JOURNAL
OF ENERGY R & D
IN
SOUTHERN AFRICA

Vol. I

No.1

November 1990

Journal of Energy R & D in Southern Africa

It is the policy of the Journal to publish original research covering the technical, economic, political and techno-social aspects of energy in Southern Africa. Only previously unpublished work will be accepted. However, conference papers delivered but not published elsewhere are also welcomed. Short comments, not exceeding 500 words, on articles published in the Journal are also invited. Announcements of relevant publications, reviews, conferences, seminars and meetings will be included.

Those wishing to submit contributions for publication should refer to the guidelines set out in *Information for Authors* printed on the inside back cover of the Journal. All contributions are refereed by experts drawn from the Editorial Advisory Panel before publication.

The Editor does not accept responsibility for viewpoints or opinions expressed, nor the correctness of facts or figures.

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EDITORIAL

BY THE NATIONAL ENERGY COUNCIL

Energy research in Southern Africa is currently being conducted over a wide front. It varies from sharply focused and specialised technical research at one end of the spectrum, to multi-disciplinary applied research into appropriate energy technology at the other. Likewise, diverse organisations are involved, from government institutions to the individual in the private sector.

It is an unfortunate fact however, that researchers and decision-makers are not adequately informed about ongoing research, and about the results and implications of research already completed.

Admittedly, researchers do publish their results in a variety of journals, both locally and internationally. But whilst this meets the needs of the researcher, it does not satisfy the needs of the energy community at large in order to gain an overall impression of the research scene and the results achieved.

To improve the communication of ongoing energy research in this country, the National Energy Council (NEC) has undertaken to offer financial support for the first two years of this new journal. Through this journal, the NEC hopes to stimulate the local energy debate, thereby providing appropriate information not only to policy- and decision-makers, but to all researchers and other interested parties. The energy sector deals with scarce resources, such as manpower, money, the natural environment and fossil fuels, all of which need to be used optimally. As always, competition is an important factor, making appropriate information essential.

The journal is being launched at a time when the NEC is changing its approach from sponsoring objective-driven research and development to one supporting output-driven research and development, where the production of tangible results involving specific receivers is stressed. The output of this project to support the initial launching of this journal is to publish six issues over the two-year contract period, resulting in an eventual subscription target of 500. It will focus on the results of applied research within Southern Africa. The readership of the journal will, hopefully, come from the ranks of the energy decision-makers and researchers from government departments, Eskom, local authorities, and oil, coal and renewable energy companies, as well as consultants and manufacturers of energy products and systems.

Much could be said about the purpose and the approach to local energy research and development. It becomes a particularly thorny issue in a relatively small geographical area such as ours, where aspects such as the following are constantly debated:

- a suitable balance between basic and applied research
- the timing and extent of local research in relation to that in other countries
- the respective R & D responsibilities of the public and private sectors
- the development of local expertise, products and solutions as opposed to acquiring them from other countries
- pure technical research versus applied multi-disciplinary and field research The journal will, no doubt, be covering the majority of these topics in due course.

Undoubtedly, the reaction to and feedback from its readers is the lifeblood of a publication of this nature. Suitable contributions, such as review articles and analyses of trends in local research and development, from researchers, decision-makers and readers in all disciplines and fields of energy, are therefore warmly welcomed. Readers may also wish to submit book reviews and reports on conferences and visits abroad.

The impact and credibility of this journal will be dependent on the contributions of the researcher, evaluator, reviewer, analyst and commentator. To assist in producing a journal of excellence, the Editorial Committee looks forward to a lively exchange of ideas with readers. Ultimately, it is hoped that this journal will contribute to a visionary, ethical and responsive energy sector.

DESIGN AND COSTING OF REMOTE AREA POWER SUPPLY OPTIONS

*A A EBERHARD and *M L BORCHERS

Most people residing in rural areas in South Africa do not have electricity. At a time when "electricity for all" is an increasingly popular slogan it is important that rational decisions be made regarding electricity supply options for remote areas. Grid extension costs are very high for small rural users and the other conventional options of diesel and photovoltaic generators need to be considered.

A design and costing micro-computer based package has been developed which allows accurate determination of comparative costs. This paper presents the range of unit costs for electricity supply from these three options for South African conditions. Photovoltaics are shown to be cost-effective for small energy uses in remote areas. The analysis is based on narrow financial criteria. A broader economic and environmental cost benefit analysis would indicate that photovoltaics have an important long-term role in future energy supply options.

ERRATA

DESIGN AND COSTING OF REMOTE AREA POWER SUPPLY OPTIONS
EBERHARD A A and BORCHERS M L

The captions for the Figures on Page 5 have been incorrectly matched with the graphs. Kindly note that the caption for Figure 1 applies to the graph presently shown in Figure 4. The caption for Figure 2 applies to the graph presently shown in Figure 1. The caption for Figure 3 applies to the graph presently shown in Figure 2. The caption for Figure 4 applies to the graph presently shown in Figure 3.

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tions are either for very small power users such as calculators and other consumer goods or for remote area power supply for telecommunications, recreational facilities, farms, water pumping, rural schools, clinics and low density rural settlements.

The viability of photovoltaics for small power applications is assisted by their modular nature. They can supply power from a few milliwatts where conventional power sources are impractical or expensive. Photovoltaics can also be assembled into megawatt plants, but they are not yet financially competitive with large-scale thermal plants connected to grid networks. They are increasingly being used for power applications in remote areas where conventional alternatives are petrol or diesel generators or long and expensive connections to the electricity grid. (Other renewable stand-alone power systems such as wind or hydro-electricity are not considered here as no reliable or up-to-date data for South African conditions have been published.)

equivalently sized systems have to be considered, i.e. each alternative must be optimally sized to meet a given power requirement at an equivalent level of reliability. Photovoltaic energy output is dependent on a variable and, in the short term, unpredictable natural power source. Diesel generators and grid lines require down-time for maintenance and may experience other failures. Yet, conventionally, little attention is given to specifying these parameters.

This is not a trivial issue as the cost of stand-alone systems is highly sensitive to specified reliability. A photovoltaic system which is designed with ten days' autonomy (i.e. power can be supplied from back-up batteries for a period of ten consecutive days without sunlight) will be very much more expensive than one designed for two or three days' autonomy. The first example is not uncommon in telecommunications applications and the latter is more common in farm or domestic situations. However, this is a crude way of specifying reliability and is not easily compared to the reliability of alternative power supply options. A sensible alternative is to specify a design loss-of-power probability (LOPP) level. For instance, a LOPP of 0,01 means that

*Energy Research Institute, University of Cape Town, Private Bag, Rondebosch 7700, South Africa

power would not be available for 1% of the time, i.e. for just under four days a year. Extensive experience with diesel generators and grid extension has enabled typical levels of reliability for particular designs to be determined. It is also possible to design photovoltaic systems according to a specified LOPP. (See [2] for a discussion of these methods. PV suppliers in South Africa do not use these sizing techniques and as a result most PV systems are not optimised in terms of reliability, size and cost.)

An elegant LOPP and photovoltaic sizing methodology has been developed by Cowan [3, 5], which relies on statistical condensations of long-term hourly solar radiation data. Data for twelve local meteorological stations have been incorporated into a micro-computer sizing tool (POWER-COST) which has been extended to allow for comparative sizing and costing of photovoltaic, diesel or grid extension supply for any specified electrical load and location [1, 6].

For most remote area applications (other than telecommunications) a LOPP of 0,01 is reasonable and this is the level which has been used to determine the cost of photovoltaic supply with POWERCOST. (POWERCOST also allows other LOPP's to be specified.)

Costing methodology

A comparative analysis of the costs of competing power supply systems presents particular problems when expenditures are distributed unevenly over the life of the system. Simply adding up all the costs over the lifetime of the project results in misleading conclusions on the least-cost option, even if inflation is incorporated. The opportunity cost and time value of money have to be taken into account. The total cost over the lifetime of the project (life-cycle cost) has to be discounted to present value using an appropriate discount factor. The present value of the life-cycle cost may be annualised, and if this is divided by the total energy output over the life of the project, then a levelised unit cost of electricity may be determined, which provides a basis for financial comparison between alternative power supply systems. A discussion of the cost comparison methodology may be found in Borden et al. [1] and Sinclair [8].

The initial equipment cost constitutes the major portion of the photovoltaic system life-cycle cost (typically around 80%) since maintenance costs are minimal. Battery replacement costs constitute the bulk of the remainder.

Unlike photovoltaic systems, diesel generator life-cycle costs are strongly influenced by operation and maintenance costs, as well as the generator lifetime. A study of diesel generator performance and costs undertaken by Morris [7] provided accurate and comprehensive information for the program. Diesel generator fuel consumption per unit energy produced varies significantly depending on the capacity at which the set is being run and the program allows these parameters to be determined before costs are calculated.

The costing of a grid extension power supply is defined by Eskom, and involves combining demand-related tariffs with extension charges from which the average unit energy cost is estimated. Extension charges vary significantly with the distance over which the grid is extended. In the case of small energy users, these costs can become significant.

DESCRIPTION OF POWERCOST

The design and costing program (POWERCOST) comprises three modules, one for each power supply option. Each module may be run individually, or a comparison between the options may be undertaken. The program contains a full set of default component efficiency and costing values used in sizing and costing. These may be displayed while running the program and may be updated or altered to suit local conditions. The program includes a solar radiation data base for twelve sites in South Africa.

Inputs required

The inputs required by the different modules of the program fall into two categories:

(1) Demand-related: daily energy and peak load, the period over which the energy is required, and supply reliability.
(2) Site-related: e.g. site location, distance from the national electricity grid, and altitude.

Outputs produced

(1) System sizes: photovoltaic system and component sizes and the diesel generator capacity.
(2) Costs: initial, operation and maintenance, equipment replacement, and unit delivered energy costs.

ENERGY COSTS

Photovoltaic systems

The cost parameter with the greatest potential to vary is the module price. A fall in module prices from R20 to R5 per peak watt will result in generating costs varying from approximately R1,50/kWh to 60c/kWh. As module prices decrease, the costs of balance of system components such as battery storage will become increasingly significant.

Photovoltaic generating costs are also dependent on solar radiation levels. The effect of relying on a design radiation figure of 4 rather than 6 kWh/m^2 day, for example, is to increase costs from about R1,50 to R2,60 per kWh. Diurnal and seasonal variations of radiation further complicate the calculations. In particular, the cost of battery storage increases markedly as the average number of days of cloud or low radiation per month increases. For example, Cape Town, with its cloudy winters, has the most expensive photovoltaic costs in South Africa even though the yearly sunshine average is amongst the highest. This is illustrated in Figure 1.

There is a caveat to the above data. The photovoltaic costs presented here assume load utilisation at design levels. Lower load factors would result in greatly increased costs. Analysis of the Edutel Project in Bophuthatswana shows how sensitive generating costs are to utilisation levels [3]. These are shown in Figure 2. In this case a 60% load factor results in a doubling of effective generating costs. Low usage levels were a result of social factors. Educational television relies not just on an appropriate technology for power but also on appropriate software and institutional support. In other cases, low usage is also likely to be due to institutional shortcomings, most particularly the availability of spares and maintenance of balance of system components. These issues need to be considered in the overall cost-effectiveness of photovoltaic systems.
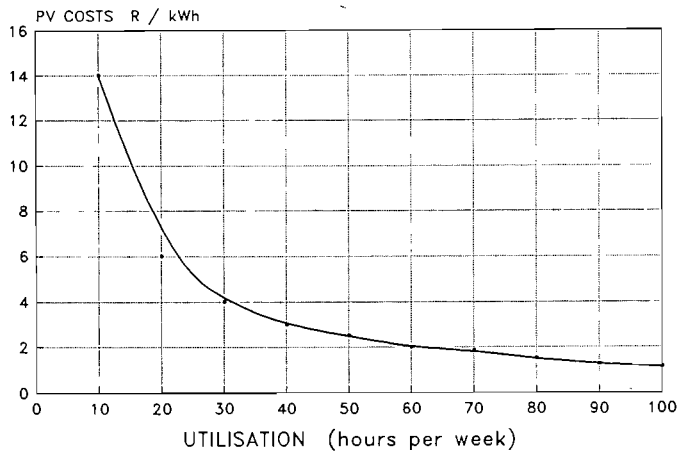
Figure 1: Photovoltaic electricity costs from various sites around the country for a LOPP of 0,01

A — Windhoek E — Upington I — Pretoria
B — Keetmanshoop F — Port Elizabeth J — Roodeplaat
C — Alexander Bay G — Grootfontein (Cape) K — Nelspruit
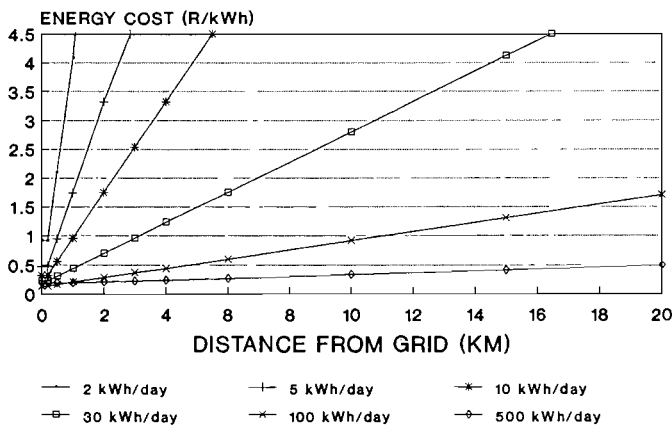D — Cape Town H — Bloemfontein L — Durban

Figure 2: Photovoltaic generating costs as a function of utilisation levels
Source: [3]

Diesel generators

The discussion above has highlighted the extent to which stand-alone generation costs are dependent on utilisation levels or load factors. Diesel generators are subject to a further cost disadvantage. They are sized according to peak demand, but the average power demand is much lower. Fuel efficiencies are lower in these operating regimes and maintenance costs higher.

