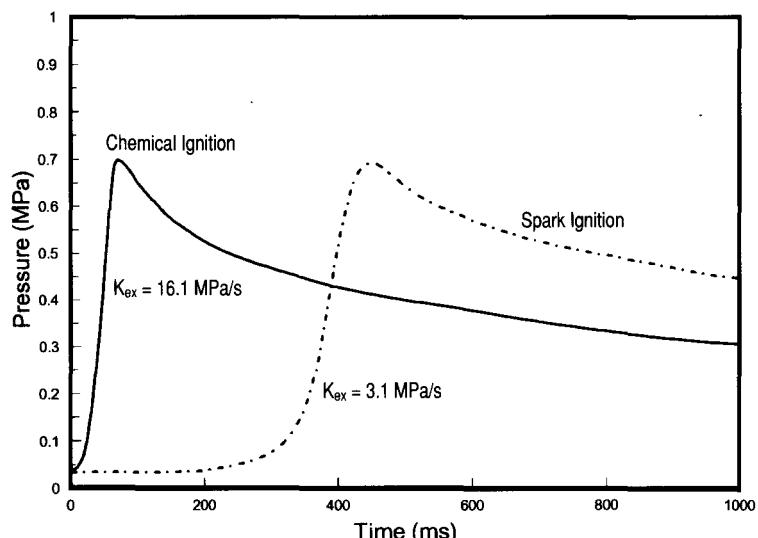
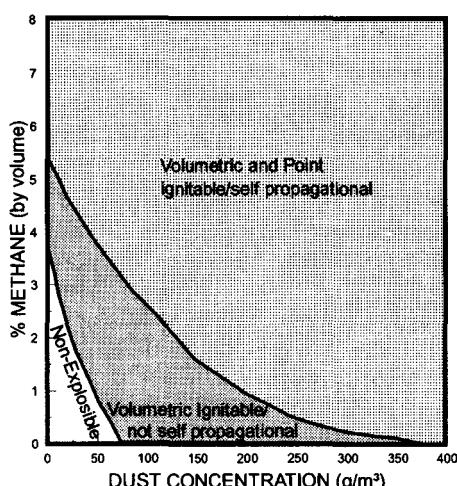


Figure 2—Time versus pressure for chemical and spark ignition of a 500 g/m³ 32 per cent volatile dust mixed with 1 per cent methane in air (after Landmans)

a) High Volatility



b) Low Volatility

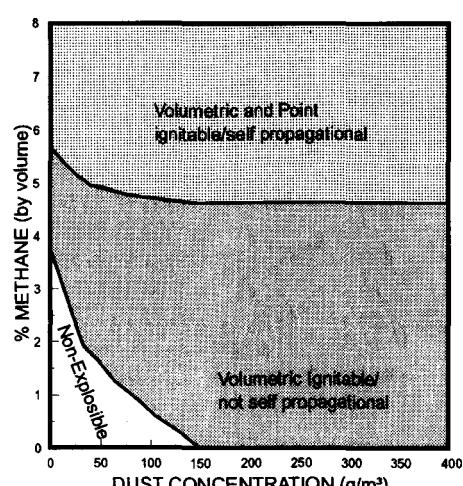


Figure 3—Ignition zones in hybrid mixtures of coal dust and methane in air for (a) a coal dust with 32 per cent volatile content and (b) a coal dust with 22 per cent volatile content

Ignition behaviour of hybrid mixtures of coal dust, methane, and air

References

1. CYBULSKI, W. Coal dust explosions and their suppression. Washington, Bureau of Mines, U.S. Department of the Interior and the National Science Foundation. TT 73-54001. 1975.
2. HELWIG, N. Investigation of the entrainment of different particle sizes in propagation of coal dust explosions (German). *Staub-Reinhalt*, vol. 26, no. 2. Feb. 1966.
3. GRAY, P. and LEE, P.R. Thermal explosion theory. *Oxidation and Combustion Reviews*. Tipper, C.F.H. (ed.). vol. 2. Amsterdam, Elsevier Publishing Company, 1967. pp. 1-184.
4. RIDEAL, E. and ROBERTSON, A.J.B. *Proc. Roy. Soc.* vol. A195. 1948.
5. LANDMAN, G.V.R. Ignition and initiation of coal mine explosions. Ph.D. thesis. University of the Witwatersrand, 1992.
6. PHILLIPS, H.R. and LANDMAN, G.V.R. The explosion potential of methane/dust mixtures at the coal face. *Fifth International Mine Ventilation Congress*, Johannesburg, 1992.
7. FIELD, P. Dust explosions. Amsterdam, Elsevier Scientific Publishing Company, 1967.

