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Enquiries may be directed to:
The Production Editor, Journal of Energy R & D in Southern Africa, Energy Research Institute, University of Cape Town, P O Box 33, Plumstead 7800, South Africa.

Tel.: (021) 705 0120

Fax.: (021) 705 6266

ENERGY IN SOUTHERN AND EASTERN SUB-SAHARAN AFRICA

*M I GIELINK

In this report a summary is made of the energy situation in a region defined by the World Energy Council as Southern and Eastern Sub-Saharan Africa. In general, the region is characterised by large population growth rates, instability, massive urbanisation, poor education, a low level of development, lack of finance and inadequate institutional structures, all of which impact on the energy sector, making the provision of sustainable and adequate energy difficult.

A large portion of the region's energy demand is derived from traditional energy sources and is consumed by the domestic sector. In many of the countries energy demand exceeds sustainable supply, resulting in deforestation, both of which need to be addressed as a priority issue.

Although commercial energy resources are abundant within the region, they are largely unexploited mainly as a result of a lack of suitably large markets, vast distances, a lack of finance, and regional instability. The promotion of the exploitation of energy resources is largely reliant on regional co-operation and energy interchange.

It proposed that any long-term cost-effective solution for the provision of adequate and sustainable energy requires regional stability and co-operation, institutional reform, the integration of traditional and commercial energy sectors, and should address the issues of deforestation and population growth.

KEYWORDS: Sub-Saharan Africa; energy

INTRODUCTION

The Southern and Eastern Sub-Saharan African Region (SESSAR) considered in this paper is bounded in the North by Zaïre, Sudan and Ethiopia, and includes certain Indian Ocean islands. The topography of the region is diverse, with tropical forests in the equatorial region and more arid savannas and desert areas further to the North and in the South. Water resources are abundant in the central equatorial areas but scarce elsewhere in the region. Other resources, such as energy and minerals, are abundant throughout the area but vary in type and location. Economic development within the region is dominated by South Africa which is responsible for some 56% of the total Gross Domestic Product (GDP) of the region(1).

The prevailing political climate of the region has greatly affected the institutional structure of all sectors, including the energy sector. As a result, energy institutions are frequently characterised by insufficient autonomy, poor accountability, and a lack of market orientation. Energy issues are often politically driven. Price controls, taxes and subsidies are common, often causing distortions in production and distribution. Co-ordination between various government departments concerned with energy is often poor, especially in relation to financing issues.

The region is characterised by population growth rates which are extremely high by world standards and by an age structure which is heavily skewed towards young people. Education levels are low and there is a serious shortage of technical skills. There are numerous health problems, such as a shortage of medical facilities, high disease rates (including AIDS), and inadequate hygiene. The major portion of the population lives in the rural areas, although the rate of urbanisation is escalating rapidly. However, in the urban areas there is an acute shortage of housing and basic facilities.

DEMOGRAPHY

Introduction

There has been rapid population growth within the region and population growth rates are significantly higher than

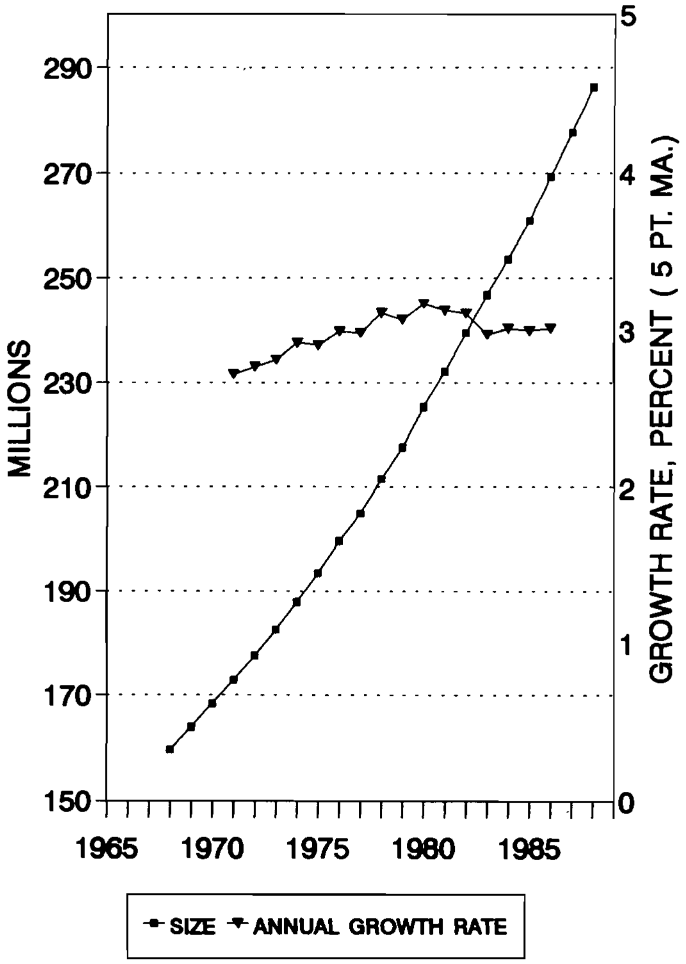

Figure 1.1: Population of the Southern and Eastern Sub-Saharan African region.

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*Research Engineer, Generation Group, ESKOM, c/o Energy Research Institute, P O Box 33, Plumstead 7800, South Africa in Western industrialised countries. In many of these countries the real GDP growth rate in local currency has not been able to keep up with the population growth rate, resulting in a decreasing trend in real GDP per capita. This has been exacerbated in many cases by a decrease in the local currency value against the US dollar.

Figure 1.1 shows the size of the population and the population growth of the region over the period 1968 to 1988. The high population growth rate (and low life expectancy) has resulted in a young population in the region. On average, over 45% of the population of countries in the region are under 15 years old and some 65% are under 25 years old(6,7). Notable exceptions include South Africa (35% and 56% respectively) and Mauritius (30% and 52% respectively). In Europe and America populations are relatively older and, on average, 19% are under 15 years of age and 35% are under the age of 25(6).

The present level of urbanisation in the region is relatively low, typically ranging between 10% and 30%, with a few notable exceptions such as South Africa (60%), Zaïre (40%), Zambia (50%) and Mauritius (41%)(5,9). Due to population pressure on the land, the associated degradation of the soil, and the poor economic prospects in the rural areas, many people are migrating from rural areas to the cities where they perceive prospects to be better. Thus urban population growth in the region is very high, far exceeding the average population growth rates. This has resulted in the proliferation of peri-urban squatter settlements, as well as the related socio-economic problems, and is creating extraordinary demands for housing, services, energy and jobs which are far beyond the capacity of most cities to fulfil.

The lack of employment opportunities in the formal sector has resulted in a fast-growing informal sector. The lack of job opportunities at home and the better prospects and living conditions abroad have influenced many of the better-educated to emigrate. This has undermined the ability of these countries' economies to develop and provide employment for the population, resulting in a serious shortage of technical expertise and skilled manpower in the energy sector.

Table 1(9)

Country	Scientists and technicians per 1 000 people (1986-88)	Tertiary graduates as a percentage of corresponding age group
Botswana	1,2	0,6
Djibouti	0,1	—
Kenya	2,5	0,2
Malawi	—	0,1
Rwanda	0,2	0,1
Sudan	0,1	0,4
Zaïre	—	0,2
Zambia	4,4	0,2
Zimbabwe	—	0,5
Canada	257	14,0
Japan	317	11,5
Spain	130	5,1
Sweden	262	10,7
USA	55	15,5

Of particular concern to the energy sector, as well as the industrial sector, is the lack of suitably qualified and competent technical and scientific personnel at all levels. This is reflected in Table 1 which shows the number of scientists and technicians per 1 000 people and the tertiary graduate ratio in the SESSAR countries and compares them to the position in industrialised countries.

Education will be a vital ingredient in any solution to the region's problems, especially with respect to the curbing of population growth, development of the economy and the provision of jobs. In this respect the creation of a technical skills resource base is essential.

Culture and Nationalism

Prior to colonisation the region was traditionally divided by the numerous tribal and linguistic groupings. These natural boundaries were replaced through European colonialism. All over Africa artificial "national" boundaries were laid down with scant regard for logic as turn-of-the-century colonisers engaged in a carve-up of the continent. This has caused much tension in many of the affected countries as various tribes, cultures and language groups were divided by the new boundaries. Liberation movements emerged, many of which are still battling to re-establish more equitable borders. The result has been the ongoing civil wars in the Horn of Africa, namely Ethiopia and Somalia, as well as in Mozambique and Angola.

These conflicts have had a profound effect on the economies and populations of the countries involved, as well as on the stability of the region as a whole. The lack of stability has had a considerable effect on the energy sector: (i) supply routes have been severely disrupted, (ii) security of supply has become a priority, (iii) there is a general lack of foreign exchange for spares and maintenance, (iv) the scope for regional interchange of energy resources has been limited, and (v) regional co-operation on energy matters has been hindered. Any long-term cost-effective energy strategy for the region, based on the interchange of resources, can be successfully implemented only once stability is achieved in the region and co-operation between countries becomes the norm.

ENERGY RESOURCES

The region as a whole has large commercial energy resources which could, if exploited and managed efficiently, supply most of its commercial energy needs for a significant time. However, these energy resources are not uniformly distributed with respect to locality or form. In general, the more southern countries have large coal resources, while the countries nearer the equator have relatively large hydro resources. Oil and gas reserves have mainly been identified along the coastline. The largest uranium reserves in the region have been identified in South Africa and Namibia, while the largest wood resources are found near the equator.

The main energy resources include oil, natural gas, hydro, coal, peat, geothermal, and wood. It is difficult to confirm the total extent of energy resources in the region as much of the area has not been accurately explored. Tables 2.1a and 2.1b give an indication of the extent of energy resources in the region. According to this data, the majority of the proven bituminous coal reserves are situated in South Africa (86%) and Botswana (12%), while the majority of the estimated reserves are situated in Botswana (44%), Mozambique (12%), and Zimbabwe (36%). The largest proven reserves of natural gas are in Tanzania (39%), Sudan (20%), Mozambique (16%), and Rwanda (9%), while 85% of the estimated gas resources are situated in Mozambique. Zaïre is endowed with 73% of the region's hydro-potential. South Africa and Namibia together account for 98% of the region's uranium reserves.

A large portion of the known resources have not yet been exploited due mainly to the lack of suitably large indigenous markets, vast distances, location, finance and, in some cases, quality(11). The energy markets of individual

Table 2.1a: Energy resources of the region(4,10,15)

Country	Forests & Woodlands M Ha	Oil M Ton				Gas (Mil. Metres Cubed)			Uranium
		Estimate	Proven	Total	Proven Recoverable	Estimate	Proven Recoverable	Total	Proven (Ton)
Angola	53,60	—	156	156	156	30 000	9 000	39 000	0
Botswana	32,56	0	0	0	0	0	0	0	0
Burundi	0,04	0	0	0	0	0	0	0	0
Comoros	0,02	0	0	0	0	0	0	0	0
Djibouti	0,07	—	—	—	—	—	—	—	—
Ethiopia	27,15	0	0	0	0	—	24 000	24 000	0
Kenya	2,36	0	0	0	0	0	0	0	0
Lesotho	—	0	0	0	0	0	0	0	0
Malawi	4,27	0	0	0	0	0	0	0	0
Madagascar	13,20	—	—	—	—	—	—	—	0
Mauritius	0,00	0	0	0	0	0	0	0	0
Mozambique	15,44	0	0	0	0	320 000	65 000	385 000	0
Rwanda	0,23	0	0	0	0	—	40 000	40 000	0
Somalia	9,05	0	0	0	0	—	6 000	6 000	6 600
South Africa	0,30	—	—	—	—	—	28 000	28 000	426 300
Sudan	47,65	—	—	—	41	—	85 000	85 000	0
Swaziland	0,07	0	0	0	0	0	0	0	0
Tanzania	42,04	0	0	0	0	26 710	163 420	190 130	0
Uganda	6,02	0	0	0	0	0	0	0	0
Zambia	29,51	0	0	0	0	0	0	0	0
Zaïre	177,59	0,1	23,6	23,7	22	—	1	1	1 800
Zimbabwe	19,82	0	0	0	0	0	0	0	0
TOTAL	480,99	0,1	179,6	179,7	219	376 710	420 421	797 131	434 700

Table 2.1b: Energy resources of the region(4,10,15)

Country	Coal: Bituminous M Ton				Coal: Lignite and Sub-Bituminous M Ton				Hydro-Potential	
	Estimate	Proven	Total	Proven Recoverable	Estimate	Proven	Total	Proven Recoverable	GWh/Year	MW
Angola	0	0	0	0	0	0	0	0	70 000	16 000
Botswana	33 000	17 000	50 000	3 500	0	0	0	0	0	0
Burundi	0	0	0	0	0	0	0	0	1 445	289
Comoros	0	0	0	0	0	0	0	0	50	10
Djibouti	—	—	—	—	—	—	—	—	—	—
Ethiopia	0	0	0	0	—	23	23	11	20 000	4 000
Kenya	0	0	0	0	0	0	0	0	4 800	1 075
Lesotho	0	0	0	0	0	0	0	0	2 000	450
Malawi	—	15,78	15,78	1,95	0	0	0	0	6 300	900
Madagascar	1 000	173	1 173	173	42,6	11	53,6	—	39 000	7 800
Mauritius	0	0	0	0	0	0	0	0	325	65
Mozambique	8 593	938	9 531	240	0	0	0	0	60 000	12 500
Rwanda	0	0	0	0	0	0	0	0	3 000	600
Somalia	0	0	0	0	0	0	0	0	250	120
South Africa	2 282	121 218	123 500	55 333	0	0	0	0	—	3 500
Sudan	0	0	0	0	0	0	0	0	1 900	380
Swaziland	1 000	549	1 549	208	0	0	0	0	3 000	600
Tanzania	1 500	304	1 804	200	0	0	0	0	20 000	6 000
Uganda	0	0	0	0	0	0	0	0	10 000	2 000
Zambia	0	0	0	0	213	69	282	69	21 406	3 924
Zaïre	720	86,6	806,6	54,3	0	0	0	0	750 000	100 000
Zimbabwe	27 008	1 535	28 543	734	—	965	965	—	13 285	2 515
TOTAL	75 103	141 819,38	216 922,38	60 444,25	255,6	1 068	1 323,6	80	1 026 761	162 728

countries in the region, with the exception of South Africa, are small and dispersed. This is due to the low level of development and industrialisation of the economies of the region. South Africa, on the other hand, has an extremely large energy market by regional standards, consuming some 74% of all final commercial energy and 41% of total final energy (including traditional energy). Thus the economic exploitation of the natural energy resources is reliant on regional markets rather than local markets and the potential for export.