The average capacity at which the generator is run is the main cost determinant of this supply option. Williams [9] reports that capacity factors of farm diesel generators vary from 0,17 to 0,34. Results are presented below for capacity factors of 0,1 and 0,4.

Petrol generators are often used for smaller power applications. Sinclair [8] reported that petrol generator costs based on a petrol price of 90c/ℓ vary from approximately R4,50 per kWh for 550 W sets to R2 per kWh for 5 kW units.

Grid extension supply

Unit energy costs are affected chiefly by the grid extension distance, particularly for small energy users (Figure 3). The discontinuity evident at the 200 m mark is explained by the

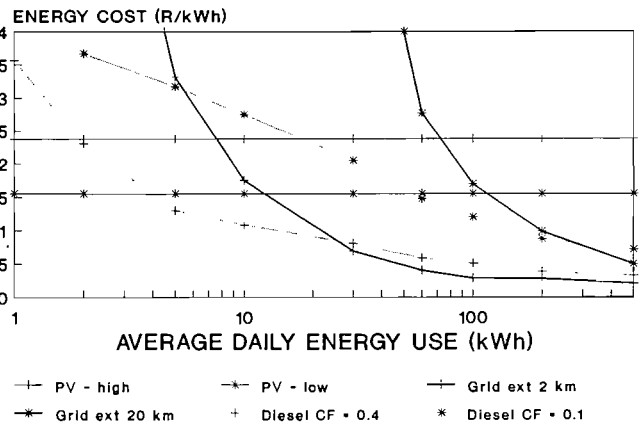extension charge subsidy, at present given by Eskom for the first 200 m of line.

Figure 3: Grid supplied energy costs for various grid extension distances

Comparative costs

Photovoltaic systems are modular and hence the cost of photovoltaic power per kilowatt hour does not alter significantly with the size of the system; the same is not true for the costs of competing power systems such as petrol and diesel generators which are size-sensitive. Comparative costs are thus presented for various daily energy demands.

Figure 4 indicates the range of costs of each option. The energy costs for diesel generators are given for two capacity factors, which represents a typical range found in practice. The photovoltaic (PV) energy costs are shown for two extremes of solar radiation. Grid extension energy costs for two extension distances are shown. It is clear from the figure that the competitiveness of each of the three power supply options varies according to the particular site conditions, which underlines the importance of the design and costing tool in selecting cost-effective options.
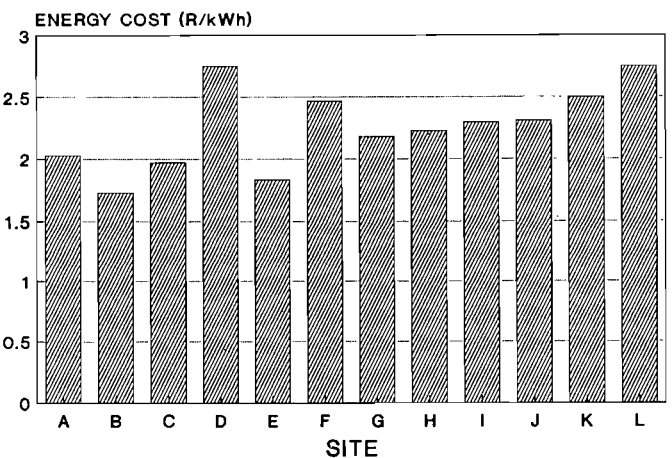
Figure 4: Energy costs from the various power supply options for various daily energy requirements

It is evident from the above figure that for energy demands of up to 4 kWh/day, photovoltaics can be cheaper than diesel (or petrol) generators with capacity factors of less than 0,4 and grid electricity extension distances of a kilometre or more. In the energy demand range of 4 to 50 kWh/day any of the three options may be competitive depending on the site, the capacity factor of the diesel set or the distance from the grid. Photovoltaics do not appear to be cost-effective for energy demands greater than

50 kWh/day and either diesel or grid extension will be cheaper.

The power range over which photovoltaics are cost competitive will increase as the price of photovoltaic modules falls and the cost of diesel-generated or grid-connected electricity rises. It makes sense, thus, for an off-grid user to explore the possibility of installing photovoltaic systems in all but large daily load demands.

FINANCING

While photovoltaics are clearly cost-effective for certain applications, their competitiveness is undermined by the absence of facilities to finance their purchase and installation. The capital component of grid extension, on the other hand, is financed over 23 years at attractive interest rates by Eskom and users are faced with affordable monthly instalments. The relatively high initial cost of photovoltaic systems means that financial assistance is essential if the technology is to be successfully disseminated, particularly in developing areas. This issue is becoming critically important in a period where the slogan "electricity for all" is too easily conflated with expectations of grid electricity. The consequence may be that the least cost, more sustainable options may be ignored.

CONCLUSION

This paper has shown that photovoltaics are a viable and appropriate technology for Southern Africa for smaller power ranges and where adequate institutional support is provided.

It should be remembered that affordability of photovoltaic systems is a critical issue in developing areas. More appropriate financing schemes will, in part, ameliorate this problem. However, there is still much scope for design practices which result in optimally sized and more affordable systems at an acceptable loss of power probability. The development of such design practices requires a thorough understanding of system dynamics, the operating characteristics of individual components, reliable data on expected loads and insolation levels, and the use of loss-of-power probability methods.

Finally, it should also be noted that the cost comparison above relied on a narrow financial methodology. A broader economic comparative analysis could incorporate less quantifiable social and environmental costs and benefits. Photovoltaic technology is based on the use of one of the most abundant elements in the earth's crust (silicon) and it relies upon a renewable energy source. With continued technical advances and cost reductions, photovoltaics have the potential to provide not only for remote area power supply needs but also, in the long term, for electrical power requirements closer to metropolitan centres. Photovoltaics will be able to do this in a sustainable and pollution-free basis — issues which will become paramount as the greenhouse effect, largely induced by thermal power stations, becomes more pronounced.

Photovoltaics remain one of the most elegant methods of generating electricity and are guaranteed an important long-term role in future energy supply options.

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VARIATION IN CETANE REQUIREMENTS OF DIESEL FUELS WITH ALTITUDE

*A C HANSEN, *P W L LYNE, *P MEIRING and **R W HAINES

The feasibility of modifying diesel fuel quality to suit engines operating at different altitudes has received very little attention. In South Africa, with the substantial variation in altitude across the country, such a feasibility study could be of considerable economic benefit. The objective of this project was to investigate the effect of altitude on the ignition quality requirements of diesel fuels with particular reference to Sasol fuels. Combustion and performance tests were carried out on a naturally aspirated ADE 236 engine with three Sasol fuels of varying cetane number, and with crude-oil based diesel fuel at three sites of different altitude. The results showed that the differences in engine performance were greater relative to altitude than between fuels. None of the combustion variables could be correlated consistently with cetane number. Peak cylinder pressures and hence engine stress were less at the higher altitudes, which suggested that fuels of lower ignition quality could be tolerated by engines at the higher altitudes.

KEYWORDS: cetane; altitude

INTRODUCTION

The altitude at which diesel engines fitted to tractors and transport vehicles operate in South Africa varies from sea-level up to approximately 1800 m. Over 80% of the tractors in the country operate at altitudes over 1400 m. The effect of altitude on the power output of diesel engines is well understood. There is a reduction in pressure, temperature and the amount of oxygen in the atmosphere as altitude increases and the result is less efficient combustion. This effect is manifested particularly at high engine loads where the greatest demand for oxygen is generated.

Provision is made for the variation, with altitude, of the ignition quality of fuels marketed for spark-ignition engines. However, the feasibility of modifying diesel fuel quality to suit the engine at different altitudes has received very little attention. The objective of this project was to investigate the effect of altitude on the ignition quality requirements of diesel fuels with particular reference to Sasol diesel fuels. Combustion and engine performance tests were carried out on three Sasol fuels of varying cetane number and crude-oil based diesel fuel at three sites of different altitude.

FUEL SPECIFICATIONS

The three Sasol fuels had cetane numbers of 45, 47 and 49 respectively while the cetane number of the crude-oil diesel was 51. Table 1 summarises the composition and properties of these fuels which were tested by Sasol Oil Research and Development, Sasolburg. Fuels CN47 and CN49 were formulated by the addition of small amounts of cetane improver to fuel CN45. Hence, the properties of fuels CN45, CN47 and CN49 are identical except for cetane number.

Diesel fuel derived from crude-oil differs substantially from CN45 in a number of the properties listed in Table 1. Apart from cetane number, the proportions of the hydrocarbon groups of which the two fuels are composed are different, with crude-oil diesel having a lower percentage of aromatics and a higher percentage of paraffins. However, in spite of the higher percentage of aromatics, the carbon-to-hydrogen molecular ratio was lower for CN45, suggesting a greater reactivity.

Table 1: Composition and properties of the test fuels

PROPERTIES	TEST FUELS			
	CN45	CN47	CN49	COD
Cetane no.	45,3	47,2	49,2	50,8
Cetane improver (% vol)	—	0,06	0,13	—
Aromatics (% vol)	28	28	28	20
Olefins (% vol)	1	1	1	2
Paraffins (% vol)	69	69	69	73
Oxygenates (% vol)	2	2	2	5
Carbon/hydrogen mole. ratio*	0,494	0,494	0,494	0,567
Gross calorific value (kJ/kg)	46109	46109	46109	45274
Density at 20 °C (kg/L)	0,811	0,811	0,811	0,853
Viscosity at 40 °C (mm² /s)	2,1	2,1	2,1	3,8
ASTM distillation at 760mm Hg: Initial boiling point (°C)	186	186	186	174
5%	190	190	190	217
10%	194	194	194	230
20%	204	204	204	254
30%	214	214	214	269
40%	222	222	222	281
50%	233	233	233	292
60%	244	244	244	305
70%	261	261	261	321
80%	282	282	282	335
90%	323	323	323	**359
95%	>350	>350	>350	>350
Final boiling point (°C)	>350	>350	>350	>350
% Recovered	93	93	93	—
% Residue	6	6	6	—

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*Dept of Agricultural Engineering, University of Natal, P O Box 375, Pietermaritzburg 3200, South Africa
**Atlantis Diesel Engines, P O Box 1222, Cape Town 8000, South Africa

*   — Measured by Department of Chemistry, University of Natal, Pietermaritzburg.
**   — Crude-oil diesel cracks at 91% at 380 °C.
COD   — Crude-oil diesel.