From Figure 3, it can be seen that the lower explosive limits for volumetric and point ignitions are obtained at different concentrations. The lower explosive limit for the highly volatile dust is alarmingly low. For example, mixtures containing 40 g/m³ coal dust and 1.4 per cent methane are within the explosive zone. Generally, the lower explosive limits for the low volatility coal dust are obtained at higher concentrations than those for the high volatility coal dust. The lower explosive limits for point ignition of lower volatility coal mixtures are obtained only at concentrations far in excess of those for volumetric ignition. The concentrations required for point ignition in the lower volatility coal are also much higher than those required for volumetric and point ignition of high volatility dust.

Ignition sensitivity

Figure 4 illustrates the sensitivity behaviour of mixtures of coal dust and methane in air. A mixture is sensitive to ignition when only a small amount of energy is required from the sources of ignition to result in an explosion of the explosive environment. A central zone of exceptionally sensitive mixtures exists for more concentrated quantities of methane and dust. As mixtures become more lean and closer to the lower explosive limit, greater ignition energies are required to ignite the mixture.

On the vertical axis in Figure 4a, the lower explosive limit of methane when volumetrically ignited is observed to be 4 per cent. This lower explosive concentration is drastically reduced in the presence of coal dust. The lower limit of explosibility is seen to connect a methane-air mixture of 4 per cent to a coal dust-air combination of 75 g/m³. Combinations containing higher concentrations of methane and dust show a drastic reduction in their minimum ignition energy levels. A large central area represents hybrid mixtures of extreme sensitivity and indicates mixtures ignitable below 15 J/l for volumetric ignition and 1 J/l for spark ignition. Figure 4b shows a much smaller central sensitivity zone for hybrid mixtures formed by a lower volatile coal dust and methane. The lower explosive limit for both volumetric and point ignition reduces, and the zone of exceptional sensitivity is reduced, for coals of lower volatility.

Any hybrid mixtures below the lower explosive limit for the specific type of ignition—volumetric or point ignition—can be considered safe. Mixtures above the lower explosive limit, but ignitable by energy concentrations so high that they are unlikely to be found in a mine, will also be safe. It is the more sensitive mixtures closer to the zone of exceptional sensitivity that can be extremely dangerous in collieries, since many of those mixtures contain coal dust and methane at concentrations far below their individual lower explosive limits.

Acceptable dust concentration levels

The flammability of mixtures of different gases with air can be determined by the Le Chatelier additive principle. Field⁷ expressed the principle mathematically as follows:

$$\frac{d}{N_d} + \frac{s}{N_s} = 1, \quad [9]$$

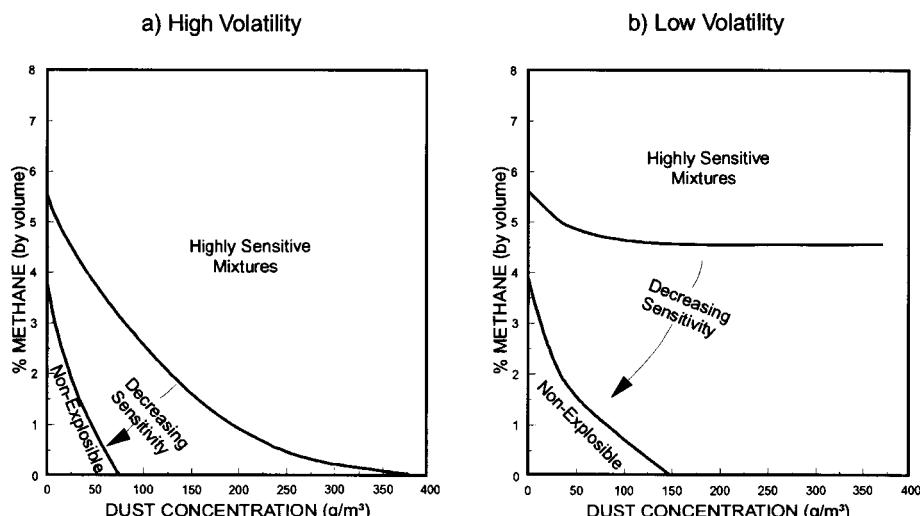


Figure 4—Ignition sensitivity zones for (a) highly volatile coal dust and (b) low volatility dust, both volumetric-ignited

Ignition behaviour of hybrid mixtures of coal dust, methane, and air

where d is the concentration of gas-free dust that produces a minimum explosive concentration with a gas at a concentration s , and N_d and N_s are the minimum explosive concentrations, or lower explosion limits, of the dust and gas respectively.