The possibility of a regional interchange of energy has been hampered by the lack of transport infrastructures in the region, rugged or inaccessible terrain, instability (civil war), lack of finance, distance to suitable markets and, most significantly, the importance that governments, institutions and utilities place on the security of energy supply. As long as the region is plagued by instability, governments, as well as the associated energy institutions and utilities, will prefer to obtain their energy offshore rather than import from within the region. They will also favour the production of the energy they require within their own country where possible, rather than import from their neighbours, irrespective of the economics.

At present, with the limited exception of electricity, the regional interchange of energy derived from local resources is relatively small, while imported energy is exported by the coastal countries to their land-locked neighbours. This has resulted in a low level of exploitation of energy resources for local requirements and an outflow of scarce foreign exchange from the region. A long-term solution to the provision of a sustainable supply of energy to the region is thus reliant on regional co-operation.

Due to over-exploitation the energy resource base is in certain sectors of the region insufficient to meet energy demand until the end of the century. This is especially true with regard to fuelwood which supplies more than 75% of the region's energy requirements(2,3,4), excluding South Africa. In most countries in the region demand exceeds sustainable supply and this is already having a marked effect on the domestic sector as well as on the many industries reliant on wood or charcoal for energy. The supply situation is expected to become far worse in the years ahead as populations grow and the demand for fuelwood escalates. Estimates based on present trends forecast that the demand for fuelwood will at least triple by 2020(11). This, together with the associated escalation in the price for fuelwood, will have serious consequences for the well-being of the region's populations. Thus the implementation of reforestation programmes is a priority issue which needs to be addressed urgently.

ECONOMICS AND ENERGY SUPPLY AND DEMAND

Introduction

Economic growth in the region, as measured by real Gross Domestic Product (GDP), is low by international standards and usually negative in per capita terms. The average GDP per capita, expressed in real US dollars, for the region as a whole has been declining since the mid-1970's. This is shown in Figure 4.1 which covers the period 1965 to 1985. The importance of South Africa's economy, which contributes 54% of the region's GDP, is evident. With respect to sustainable development, the performance of the region is particularly poor, with much environmental degradation and loss of natural resources, which is not reflected in GDP figures.

The economy of the region is generally dualistic in nature, with formal and informal sectors. In some countries, the informal sector accounts for a considerable portion of the economy. The formal sector includes activities such as mining, industry and commercial agriculture. The informal sector is characterised by subsistence activity and the government plays virtually no role whatsoever. The linkage between the two sectors is limited and, in many cases, results in serious institutional shortcomings.

Economics and energy

With the exception of South Africa, per capita final consumption of commercial energy is low, typically ranging between 0,01 tons of oil equivalent (toe)** and 0,4 toe

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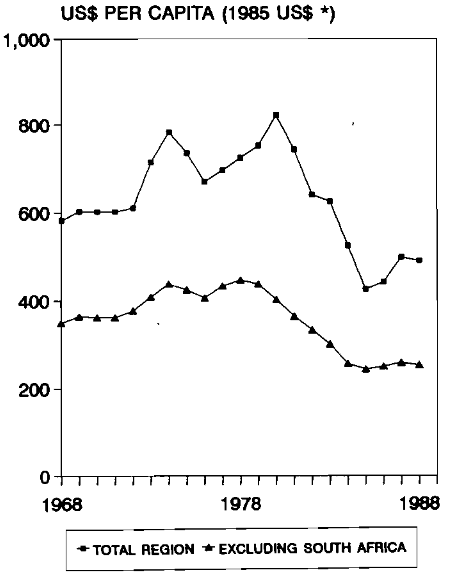
**1 toe = 42 × 10^9 Joule

Figure 4.1: Average GDP per capita for the region (including and excluding South Africa)



* GDP per capita is based on current local GDP converted to US$ at current exchange rates and then deflated with the US$ deflator for 1985.
ECOTOT1/GDP10

Figure 4.2a: Final consumption of commercial energy per capita

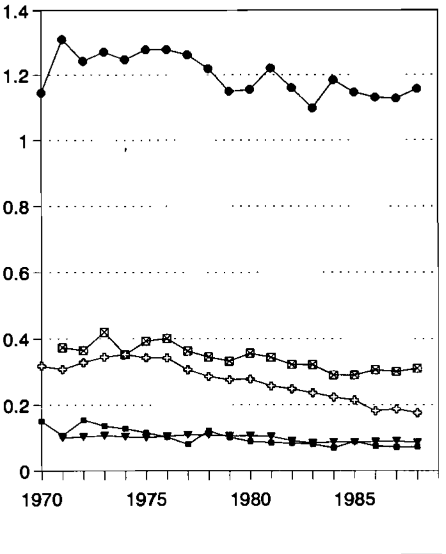
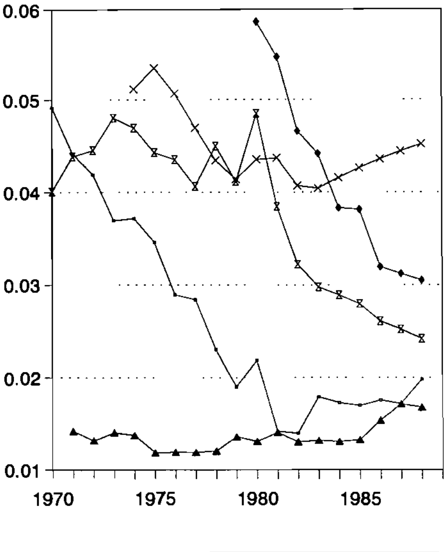


Figure 4.2b: Final consumption of commercial energy per capita



per capita, reflecting the low level of development in the region. Conversely, South Africa displays a per capita consumption closer to that of developed nations. Excluding South Africa, the SESSAR's average final per capita consumption of commercial energy is 0,06 toe per capita. Including South Africa, this figure increases to 0,2 toe. Figures 4.2a and 4.2b show the trend in the final consumption of commercial energy per capita for selected countries of the region for the period 1970 to 1988. In general, per capita consumption of commercial energy is declining, as would be expected for a region which has an economic growth rate that is on average lower than the population growth rate. It is expected that once growth in real GDP per capita is achieved this trend could be reversed.

As shown in Figure 4.3, total final energy intensities (including traditional energy) vary greatly through the region. This can be attributed largely to variations in development, the use and availability of traditional fuels, the availability of local commercial energy resources, as well

Figure 4.3: Total final energy intensity (Traditional + Commercial)

COUNTRY	SYMBOL
ANGOLA	1
BURUNDI	11
ETHIOPIA	14
KENYA	8
MADAGASCAR	9
MAURITIUS	2
MOZAMBIQUE	15
SOUTH AFRICA	5
RWANDA	6
SOMALIA	10
SUDAN	4
TANZANIA	16
UGANDA	12
ZAIRE	13
ZAMBIA	3
ZIMBABWE	7

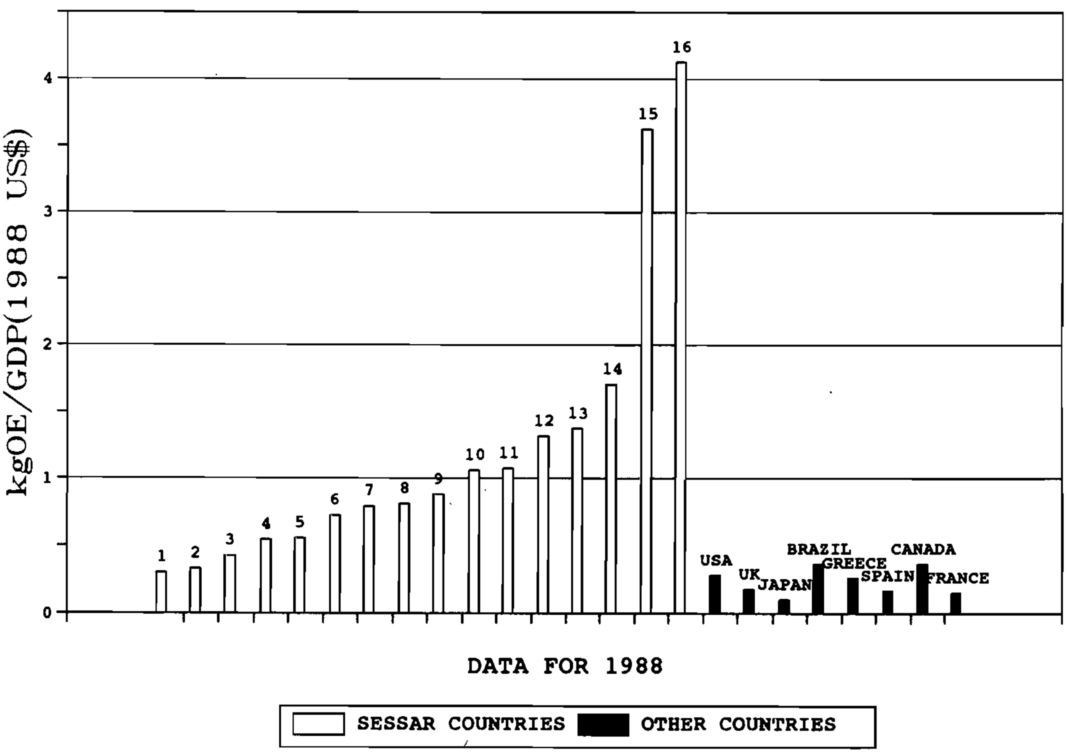
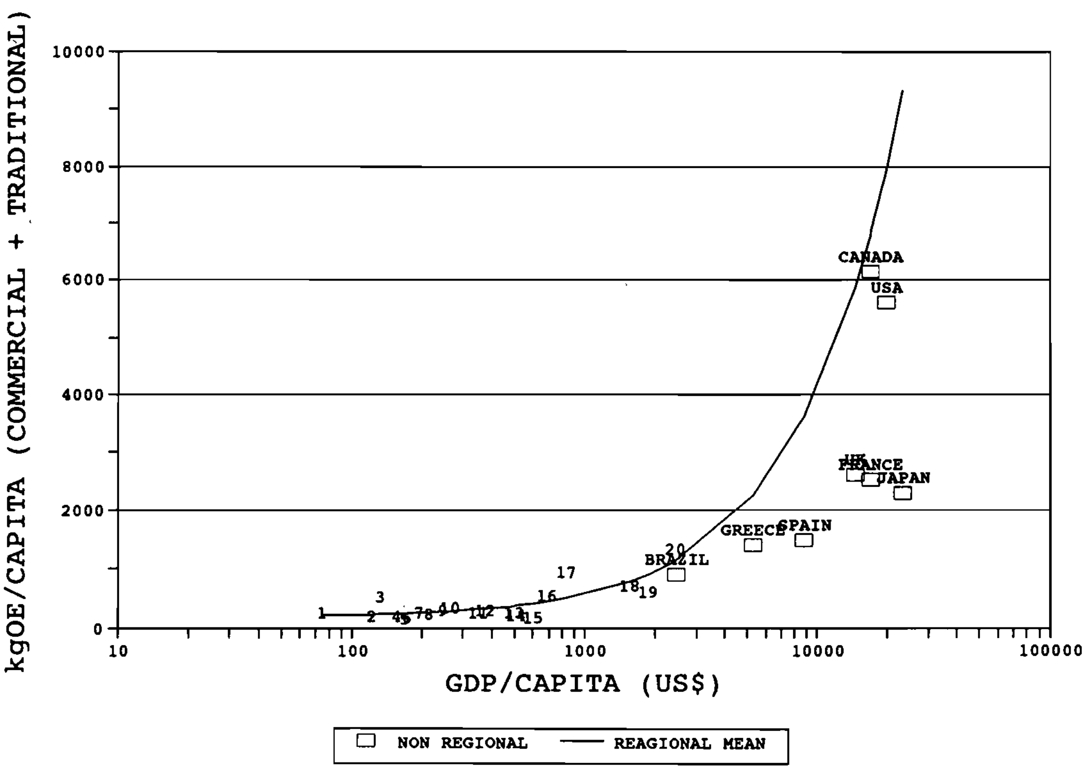


Figure 4.4: Energy per capita vs GDP per capita — 1988

COUNTRY	SYMBOL
ANGOLA	15
BOTSWANA	18
BURUNDI	8
ETHIOPIA	2
KENYA	12
LESOTHO	9
MADAGASCAR	5
MALAWI	4
MAURITIUS	19
MOZAMBIQUE	1
SOUTH AFRICA	20
RWANDA	11
SOMALIA	6
SUDAN	13
SWAZILAND	17
TANZANIA	3
UGANDA	10
ZAIRE	7
ZAMBIA	14
ZIMBABWE	16



as the effects of civil war in certain countries. Most countries display energy intensities higher than major industrialised nations, which can mainly be ascribed to the large reliance on traditional energy in the form of fuelwood and charcoal which have a much lower end-use efficiency than the commercial energy forms. These high energy intensities can also be partially described by inadequate demand-side management, the low priority of conservation and efficiency issues, inadequate pricing structures, price subsidies, as well as the large informal sector which is not reflected in the measurement of GDP. In general, there is no clear historic trend in energy intensities in the region because in some countries intensities are declining, while in others they are increasing.