The presence of heavier hydrocarbon molecules in the crude-oil diesel, which were probably paraffinic, caused the 90% recovery to occur at a higher temperature. The calorific value of CN45 was approximately 2% higher than that of crude-oil diesel, while the viscosity was 45% lower. Figure 1 illustrates the distillation curves for CN45 and crude-oil diesel. It is evident that CN45 has a higher volatility than crude-oil diesel. A 60% recovery is achieved before 250 °C is reached in the case of CN45, whereas less than 20% crude-oil diesel fuel is recovered by the same temperature.
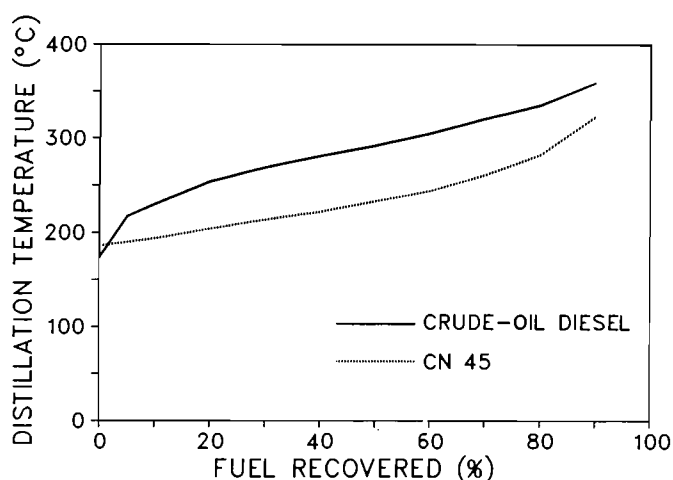

Figure 1: Percentage fuel recovered versus distillation temperature for fuel CN45 and crude-oil diesel

Lefebvre[1] emphasised that both physical and chemical properties should be considered when assessing the impact on combustion performance of a change in fuel type. He pointed out that the physical properties of importance were those which governed fuel evaporation rates, namely volatility and viscosity. The mean drop size of the drops in the spray was influenced significantly by viscosity, with a higher viscosity delaying the onset of atomisation after fuel injection by resisting break-up of ligaments in the spray. In general, evaporation rates were inversely proportional to the square of mean drop size. Hence, with CN45 it would be expected that the onset of atomisation of the fuel jet would occur earlier than for crude-oil diesel. The size of the fuel drops would also be smaller, thus leading to a greater overall droplet surface area and increasing the evaporation rate of CN45 as compared to crude-oil diesel. These effects should promote the rate of preparation of fuel for combustion to take place. The lower ignition quality of CN45, as compared to crude-oil diesel, could be offset by a higher rate of physical preparation of CN45 after the start of injection when tested in a production engine. The object of this project was to investigate the effects of these and other differences on both combustion and engine performance with varying engine load conditions and with varying altitude.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Engine and Instrumentation

All the testing was carried out on a naturally aspirated ADE 4.236 engine which was typical of those used in the majority of agricultural tractors and in numerous light transport applications. The engine was mounted on a test bed with a conventional cooling system and was loaded by an AW dynamometer which provided measurements of torque and speed. Fuel consumption was measured with the aid of a Micro-Oval flowmeter. Important steady-state temperatures that were monitored included oil temperature, coolant temperature, exhaust temperature, fuel temperature and intake air temperature at the inlet valve. Correlations of air flow rate with engine speed were established from laboratory tests with a parabolic orifice at the air inlet in conjunction with a surge chamber to eliminate pulsations. These correlations were then applied to the data in the determination of volumetric efficiency which was a significant variable in the computation of heat release rates of the fuel.

Cylinder pressure was monitored by a Kistler 6121 pressure transducer mounted flush with the cylinder head and positioned in line with the piston bowl lip. Injection timing was determined from the signal of a needle-lift transducer of the inductive type, and crank rotation was monitored with an optical shaft encoder providing a top dead centre (TDC) reference and trigger pulses at each half degree crank angle increment. These pulses were used to trigger the data acquisition system to capture the data.

A multi-channel data acquisition system described by Hansen et al.[2] was used to monitor and record the signals emanating from the numerous transducers. The system incorporated a means of recording both high-speed and steady-state variables simultaneously, as well as the display, processing and storage of data.

The engine and dynamometer which were mounted on the same frame were transported from site to site on the back of a truck, while the data acquisition system was carried out separately. Hence it was necessary to arrange the links between the transducers on the engine and dynamometer, and the data acquisition system so that connection and disconnection at each site was efficient and reliable.

Test Procedure

A rigorous calibration and test procedure was established in order to clarify the differences between fuels. An attempt was made to test the fuels under approximately the same ambient conditions from day to day by testing during the same period each day at each site. Table 2 provides details of the three sites and their altitudes. The first test was carried out at the Agricultural Engineering laboratories situated at Ukulinga Research Farm of the University of Natal, and this test was repeated at Ukulinga as a check to isolate any changes in the response of the instrumentation that might have occurred during the course of the tests at the other altitudes.

Table 2: Sites and altitudes of engine tests

Site	Altitude Height (m)	Difference (m)
1. Mt Edgecombe	100	700
2. Ukulinga	800	590
3. Weston	1390	

At the commencement of each test the engine was warmed up until the thermostat for regulating the coolant opened. The speed and torque were calibrated and checked again after each test. After noting ambient pressure and temperature, steady-state and high-speed data were recorded systematically at the 17 load points covering the torque-speed range of the engine.

The steady-state data included speed, torque, fuel consumption and oil, coolant, exhaust and inlet manifold temperatures, as well as smoke density. High speed data capture involved the recording and averaging of 89 consecutive cycles of cylinder pressure and needle lift data with a drift in steady-state conditions of less than 2%.

Heat Release Model

The heat dissipated in the combustion chamber is the result of the exothermic reaction between the molecules of fuel and the oxidant contained in the air. Therefore the heat released gives a direct indication of the combustion rate. Heat release models are useful tools in the assessment of combustion quality. The objective of this work was to compare the combustion quality of different fuels without striving for absolute measurements. A zero-dimensional heat release model based on that of Hayes et al.[3] was applied in the combustion analysis of the fuels. As the model made use of measured combustion pressure, it was diagnostic rather than predictive in form.

Hayes et al. concluded that this simple model was a good diagnostic indicator for the quality of the cylinder pressure data. However, the heat release analysis was sensitive to the values of initial cylinder mass and residual. Only three inputs were required by the model:

(a) engine speed,

(b) an experimental cylinder pressure history, and

(c) an estimate of the initial mass in the combustion chamber.

Since its application by Hayes et al.[3], the model has been used in projects related to the combustion of alternative fuels by a number of researchers including Clevenger et al.[4], Lehman[5], and Savage et al.[6]. In each project the model has demonstrated its simplicity and value as a diagnostic tool for investigating alternative fuels for diesel engines.

The simple heat release model was based on the first law of thermodynamics without chemical equilibrium. Hayes et al. made the following assumptions for the derivation of the model:

(a) Gas properties were uniform throughout the combustion chamber.

(b) Specific heat of air was calculated as a function of bulk gas temperature in the combustion chamber.

(c) Heat transfer to the wall was modelled by a uniform heat transfer coefficient.

(d) Wall temperatures were assumed to be constant and equal for all surfaces.

(e) The effects of combustion were simulated by an equivalent heat transfer rate.

(f) No dissociation of chemical species was taken into account.

The following equation was used to determine the apparent rate of heat release:

$$\frac{dQ_{HR}}{d\Theta} = \frac{\gamma}{\gamma - 1} \; P.\frac{dV}{d\Theta} + \frac{1}{\gamma - 1} \; V.\frac{dP}{d\Theta} - \frac{dQ_W}{d\Theta}$$

where:

Θ — crankshaft angle,

$\dfrac{dQ_w}{d\Theta}$ — rate of heat transfer to cylinder walls,

P — cylinder pressure,

V — cylinder volume, and

— polytropic exponent or specific heat ratio.

The equation was solved by using measured cylinder pressure and rate of pressure change, calculated from the experimental data along with the cylinder volume and the rate of change of cylinder volume. A number of refinements and improvements to the model of Hayes et al. were carried out. Hayes et al. indicated that their model was sensitive to the values of initial cylinder mass and residual fraction, and improved methods for estimating these quantities needed to be developed. Savage et al.[6] calculated the initial mass in the chamber using the ideal gas law with the temperature of air at 350K at the closing of the intake valve. Lehman[5] also used the ideal gas law in determining the initial mass. However, he used atmospheric temperature and pressure and the displacement volume as well as a volumetric efficiency factor set at 0,87. Lehman accounted for the residual mass by increasing the initial mass by 5%.

In this study, measured volumetric efficiency was used rather than the assumption of a particular value. Volumetric efficiency was determined for the engine over a range of engine speeds. The results were used to determine a regression equation which was added to the model to incorporate the effect of speed on volumetric efficiency. An investigation was also carried out to analyse the influence of engine torque on the volumetric efficiency. The result showed that torque had a minimal effect when compared to engine speed. A regression equation was developed that was based on speed only and neglected the small effects on volumetric efficiency resulting from an inlet air temperature increase with increased load. However, the effect of inlet temperature was included by using the ideal gas law in calculating the mass of air in the cylinder at inlet valve closing.

A further improvement to the model was the calculation of the percentage fuel mass burnt during the cycle. This calculation required the input of the carbon-hydrogen-oxygen (CHO) ratio and calorific value of the fuel and also the fuel consumption rate.

The percentage fuel mass burnt when accumulated over the cycle provides a means of accounting for the total heat generated by the fuel calculated via the heat release model as compared to the actual potential heat supplied to the combustion by the injection of fuel. Theoretically, if all the heat were accounted for, the percentage fuel mass burnt would be 100%. However, inaccuracies in the measured variables such as engine speed and fuel consumption and in the calculated variables such as initial mass and heat transfer rates will cause the percentage mass burnt to deviate from 100%. Nevertheless, this variable provides a valuable means of checking the differences and of comparing different fuels. The summation of the energy release was initiated at the start of combustion and

terminated at 60 degrees crank angle after top dead centre. Based on calculations of heat release rates from ignition to exhaust valve opening, very little heat is released at high loads beyond 60 degrees crank angle after top dead centre. The error incurred from this assumption was regarded as negligible.

In addition to calculating the percentage of mass of fuel burnt, various methods of separating the premixed portion of the heat released from diffusive burning and quantifying these portions were investigated. Theoretically, there is an overlap of the two phases during the initial stages of burning. Hansen et al.[7] assumed that the diffusion burning started at the end of premixed combustion, thus ignoring the portion of diffusion burning taking place before this point.

The procedure used in this analysis for determining the percentage of premixed heat release relies on two assumptions. Referring to Figure 2, it was assumed that the shape and therefore the rate of heat release in the premixed phase was symmetrical about the first peak rate of heat release. This assumption meant that the premixed rate of heat release increased and decreased in an identical pattern. It also defined the end point of the premixed burning on the heat release curve.

Secondly, it was assumed that the rate of diffusion burning increased linearly from zero to meet the point defining the end of premixed burning as shown in Figure 2. Although it was more likely that this rate of burning would be non-linear, no research has been done to define this curve experimentally because of the difficulty of separating the two modes of burning. While the proposed method did not provide a very accurate indication of the division between the two modes, it did supply a satisfactory estimate via a simple calculation procedure. For carrying out comparisons of combustion between fuels this approach was regarded as acceptable and superior to many other methods of quantifying the premixed and diffusion phases of burning.
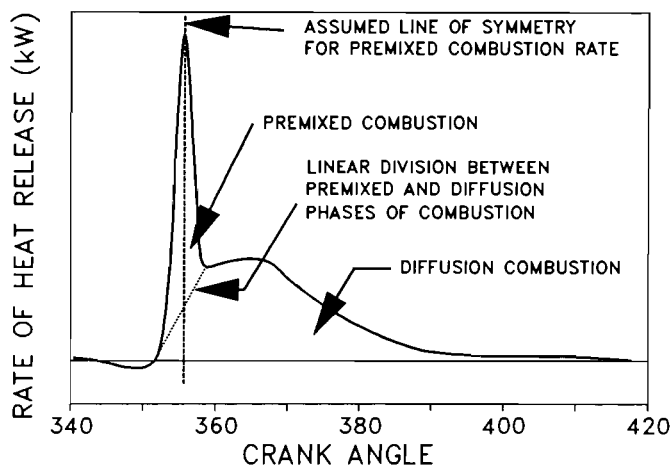

Figure 2: The division of the premixed and diffusion phases of combustion

The use of the pressure derivative in the heat release model required that the pressure trace be averaged and smoothed. Any slight disturbances in the pressure data would cause oscillations in the pressure derivative and hence the calculated heat release[8]. Lehman[5] included a spline-smoothing algorithm in his model to smooth the pressure data. The same algorithm was used in this model. The pressure data were also averaged before smoothing over a large number of cycles to reduce further the inaccuracies resulting from a disturbed pressure trace.

The original model by Hayes et al.[3] incorporated the specific heat capacity for air which was based purely on the bulk gas temperature. The specific heat capacity was then used to determine the polytropic exponent. However, Gülder[9] developed a set of empirical equations for the specific heat capacity of combustion gases. The equations incorporated the effects of pressure, temperature, equivalence ratio, and the hydrocarbon molecular ratio on the specific heat capacity. The Gülder empirical equations were incorporated in the heat release model, replacing the original procedure for determining specific heat.

RESULTS AND DISCUSSION

During the testing of the four fuels, which took place in the middle of winter, no cold-or hot-start problems were encountered. The engine started immediately on all the fuels at the three altitude sites.