When no methane is present and the second term in Equation [9] becomes zero, the dust concentration d is required for an explosion to take place becomes N_d . If, however, a concentration of only $N_d/2$ exists, only half of the required concentration is present and a safety factor of 2 exists. If, for example, the lower explosive limit of a dust for volumetric ignition is 100 g/m³, limiting concentrations to 25 g/m³, this will result in a safety factor of four. The same argument holds for mixtures in which methane is the only combustible component. For point source ignition, the lower explosive limit of a methane/air mixture is 5.7 per cent, but 1.4 per cent is the maximum allowed by law. This results in a safety factor of about 4.

For hybrid mixtures of coal dust and methane in air, Le Chatelier's principle can be used to determine concentrations for each individual combustible component that result in an acceptable safety factor. Figure 5 shows different values of s/N_s plotted against d/N_d . A line connecting all possible concentrations of s and d connects unity on the s/N_s axis and unity on the d/N_d axis. Since this is the lower explosive limit for hybrid mixtures and s and d for the particular source of ignition, it is also a line representing a safety factor of 1. When s and d are halved proportionally, the line so formed represents a safety factor of 2. For mechanized excavations, therefore, the upper dust concentration can be determined that will provide an acceptable safety factor.

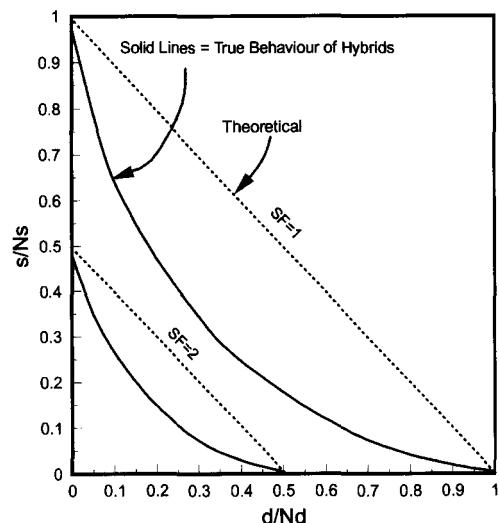


Figure 5—Le Chatelier's additive principle rearranged to illustrate how a safety factor can be determined for coal dust and methane concentrations in air

Conclusion

It has been shown that the explosibility of hybrid mixtures of coal dust, methane, and air is influenced by both the properties of the coal dust and the geometry of the source of ignition. In some collieries, excessive levels of fully dispersed coal dust in the air, in the presence of methane concentrations far below the lower explosive limits, can substantially increase the risk of an explosion. A safety factor approach can be used to determine concentration levels of dust and methane that will provide an adequately safe environment in which to work. ♦

New Dean of Engineering at Wits

Professor Jan Reynders, Head of the Department of Electrical Engineering at the University of the Witwatersrand has been appointed Dean of the Faculty of Engineering for a three-year term commencing in January 1995. He will succeed Professor Roy Adams.

Professor Reynders began his career as an apprentice electrician with the Johannesburg City Electricity Department. He went on to university, completing a Bachelor's Degree and a Ph.D. in partial discharge activity in synthetic insulation. He found the teaching and research environment extremely stimulating and has played a leading role in developing a centre of excellence in high voltage and insulation teaching and research.

He has been elected to serve in several significant positions, among them are President of the South African Institute of Electrical Engineers and Chairman of the South African National Committee of Cigre where he serves as a member of the

International Administrative Council of Cigre and has been a member of its International Technical Committee.

The newly released Mission Statement of the University has identified Engineering as a major area for growth. 'Standards must be maintained,' he says. 'We will build onto our extremely successful extended curriculum programmes which bring young people with potential up to the levels necessary for University study in Engineering. Different entry levels, but the same output level is what we are achieving. A further challenge that the Faculty is facing, very squarely, is to provide the high level of manpower required to stimulate high tech industry. This must be achieved in a climate of tightening government expenditure. Over the years we have cultivated a very good relationship with our profession and industry and with their support we will be able to meet these challenges.' ♦

Issued by: University of the Witwatersrand.