Figure 4.4 shows the relationship between the wealth of a country expressed in GDP per capita and the amount of energy (including traditional energy) used on a final per capita basis for countries of the region and selected developed countries. It is apparent that, on a world scale, the African countries are low on GDP per capita and low on per capita final energy consumption. However, with some exceptions, they obey a straight line relationship and therefore conform with the generally accepted relationship between wealth and energy. The large and inefficient use of traditional energy in the region has contributed to the fact that the regional mean is somewhat higher than that of developed countries. It is therefore evident that as the economies of the countries of the region improve, so will the demand for energy. Thus the provision of adequate energy supplies, both traditional and commercial, must be planned for and integrated in such a way so as not to stifle economic growth(10).

Energy supply and demand

The distinctive energy mixes and usage patterns in the region make it necessary to distinguish between the commercial and traditional components of conventional energy forms. Commercial energy in the form of oil, coal, electricity, etc. is generally used in the formal sector of the economy and in the urban areas. Traditional fuels, customarily in the form of fuelwood and to lesser extent charcoal, are generally used in the rural and peri-urban areas, the informal sector, as well as in certain industries in a number of countries, and constitute the greatest consumption of energy in the region. Alternative energy forms include solar, wind, and the biomass resource, and although they do not make a significant contribution to the total energy mix, they are used in rural areas far from the grid.

Energy consumption in the region is dominated by South Africa. As previously mentioned, it has been estimated that South Africa accounts for 41% of all final energy consumed in the region. The estimate for commercial energy consumption is much higher at 75% and that for traditional energy lower at 11%. Table 4.1 shows the final consumption of energy by South Africa as a percentage of the region.

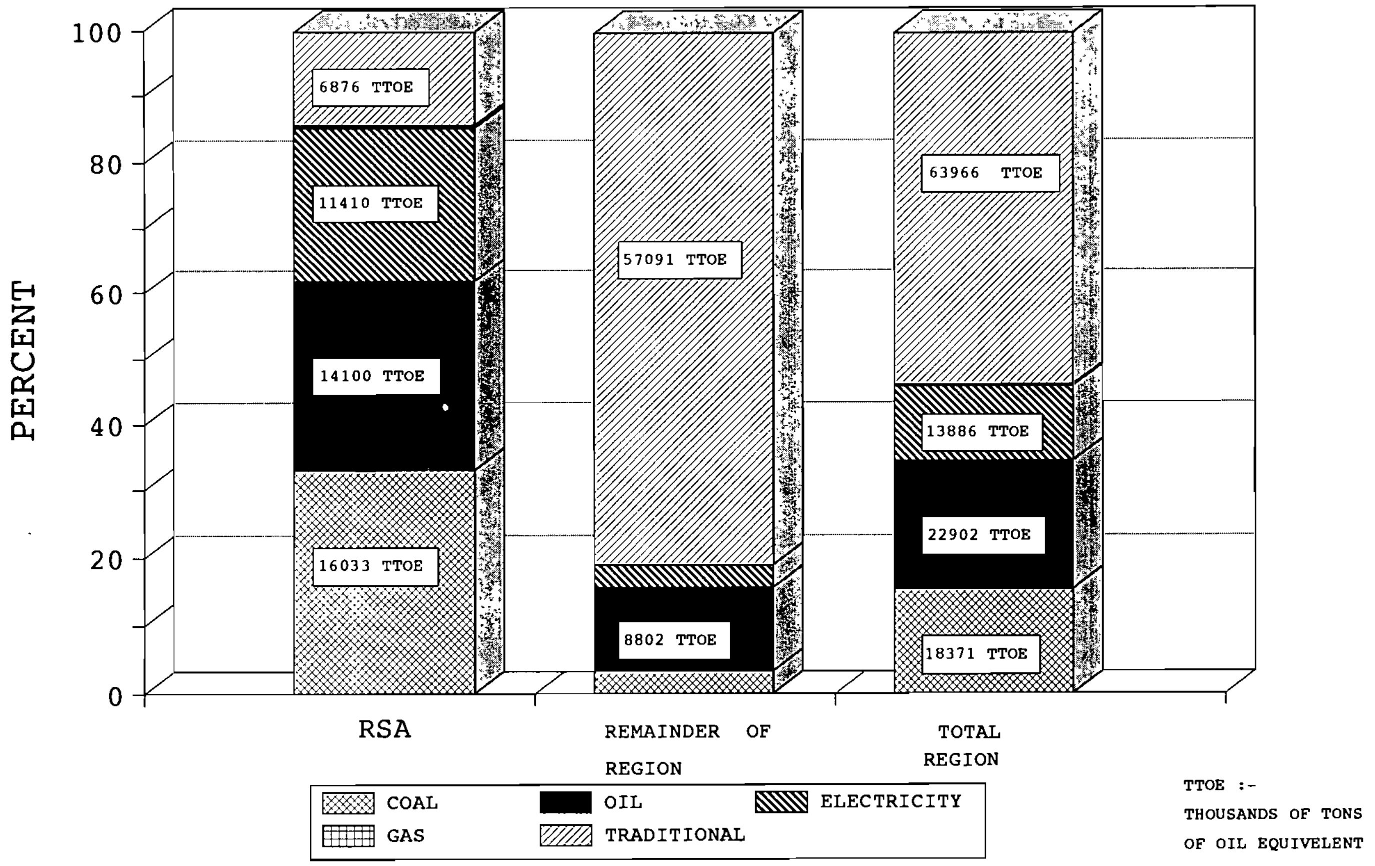
Table 4.1: Carriers as per cent of regional carriers(2,4)

	COMMERCIAL					TRADITIONAL	TOTAL
1988	COAL	OIL	ELECTRICITY	GAS	TOTAL		(TRAD+COM)
RSA	87,3	61,6	82,2	69,3	75,3	10,7	40,7
OTHER	12,7	38,4	17,8	30,7	24,7	89,3	59,3
SESSAR	100,0	100,0	100,0	100,0	100,0	100,0	100,0

(REFERENCES: 2,4)

Total final consumption data for the region are presented in Figure 4.5 in percentage and magnitude terms. The

Figure 4.5: Total final consumption carriers as a per cent of total



graph has been drawn to include and exclude South Africa, as that country's extraordinarily large consumption of commercial energy distorts the regional statistics. The total final consumption of energy in the SESSAR was estimated at 119,6 million tons oil equivalent (mtoe) in 1988, of which 55,6 mtoe was in the form of commercial energy.

The reliance on fuelwood for energy needs is mostly high but varies from country to country, ranging from 96% in Tanzania to 15% in South Africa, as shown in Table 2. In general, the more developed countries rely on traditional energy for a smaller proportion of their energy requirements. Excluding South Africa, traditional energy represents on average 80% of the energy needs for the remainder of the region. Including South Africa, the regional reliance on fuelwood decreases to 54% due to the large use of commercial energy by that country relative to the rest of the region.

Table 2: Traditional energy as a percentage of total energy(2,3,4,8)

Country	Per cent traditional
Tanzania	96
Uganda	94
Burundi	94
Rwanda	92
Ethiopia	92
Mozambique	89
Malawi	87
Zaïre	83
Kenya	78
Sudan	76
Lesotho	75
Angola	60
Botswana	53
Zimbabwe	38
South Africa	14

The household sector is the largest single consumer of energy in the region. Traditional fuels on average account for 90% of energy consumed by this sector, excluding South Africa(3). The heavy reliance on traditional fuels can be attributed to the rural subsistence nature of a large proportion of the region's population, for whom commercial fuels are expensive and not easily accessible, together with the low level of economic development, and the extensive and rapidly growing squatter settlements in the peri-urban areas.

The extension of grid systems to rural areas and the introduction of small-scale power generation by new technologies, such as photovoltaics, could reduce the usage of non-commercial energy sources, though finance is a restraining factor. In certain countries dependence on non-commercial sources of energy is increasing. This is because existing infrastructures have weakened and biomass fuels are being used even in urban areas.

The commercial energy mix of countries within the region varies considerably and is to a large extent dependent on the availability of indigenous energy resources. Table 3 shows the importance of the various energy carriers for selected countries and the region as a whole. A common trend is the reliance of almost all the countries on imported oil. This exerts strong pressure on the economies of many countries and uses up scarce foreign exchange earnings. In Tanzania, for example, although oil constitutes only 7% of the total energy consumed, it cost the nation over 60% of its total export earnings in 1985(12). The role of coal in the energy sector varies considerably within the region. On one end of the scale, South Africa relies on coal for some 81% of its primary energy requirements, while Ethiopia on the other hand does not consume coal in any significant amount. In contrast to many developed countries, the region relies on gas for only a minor proportion of its energy needs.

Table 3: Total final consumption components as a percentage of national total commercial energy (for 1988 unless indicated)(2,4,16)

Country	Coal	Oil	Electricity	Gas
Angola	0,0	62,21	8,4	19,4
Ethiopia	0,0	91,3	8,7	0,0
Lesotho	36,0	56,0	8,0	0,0
Malawi (1986)	9,6	68,9	21,5	0,0
Mozambique	8,7	76,2	15,1	0,0
South Africa	38,3	33,7	27,3	0,7
Swaziland (1985)	37,7	45,9	16,4	0,0
Tanzania	0,3	88,5	11,2	0,0
Zimbabwe	51,0	25,9	23,1	0,0
SESSAR (excl. RSA)	17,0	64,0	18,0	1,0
SESSAR (incl. RSA)	33,0	41,2	25,0	0,8
France	10,2	56,2	17,2	16,4
Japan	13,4	61,2	20,5	4,9
UK	10,3	46,2	15,3	28,2
USA	10,1	52,1	15,5	22,1

Sectoral consumption of commercial energy displays similar trends throughout the region. The transport and industrial sectors are responsible for the greatest demand for commercial energy, while the domestic sector's demand is met mainly by traditional fuels. Overall, the domestic sector is the single largest consumer of energy in the region.

Electricity is becoming increasingly important as an energy carrier in the region as a whole. In the more developed countries, such as South Africa, Zambia, and Zimbabwe, electricity is relatively more important. However, lack of finance, the squatter nature of the peri-urban housing, the low affordability levels of consumers, low load factors, large distances and large rural populations are hampering electrification projects. At present only a small percentage of the population has access to electricity, as shown in Table 4. It has been estimated that less than 10% of the total population of the SESSAR has access to electricity(13).

Table 4(17,18)

Country	Percentage of population with access to electricity	Year
Botswana	3,6	1983
Ethiopia	4,2	1885
Kenya	5,1	1987
Lesotho	1,5	1982
Malawi	2,4	1987
Mozambique	2,7	1985
Rwanda	0,5	1982
Swaziland	9,4	1986
South Africa	33,0	1990
Tanzania	13,3	1985
Zaïre	2,1	1982
Zambia	8,0	1982
Zimbabwe	16,2	1987

Any further economic/industrial development in the region, together with further rural and urban electrification, will result in an increase in the relative importance of electricity. However, traditional energy will remain an important source of energy for the foreseeable future and will parallel population growth.

Institutional aspects

Existing energy institutions are heavily influenced by politics. As a result, they tend to have insufficient autonomy and are often directly controlled by central government. There is often a lack of accountability and little market orientation. Price controls, subsidies and taxes are common and result in distortions in production and distribution patterns. Various energy functions are frequently split across several different government departments and co-ordination between these can be poor. This is especially the case as far as co-ordination between the commercial and traditional energy sectors is concerned(14), as well as in the case of energy project financing with foreign capital. The institutional structures, in many cases, lack adequate organisation, which makes the collection of reliable data on the status of resources and the consumption of energy by locality and sector very difficult(14). These factors have precluded the possibility of integrated planning at a national level to check the continual deforestation and to guarantee the sustainability of energy supply.

The fact that decisions on energy issues are politically driven rather than market-orientated is probably the most significant institutional shortcoming throughout the region, and one that should be addressed as a first priority.

ENVIRONMENTAL ASPECTS

Environment-related priorities in this region differ greatly from those in developed countries, for three reasons:

(1) Governments are generally far more concerned with economic growth than environmental protection.
(2) The levels of greenhouse gas emissions are relatively low by international standards (with the exception of isolated areas in South Africa).
(3) The level of affluence is so much lower in the region that most people are concerned with primary subsistence issues.

Some of these primary subsistence issues are environmental in nature, such as water depletion and land degradation. Table 6.1 shows the net additions to the greenhouse heating effect by carbon dioxide emissions attributed to the use of fossil fuels and the loss of "carbon dioxide sink" due to land use change (deforestation).

Table 6.1: Net attributed additions to the greenhouse heating effect by carbon dioxide in 1987(15)

LOCATION	COUNTRY	NET ADDITIONS ATTRIBUTED TO FOSSIL FUELS			NET ADDITIONS ATTRIBUTED TO LAND USE CHANGE		
		000's TON CARBON	AS % OF SESSAR	AS % OF WORLD	000's TON CARBON	AS % OF SESSAR	AS % OF WORLD
SESSAR	RSA	33250	86.0	1.36	-	-	-
	ZIMBABWE	1800	4.7	0.07	1800	3.0	0.15
	ZAMBIA	297	0.8	0.01	1800	3.0	0.15
	MALAWI	54	0.1	0.00	6800	11.2	0.57
	OTHER	3274	8.5	0.13	50400	82.9	4.20
	TOTAL	38675	100	1.59	60800	100	5.07
REMAINDER OF WORLD	USA	525710		21.56	2600		0.22
	UK	68210		2.80	-		-
	JAPAN	105850		4.34	-		-
	BRAZIL	21470		0.88	540000		45.00
	OTHER	1678885		68.84	596600		49.72
	TOTAL	2400125		98.41	1139200		94.93
WORLD	TOTAL	2438800		100	1200000		100

The region's usage of fossil fuels for energy contributes only 1,58% of the world's net addition by carbon dioxide emissions to the greenhouse effect. However, South Africa is responsible for 86% of the region's total. Thus the remainder of the region's contribution to the greenhouse effect through the use of fossil fuels is presently minimal. The region's net contribution to the greenhouse effect attributed to the loss of the "carbon dioxide sink" as a result of land use change (deforestation) is almost double that attributed to the use of fossil fuels. Deforestation in the region is mainly attributed to the use of wood for energy as well as the clearing of forests for agricultural land. Thus it has been argued that in this region it is more appropriate to spend money on reforestation than on high technology emission control equipment.