The results from only three load points were selected to illustrate the differences between fuels at each altitude. These points were selected so that results could be obtained for two engine torques, 50 Nm and 200 Nm, at 2200 r/min, the rated speed of the engine. The third point was also at 200 Nm but at a lower speed of 1500 r/min, which coincided with the speed at maximum torque. The effects of changes in load at constant speed and of changes in speed at constant load could therefore be examined. The torque value of 200 Nm was close to the maximum at rated speed and therefore represented the point where maximum thermal stress of the engine was likely to occur.

The low load of 50 Nm was used as opposed to no load because, at the no load condition, combustion from cycle to cycle tended to be erratic. In some cycles no combustion took place at all. Hence the averaged pressure obtained from 89 cycles was not representative of the actual combustion taking place. Therefore heat release computations which were strongly dependent on the measured pressure were inaccurate. By placing a low load on the engine a more stable running condition was achieved.

Engine Performance

At all the load settings the speed and torque varied by less than 2% from the target values. Figure 3 illustrates the variation in specific fuel consumption at each altitude for each fuel at the three load conditions. As expected, the specific fuel consumption decreased as the load was increased, and at the lower speed which coincided with the point of maximum torque the values were close to the optimum for the engine. At the load of 200 Nm it was apparent that the specific fuel consumption tended to increase as the altitude increased. Again this trend was expected as the reduced air density at the higher altitudes caused less efficient combustion and therefore less power to be produced per unit of fuel consumed.

Referring to Figure 3, it can also be seen that there is a reversal in trends for the low load setting as the specific fuel consumption decreases from an average for the four fuels of 438 g/kWh at the lowest altitude to 419 g/kWh at the highest altitude. As described later, this improvement in engine efficiency at light loads for the higher altitudes was ascribed to a greater percentage of energy released from the fuel earlier in the expansion stroke of the engine.
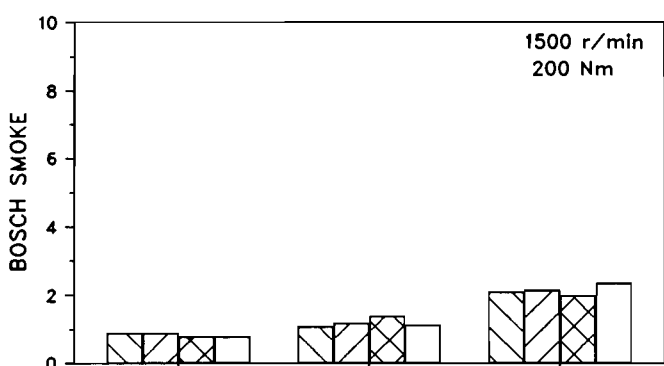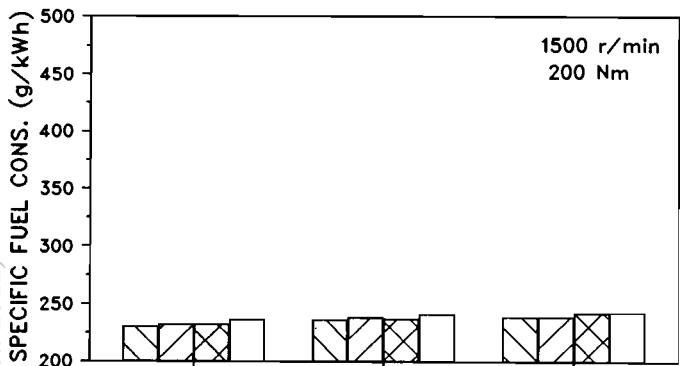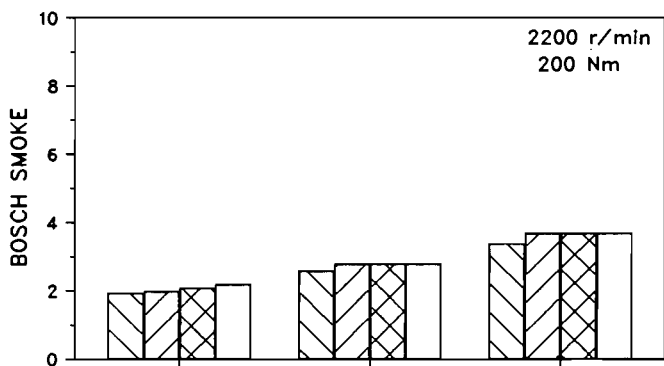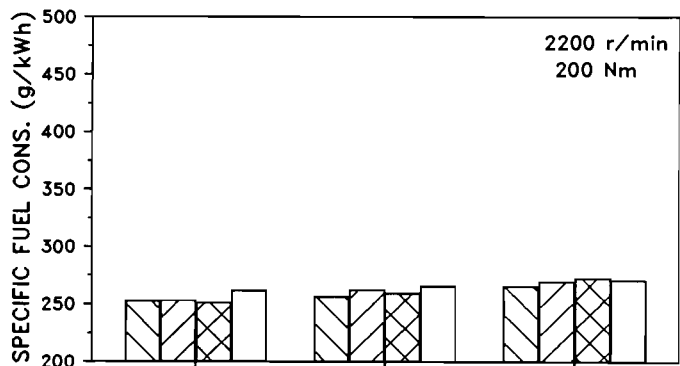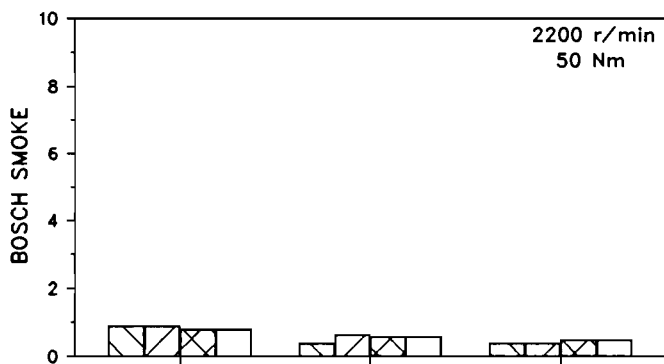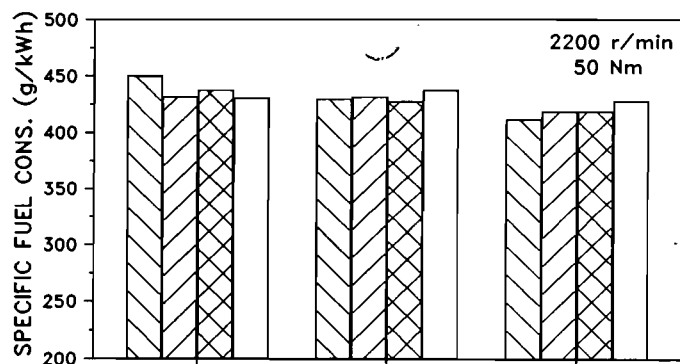
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Figure 3: Variation of specific fuel consumption and Bosch smoke density with altitude at three load settings for four test fuels

At the load of 200 Nm it was evident from Figure 3 that crude-oil diesel caused a higher specific fuel consumption than CN45 at all the altitudes. These differences were partly due to the slightly lower calorific value of crude-oil diesel. Fuels CN47 and CN49 tended to be similar to CN45, although at the highest altitude and at the engine speed of 2200 r/min and a load of 200 Nm the specific fuel consumption appeared to increase with the addition of ignition improver. Under high load conditions it was concluded that CN45 used at the higher altitudes should result in approximately the same power output per unit mass of fuel as crude-oil diesel fuel at low altitudes. However, the variations illustrated in Figure 3 were small and would not be detected by an engine operator under practical conditions.

The measurements of smoke density also provided some distinct trends with altitude, as shown in Figure 3. These trends tended to follow the variations measured in specific fuel consumption. The smoke density increased as the load was increased. Also, as the altitude increased, the smoke output increased at the high load but decreased at the low load. These variations could be expected as, with a decrease in efficiency, the smoke output normally increases due to the less efficient combustion. Again, at the higher loads the smoke output caused by crude-oil diesel was generally slightly higher than for CN45. This effect was attributed to the higher viscosity of the crude-oil diesel fuel and to the heavier fractions of hydrocarbons it contained. It was concluded from Figure 3 that differences caused by changes in altitude were significantly greater than differences observed between fuels.

An overall assessment of the engine performance on the four fuels indicated that in spite of the variation in cetane number the differences between the fuels were not significant. No distinct advantages relative to altitude could be isolated for particular fuels. Nevertheless, it was necessary to establish the effects of the fuels on the engine to a greater depth by analysing the combustion characteristics.

Combustion Analysis

The primary objective of the project was to investigate the effect of altitude on the ignition quality requirements of diesel fuels. Therefore it was appropriate as a first step to investigate the effects of ambient conditions at the different altitudes on the ignition delay characteristics of the fuels. This analysis was of particular importance as cetane number, which is related to ignition, is still the universally accepted method for describing the combustion quality of diesel fuels.

The ignition delays for three load settings are illustrated in Figure 4. Ignition delay was based on the time lapse between the start of injection and the point at which the computed energy release rate first became positive. On average the ignition delays at the high load and high speed setting are the shortest as a result of higher bulk gas temperatures which assist in the preparation of the fuel for combustion.

A relatively small increase in ignition delay occurs when moving from the lowest to the highest altitude for all three test points. This expected trend was attributed to reduced air density as well as temperature and pressure in the combustion chamber, thus affecting the fuel preparation phases in the ignition delay period.

A survey of the results in Figure 4 indicated that in general, at the higher load, the two fuels with the ignition improver were less affected by altitude than the other two fuels. This result would indicate that the ignition improver, regardless of the differences in altitude, continued to provide the necessary chemical radicals that participate in the precursive reactions during the ignition delay. Except for the low load condition, CN45 exhibited ignition delays that were generally much the same as crude-oil diesel. It was possible that this similarity was caused by a higher rate of physical preparation of CN45 to offset its lower ignition quality when tested in the direct injection ADE 236 production engine, as opposed to the engine that is used to measure cetane values. In addition, the synthetic fuel was still able to produce the necessary radicals to prevent any reduction in the rate of chemical preparation of the fuel.

Turning to the combustion events after the ignition delay, the variables of importance that were related to the measured combustion pressure were the peak pressure and the maximum rate of pressure rise. Taylor et al.[10] concluded that peak cylinder pressure was the single variable that provided the best correlation with thermal loading and hence with engine life. Therefore it is important to examine the results for this variable closely. Figure 5 illustrates the peak pressure and maximum rates of pressure rise obtained for the three load conditions. It should be noted that the axes for the peak pressures have been expanded so as to amplify the differences.

It is evident from Figure 5 that there is a significant decrease in peak pressure with altitude at all three load points. The average peak pressure for the four fuels was determined for each altitude and is illustrated in Figure 6. It can be seen that the relationship between peak pressure and altitude is almost linear. The decrease in pressure
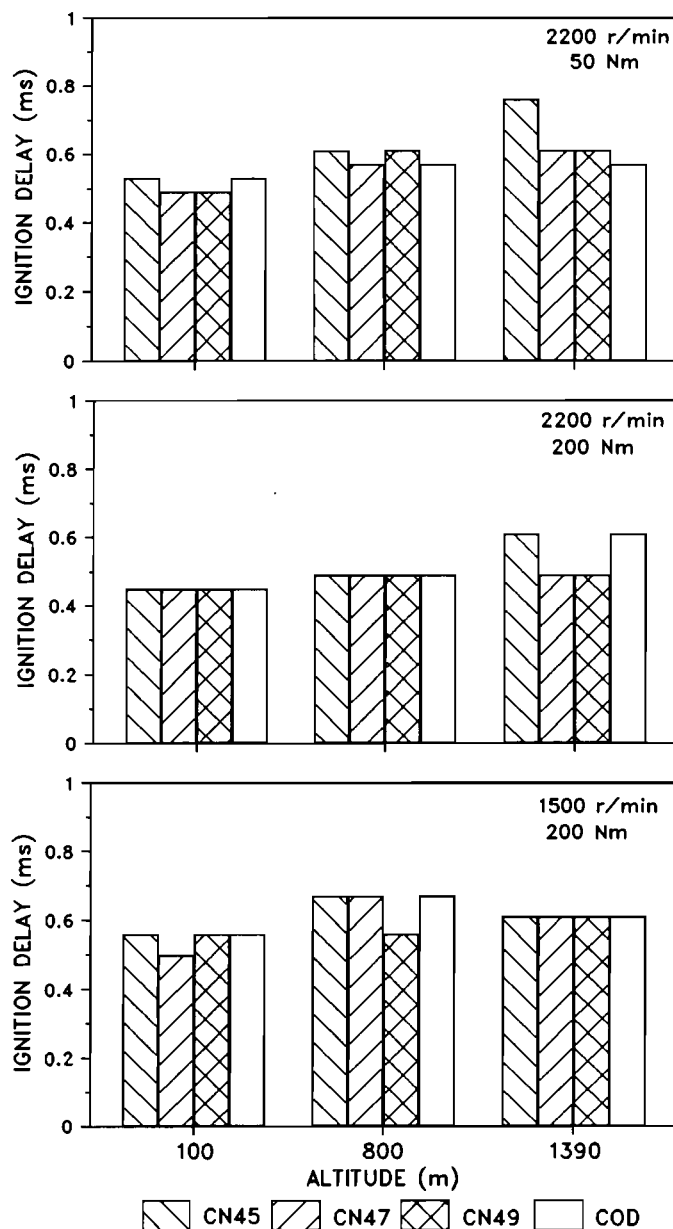

Figure 4: Variation of ignition delay with altitude at three load settings for four test fuels

from lowest to highest altitude was approximately 6% and 8% at the high load and 17% at the low load.