It follows that the main environmental concerns in the region are with resource extraction rather than emissions. Deforestation, the loss of arable land, and water depletion are all serious problems and result in poverty, hunger and general economic decline. This in turn places additional pressure on the remaining resources.

Traditional concerns of developed countries, such as atmospheric pollution and related consequences, namely global warming and acid rain, are of relatively little concern to the majority of the population as there are more pressing environmental issues in the region which deserve greater attention. This does not mean that the traditional concerns of the developed countries are of little significance. Air pollution, for example, is quite a serious problem in parts of South Africa. However, the demands on scarce capital and especially the foreign exchange required for pollution abatement technology, discourage any serious attempts to address this issue at present.

CONCLUSIONS

The large population growth, the related lack of economic growth, relatively low urbanisation levels, a high illiteracy rate, and instability in the region are reflected in the energy usage patterns. The use of traditional fuels is high, and household consumption takes a large share of total energy use. Cooking with fuelwood generally dominates the energy flows and consumption almost parallels population growth(8). This has resulted in deforestation, desertification and siltation in many areas where a sustainable supply cannot be achieved.

The rapid urbanisation, resulting mainly from lack of farming land due to rapid population growth, as well as the "bright lights" syndrome, in the region could potentially shift energy consumption patterns increasingly towards commercial energy. However, the squatter-type nature of much of peri-urban housing and a lack of funding is making electrification difficult as these settlements still rely to a large extent on wood and charcoal for their energy needs.

It follows that reforestation programmes need to be implemented as a priority issue in order to (1) obtain a sustainable supply of fuelwood, (2) prevent further deforestation and associated social and environmental impacts, and (3) ensure security of supply to the domestic sector which is the largest single user of energy in the region.

Thus population growth and the associated lack of per capita economic growth are major problems in the region. A large proportion of the region's difficulties in the energy and socio-economic sectors can be attributed to rapid population growth. As long as population growth is accompanied by economic stagnation and unrest, the expansion of the low-income class will persist and an almost constant increase in demand for fuelwood will prevail, being directly related to population growth. A significant reduction in population growth and/or rapid economic growth, causing an increase in real income per capita, would result in fuelwood demand at first increasing and then declining due to inter-fuel substitution(8).

The region as a whole has large commercial energy resources, many of which have not yet been exploited. The promotion of the exploitation of energy resources in the region is reliant on regional co-operation and energy interchange. A change from confrontational to co-operational politics could enable the regional interchange of energy and the utilisation of local energy resources to be used for the benefit of the whole region. This would (1) enable more efficient use being made of the region's resources, (2) reduce the outflow of scarce foreign exchange from the region as a result of the associated decrease in the dependence on imported commercial energy, and (3) improve the security of energy supply to the region as a whole. This can become a reality only once political stability is achieved in the region.

The energy community transcends political and ideological barriers, and through its regional initiatives it can play a leading role in paving the way for regional co-operation between governments. However, without institutional reform and the establishment of integrated sectorial policy and planning, at national as well as regional level, encompassing both the commercial as well as traditional energy sources, deforestation will continue unabated and a solution to the provision of sustainable energy will be impossible.

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DEVELOPMENT OF A PROBE FOR TRANSIENT HEAT TRANSFER MEASUREMENT

*A B TAYLOR

Transient heat transfer rate at a surface can be calculated from measured transient surface temperature by solving the Fourier heat transfer equation with the aid of Fourier analysis. As part of an investigation into combustion stress in diesel engines, a heat flux probe was developed which measured transient surface temperature and the temperature gradient at the face of the probe. A unique method of processing and capturing the probe signals was used in order to achieve an accurate and representative record of the average surface temperature throughout the cycle in a diesel engine. Accurate calibration of the probe was achieved with the aid of measured combustion chamber pressure, heat release analysis and the gas laws. A level of accuracy and repeatability was achieved which enabled the effect of small changes in engine timing or fuel formulation on heat rejection to be quantified. While the probe is discussed in the context of diesel engine research, it may have numerous applications in other fields of research and industry.

KEYWORDS: surface thermocouple; heat transfer; heat release

INTRODUCTION

Heat transfer from the hot combustion chamber gases to the cooling system of an internal combustion engine accounts for approximately one-third of the energy that is released by fuel combustion. Changes in fuel formulation and engine design or adjustment can have a significant effect on the nature and amount of heat rejection to the coolant. It is for this reason that, if detailed fuel or engine testing is to be carried out, the ability to measure heat transfer in the combustion chamber is beneficial.

As part of an investigation into combustion stress in diesel engines, which was carried out at the Department of Agricultural Engineering at the University of Natal in Pietermaritzburg, a transient heat flux probe was developed(1). The design, construction, application and numerical methods related to the use of the probe will be discussed. Although the probe was developed specifically to assist in the investigation of combustion-related stresses in diesel engines, it can be applied in numerous applications in all types of engines and other machines, and has already contributed to the development of a new heat transfer model(2).

DESIGN AND CONSTRUCTION

The rate of heat transfer across a surface can be determined from the measured temperature gradient at the surface or from the measured surface temperature, recorded as a function of time. It was decided that any device designed to determine surface heat transfer rate should measure both the surface temperature and the temperature gradient at the surface. A probe was constructed to have the same external dimensions as a Kistler 6121 pressure transducer, thus allowing the probe to be inserted into the pressure transducer housing of the test engine in such a manner as to place the face of the probe flush with the cylinder head surface. The probe construction is illustrated in Figure 1. A fast-response surface thermocouple was built on the face of the probe, while a second junction was fitted 2,3 mm from the face.

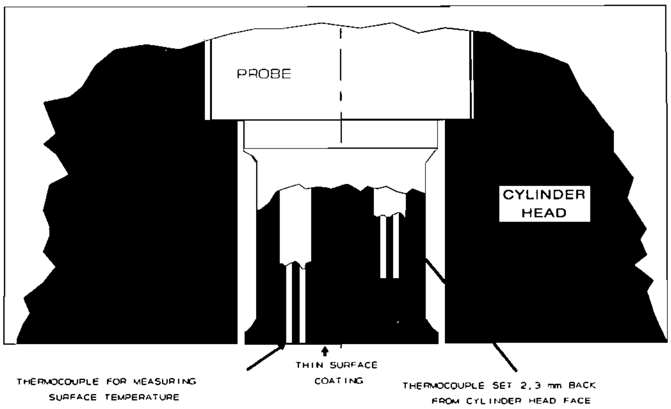

Figure 1: A schematic cross-section of the surface temperature and heat flux probe

To ensure that the rate of heat transfer through the probe was similar to that through the surrounding cylinder head, the probe was machined out of cast iron. Before designing the surface thermocouple, a study of probes used by other researchers was conducted. It was concluded that with the available facilities the design used by Hohenberg(3) would be the most expedient to manufacture. The design was also well suited to the relatively limited diameter of the probe. The construction involved drilling through the length of the probe and bonding a commercial type K thermocouple in the hole with the end protruding beyond the face of the probe.

The commercial thermocouple unit was made of a 1,5 mm stainless steel tube with two 0,25 mm conductors within. The conductors were insulated by ceramic magnesium oxide powder within the tube. The thermocouple was machined away at the face of the probe, and the ceramic powder was removed to a depth of approximately 1 mm. The powder was replaced by a ceramic cement which was capable of resisting cylinder pressure

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*Fuel Research, Sasol Oil Research and Development, P O Box 1, Sasolburg 9570, South Africa forces at the high temperatures which exist in the engine. The ceramic cement used for both the face of the probe and to bond the thermocouple into the probe was Kyowa HC-25A high temperature strain gauge cement.

After the thermocouple had been machined away, a situation existed where the chromel and alumel wires had been brought through to what would be the surface of the combustion chamber. These wires, which normally formed the thermocouple junction, were insulated, supported and sealed by the ceramic cement. The face of the probe was then coated with a thin vapour-deposited gold layer. This process was carried out in a vacuum chamber at extremely low pressure.

The gold coating formed two thermocouple junctions by contacting the chromel and the alumel simultaneously. The two junctions being chromel-gold and gold-alumel. As long as the temperature of the two junctions was identical, the presence of the gold would not have played any role in the voltage between chromel and alumel. The junction would thus respond as a chromel-alumel junction. The thickness of the gold was estimated to be less than 5 μm. The result was that the junctions were within 5 μm of the surface and had negligible thermal capacitance. The output voltage, measured between the chromel and alumel conductors, would thus have responded rapidly to changes in surface temperature.

The gold film played a second important role in that it served to ground both the chromel and alumel conductors. The effect of signal noise in the conductors, which were unscreened over a length of approximately 20 m, was thus reduced. This was in fact so effective that failure of the contact between the gold film and the probe resulted in the signal being obscured by noise. A second commercial thermocouple junction was placed within the probe at a point 2,3 mm from the face of the probe. Temperature gradient was calculated from the difference between the temperatures of the two junctions.

The calculation of the heat transfer rate from both the transient surface temperature and the temperature gradient relies on the assumption of single dimensional heat flux in a direction perpendicular to the surface. In order to encourage single dimensional heat flux, an effort was made to thermally insulate the probe in the transverse direction. This was done by creating an air gap between the probe and the surrounding cylinder head. From within 1 mm of the probe face to a point well beyond the second junction, the diameter of the probe was slightly reduced. The clearance between the probe and the cylinder head at the face of the probe was minimal. This created a seal reducing the flow of combustion gases into the air gap between the probe and the cylinder head. The insulation properties of an air gap are eleven times better than that of a ceramic layer of equivalent thickness(3). It was thus reasonable to assume that heat flux within the probe approached being single dimensional.

SIGNAL PROCESSING

Temperature-compensated thermocouple cables were used to carry the voltages from the two probe junctions over a distance of approximately 20 m to the instrumentation. The signal from the junction imbedded within the surface did not fluctuate within the engine cycle and was processed and recorded by a type K thermocouple panel meter. The surface temperature signal, on the other hand, did fluctuate significantly within the engine cycle. Heat transfer calculation from surface temperature is highly dependent on the rate of change of surface temperature with time. It was thus necessary to record surface temperature with the highest possible accuracy and resolution, which was achieved by using two different instruments. The steady component of the signal or the average of the surface temperature signal was processed and recorded by a type K thermocouple panel meter. This device also compensated for cold junction voltage.

A Tektronix model 5A22N differential amplifier capable of eliminating a large voltage offset while operating at an exceptionally high gain was used to remove the signal offset and amplify the cyclic range of the surface temperature signal. This unit formed part of a Tektronix model 5223 digitising oscilloscope system, and the processed signal was available as an analog output from the oscilloscope. The signal was then passed through a second stage of amplification before being recorded. The processed offset and range components of the surface temperature signal were then fed, along with all other signals from the engine, into a microprocessor-based high-speed data capture system which had been developed during the project(1).

The unsteady component of surface temperature was recorded at each ½° of crank shaft rotation over the full engine cycle for 91 successive cycles. The reason for recording multiple cycles was to allow a representative average cycle to be calculated. The process of recording and averaging 91 successive cycles had an additional benefit in that the amplitude of any random noise was reduced by a factor of 91. The 91 successive cycles recorded far exceeded the number recorded by other researchers who conducted similar tests with success(4,5,6). The actual surface temperature throughout the engine cycle was then reconstructed from the average of the unsteady component and the time-averaged surface temperature. The temperature-dependent temperature-to-voltage gain or Seebeck coefficient was also accounted for at this stage. Figure 2 illustrates a typical measured surface temperature profile in which the range between maximum and minimum temperature was approximately 50 °C. The data represent the temperature between bottom dead centre (BDC) at the beginning of the compression stroke through top dead centre (TDC) to BDC at the end of the expansion stroke.

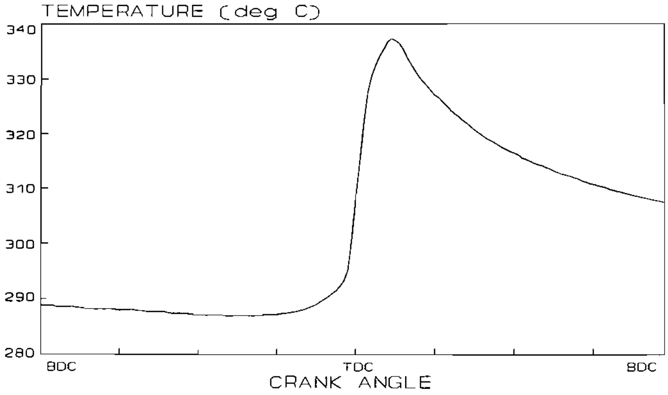

Figure 2: An example of surface temperature measured with the engine operating at 2 000 r/min and 170 Nm

HEAT TRANSFER CALCULATION

The calculation of the heat transfer rate from a measured time history of surface temperature requires an accurate knowledge of the thermal properties of the materials within the probe. Even if the material properties are known, construction variables such as the thermal contact resistance between components can result in uncertainty of the probe properties(3,7). The fact that the probe supplied two signals which could be used to calculate the heat transfer rate was used to overcome the problem. The probe was calibrated by correlating the results calculated from these signals with each other and other variables which were measured. The emphasis was again focused on achieving absolute consistency and sensitivity.

The transient surface temperature recorded by the surface thermocouple was used to calculate the transient surface heat transfer rate at the probe. The average heat transfer rate was indicated by the difference between the temperatures of the two junctions in the heat flux probe. The integral of the transient heat transfer rate was also used to determine the average rate of heat transfer.