Differences in peak pressures between fuels were noticeably smaller than differences caused by the changes in altitude. No distinct trends could be isolated at the high load. However, at the low load, the peak pressure within the synthetic fuels generally increased as cetane number increased. This increase appeared to be greater at the higher altitudes, as shown in Figure 5. Crude-oil diesel fuel produced the lowest peak pressures at the low load setting.

With reference to engine stress, it was concluded from the peak pressures that the synthetic fuels would have no worse effect on engine life than crude-oil diesel within the altitude range of 0 to 1400 m. It was also evident that engine stress was less at the higher altitudes, which would imply that lower cetane fuels could be tolerated at the higher altitudes.
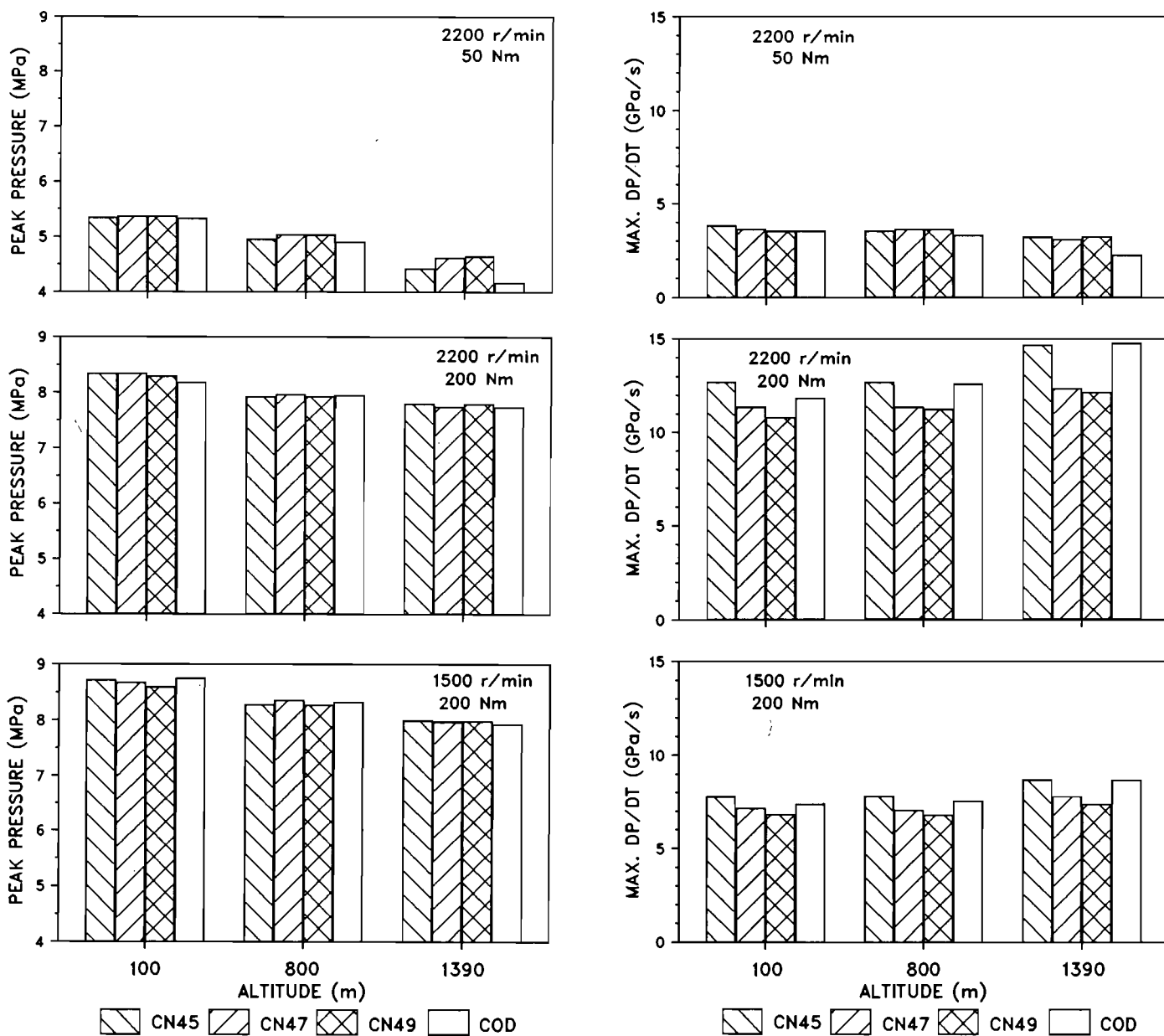
Figure 5: Variation of peak pressures and maximum rates of pressure rise with altitude at three load settings for four test fuels
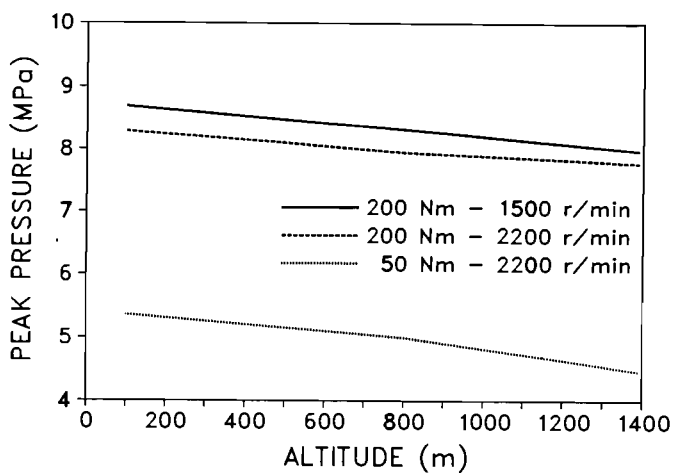

Figure 6: Average peak pressure versus altitude for three load settings

The maximum rates of pressure rise, which have been regarded previously as an important indicator of thermal stress, exhibited greater variations than peak pressures, as shown in Figure 5. The combination of the highest speed and highest load caused the greatest rate of pressure rise. Some definite trends were evident with respect to altitude. At the lowest load there was a decrease in maximum rates of pressure rise as the altitude increased, with crude-oil diesel exhibiting the greater rate of decrease. The maximum rates of pressure rise of the synthetic fuels as a group decreased at a much lower rate with increasing altitude at the lower load. At the higher load the maximum rates of pressure rise increased with increasing altitude, with crude-oil diesel and CN45 experiencing approximately the same rates of increase, while the synthetic fuels with ignition improver provided much slower rates of increase. The differences between crude-oil diesel and CN45 at the higher load were regarded as insignificant. Chan et al.[11] indicated that combustion noise was directly related to the rate of pressure rise in the cylinder. Hence CN45, even with its lower cetane number, should generate the same levels of combustion noise as crude-oil diesel.

Maximum rates of pressure rise are also directly related to peak rates of energy release in the combustion chamber. Hence the conclusions that can be drawn from the results in Figure 5 are that the ignition improver is an efficient attenuator of maximum rates of energy release and that
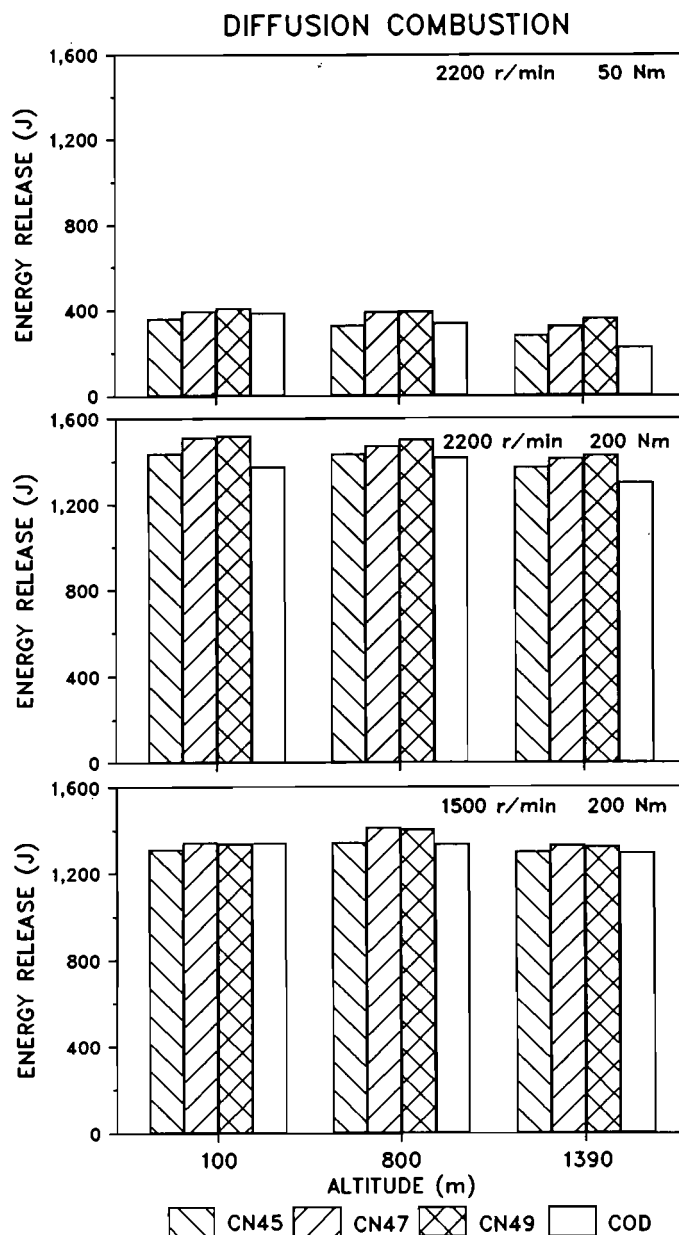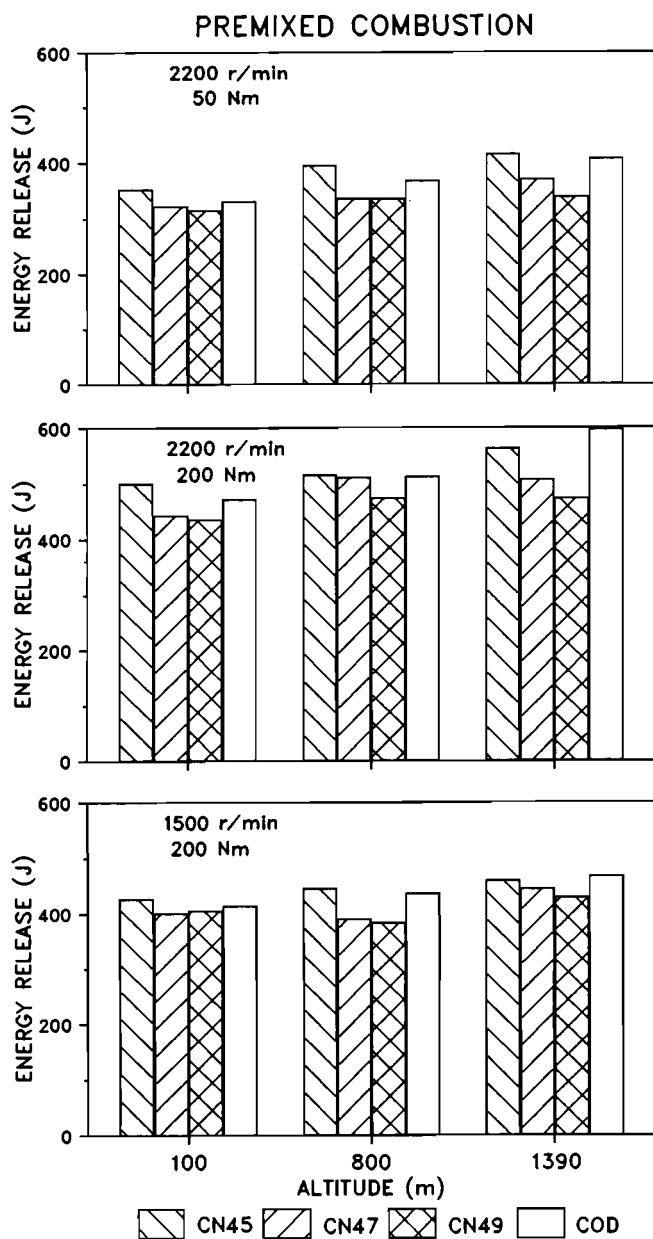
Figure 7: Variation of premixed and diffusion energy released with altitude at three load settings for four test fuels

this property becomes more effective as the altitude is increased. It is also apparent that there is a fairly major step down in maximum rates of pressure rise from CN45 to CN47 but a somewhat smaller decrease from CN47 to CN49. This result would indicate that the ignition improver is less effective with increasing concentrations in reducing rates of pressure rise.

Analysis of the rates of heat release provided some definite trends between fuels and relative to altitude. Figure 7 shows results of the premixed energy released and the diffusion energy released for the three load conditions. At the light load approximately equal portions of energy are released in the two phases due to the small amount of fuel injected. However, as the load is increased, more fuel is injected after the start of combustion, causing more diffusion burning to take place. Hence, at 200 Nm a major portion of the burning occurs in the diffusion phase, as illustrated in Figure 7.

At all three load conditions the energy released in the premixed phase increases with increasing altitude for the crude-oil diesel fuel. The same trend applies to the synthetic fuels but not as consistently. Within the group of

synthetic fuels it is also evident that in virtually all cases the premixed energy released decreases as the cetane number increases. This would be expected as the ignition delay would tend to be reduced by the ignition improver causing a shift in energy released from the premixed phase to the diffusion phase. The diffusion burning results in Figure 7 support this observation. An increase in the proportion of energy released in the diffusion phase would cause a decrease in energy efficiency as it would imply a shift in energy released to later in the expansion stroke. In addition, an increase in smoke output might be expected with burning later in the expansion stroke as combustion temperatures decrease, thus making it difficult to sustain combustion. Referring back to the engine performance results, these effects are partly evident.

CONCLUSIONS

1. Differences in engine performance were greater relative to altitude than between fuels. The differences between fuels were not significant.

2. None of the combustion variables that were measured

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or calculated could be correlated consistently with cetane number, thus emphasising the inadequacy of the cetane scale in quantifying the combustion quality of Sasol fuels and of fuels containing ignition improver.

3. The differences between fuels in terms of peak cylinder pressure, which correlates strongly with thermal stress in the engine, were distinctly smaller than differences caused by the changes in altitude. Peak pressure and hence engine stress were less at the higher altitudes, which suggested that lower cetane fuels could be tolerated by engines at the higher altitudes. The fuel CN45 exhibited a higher peak pressure than crude-oil diesel at the lowest altitude under the highest engine load, thus supporting the use of lower cetane fuels at high rather than at low altitudes.

4. The ignition improver is an efficient attenuator of maximum rates of pressure rise and hence of energy release, and this property becomes more effective as the altitude is increased. As the concentration of ignition improver is increased, the effect it has in reducing rates of pressure rise decreases.

5. The fuel CN45 compared very favourably with crude-oil diesel of CN50,8 with respect to all the engine performance and combustion variables measured at all four altitudes.

6. On the basis of these results, we believe that it would be worthwhile to investigate the possibility of marketing lower cetane fuels particularly for use at high altitudes.

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PHOSPHATIC DEPOSITS IN BOILERS USING SOUTH AFRICAN COALS

*R K DUTKIEWICZ

Phosphatic bonded deposits in boilers using South African coals are more prevalent than in boilers using northern hemisphere coals. It is postulated that the incidence is due to the high phosphorus content of South African coal, but the susceptibility to deposit formation is a function not only of phosphorus but also of the boron and fluorine content of South African coals.

KEYWORDS: boiler deposits; phosphatic

INTRODUCTION

Deposits on boiler tubes have manifested themselves on numerous occasions causing serious operating problems. A great amount of interest has been focused on the so-called "high-temperature bonded deposits" which occur under certain critical conditions of temperature, usually in the superheater or re-heater, though a number of deposits have occurred in the furnace itself. These deposits form at temperatures appreciably below the fusion temperature of the ash and it is therefore difficult to predict their occurrence purely from a knowledge of the ash characteristics. Such deposits are particularly troublesome because they obstruct gas flow and are difficult to remove.

The characteristics of the high-temperature bonded deposits are that they consist of a relatively thin inner layer of distinctive appearance and composition, and an outer layer which is often more friable than the inner layer and often consists of normal ash. The inner layer is firmly attached to the tube or other metal surface and shows signs of having been produced from a liquid phase. The outer layer forms the bulk of the deposit, though the material of the inner layer often extends into the outer layer as a bonding agent.

Such bonded deposits have been classified into four main types: alkali, calcium, silica, and phosphatic, depending on the principal bonding agent, though a number of types can co-exist in one bonded deposit. All the types appear to originate from volatilisation of compounds in the coal, one then being selectively deposited on a surface. These deposits are therefore high in concentration of the chemical which acts as the bonding agent, and much higher than the concentration of the chemical in the coal or in the ash. The process is complicated by chemical reactions which occur during combustion or during deposition on the heating surface. Thus the metal of the surface can take part in the final reaction or can act as a catalyst for the formation of the bonded deposit.

Deposits rich in phosphorus have been identified in certain stoker-fired boilers, though reports from European experience show that the occurrence is rare. Phosphorus is

*Director, Energy Research Institute, University of Cape Town, P O Box 33, Plumstead 7800, South Africa

present in coal usually as the mineral fluorapatite $[CaF_2.3Ca_3(PO^4)_2]$ which readily loses fluorine as hydrogen-fluoride when heated in moist air. Under reducing conditions and at temperatures above 1600 °C, elemental phosphorus is evolved. It was originally postulated that oxidation in the presence of water vapour could produce pyrophosphoric acid $[H^4.P^2.O^7]$ which could condense on boiler surfaces and react with ash to form hard insoluble crystalline phosphate. The mechanism is probably more complicated than this and will be discussed in more detail later.

Because of the relatively rare occurrence of phosphatic deposits in Europe, little basic research has been carried out on this deposit form compared with the amount of work carried out on other deposits.

One of the most thorough pieces of research carried out in the field of boiler deposits is the work of the Boiler Availability Committee (BAC) during the period 1946 to 1951[2,3,4,5]. They classified deposits into the high and low temperature types and postulated the formation mechanism for each type of deposit. The BAC also carried out research on an experimental boiler with a travelling grate and a steaming capacity of 10 000 kg/hr, and a pressure of 68 bar.

Arising out of their work, they classified British coals into high, medium, and low categories in terms of their chlorine, sulphur, and phosphorus constituents. They recommended that coals in the high category should be avoided in order to maintain trouble-free operation. Their classification is given in Table 1.

Table 1. Coal classification proposed by the Boiler Availability Committee[5]

Constituent	Classification limits (% in coal)		
	High	Medium	Low
Chlorine	>0,30	0,15 - 0,30	<0,15
Sulphur	>1,80	1,30 - 1,80	<1,30
Phosphorus	>0,03	0,01 - 0,03	<0,01

They also correlated various deposit problems with elemental contents and analysed the deposits formed. Their analysis of deposit constituents for coals with a high phosphorus content showed that the maximum phosphorus concentration was in deposits on the top of the superheater, and this concentration was 0,9%.

Comparison of South African coals with the BAC recom-

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mendations would show that most of them are in the high category for phosphorus and 85% of Witbank coals would not be acceptable in terms of the BAC recommendations.

It is apparent therefore that either South African coals are very different from U.K. coals in their propensity to form phosphatic deposits, or else the BAC accepted a nominal phosphorus concentration since the incidence of such deposits was rare, and therefore did not warrant more research to determine the true danger level for phosphorus. It will be shown later however that the formation of phosphatic deposits is not only a function of the phosphorus content.

PHOSPHATIC DEPOSITS IN SOUTH AFRICA

Incidence of deposition

Since, in terms of the BAC classification, 85% of South African coals should be causing phosphatic deposits, it is necessary to determine the incidence of such deposits in South Africa. However, information on the occurrence of phosphatic deposits is poor, mainly due to the fact that they are often not recognised as being phosphatic, and are lumped in the general category of bonded deposits.

The earliest report on phosphatic deposits was the work of de Villiers at Pretoria Power Station in 1950, followed by the work of Osborne at Johannesburg's Orlando Power Station in 1952. Both these investigations were on water-tube boilers, and whilst the mechanism of bonded deposit formation is applicable, there was no equivalent work on shell boilers until the pioneering work of Darazs and Clark[6] in 1976.

Additional work has also been carried out by the Natal Associated Collieries on incidents of phosphatic deposition when using Natal — and specifically, Utrecht — coals. Early work was also reported by Eskom[10] from a number of power stations using water-tube boilers.

Work carried out by Walters and Breedt[12] on phosphatic deposits was aimed mainly at methods of alleviating phosphatic deposits. The work was carried out on a John Thompson 3-pass horizontal shell boiler with an evaporation of 4500 kg/hr. The coal used was Boschmans peas having a phosphorus content of the phosphorus of between 0,250% and 0,276%. This coal was chosen because it is known as the coal with the highest phosphorus content in the country. With no steam injection into the combustion chamber, the deposits had a P_2O_5 content of 30,7%.

Whilst there is ample evidence from this work that phosphatic deposits occur, there is little information from which the susceptibility of a particular coal to the formation of deposits can be determined.

Pretoria Power Station

The first significant report of phosphate bonded deposits is that of de Villiers[7]. This report was based on work carried out at the Pretoria Power Station, where severe deposits required the boilers to be cleaned every six months. This cleaning took three weeks to complete. The deposits occurred on the gilled tubes of the economiser and so decreased the cross-section for gas flow that after six months the boiler output had dropped by 40%.

From the tests carried out by de Villiers, it is evident that the maximum rate of deposit growth occurred immediately after the boiler had been cleaned, indicating that the temperature conditions might be optimal for condensation of the phosphatic constituent under bare tube conditions. Under such conditions the temperatures of interest are:

Temperature of gas: entering economiser 315 °C
leaving economiser 205 °C
Temperature of water: entering economiser 66 °C
leaving economiser 120 °C

Using these values and the results of temperature measurements on the gills of the economiser tube, it was computed that the deposit surface temperature was approximately 215 °C. However, additional tests with a boiler which was banked on a number of occasions, showed that the deposit grew faster under the banking procedure than under constant steaming conditions.

The amount of phosphate in the deposit was found to be between 14% and 40% in terms of P_2O_5, depending on the site from which the sample was taken. By comparison, the percentage of P_2O_5 in the ash from a sample of the coal used for firing was 0,7%.

De Villiers[7] postulated that the deposit originated from fluorapatite in the coal, the apatite being decomposed in the coal-bed on the grate by reaction with silica. The resulting phosphorus pentoxide gas reacts with water vapour to form meta-phosphoric acid which then deposits on surfaces below 315 °C. Subsequently ash will deposit on the layer of viscous phosphoric acid and will fuse and react with the acid to form a hard layer.

Orlando Power Station

At the same time as phosphatic deposits were being experienced at the Pretoria Power Station, similar problems were being experienced at Orlando Power Station in Johannesburg. These problems were reported by Osborne[9,11] in 1954.

This power station was commissioned in 1941, but for the first five years had very low steaming rates and no deposition problems. However, by 1946 there was evidence of serious deposition on the economisers of all boilers. The deposits were extremely hard and eventually the only way of removing the scale was to take out the economiser tubes and to de-scale them by turning in a makeshift lathe.

Comparison with deposition experience in British practice showed that, whilst the British deposits were predominantly sulphatic, the Orlando deposits were phosphatic. Analysis of the scale showed that the highest concentration was of phosphorus which, as P_2O_5, accounted for between 39% and 57% of the scale mass. Surprisingly, the next highest component was boron, as B_2O_3, which accounted for between 8% and 26% of the scale. X-ray analysis of the scale confirmed the presence of boron phosphate.

Osborne[9,11] carried out an analysis of the boron and fluorine content of the coals being used at Orlando, mainly New Clydesdale and Douglas coals, and found that the percentages of boron and fluorine were:

Table 2. Boron and fluorine content of New Clydesdale and Douglas coals

	In coal	In ash
Boron	0,0034%	0,011%
Fluorine	0,0096%	<0,005%

These figures and subsequent experiments on the reaction of the component constituents led Osborne to hypothesise that the reactions affecting the formation of phosphatic deposits involved boron fluoride as well as phosphates. He postulated that in the bed, in the presence of a reducing atmosphere, the apatite decomposes to calcium fluoride and calcium phosphate. In addition, calcium phosphate and silica react to form calcium silicate and phosphorus pentoxide. The boron compounds in the coal would initially react to form boron oxide and would thereafter react with calcium-silicon-fluoride, which would have been formed in the bed.