If the assumption is made that the heat transfer in the combustion chamber wall is single dimensional, then the relationship between temperature T, time t and distance from the surface x, is described by the Fourier equation:

$$\frac{\delta T}{\delta t} = \alpha \cdot \frac{\delta^2 T}{\delta x^2} \qquad (1)$$

The constant α represents the thermal diffusivity of the wall material. By solving the equation, it is possible to derive an expression describing temperature as a function of time and distance from the wall.

The measured combustion chamber wall temperature was represented by values recorded at discrete time intervals. Information in this form is not easily applied in mathematical equations. A means of expressing these recorded data as a function of time was required. This was achieved by performing a Fourier analysis on the recorded surface temperature data. Surface temperature was then expressed as a Fourier sine expansion of the form:

$$T_{w(x=0)} = T_{wm} + \sum_{i=1}^{\infty} [A_1.\cos(i\phi t) + B_1.\sin(i\phi t)] \qquad (2)$$

Where $T_{w(x=0)}$ is the transient wall temperature at the surface,
T_{wm} is the average surface temperature,
ϕ is the angular frequency of the engine cycle
and A and B are the Fourier coefficients.

By solving the Fourier equation and expressing the result in the form of a Fourier sine expansion, it is possible to derive an equation for temperature as a function of time, location and the Fourier coefficients. This equation can then be differentiated with respect to x for the conditions at the surface to yield an equation for the temperature gradient at the material surface(4). The rate of heat transfer across the material surface is equal to the product of the temperature gradient and the thermal conductivity of the material. The following equation for the rate of heat transfer at the surface can then be derived:

$$q_{(x=0)} = - q_m - K_w \cdot \sum_{i=1}^{\infty} \left[\frac{i\phi}{2\alpha}\right]^{1/2} . [B_1 - A_1)\sin(i\phi) + (B_1 + A_1)\cos(i\phi t)] \qquad (3)$$

where q_m is the average rate of heat transfer and K_w is the thermal conductivity of the cylinder wall material.

By substituting the Fourier coefficients determined from the Fourier analysis of each set of recorded data into this equation, it was possible to calculate the transient surface heat transfer rate. When performing the Fourier analysis of recorded data, a number of alternatives arose. Firstly, the time required to perform the analysis was highly dependent on the order of the analysis selected. While increasing the order tended to improve the accuracy, it also took longer to reach completion. Secondly, a higher resolution of the recorded data was also responsible for extending the time taken to complete the analysis. It was thus necessary to determine what resolution and order were required to achieve an expression which represented the recorded data adequately.

Due to the fact that the rate of heat transfer is highly dependent on the rate of temperature change, any noise in the recorded surface temperature was magnified in the calculated heat transfer rate. The fact that the surface temperature was recorded at high gain and that the conductors were unscreened over a considerable length, resulted in high frequency noise in the recorded signals. While much of the noise was eliminated by the averaging process, it became evident that data smoothing was required. A study was carried out into the simultaneous effects of smoothing, changing the data resolution and changing the order of the Fourier analysis.

An attempt was made to reach a situation where smooth results could be achieved rapidly without compromising accuracy. It was found that by reducing the resolution to two crankshaft degrees, the time required to conduct the analysis was greatly reduced. In order to avoid discarding valuable recorded data and to achieve smoothing, a method was required which would take all data into account. This was achieved by performing a weighted five-point moving average on the half degree data at each two-degree interval. A Fourier analysis was then conducted on the smoothed two-degree data. This resulted in a situation where the speed of analysis was greatly increased, where data were smoothed, and where all recorded data had contributed to the data which were analysed.

A 200th order Fourier analysis was conducted with unsmoothed data at half-degree resolution and then repeated with an order of 100 on the smoothed two-degree data. It was found that the peak rates of heat transfer differed by 0,4%, while the integral of the heat transfer curves differed by 0,7%. The smoothed data yielded a far smoother curve, while the analysis was eight times as fast. It was concluded that the impact of the smoothing and reduction of resolution on the calculated rate of heat transfer was negligible. It was also found that increasing the order of the analysis beyond 120 made no significant improvement to the results. 120th order Fourier analyses on smoothed two-degree data were thus used for the calculation of heat transfer rate.

PROBE CALIBRATION

It is evident from Equation 2 that the temperature distribution in the combustion chamber wall is determined to a large extent by the material properties. Morel, Keribar and Blumberg(8) indicated that, given a particular rate of heat transfer, the magnitude of the temperature swing during the engine cycle depended on material properties. Increased heat capacity and thermal conductivity both reduced the temperature swing of the combustion chamber surface. The heat flux probes which were used for the project were made up of seven different materials, namely

(i) chromel,
(ii) alumel,
(iii) gold,
(iv) cast iron,
(v) stainless steel,
(vi) ceramic cement, and
(vii) magnesium oxide.

All these materials played a role in the nature of the heat transfer through the probe. The role played by the different materials was thus investigated in order to gain an understanding of what was actually being recorded. The cast iron, stainless steel, ceramic cement and magnesium oxide were not considered to have had a significant effect on the probe output. The relative locations of these materials was thought to encourage single dimensional heat flux in the probe. The mass of gold present in the probe was such that it would not have made a significant contribution. The important materials in the probe were chromel and alumel. The heat capacity of any particular alloy type tends to vary by a small amount with a changing alloy proportion. Thermal conductivity on the other hand varies considerably with alloy proportion.

Chromel and alumel, both being nickel-based alloys, can be expected to have similar heat capacities. This cannot, however, be said for their thermal conductivities. The temperature swing of the chromel and alumel surfaces could thus differ. It was also clear that the temperatures of the chromel and alumel surfaces would not necessarily be the same at any point in the engine cycle. The output voltage of the probe is the sum of the voltages of the two junctions, namely the chromel-gold junction and the gold-alumel junction. The fact that the temperatures and Seebeck coefficients of the two junctions could differ implied that the surface thermocouple would no longer behave as a type K thermocouple. The output voltage of the probe would thus represent a weighted average of the temperatures at the two junctions.

The Seebeck coefficients of the two junctions would determine the weighting of the two junction temperatures in the resulting average. These junction gains can be assumed to be constant over the relatively small range of temperature swing. The result is that the rate of heat transfer calculated from the average temperature is a weighted average of the heat transfer actually occurring in the two materials. In the application of Equation 3 for the calculation of surface heat transfer, it was difficult to determine what value to use for thermal conductivity. It was understood that the correct value would be a weighted average of the conductivities of the two materials. The correct weighting would be some function of the two junction gains.

It was concluded that, although the recorded voltage did not represent an actual temperature exactly, it did represent an average of the surface temperatures. The assumption was made that the average temperature-to-voltage gain did not differ significantly from that of a type K thermocouple because junction gains are almost linear over a small range. There was also no doubt that increases in temperatures would yield increases of the same order in the output voltage. The shape of the surface temperature curve is, however, of greatest importance in the calculation of heat transfer and was correctly represented by the recorded data. The form of the calculated rate of heat transfer would thus represent the actual situation, although the range would not necessarily be correct.

The results of Taylor(9) and Timoney(10) indicated that if the rate of heat transfer was correctly calculated, then all the injected fuel would be accounted for by heat release analysis. It was thus decided that this fact should be used to determine the unknown average thermal conductivity. The range of the calculated heat transfer curve was scaled in such a manner that the calculated fuel consumption equalled the measured fuel consumption. The calculated rate of heat transfer was scaled by entering a hypothetical material conductivity. This was done at eight different engine speed and load conditions for tests on two different fuels. An average value was then calculated. The average value represented the average thermal conductivity of the relevant probe materials. The value was found to be within 7% of 61 W/m.K on a 95% level of confidence. This value was then used consistently throughout the project. Error in the value subsequently had no effect on the relative comparisons of different tests.

In the application of Equation 3, knowledge of the average rate of heat transfer is required. The rate of heat transfer is equal to the product of temperature gradient and thermal conductivity. The average temperature gradient was initially calculated from the temperatures recorded by the two thermocouples in the probe. The temperature gradient was assumed to be equal to the difference between these two values divided by the distance between the second probe and the surface. As was the case with the surface thermocouple, the correct thermal conductivity of the material between the surface and the second thermocouple was unknown. This was because there were two materials of unknown thickness, as well as contact resistances between the surface and the second thermocouple.

An additional limitation was that the resolution of the measurement of temperature difference was only 2 °C. This resulted from the fact that the average surface temperature and the temperature at the second thermocouple were recorded with a resolution of 1 °C. This and the small range of the temperature difference of less than 70 °C could lead to errors in the calculated heat transfer rate of more than 2,9% of full range.

A better method for the calculation of the average rate of heat transfer was thus required. By calculating the polytrophic constant of compression from pressure data throughout the compression curve, it is possible to determine where in the cycle adiabatic compression occurs. Adiabatic compression implies that there is zero nett heat transfer to the air in the combustion chamber. Initially it was assumed that the surface heat transfer curve should be zero at the point where adiabatic compression occurred. This allowed the surface heat transfer curve to be offset by the correct amount and obviated the need to determine the average heat transfer rate prior to calculation. An example of the calculated rate of heat transfer over an entire engine cycle is illustrated in Figure 3. The average rate of heat transfer could then be calculated by integrating the surface heat transfer rate throughout a cycle.

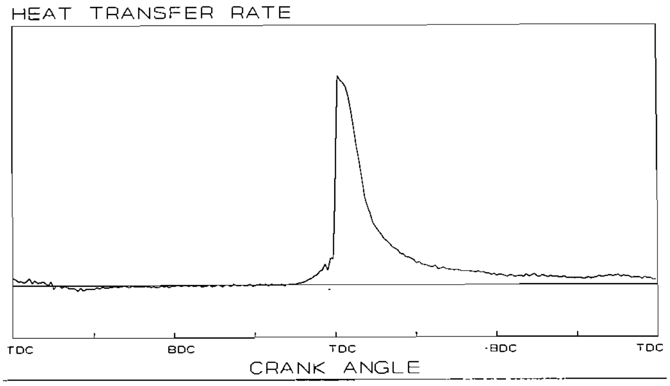

Figure 3: An example of the surface heat transfer rate calculated from the measured surface temperature for an entire engine cycle

It was thus possible to compare the temperature difference between the surface and the second thermocouple with the calculated average heat transfer rate. The average heat transfer rate was known to be directly proportional to the temperature gradient. The average heat transfer rate was plotted against the measured temperature difference for a large number of load conditions taken from different tests. This showed that at a particular speed the relationship between the two variables was linear, but the regression lines did not pass through the zero intercept of the graph. This implied that a temperature gradient of zero would not occur when the rate of heat transfer was zero, which was known to be incorrect. Readings taken at two different speeds formed separate lines with different offsets. The conclusion was drawn that the criteria used to determine the offset of the heat transfer curve was slightly incorrect. This implied that zero heat transfer at the surface does not correspond with the point of adiabatic compression of the bulk gas in the combustion chamber.

This observation was supported by the findings of Lawton⁽⁵⁾ who indicated that the zero heat transfer rate at the wall surface occurred far earlier in the cycle than the point of adiabatic compression. The explanation for this is that during the intake and early compression strokes, the boundary layer is heated by the combustion chamber walls. The temperature of the boundary layer is thus considerably higher than the bulk gas temperature. Compression results in an increase in air temperature at a rate determined by the gas laws. The temperature of the boundary layer which is higher at the outset remains higher than the increasing bulk gas temperature. The heat transfer at the combustion chamber surface is determined by the temperature difference between the wall and the boundary layer.

The temperature of the boundary layer will reach the wall temperature earlier in the cycle than the bulk gas. At the point where the boundary layer temperature equals the wall temperature, there can be no heat transfer between the wall and boundary layer. At this point the boundary layer is hotter than the bulk gas and thus heats the gas in the combustion chamber. Heat would thus be removed from the boundary layer, retarding its temperature increase due to compression. Beyond this stage the boundary layer also loses heat to the combustion chamber walls. The bulk gas temperature continues to increase at a rate slightly higher than that due to compression, yielding a polytrophic constant greater than that for adiabatic compression. The bulk gas temperature will thus soon equal that of the boundary layer, which results in adiabatic compression of the bulk gas. The bulk gas will consequently experience adiabatic compression later in the cycle than the point where zero surface heat transfer occurs.

Lawton⁽⁵⁾ did not, however, have any means of determining where in the cycle zero heat transfer occurred. The results of Lawton⁽⁵⁾ indicate that this occurred at bottom dead centre, which is not credible because compression has not yet commenced at this point. Rao and Bardon⁽¹¹⁾ stated that, due to high turbulence in the engine, the boundary layer is very thin and would have negligible thermal capacitance. This statement contradicts the observations of Lawton⁽⁵⁾. It was concluded that, although the phenomenon described by Lawton⁽⁵⁾ did in fact take place, the effects were possibly not as significant as he had made them out to be.

In an attempt to determine the true point at which zero heat transfer took place, the heat transfer calculation was repeated for numerous sets of independent data while the assumed zero point was varied. Linear regressions of average heat transfer rate on temperature difference were conducted for each assumed zero point. Changing the zero point resulted in the regression lines being shifted vertically. By a process of interpolation and iteration, three different zero points were achieved for the three different engine speeds used for testing. These zero points resulted in all the calculated rates of heat transfer falling on the same line, which passed through the zero intercept of the graph. The consistency with which heat transfer was determined is illustrated by Figure 4.

A linear regression showed that 99,1% of the variation in the calculated average rate of heat transfer was accounted for by the measured temperature difference. The offset from zero of the regression line at the point where the temperature difference was zero was found to be 0,22% of full scale, which was proved to be insignificant. Error in the determination of the temperature difference made a greater contribution to variation in the regression than errors in the calculated average rate of heat transfer. There was, however, no means by which the actual confidence interval of the heat transfer measurement and calculation could be determined.

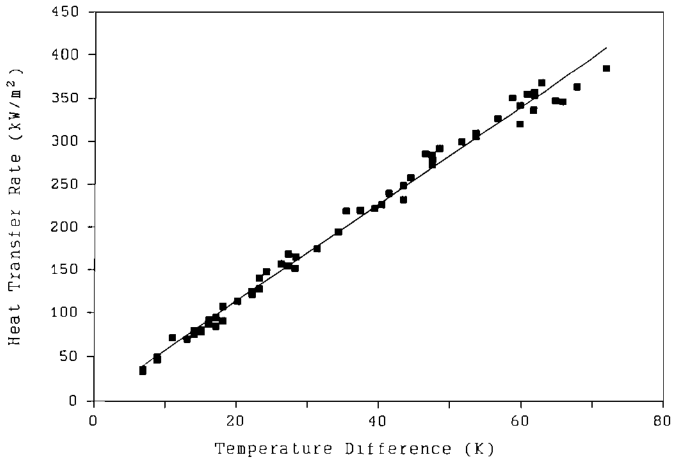

Figure 4: Calculated average rate of heat transfer plotted against the measured temperature gradient

A statistical analysis of the data displayed in Figure 4 was conducted and showed that all recorded data fell within the 90% confidence interval for predictions of the regression. The 90% confidence interval was equivalent to less than 8% of the full range. The confidence interval of the measured temperature difference was at least 6% of the full range, due to poor resolution and measurement error. This indicated that the 90% confidence interval of the calculated rate of heat transfer may have been as small as 2% of the full range. Differences in the average rate of heat transfer were measured with different fuels at the same engine condition. These differences amounted to as much as 10% of the full scale. On the basis of the deduced confidence interval, there can be no doubt that the measured differences between fuels were significant.

The calculated zero heat transfer points were as follows:

1 000 r/min @ 113,0° crank angle before top dead centre.
1 700 r/min @ 103,0° crank angle before top dead centre.
2 000 r/min @ 91,5° crank angle before top dead centre.

The fact that the point advanced with decreasing speed was credible in that heat transfer, which was the cause of the effect, is highly dependent on time. Reduced time due to increased speed should thus reduce the role played by the effect and cause the zero point to approach the point of adiabatic compression. The point of adiabatic compression was found to be in the region of 55° crank angle before top dead centre. The analysis illustrated the sensitivity with which the instantaneous heat transfer rate was calculated. The good correlation between calculated heat transfer rate and measured temperature difference illustrated the consistency with which the heat transfer rate was calculated. The high linear correlation coefficient indicated that the assumptions made in the calculation of heat transfer rate had been valid.

The gradient of the regression line correlating the average heat transfer rate with the temperature gradient was an indication of the thermal conductivity of the materials in the probe, between the surface and the second junction. The gradient was theoretically directly proportional to the value calculated for the average thermal conductivity of the materials in the surface thermocouple. The method of calculation of the average thermal conductivity could thus be verified by investigating the gradient of the regression line. The thermal resistance per unit area of the materials between the surface and the second thermocouple could be calculated from the gradient of the regression. The thermal resistance could also be calculated from the probe geometry, thus allowing a comparison to be carried out.

The thermal resistance was calculated by multiplying the distance between the surface and the second thermocouple with the inverse of the gradient of the regression line. The thermal resistance was the result of the contribution of the following separate resistances:

(i) the resistance of the cast iron probe material,
(ii) the contact resistance between the cast iron and the ceramic cement,
(iii) the thermal resistance of the ceramic cement, and
(iv) the contact resistance between the ceramic cement and the second thermocouple.

The distance between the second thermocouple and the surface was 2,3 mm. It was assumed that this was made up by 0,3 mm of ceramic cement and 2 mm of cast iron. The thermal conductivities of the ceramic cement and the cast iron were 2,3 W/m.K and 58 W/m.K respectively. From this information it was possible to calculate the contact resistances between the cement and the metals. The fact that the ceramic cement was bonded to both the cast iron and the thermocouple would result in low contact resistances. The calculated contact resistance of 6,7E-06 m^2 K/W confirmed this observation. A second approach was to assume that the contact resistance was negligible and then calculate the thicknesses of the cast iron and ceramic cement. The calculation indicated that the thicknesses of the cast iron and ceramic cement were 1,968 mm and 0,332 mm respectively. The fact that both these calculations yielded credible results indicated that the use of the heat release analysis was valid.

RESULTS

The measurement and calculation of heat transfer rate in the engine was a complex process. It was therefore necessary to validate all the data recorded by the heat flux probe and verify the associated experimental techniques. This was done by plotting the calculated average rate of heat transfer against the measured temperature difference in the probe for every reading used. This is displayed in Figure 4. The regression of heat transfer rate on temperature difference yielded a R^2 value of 99,1%. This indicated that 99,1% of the variation in the calculated heat transfer rate was explained by the measured temperature difference. A study of the residuals of the regression showed that the maximum residual was 5% of full scale. Much of this error could be ascribed to the low resolution with which the temperature gradient was recorded. The average residual was found to be less than 2% of full scale. It was concluded that the entire measurement and calculation procedure for the determination of heat transfer at the probe was consistent to within 2%.

The probe was used in an extensive investigation into the relationship between combustion parameters and heat rejection from the combustion chamber of a direct injection diesel engine(1). In the investigation surface temperature measurements and heat transfer calculations were made at 84 different test conditions. The variations in test conditions included changes in parameters such as fuel formulation, engine speed, engine load and injection timing. The large sample size of 84 observations of each variable allowed the execution of multivariate regressions with a high degree of confidence.

The average surface temperature ranged from 140 °C to 353 °C. It was found that 99,33% of the variation in measured surface temperature could be accounted for by a multivariate regression using engine and fuel parameters which were measured independently of the heat flux probe. The maximum rate of heat transfer calculated from the measured surface temperature ranged between 773 kW/m^2 and 6256 kW/m^2. The results showed that 96,8% of the variation in the maximum heat transfer rate was accounted for by variations in measured engine data. The average rate of heat transfer calculated from the measured surface temperature ranged from 71 kW/m^2 to 386 kW/m^2. It was further shown that 98,25% of the variation in the calculated average heat transfer rate was accounted for by measured variations in engine parameters.

These results illustrated that the probe was capable of detecting changes in the cylinder wall temperature and heat transfer rate across a wide range of conditions. The fact that the vast majority of the variations in the measured temperature and calculated heat transfer rate could be accounted for by variations in independently measured parameters proved that the repeatability of the heat flux measurement probe was high. Figure 5 illustrates the manner in which the measured surface temperature varied as a function of engine load and crankshaft position.

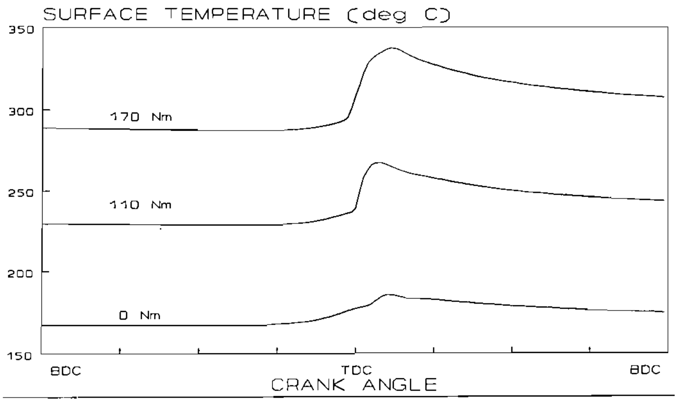

Figure 5: Measured cyclic surface temperature recorded at 2 000 r/min and varying load

The sensitivity of the probe and the related heat transfer calculations is illustrated by the results which are plotted in Figure 6. The data represent the transient rate of heat transfer calculated from the measured surface temperature which was measured in an engine while running on three different fuels at exactly the same speed and load. The fourth curve is the heat transfer which resulted after the timing had been advanced by four crankshaft degrees while the engine was running on one of the fuels. Advancing the timing had a significant effect on the heat rejection, as can be seen in Figure 6. These results illustrate that the probe was sensitive to relatively small changes in the heat transfer rate. It can be seen that the heat transfer rate was relatively consistent prior to combustion. Slight variations in the heat transfer rate prior to combustion were expected as a result of differences in wall temperature.

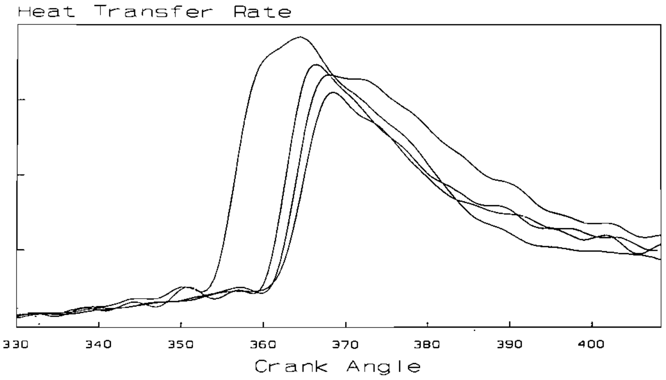

Figure 6: Heat transfer rate calculated from measured surface temperature with the engine operating at 2 000 r/min and 170 Nm on three different fuels and with advanced timing

CONCLUSIONS

The construction and implementation of the heat flux probe is relatively complex. Despite a number of theoretical limitations to the accuracy of the probe, it proved to be adequately accurate for the purpose of the investigation into the relationship between heat rejection and combustion. Contrary to initial fears that the durability of the probe would be limited and that the gold foil thermocouple would require frequent replacement, the probe proved to be very durable and, apart from routine cleaning, it operated without fault for approximately 30 engine hours. At the end of the project there was no evidence of any deterioration of the probe. Had the probe not successfully measured heat transfer rate, the relevant investigation would not have reached completion(1).

While the development of the probe has been discussed in the context of diesel engine testing, the design and numerical methods used for the probe could be applied in any application in which transient surface temperature and transient heat flux measurements are to be carried out. The probe has already contributed to the development of a heat transfer model for predicting heat transfer in the combustion chamber of a diesel engine(2). Possibly, one of the most obvious applications for a heat flux probe would be an investigation into the role of spark ignition knock in engine failure. The heat transfer measurement theory could also have a significant number of industrial applications.

ACKNOWLEDGEMENTS

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THE DEVELOPMENT OF A HORIZONTALLY-CONFIGURED CIRCULATING FLUIDISED BED COAL GASIFIER

*M R JUDD and **M PILLAY

A new type of fluidised bed coal gasifier is being developed under the auspices of the South African National Energy Council. A special feature of the gasifier is that the exothermic combustion reactions are effectively separated from the endothermic gasification (steam-char) reactions by means of an internal partition in the gasifier. Solid material in the gasifier is made to circulate between the two zones created by this internal partition, and the gasifier is thus a type of circulating fluidised bed. Because of the separation of the two reactions into two separate zones, it is possible to produce a relatively high Btu gas, even though the gasifier is air-steam blown. For a relatively cheap coal this has economic advantages over oxygen-steam blown systems.

The original configuration of the gasifier was vertical, with the internal partition being a draft tube. This design is now superceded by a horizontal version, with considerable additional benefits.

A review of the history of the development of the process and the development of ancilliary equipment (such as feeders, ash removal and other devices) is presented.

KEYWORDS: horizontal; coal; gasifier

BACKGROUND

Coal is South Africa's only real energy source. It is also a major source of foreign revenue and should be utilised as efficiently and economically as possible.

However, coal-fuelled devices require coal of a higher quality (in terms of CV, ash, particle size, etc.) than can be provided straight from the mines in South Africa and this has led to the development of the enormous coal-beneficiation industry — and the attendant undesirable generation of huge quantities of discard coal fines. There are nearly 300 million tons of such material dumped in the RSA, over 90% being bituminous discards and the remainder being bituminous slurry, anthracite discards and unwanted duff coals(1). Many discard piles have been on fire for years and pollution levels are amongst the highest in the world(2).

It is against this serious backdrop that research was commenced at the University in the early 1980's into the development of a new type of gasifier that would utilise low grade fine RSA coals. There seemed a very real opening for a new type of unit because although the RSA was gasifying more coal than any other country in the world, none of the three general types of gasifiers currently operating (Lurgi, Koppers-Totzek and Staged fixed-bed units) could satisfactorily process the general range of RSA coals available. The Lurgi's refused fines and produced some difficult by-products; the K-T's needed specially selected high reactivity fuels and even with these produced a further discard of a carbon-rich fly ash; and the staged fixed-bed units needed special fuels and also produced troublesome by-products.

The major coal consumers all launched search programmes in the early 1980's to find an economical alternate gasifier: Sasol, embarrassed by excessive fines production, wanted a fine-coal gasifier; Eskom, in response to pressures to reduce pollution, wanted a gasifier for IGCC; and a host of other companies such as AECI, Gencor, Iscor, Highveld Steel, etc. — the list is long —wanted a cheap, flexible new gasification process for synthesis and/or industrial gas.

The search is even now still intense, with the National Energy Council having just completed a major evaluation of Gasification Technology(3), and certain other industrial groups actively co-developing with overseas gasification partners.

FLUIDISED BED PROCESSING

It was decided that, of the multitude of gasification processes being developed, those in which the coal is fluidised look the most promising. (Full reviews are available elsewhere(3,4,5) and only the key issues are addressed here.)

The fluidised bed gasifier (FBG) is not only able to be fed with coals of a very wide range of size and properties, but it also produces very small amounts of (generally unwanted) tars and oily liquids. However, the FBG has never been commercialised in South Africa. This is partly due to some of the inherent problems in the technology, such as high fines recycle loads, relatively poor fines burnout, low H_2/CO ratio in the product gas, potential oxygen breakthrough, high reaction intensities and afterburning in the freeboard, erosion, gas reversion in the bubble phase, difficulties in coal feeding and ash removal, etc.

NEW PROCESS — VERTICAL CONFIGURATION

In this research project, the new process developed was designed to modify the existing FBG process which would, in practice, attempt to overcome the disadvantages listed above.

In essence, this modification consisted of dividing the fluidised bed into two separate compartments or zones by the inclusion of a vertical surface.