Fuel Research Institute

Work carried out in 1976 by Darazs and Clark[6] tried to simulate fouling deposits using an Adamson Triple Pass Economic Boiler. Originally Koornfontein peas were to be used but, due to difficulties in obtaining Koornfontein coal, Tavistock peas were used. This coal had a phosphorus content of 0,028%, together with a fluorine content of 0,004%, and a boron content of 0,028%.

The deposits which were obtained were relatively low in phosphate with most of the deposits being friable, with a phosphate content as P_2O_5, of between 2,3% and 3,1%. Only one sample was obtained which could be considered as phosphatic. This sample had a hard constituent layer and a P_2O_5 content of 12,6%.

Natal Associated Collieries

Work carried out by Coles[8] during the period 1977 to 1989 involved an assessment of phosphatic deposits in five water-tube and shell boilers using Natal Utrecht Region coals. An analysis was carried out on the various coals supplying these boilers and the phosphorus content was in the range 0,038% to 0,088%. The deposits had P_2O_5 concentrations of between 27,6% and 35,6%.

Eskom Power Stations

Bond and Wyndham[10] reported on bonded deposits in Eskom water-tube boilers in 1950. They detailed the phosphatic deposits in nine incidents over a period of two years. Two of the incidents were due to Natal coals, whilst the others were due to Witbank and Vereeniging coals. They detailed the chemical analysis of the deposits and remarked on the presence of high boron concentrations. However, they also commented on the low levels of potassium and sodium, and came to the conclusion that this supported the contention that ". . . alkali sulphates and phosphates play a very small part, and that aluminium and iron salts form the main bonding material".

The results of this investigation will be analysed in more detail later.

Other work

A further incident of phosphatic deposit occurred in 1986 in Cape Town with a boiler operating on Tavistock coal. A sample of the deposit obtained from the tube-plate showed a P_2O_5 concentration of 19,8%. Unfortunately no coal sample was available. A number of other incidents have been summarised in[19].
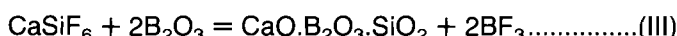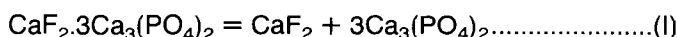
Summary

An analysis of a number of incidents of phosphatic deposits where deposit analyses have been made, shows that the deposit is rich in B_2O_3, silica, and alumina. There is very little sulphate or iron in the deposits. Figure 1 shows the relative concentrations of the main deposit constituents for a typical deposition incident.

It has been postulated that the main constituent of the bonded phosphatic deposit is boron phosphate. This has been demonstrated in the deposits at Orlando Power Station as reported by Osborne[9,11], but no other similar analyses have been made of the other deposits. The ratio of P_2O_5 to B_2O_3 in South African coals varies between 1,1 to 14,5 with the deposits from Natal coals being higher in phosphate than the Transvaal coals. Figure 2 has been drawn to show the relationship between the amount of boron and phosphorus in each of the deposits for which sufficient information is available. Superimposed on the graph is the line for the relationship of boron and phosphorus if the deposit had been purely BPO_4. It will be seen that all the Transvaal coal deposits lie close to the theoretical line, whilst two of the seven Natal coals can be considered as being sufficiently close to the BPO_4 line. It appears therefore that the Transvaal coals appear to fall into the deposit formulation mechanism proposed by Osborne, which results in a deposit mainly of BPO_4. The Natal coals have more boron than is required to satisfy the boron-phosphate relationship. The excess boron could be in the form of boron fluoride, but this requires further analysis. However, it is obvious from this analysis and that of the relationship between the various constituents in coal, which will be described later, that the Natal coals behave differently from the Transvaal coals.

MECHANISM OF DEPOSIT FORMATION

The most thorough analysis of the mechanism of phosphatic deposition has been carried out by Osborne[9]. The mechanism postulated can be divided into three sections: in the fuel-bed, in the gas stream, and on the tube.
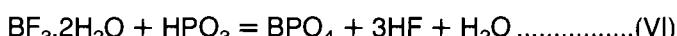
In the fuel-bed:

$$CaF_2.3Ca_3(PO_4)_2 = CaF_2 + 3Ca_3(PO_4)_2 \quad \text{......................(I)}$$

$$Ca_3(PO_4)_2 + 3SiO_2 = 3CaSiO_3 + P_2O_5 \quad \text{......................(II)}$$

$$CaSiF_6 + 2B_2O_3 = CaO.B_2O_3.SiO_2 + 2BF_3 \quad \text{..............(III)}$$

where the $CaSiF_6$ is formed in the fuel bed by the reaction of calcium fluoride and silica.

In the gas stream:

$$P_2O_5 + H_2O = 2HPO_3 \quad \text{..(IV)}$$

$$BF_3 + 2H_2O = BF_3.2H_2O \quad \text{..(V)}$$

and on the tubes:

$$BF_3.2H_2O + HPO_3 = BPO_4 + 3HF + H_2O \quad \text{................(VI)}$$

The origin of the phosphorus is assumed to be fluoro-apatite, a constituent of coals reported from the U.K.

Whilst the results of the reactions are consistent with the results found by Osborne[9], it is not clear whether this is the only route for phosphatic deposits or whether the final result might not depend on the relative concentrations of the various constituents of the coal, and especially phosphorus, boron, and fluorine. If the basic origin of the

phosphorus is apatite, then there is a fixed relationship between the fluorine and phosphorus in the coal. There is however no necessarily fixed amount of boron.

The mechanism represented by equation (II) above is different from that proposed by de Villiers[7] and it is the latter's version that is accepted by Kunstmann et al.[13]. Their form of the equation is:

$$Ca_3(PO_4)_2 + 3SiO_2 + 5C = 3CaSiO_3 + 5CO + 2P ..(VII)$$
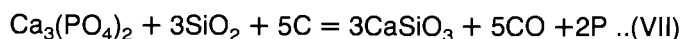
However, it does not matter whether it is the phosphorus or the phosphorus pentoxide which is liberated because under the conditions in the boiler both paths lead to the formation of meta-phosphoric acid.

The mechanism for the volatilisation of boron is however unclear. Osborne postulated that it is the formation of $CaO.B_2O_3.SiO_2$ which is a necessary step in the volatilisation of BF_3. This mechanism requires the formation of $CaSiF_6$ on the grate. However, Kunstmann et al. has pointed out that this compound is thermally unstable at the temperatures existing in a boiler. Experiments carried out by Kuntsmann et al. showed that $CaSiF_6$ begins to decompose at 200 °C and is completely volatilised by 500 °C. They therefore came to the conclusion that this could not be a mechanism for the production of BF_3. They postulate that the formation of BF_3 can occur by the direct volatilisation of B_2O_3 in the presence of calcium fluoride. This equation appears as:

$$7B_2O_3 + 3CaF_2 = 3CaB_4O_7 + 2BF_3 ....(VIII)$$
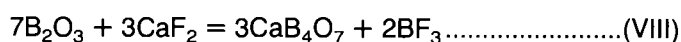
They also showed that all the fluorine present in the coal would be volatilised, part to BF_3 and the rest as HF.

It was found that B_2O_3 could also be volatilised at the conditions occurring on the grate, especially in the presence of a reducing atmosphere.

The results of their experiments led to the following conclusions:

(i) Neither the knowledge of the boron content of a coal nor its fluorine content can be used to predict how much boron will be volatilised.

(ii) Other factors affecting the amount of boron volatilised include the amount of boron, its state of combination, and the temperature prevailing.

(iii) The composition and flow rate of gases passing through the bed affect boron volatilisation. Whatever the mechanism of phosphoric acid and boron fluoride formation, the result is the deposition of meta-phosphoric acid. Deposition will occur at a dew-point depending on the concentration of the acid and on the ratio of P_2O_5 to H_2O in the flue gas. Dutkiewicz and de Kock[18] have shown that the "danger area" for phosphatic deposition is a surface temperature between 310 °C and 350 °C. Surfaces hotter than this are above the dew-point, whilst temperatures below this result in the deposition of acids which are so weak as not to be a problem. Temperature measurements in an operating shell boiler show that there is usually a large temperature gradient at the outlet of the furnace. Parts of the furnace outlet can be at the danger temperature even if the average temperature is below the danger limit. This would account for the success that has been achieved in steam injection into shell boilers to achieve improved availability. Such a procedure is described by Walters and Breedt[12]. The mechanism here is the increased turbulence in the boiler which results in a decrease in the

temperature gradient existing at the back end of the furnace.

On the cooled surface the phosphoric acid deposits with the boron fluoride to form boron phosphate. During this process ash being transported out of the furnace will tend to stick to the acid which is described as a viscous liquid. Chemical reaction between the ash constituents and the acid will result in a complex mixture of compound. These will be bonded into the matrix of boron phosphate, producing a hard layer.

The result is a hard scale which is not water-soluble and has a coefficient of expansion approximately equal to that of steel, resulting in a very tenacious layer.

CONSTITUENTS OF SOUTH AFRICAN COALS

Phosphorus

It has already been shown that South African coals have a much higher phosphorus content than European coals. It has also been shown that phosphatic deposition does not appear to start at the 0,03% phosphorus-in-coal limit set by the U.K. Boiler Availability Committee.

An analysis can be made of the levels of phosphorus in South African coals using the published data on coal analyses produced by the Division of Energy Technology of the CSIR[16,17]. The 1982 to 1985 data have been used for this analysis rather than the later 1987 data, since most of the incidents reported were earlier than 1987. Though a number were earlier than 1960, the relevance of the new data to those episodes could be queried. However, the reason for carrying out this analysis is to determine eventually how many coals are at risk of producing phosphatic deposits.

The data of [16] have been used, abstracting the values for either peas or smalls as being the coals of interest to operators of shell boilers. Figure 3 shows the percentage of collieries having a phosphorus content greater than the value on the abscissa.

It is evident that over 70% of South African coals are well over the limit of 0,03% set by the U.K. Boiler Availability Committee[5]. Half of the South African coals have a phosphorus content of greater than 0,07%, whilst 30% of coals have a concentration of greater than 0,1%.

The coals that have been known to give problems are shown in Table 3. The values of the phosphorus content for these coals have been obtained from the research carried out on the incidents of deposits or, where not available, have been abstracted from[16].

Table 3. Coals causing phosphatic deposits

Region	Colliery	%	Ref.
Witbank	Douglas	0,154	9,16
Witbank	New Clydesdale	0,081	9,16
Witbank	Boschmans	0,250	12
Witbank	Phoenix	0,202	16
Witbank	Witbank	0,122	16
S. Rand	Springfield	0,052	16
O.F.S.	Cornelia	0,155	16
Witbank	Tavistock	0,070	16

This table must not be taken as prescriptive, since some of the coal analyses have been taken some years after the relevant incident. Also, the phosphorus concentration is a

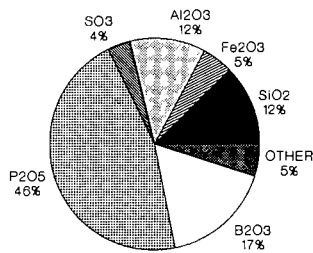**FIGURE 1. COMPOSITION OF BONDED DEPOSIT**
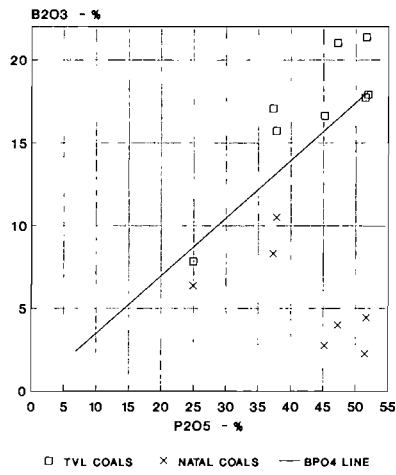

FIGURE 2. RATIO OF P AND B IN DEPOSITS

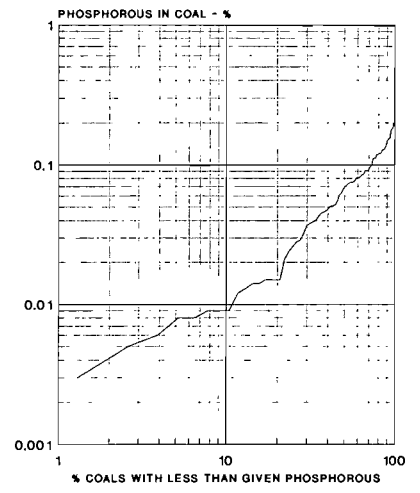**FIGURE 3. PHOSPHORUS IN S.A. COALS**

FIGURE 4. PHOSPHORUS AND BORON IN SOUTH AFRICAN COALS
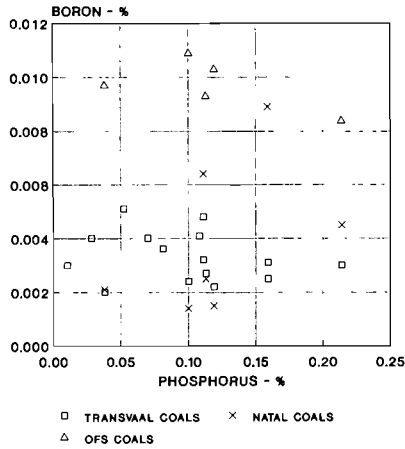

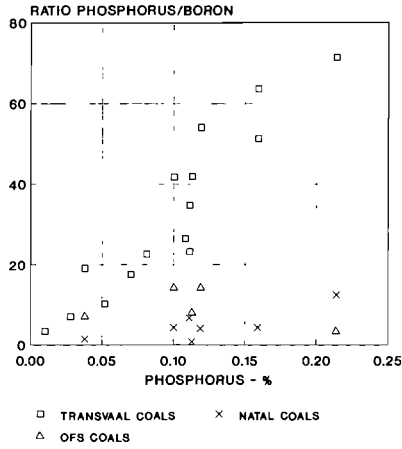**FIGURE 5. PHOSPHORUS AND BORON IN SOUTH AFRICAN COALS**

FIGURE 6. FLUORINE AND PHOSPHORUS WITBANK COALS (Kuntsmann et al.)
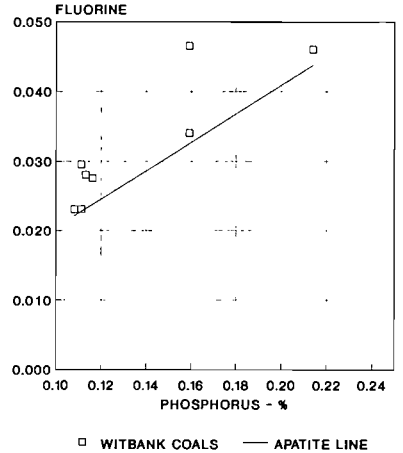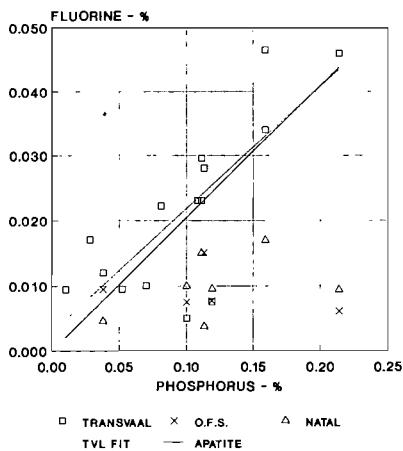

FIGURE 7. PHOSPORUS AND FLUORINE IN SOUTH AFRICAN COALS

function of the seam being mined. For instance, whilst Tavistock coal is known to have given problems, most of these occurred when a specific section was being mined. A change in locality removed the problem. Thus the Tavistock concentration of 0,070% is most probably not a phosphatic coal. The Springfield coal analysis was also carried out some time after the incident, and the concentration of 0,052% should not be taken as a lower limit of problem coals.

However, it would appear that any coal with a phosphorus content of more than 0,01% may lead to phosphatic deposition problems. This means that 30% of South African coals have a potential for phosphatic deposition.

Boron

It has already been shown that boron is an important constituent of phosphatic deposits. Kuntsmann et al.[13] carried out an analysis of boron and fluorine in certain South African coals in 1963. Of interest in the mechanism of phosphatic deposits is the ratio of boron to phosphorus. Unfortunately, Kuntsmann et al. did not analyse for this component. An analysis has therefore been attempted, as shown in[19], to compare the boron and phosphorus constituents of coal by using the data of Kuntsmann et al. or alternatively, of Boshoff[16].

No discernible trend could be found in these values. However, if the values are compared in terms of the ratio of phosphorus to boron, then there appears to be a general increase in the ratio with increasing phosphorus content.

Because of the small number of samples where boron and phosphorus were obtained, it was decided to increase the sample size by using all of the phosphorus values of Kuntsmann et al. and to add these to the phosphorus determinations of Boshoff. The values so obtained are illustrated in Figures 4 and 5. Figure 4 shows the relationship between the phosphorus and boron contents, but without there being any significant trend. Figure 5, which plots the ratio of phosphorus to boron, shows a significant trend, with the ratio increasing with increasing phosphorus for the Transvaal coals. There does not appear to be a similar trend for the Natal coals, nor for the O.F.S. coals. The Natal coals show a much lower ratio than the Transvaal coals, whilst the O.F.S. coals are, with one exception, similar to the Transvaal coals.

The increase in the phosphorus-boron content means that the amount of boron which is available for reacting with the phosphorus decreases. This could impose a brake on the incidence of phosphatic deposits from coals with increasing phosphate content. It has been shown by Osborne[9,11] and by Kuntsmann et al.[13] that a significant amount of boron remains in the ash and is therefore not available for phosphatic deposition. It could mean that in South African coals there is always a surplus of boron, and deposition is not affected by the boron content. It would however, be interesting to determine in which form the boron is present in coals, and whether there is any palaeophytological reason why there should be a correlation between boron and phosphorus in Transvaal coals.

Care must be exercised in interpreting Figures 4 and 5 since there is a difference of 20 years between the two analyses of Kuntsmann et al.[13] and Boshoff[16].

Fluorine

Until fairly recently the role of fluorine was underestimated in the formation of phosphatic deposits. Osborne found

evidence of hydrofluoric acid in the boiler, and Kuntsmann et al. have considered the role of fluorine.

The first question that needs investigation is whether the fluorine in coal is due to fluoro-apatite as predicted by U.K. experience. Kuntsmann et al. carried out analyses for fluorine at the same time as they investigated the boron quantities. They also carried out phosphorus determinations, but only on seven Witbank coals. Figure 6 shows the relation between phosphorus and fluorine from the limited Witbank coal analysis. Superimposed on this graph is the theoretical line for apatite. It appears from this that the main constituent could well be fluoro-apatite, though there seems to be some other fluorine present which Kuntsmann et al. postulate as being probably fluorspar. However, the sample size is too small for an adequate analysis, and an attempt was made to get a larger sample by amalgamating the data of Kuntsmann et al. and that of Boshoff[16], in a manner identical to that carried out for the boron content.

Figure 7 shows the correlation between the phosphorus and fluorine for a series of coals from the Transvaal, O.F.S., and Natal fields. On this graph there is superimposed the mean Transvaal coal line, derived by the least squares method, and the theoretical line, which would have been due to apatite alone. It appears from this that there is a good probability that the main source of fluorine and phosphorus in the coal is in fact fluoro-apatite.

Relation between boron and fluorine

There is seen to be some correlation between fluorine and phosphorus and between boron and phosphorus. A correlation was therefore attempted between boron and fluorine. This showed that there was no significant correlation, though the trend for Transvaal and O.F.S. coals seems to be a hyperbolic function with boron decreasing as fluorine increases.

CONCLUSIONS

General

It is likely that some 30% of South African coals are at risk in the production of phosphatic deposits. The relation between the various precursors of phosphatic deposition is, however, not fully understood. It is accepted that the basic constituent of coal which predisposes towards phosphatic deposits is phosphorus and it appears that any coal with a phosphorus content of greater than 0,01% must be considered susceptible. However, it is now recognised that both boron and fluorine play a part in the volatilisation and deposition process.

Besides the role of the coal constituents in the formation of phosphatic deposits, it is likely that there is a critical temperature range at which deposition will occur. This temperature is associated with the condensation temperature of meta-phosphoric acid and is in the range 310 °C to 350 °C. At temperatures above this the acid does not condense, whilst at temperatures below this the acid is so weak that it does not produce the strong tenacious deposit which is characteristic of phosphatic boiler deposits. Any action, such as the injection of steam, which ensures good mixing of the flue gases, will result in the critical temperature being experienced in the combustion chamber itself rather than on the boiler heating surfaces, and will reduce the incidence of bonded phosphatic deposits.

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DETAILS OF AUTHORS

1. **BORCHERS M L**
   BSc (Eng), MSc (Eng)
   Energy for Development Research Centre, Energy Research Institute, University of Cape Town, Private Bag, Rondebosch 7700, South Africa
   Tel. : (021) 650 3230, Fax. : (021) 650 2830

2. **DUTKIEWICZ R K**
   Pr Eng, PhD, FIMechE, Hon. F(SA)IMechE, MBINM, MIProdE, FInstF, CEng
   Professor of Applied Energy and Director
   Energy Research Institute, P O Box 33, Plumstead 7800, South Africa
   Tel. : (021) 705 0120, Fax. : (021) 705 6266

3. **EBERHARD A A**
   BSc (Chem Eng), BA, PhD
   Leader
   Energy for Development Research Centre, Energy Research Institute, University of Cape Town, Private Bag, Rondebosch 7700, South Africa
   Tel. : (021) 650 2827, Fax. : (021) 650 2830

4. **HAINES R W**
   MSc (Eng)
   Atlantis Diesel Engines (Pty) Ltd, P O Box 1222, Cape Town 8000, South Africa
   Tel. : (0226) 38911, Fax. : (0226) 38600

5. **HANSEN A C**
   Pr Eng, PhD
   Senior Lecturer
   Department of Agricultural Engineering, University of Natal, P O Box 375, Pietermaritzburg 3200, South Africa
   Tel. : (0331) 95 5911, Fax. : (0331) 61 896

6. **LYNE P W L**
   Pr Eng, MSc (Eng)
   Senior Lecturer
   Department of Agricultural Engineering, University of Natal, P O Box 375, Pietermaritzburg 3200, South Africa
   Tel. : (0331) 95 5911, Fax. : (0331) 61 896

7. **MEIRING P**
   Pr Eng, MSc (Eng)
   Professor and Head
   Department of Agricultural Engineering, University of Natal, P O Box 375, Pietermaritzburg 3200, South Africa
   Tel. : (0331) 95 5911, Fax. : (0331) 61 896

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   Louw [2] states that . . .
   Full references for books and journals must appear at the end of the ariticle in numerical sequence. For references to books, all relevant information should be provided, that is author(s) surname and initial(s), full title (and subtitle, where applicable), publisher, place of publication, date of publication, and page reference. For periodical references, the author(s) surname and initial(s) must be provided, as well as the full title and subtitle (if applicable) of the article and the periodical, volume number, part, date, and page reference. Numbers identifying all references at the end of the contribution should be enclosed in brackets.

8. Standard International (SI) units must be used.

9. All mathematical expressions should be type-written. Greek letters and other symbols not available on the typewriter should be carefully inserted in ink. A list of symbols marked for the use of the Editor, if not included in the body of the text, should accompany the contribution on a separate page. A nomenclature defining symbols must be included. Numbers identifying mathematical expressions should be enclosed in parentheses. All tables and mathematical expressions should be arranged in such a way that they fit into a single column when set in type. All table columns should have an explanatory heading. Equations that might extend beyond the width of one column should be rephrased to go on two or more lines within column width.

10. Line drawings (not photocopies) and accompanying lettering should be of a sufficient size to allow for reduction if necessary. Photographs of equipment must be glossy prints and should be used sparingly.

11. The body of the contribution should be preceded by an Abstract not exceeding 500 words, which should be a résumé of its essential contents, including the conclusions. Below the Abstract the maximum of four Keywords should be included which reflect the entries the author(s) would like to see in an index. The Keywords may consist of more than one word, but the entire concept should not be more than 30 characters long, including spaces.

12. No contribution or figures will be returned following publication unless requested by the author(s) at the time of its original submission.

13. In a covering letter, the author(s) must state that the contribution has not been published, is not being published or being considered for publication elsewhere, and will not be submitted for publication elsewhere unless rejected by the Editor of the *Journal of Energy R & D in Southern Africa* or withdrawn by the author(s).

14. Authors must supply the following personal information: surname, initials, address, qualifications, occupation and/or employment.

15. Authors whose contributions are accepted for publication will receive a free copy of the issue and 5 copies of their contribution.

16. Neither the Editor nor the Publisher accept responsibility for the opinions or viewpoints expressed, or for the correctness of facts and figures.

17. The Editor reserves the right to make editorial changes to all contributions.

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