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*Associate Professor, Department of Chemical Engineering, University of Durban-Westville, Private Bag X54001, Durban 4000, South Africa

**Research Assistant, Department of Chemical Engineering, University of Durban-Westville, Private Bag X54001, Durban 4000, South Africa

In the initial work the surface took the form of a draft tube mounted axially in the reactor (as shown in Figure 1 below).

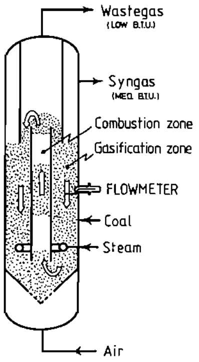


Figure 1: Vertical configuration

By supplying reagent gases at appropriate rates through the specially designed distributors, the solids in the bed could be made to circulate strongly in the reactor — up the draft tube where the solids are in a slugging transport regime and downwards in the annulus region, in a dense partly fluidised bed regime. Coal was introduced into the downward-flowing annulus.

HOT EXPERIMENTS

The first practical hot studies on a large (500 × 4 000 mm) model of this system were reported in detail by Judd and Meihack(6) where it was shown that the deep circulating bed configuration had a remarkable ability to retain fines. It was shown that with air being supplied to both parts of the bed a 96%-98% burnout was possible on a dry (or slurry) feed of a 20 micron carbon-rich fly ash. The reason for this remarkable performance was ascribed to the high residence time that the fly ash could have in the bed as it was entrained downwards in the down-flowing solids in the annulus region.

This characteristic also made it possible to process friable discard that was prone to shattering and the formation of cenopheres/fines.

Parallel cold studies confirmed that downward entrainment of fines was a new and controllable processing technique. (Subsequent to this work, papers have appeared reporting on the exploitation of this technique for the enhanced retention of fines(7).)

To supply two different reagents to the two different zones was a more difficult task and it required the authors to gain a full understanding of the hydrodynamics of circulatory solids flow and, in particular, an understanding of pressure balancing. A major contribution to this was made by Rudolph(4) who was seconded to the project by the then interested industrial partner. In an intensive cold and hot model study Rudolph uncovered the principal hydrodynamic elements of the process in a simple model which enabled the authors to design the distributor and gas separating hood and modify the large reactor at the University of Natal to operate as a gasifier.

The experiments were only partly successful, mainly due to the fact that the reactor shell had been built before Rudolph's theories were available and it was impossible to lengthen the vessel to achieve the correct pressure balance necessary to achieve complete separation of gases, both in and after the reactor. Nevertheless, the reactor was run hot (16 runs over about 300 hours), testing various aspects of the draft-tube concept. Run lengths of typically 1 to 2 days were ended by either mechanical failures of the gas sampling systems, or the primitive coal screw-feeding system, or also, often merely by operator fatigue as the whole operation was being run by only two or three available people. Nevertheless, the idea was proven in principle that zonal separation was possible within a fluidised bed and that in the context of gasification this meant that it was possible to separate the combustion (oxidation) reactions from the gasification (CO, H_2-producing) reactions, and hence achieve air-blown gasification instead of the expensive oxygen-blown gasification through the normal method.

The separation of the zones and the avoidance of reagent cross-flow between the zones was not, however, perfect and further cold and hot model development work by Pillay(8) finally showed that zero cross-flow could not be achieved. Nevertheless, a number of distinct advantages of the process remained.

Firstly, it became evident that the outer downward-flowing region behaved in many ways similarly to a Lurgi gasifier, except that it did not produce tars/oils. Long residence times of coal could be achieved, leading to the potential for excellent coal burn-out even in the case of low-reactivity coals. Experiments with low-reactivity high-ash discard coal from the Platberg dumps in Natal show that gas could be produced. The gasification in the outer downward-flowing region also offered other advantages, e.g. the feed coal, which shattered on the sudden arrival in the ± 900 °C bed from the feeder, was dragged down, initially pyrolysing under a steam atmosphere to a most reactive char which then gasified. But unlike the Lurgi, the (largely undesirable) pyrolysis products were reformed in the hot upper section of the outer region and tars/oils were hardly produced.

Secondly, coal was dispersed into the circulating burden of ash and refractory sand, and clinkering and caking was thus not a problem.

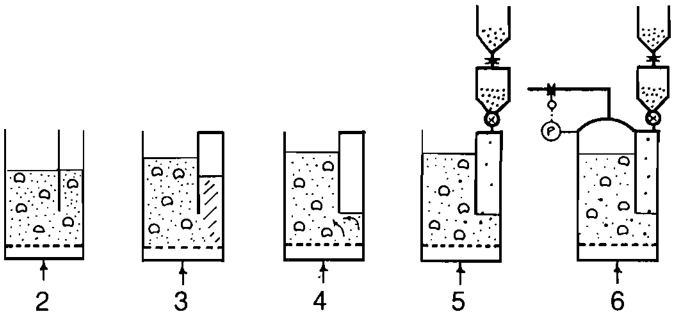
Thirdly, and of great significance, the gasification products (H_2 and CO) were formed in an essentially oxygen-free environment, thus avoiding any problem of reversion which is a prevalent problem in most FBG's.

Coal which was not converted cycled into the central draft tube where the rapid combustion process occurred. Most of the fines were elutriated into the lower value flue gas. Any coal still unburned recycled back into the outer region, but probably in a condition of greater reactivity to steam due to its pass through the combustion zone. The gas produced had a high H_2/CO ratio(4) and, due to the coal-rich mode of operation, no freeboard reactions were detected.

FEEDERS, ASH REMOVAL AND OTHER DEVICES

Arising from the critical re-evaluation of Rudolph's circulation model(4) and some definite experimentation by Pillay(8), an unexpected phenomenon in fluidisation was discovered, namely that if a fluidised bed was partitioned and the one partitioned compartment was sealed, the fluidised bed retreated to the bottom of the partition, as is shown in Figures 2 to 4. A simple adaption of this phenomenon, shown in Figures 5 and 6, lead to a new method of coal feeding below the bed surface, even into a pressurised fluidised bed system(9).

The idea was patented(10) and tested hot in the pilot plant facility at the University of Natal and later in an industrial fluid bed boiler. The principle was further extended to develop an improved sensor for measuring pressure(11) and this too was demonstrated in an industrial fluid bed reactor. In further discussion of this principle, it was realised that it could be applied in such a way that it would be possible to remove hot solids from a fluidised bed without the need for hot valves. This idea was also refined and tested on the hot pilot facility and the necessary data for design measured(8).



Figures 2-6: Principle of coal feeder system

New types of bed level detecting probes were also developed(8). One other major problem was the on-line detection and measurement of particle circulation. Originally this was measured by tracking a radioactive particle(18) at operating temperatures, but a probe which responded to particle movement was later developed by Bernhardt(19). This was found to be suitable for industrial use.

IMPROVED PROCESS — HORIZONTAL CONFIGURATION

One of the problems with the vertical configuration was that it soon became apparent that the flow regime in the draft tube was highly scale-dependent and that there was considerable doubt about whether the reactor could ever be scaled up to a large industrial size. A lot of effort had been expended in establishing a particular type of behaviour of the gas slugs in the draft tube (viz. square-nosed slugging(12)), but this particular regime could only be achieved with quite small draft tube sizes.

However, if the gasifier were oriented horizontally and the draft tube converted into a slot (see Figure 7), the whole system became effectively a 2-D system and offered the advantage that if one experimented on a "slice" of the vessel, one could scale up with much greater certainty simply by extending in the horizontal direction.

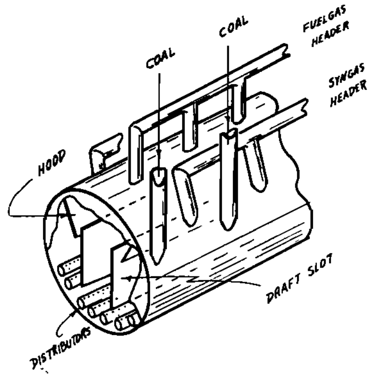


Figure 7: Horizontal configuration

A series of small-scale cold slice models were built, tested and modified, until a near optimum geometry was developed. The slice model was code-named the "Camembert" and soon a large 2 000 × 400 mm cold model was erected at the CSIR for independent testing and analysis.

The Camembert far exceeded design expectations, the undesired cross-flow of gas was reduced and the particle circulation increased. Innovative experimentation by Engelbrecht(13) led to a practical bubble-cap partitioned-distributor design and the data generated enabled computer simulation of a possible industrial version.

In these cold model studies a further interesting fluidisation phenomenon was discerned, namely that a standing wave formed on the surface near an inclined surface. The phenomenon was capitalised on to improve the post-gasifier (hood) separation of the gases from the two zones of the gasifier.

Following the success of the CSIR model studies, an intensive patenting programme was embarked on and the design patented locally and in a number of overseas countries(14).

SIMULATION, MODELLING STUDIES AND KINETIC DATA

Following the patenting process, the next logical step was to build a hot pilot plant of the process. Expenditure for such a project has been estimated from as little as R0,5 million to as high as R10 million and a comprehensive study of the future development of the process is now in progress(3).

Pending the outcome of the study, research is being undertaken in control and computer simulation and modelling studies. Both in-house and proprietary programs (e.g. REACTION, ASPEN, CHEMCAD, etc.) are in use.

These have required kinetic data on the various processes occurring in the gasifier. In the case of combustion, the process is very rapid and there is also a considerable wealth of information. On the other hand, the data on the kinetics of the steam-char reaction for RSA coals was non-existent. A micro fixed-bed reactor was therefore developed, and a range of coal types have been studied under projected reactor conditions yielding the first database on RSA char-steam reactivities(16). Parallel work on devolitisation has also been undertaken(17).

PROCESS CONTROL

The control of the circulating bed gasifier requires the simultaneous control of both the fluidisation hydrodynamics and also the thermodynamics and reaction kinetics. To be industrially acceptable, the process must be both intrinsically controllable and also reasonably robust to mild process perturbations. The study of the control problem has necessitated the building of further models to identify interactions and sensitivities to various potential malfunctions. This work is presently in progress and firm conclusions about the overall controllability of the process are expected by the year end.

HEAT TRANSFER STUDIES

One special feature of the process is the employment of an inert solid phase (ash + refractory sand) to transfer heat from the hot combustion zone (in the draft slot) to the cold gasification zone (in the outer regions). The sand acts effectively as an allothermal agent and it is the sand's capacity to heat up and cool down rapidly that is an important factor in determining the coal processing capacity of the gasifier. Accordingly, a 150 × 2 000 mm test reactor has been built in which sand can be switched from combustion to gasification conditions. This highly instrumented rig is starting to provide the necessary data on the unsteady-state heating/cooling process.

CONCLUSIONS

The final outcome of this gasifier development is now imminent and, as alluded to above, decisions are expected shortly as to whether the hot pilot plant should be built or the development programme terminated. It seems appropriate perhaps to conclude by a summary of the principal advantages that the authors hope for in the process, together with the potential disadvantages that have been identified so far.

Principal hoped-for advantages of the process

(1) Use of air (or possibly enriched air) instead of oxygen.
(2) Potentially capable of handling fine feedstocks, without the need for special feed pretreatment/screening and showing a good burn-out of fines, latent or existent. No separate fines recycle system.
(3) High H_2/CO ratio in the so-called "syngas" stream.
(4) Low reversion of the "syngas" gas stream, in the gasifier itself.
(5) Capable of handling low-reactivity coal, maybe also discard-grade coals.
(6) Capable of operation at high pressure (a simple cylindrical reactor).
(7) Potentially an exportable technology, and job-creating process for RSA.

Reasons for hoped-for advantages

(1) With the zonal separation in the reactor only a very small amount of N_2 will appear in the medium Btu gas stream.
(2) Downward-flowing region in the reactor shows a remarkable capacity for retaining ultra-fines until they have burned out.
(3) The high H_2/CO ratio observed in hot experiments is not fully understood. It is possibly due to the separation of the various gasification reactions.
(4) Low reversion is due to the absence of both bubbles and O_2 in the gasification zone.
(5) Low capital cost because of: low headroom required, low vessel cost, low royalities, low feed preparation costs, local manufacture costs, no complex valves, no water jackets.
(6) Unreacted coal cycles between the combustion and the gasification zones; being "reactivated" in the combustion pass, by physical rupture, etc.
(7) Simple vessel design should readily permit pressurisation.
(8) Home-grown technology which may in the end work better for South African coal than any of the other gasification processes.

Potential disadvantages that have been identified

(1) The sand-filled seals, which separate the two gas streams leaving the gasifier, may fail if the pressure differential between the two gas streams is not kept within, say, 10 ins w.g. This probably makes the gasifier unsuitable for a chemical or a synfuels plant requiring syngas (from a safety point of view). But the process could be a satisfactory generator of fuel gas for general industrial use or for IGCC.
(2) Since the gasifier produces two separate gas streams, and *if* it is desired to maintain these two streams separated, then two gas clean-up systems will be required (capital cost problems). But if only a fuel gas is required, the two streams could be combined for a single cleaning.
(3) The scale-up rationale consists essentially of increasing the length of the gasifier. As length is increased, more feeders, more gas manifolds, more ash removal points, etc. are needed. The economy of scale may thus not favour very large units.
(4) Control of the system may be difficult due to the complex interaction between the requirements for particle circulation and the requirements for autothermacity. Also, the unit may be too sensitive to any axial maldistribution of the feed (reactant) gases (such as might be caused by local blocking of the distributor).

ACKNOWLEDGEMENTS

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OVERVIEW OF THE FIRST WORLD COAL INSTITUTE CONFERENCE ON COAL IN THE ENVIRONMENT, HELD IN LONDON, ENGLAND, 3-5 APRIL 1991

*C W LOUW

INTRODUCTION

The World Coal Institute (WCI) which organised and sponsored the Conference on "Coal in the Environment" is a non-profit, non-governmental association of coal-producing enterprises. Membership of the WCI is open to coal producers from anywhere in the world. Present membership is drawn from countries of six continents, including South Africa.

The Conference attracted world-wide attention, being attended by 520 delegates from 43 countries. South Africa was well represented with 16 delegates from both the public and private sectors.

The aims of this Conference were spreading understanding of the world-wide importance of coal, highlighting the environmental issues facing coal development now and in the future, and providing a comprehensive and authoritative coverage of the very latest in clean coal technologies. The programme comprised a main stream session that was complemented with parallel technical and poster sessions, as well as an exhibition which focused mainly on clean coal technologies. In addition, addresses were presented at luncheons by various distinguished international guests including persons such as the Right Honourable John Wakeham, UK Minister of State for Energy, and Mr George Bartlett, South African Minister of Mineral and Energy Affairs.

MAIN VIEWPOINTS

A number of important viewpoints on various aspects relating to the coal/energy/environmental interface emanated from the presentations and discussions during the Conference. A synthesis of these is presented below:

Coal in the global energy economy

Coal, by virtue of its abundance and wide geographical spread, is regarded as a vital and secure source of energy for the future. Coal reserves are sufficient to last well over 200 years at 1990 levels of production and will outlast known oil and gas reserves which are expected to last for not much longer than 50 years. However, coal's lifetime as a resource is not unlimited, and accordingly steps to ensure its sustainable use are a necessity.

The past history of coal has been one of maximum exploitation with little regard for environmental consequences. Consequently, coal's public image has to be improved and its public acceptance needs to be won back. Although coal will play an increasingly important role as a primary energy source in the world it can expect stiff competition from other resources, especially from natural gas in the near-to medium-term and from nuclear power in the longer term.

Environmental constraints do pose a significant threat to coal's future and must be taken seriously. Elements which are considered critical for ensuring coal's prominence as a clean and strategic fuel in the future global energy mix include technology innovation across the broad spectrum of coal utilisation, technology modernisation, policy and research agendas which are focused on global climate change, initiatives which are environmentally prudent and have merit in their own right, and training and education of the next generation of engineers, scientists and technologists whose work will shape the long-term viability of coal.

The coal industry should not only be concerned with supplying coal as an energy source, but should also ensure that coal is used in an efficient and environmentally responsible manner by providing expert advice on all aspects of coal utilisation and by becoming more involved in the development of clean coal related technologies.

Environmental challenges and responses

The production and utilisation of coal on a large scale have an inevitable impact on all three of the environmental media, i.e. atmosphere, water, and soil. Increased use of coal will tend to lead to more pressure on these media. The added burden of solid and liquid wastes resulting from the application of clean coal technologies, notably air pollution control systems, is amongst the new environmental issues that will require urgent attention.

There is no universal panacea for the treatment of pollution emissions and wastes resulting from the utilisation of coal. The environmentally related solutions adopted will depend very strongly on local circumstances. In this regard it was emphasised that an integrated approach to environmental protection needs to be followed whereby such emissions and wastes are considered throughout the whole of a project.

The single most important environmental challenge is the curbing of greenhouse gas emissions resulting from fossil fuel combustion. The argument that coal used for power generation accounts for only 8% of the global warming problem simply will not carry sway in a world where strong environmental concerns and beliefs are increasingly being voiced through political action and regulatory change.

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*Head, Coal R & D, National Energy Council, Private Bag X03, Lynnwood Ridge 0040, South Africa

There is, as yet, no clear scientific evidence of an enhanced global greenhouse effect which could have detrimental consequences for the environment. However, it is virtually certain that the troposphere is warming very slowly in response to the continuously increasing concentrations of greenhouse gases, but the signal is still too small to be detected above the large natural climate variations, partly because it is being delayed by the thermal inertia of the oceans. Prediction of the magnitude and timing of the greenhouse warming and the concomitant changes in rainfall and other climate parameters is still too uncertain to provide firm guidance for major policy decisions.

Although scientific evidence for the enhanced global greenhouse effect is not yet clear cut, the implications of that evidence are sufficient to warrant the promotion of cost-effective measures which can be applied until more certainty is obtained. Such measures should include reasonable and practicable steps to reduce energy consumption, utilise all fuels more efficiently, and explore economically promising alternatives to fossil fuels. In addition, adaptive strategies should be developed without delay for the areas of agriculture, forestry, water supply and coastal defences, whereby the economy would be made less vulnerable to climatic changes when they do occur.

The application of appropriate fiscal measures is an important instrument to aid the curbing of greenhouse gas emissions; the rationale behind this approach being that energy should be more expensive to reflect its cost to the environment and to discourage its use through the higher price, thereby reducing emissions of greenhouse gases. Levies rather than taxes seem to be favoured because the former have a much stronger steering effect and can therefore be employed for specific purposes, e.g. financing investments into energy-efficient technologies. The extent to which such measures would affect the competitiveness of countries was unfortunately not discussed.

The targets adopted by several countries for stabilising greenhouse gas emissions do not appear to be mandatory and most carry carefully devised caveats which protect their national interests. Moreover, these decisions would appear to have been made at a political level without evaluating the economic and social consequences of such measures.

There is a need to evaluate properly the various response measures proposed for stabilising greenhouse gas emissions, especially in relation to determining the costs and benefits involved before committing the world economy to an unnecessarily costly or irrevocable response strategy.

Present and prospective technical solutions

It is of common concern to all countries that the continued use of coal should be based on the best available clean coal technologies and that improved methods of using coal are continuously supported at all stages of their development from research through development and demonstration to proving on a commercial scale.

Much simple yet effective advice and technical knowhow is already available to make immediate improvements to the oldest and most poorly operated plant, whilst more sophisticated systems can follow to bring all countries eventually up to the highest performance standards.

A comprehensive suite of clean coal technologies is available, but further development is required to improve their efficiencies. Moreover, the experience gained from demonstration plant experience in advanced clean coal technologies needs to be rapidly translated into a commercial scale, both for new plant construction and for the improvement of existing plants.

Due to its cleanliness and processing flexibility, coal gasification will emerge as the major coal conversion technology for power generation of the 21st century.

Despite the potential of clean coal technologies, it would be a mistake not to recognise that the potential to use coal and to control emissions may be irrelevant to many in the environmental community who may be fundamentally opposed to fossil fuels and are particularly anti-coal. Their views may not be widely held, but their political and public influence is substantial and growing.

International co-operation and technology transfer

The international community in the coal sector can be of greatest assistance to developing countries by aiding them in their efforts to undertake the structural and institutional reforms required to produce a more energy-efficient sector.

It would be in the interest of all nations if developing countries were given ready access to the new range of clean coal technologies currently being developed and demonstrated in industrial countries. However, given the current debt problems and resource constraints confronting most developing countries and the fact that most pollution to date was caused by developed countries, the most appropriate principle would seem to be that the developed countries mobilise and provide the necessary additional resources to allow the successful introduction of clean coal technologies to developing countries. A first step in this direction is to be seen in the creation of centralised funding facilities such as that which has already been set up by the World Bank.

Transfer of technology should be done within the framework of a technology policy which sets long-term goals.

Selection of the proper technology and its adaptation to local conditions are essential. Only commercially proven technologies should be transferred to developing countries.

Any type of technology transfer should be integrated with follow-up training programmes. Consultation and documentation centres should also be opened to provide services to industry and domestic users of coal.

Transfer of clean coal technologies to developing countries will not only increase the share of coal in the primary energy demand of these countries, but will also help increase their economic welfare and at the same time preserve the environment.

CONCLUSIONS

The Conference did not feature a formal concluding session. The conclusions offered here are based upon the author's evaluation of the presentations and views expressed at the Conference, particularly taking into account the South African energy, environment and socio-economic situation. These conclusions are as follows:

- The interaction of energy and the environment is a field which is interwoven with many complexities and in which economic constraints play an important role. Management of the energy/environment interface will require a balanced and pragmatic approach wherein both energy security and environmental safety are given due consideration.

- The integrated energy/environment policy currently endorsed by the National Energy Council(1) appears to be basically sound and in line with broad international thinking. However, a *sine qua non* for the successful implementation of this policy will be the full co-operation between all interested parties in the public and private sectors as well as the general public. This needs to be reinforced, on the one hand, by a properly integrated National Environmental Management System that will hopefully be adopted shortly and, on the other hand, by an energy-related education/information drive aimed at the broad community in South Africa.
- The world is unlikely to accept further use of coal without significantly improved environmental performance. It can therefore be expected that South Africa, with coal as its most important energy source, will become increasingly subjected to environmental pressures both from within and outside the country. In order to effectively counteract this situation a pro-active approach will be needed to stimulate the clean and efficient use of coal throughout the entire chain of coal utilisation. It would seem expedient that such an approach be complemented with the introduction of cost-effective fiscal and regulatory measures which are appropriate for South African conditions.
- A comprehensive suite of advanced clean coal technologies is being developed in the USA and Europe. These programmes are excessively costly, and a small country such as South Africa cannot afford to partake in the basic development of such technologies. However, it will be prudent with a view to long-term planning that hands-on experience be obtained in some of the better developed clean coal technologies which are associated with power generation. In this regard an opportunity appears to exist to carry out a demonstration project entailing the repowering of one of the "mothballed" coal-fired power stations in the Eastern Transvaal Highveld using coal gasification. Such a project should be given serious consideration and could well be undertaken as a joint venture between government, the coal industry and other parties.
- In a broader context it is essential that South Africa with its well-developed infrastructure, available expertise and strong leadership core should really become more geared towards creating prosperity for its **entire** community, giving due regard to the maintaining of a proper balance between socio-economic development and environmental protection. This approach will ensure the possibility of exercising energy and environmentally related options in the near to medium term that will ultimately benefit all its citizens.

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DETAILS OF AUTHORS

GIELINK M I
BSc (Mech Eng)(U.N.)
Research Engineer, Generation Group, ESKOM, Megawatt Park. Presently seconded to SANCWEC and based at the Energy Research Institute, P O Box 33, Plumstead 7800, South Africa.
Tel.: (021) 705 0120, Fax.: (021) 705 6266

Michael Gielink graduated with a BSc (Mech Eng) from the University of Natal, Durban, in 1986. In 1989 he worked for Air Products PLC (UK) and Thames Water PLC (UK) as a research assistant on a temporary basis. In 1990 he commenced working for ESKOM and spent time in the operating departments of Koeberg and Wilge power stations. He was then transferred to Rosherville Engineering and was responsible for completing a report on the findings of a life extension (LIFEX) investigation on the turbine plant of Ingagane power station. He also concentrated on the general maintenance of turbine plant. In January 1991 he was seconded to the South African Committee of the World Energy Council (SANCWEC) in order to assist with the research necessary for South Africa's input into the World Energy Council's Commission entitled "Energy for Tomorrow's World".

JUDD M R
Pr.Eng, PhD(UCT), MIChE, M(SA)IChE, CEng(UK)
Associate Professor, Department of Chemical Engineering, University of Durban-Westville, Private Bag X54001, Durban 4000, South Africa
Tel.: (031) 820 2483, Fax.: (031) 820 2755

Robin Judd obtained his PhD (under the auspices of Dr John de Kock and Prof. John Davidson) in the field of "Aggregative Fluidisation" in the days when one could boast that one had read essentially all the papers on fluidisation!

He worked in a production capacity with AECI, and later with Shell & BP SA Petroleum Refineries in Durban. He joined the University of Natal in 1970, later to become Head of Department of Chemical Engineering for his last six years there.

Professor Judd has been active in fluidisation research both academically and in local industry. His particular interest is to tailor/modify fluidised systems for new applications. He has published in numerous international publications and holds several patents in the field.

LOUW C W
BSc and MSc (University of Stellenbosch), PhD (Rand Afrikaans University), Sci. Nat. Chief Energy Specialist, Coal Division, National Energy Council, Private Bag X03, Lynnwood Ridge 0040, South Africa
Tel.: (012) 348 9564/5/6, Fax.: (012) 348 9676

Initially Dr Louw was concerned with air and environmental related pollution research, playing a leading role in the Air Pollution Research Group of the Council for Scientific and Industrial Research (CSIR). Subsequently, he managed the national programmes of Weather, Climate and Atmosphere Research and Remote Sensing within the Foundation for Research Development of the CSIR.

Besides publishing and presenting numerous research papers at local and overseas conferences, mainly in the field of air- and environmental-related pollution, he served on several national expert scientific committees and councils. In 1989 the National Association for Clean Air Individual Award was awarded to him in recognition for his key role in the management and development of air pollution research in South Africa.

Since joining the National Energy Council Dr Louw is involved in managing coal R & D as well as the energy/environment interface.

PILLAY M

Research Assistant, Department of Chemical Engineering, University of Durban-Westville, Private Bag X54001, Durban 4000, South Africa
Tel.: (031) 820 2483, Fax.: (031) 820 2755

Maggie Pillay is a Research Assistant in the Chemical Engineering Department of the University of Durban-Westville. She has been active in the co-development of a new fluidised gasification process at the University. She intends to resume full-time studies in Chemical Engineering in 1992.

TAYLOR A B

B Eng (Mech)(Stellenbosch), MSc (Eng)(Natal), PhD (Natal)
Fuel Research, Sasol Oil Research and Development, P O Box 1, Sasolburg 9570, South Africa
Tel.: (016) 708 2516/708 2946, Fax.: (016) 708 2711

Andrew Taylor graduated from the University of Stellenbosch in 1984 and after completing a project in the employment of BMI, registered with the Department of Agricultural Engineering, University of Natal, to complete a Masters degree. After graduating with an MSc degree in 1987 for research into the combustion of alternative fuels in diesel engines, he was employed by Sasol and posted to the University of Natal where he investigated the relationship between diesel combustion and engine durability. He was awarded a PhD degree in 1989 for this research which successfully identified the causes and mechanisms of combustion-related engine failures.

During 1990 Dr Taylor was involved in work for the Combustion Engine Technology Programme at the CSIR where he investigated heat transfer in diesel engines and microprocessor applications in engine condition monitoring.

Dr Taylor has spent the last year at the Fuel Research laboratory of Sasol Oil R&D where he has concentrated on evaluating current and future diesel formulations, as well as the development of new test facilities and techniques.

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