A forecast of the coal and uranium requirements for electric power generation in South Africa

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SYNOPSIS

This paper describes briefly a computerised model of the South African electricity system which has been developed jointly by the Atomic Energy Board and the Electricity Supply Commission. The results of an analysis of this system have been subjected to a fairly extensive sensitivity analysis which reveals that up to the year 1990 between 680 and 700 million tons of coal will be required for electric power generation, together with between 7 000 and 10 000 tons of uranium. This result is fairly insensitive to data variations, but the prediction of a cumulative requirement up to the year 2000, of between 1 300 and 1 800 million tons of coal and 25 000 to 70 000 tons of uranium, proves to be very data-sensitive.

SINOPSIS

Hierdie verhandeling gee 'n kort beskrywing van 'n komper model vir die Suid-Afrikaanse elektrisiteits sisteem wat gesamentlik ontwikkel is deur die Raad op Atoomkrag en die Elektrisiteitsvoorsienings Kommissie. Die resultate van die ontleding van hierdie sisteem was onderwerp aan 'n taamlike deeglike sensitiewe analise wat aan die lig gebring het dat tot die jaar 1990 tussen 680 miljoen ton steenkool asook tussen 7 000 en 10 000 ton uraan nodig sal wees vir die opwekking van elektrisiteit. Hierdie resultaat is taamlik opgevoelig tot data variasies, maar die voorspelling van die toenemende benodiging tot die jaar 2000 van tussen 1 300 en 1 800 miljoen ton steenkool en tussen 25 000 en 70 000 ton uraan is bewys baie data-sensitief te wees.

INTRODUCTION

South Africa is reported to have saleable coal reserves of a little under 11 500 million tons (Van Rensburg, *et al*, 1969) and low-cost uranium oxide reserves of around 300 000 tons (Roux, 1971). Taking into consideration the calorific value of this coal and comparing the relative fuel requirements of modern coal-burning and nuclear power stations, one ton of uranium is equivalent to approximately 16 000 tons of coal. In other words, even if we do not allow for the future technical development of nuclear power stations, our uranium reserves are equivalent to approximately 4 500 million tons of coal. However, it is highly probable that in the 1980's a type of nuclear power station will be available which will be capable of producing at least 40 times as much power from a given amount of uranium as the current generation can, so it is fair to say that our coal and uranium reserves are at least equivalent in terms of potential electrical energy production. The relative use to which these two materials are put thus merits very careful consideration, because no country can afford to penalise its competitive international standing by adding unnecessarily to its energy costs.

An examination of the characteristics of the South African electricity system and the locations of the coal deposits immediately provides a broad insight into the possible solution to the problem of how best to utilise our coal and uranium reserves. An oft-repeated characteristic of the system is that it currently has five widely-scattered load centres: two inland and three on the coast. The coalfields are inland, situated close to the inland load-centres. The transportation of coal to the three coastal load centres is costly. Factors are displayed in Table I which, if applied to the pit-head cost of coal, give its approximate cost at the various other load-centres.

TABLE I

Region	Approximate delivered coal cost divided by pit-head cost
Durban	2,55
Port Elizabeth	3,06
Cape Town	3,5
Kimberley	1,25

An alternative to transporting coal to the coastal load-centres is to generate the electricity inland, on the coalfields, and to use high-voltage transmission lines to feed the coastal areas. Yet another alternative is to meet increments in demand in the three coastal areas with nuclear power stations, for which only a trivial amount of fuel is required annually. The relative overall cost of these methods, together with considerations involving the current-carrying capacity of the existing transmission lines, controls the choice between them for at least the next 20 years. It is possible that after this time limitations on cooling water availability at the coalfields may prove to be the most important consideration. An important product of the analysis of this problem is, of course, a prediction of the relative demand for the two raw materials: uranium and coal.

An investigation (South African Atomic Energy Board, 1968) carried out in the late sixties indicated that nuclear power was likely to be economically viable in this country from 1978 onwards. It was found that the growth of demand in the Western Cape, together with the remoteness of this area from the Transvaal coalfields, appeared to justify the installation of a nuclear power station there in preference to the alternative of increasing the number of transmission lines to the region.

It became apparent that if the study were to be increased in complexity to take the Republic as a whole

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into consideration, allowing full interplay between the various sizes and types of power-producing plant, and allowing the advantages of the high-voltage transmission line system to be included in the simulation, then an enormous number of parameters would be involved. Further, if a long-term study is contemplated, the problem is aggravated further by uncertainties in the cost escalation of capital items, the variation in electrical demand with time and the relative future cost of competing fuels. All these considerations imply that sensitive studies will be necessary. The use of computers for investigations of this magnitude is, therefore, not only desirable, but inevitable.

Thus, it is not surprising that soon after the preliminary investigation was completed, the Atomic Energy Board and the Electricity Supply Commission agreed to develop jointly a computerised model of the South African electricity system. This has now been very largely completed (Tremeer, 1971). The model which has been developed has the capability of minimising overall system costs over a chosen period of time for a given set of initial assumptions, taking full account of the two-dimensional nature of the problem, the great variety of size and type of plants available to generate electricity within the country, as well as the facility which exists for importing power from Caborra Bassa.

A preliminary investigation using this model (Tremeer, *et al*, 1971) indicated that on purely economic grounds the introduction of nuclear power to the Cape could be deferred until 1980. However, since South Africa's first major nuclear installation is being considered, it has been thought prudent to retain 1978 as the date for full-power operation of this plant. As a result of this it has been decided to present in this paper a study of the possible requirements for coal and uranium for the purposes of electricity generation for the 22-year period from 1978 to the year 2000.

BRIEF DESCRIPTION OF THE MODEL

The program, which is written in FORTRAN IV, is intended for the long-term analysis of an interconnected electricity system having discrete load-centres. It consists of a steering program which controls the overall logic of the operation, plus 25 subroutines which perform specialised functions such as merit-order sorting, calculation of load factors, updating fuel requirements and controlling the flow of data.

The length of the study period is flexible up to a maximum of about 50 years, depending on how long plants selected for installation in the last year of the study are required to operate beyond this time, before decisions are allowed to be made regarding their economic viability.

Data are required which specify completely the composition and characteristics of the electricity system as it exists at the beginning of the study period. Similar data for all possible types of plant which could be installed over the duration of the study, whether nuclear or coal-fired, must also be specified. In addition, estimates of the cost of additional transmission lines, the expected growth of demand for electricity, the pattern of electricity usage (that is, the expected percentages of plant required for base-load, intermediate, and peaking operating) and the amount of reserve capacity are needed.

Each year of the study is divided into three-month periods and the electricity requirement for each of these is studied independently. Load-growth data over the duration of the study are prepared by a separate subroutine which accepts the co-ordinates of any number of points on the national load-growth curve and interpolates them for intermediate values for each growth region. This information, together with that on the maximum allowable size for new installations, enables the subroutine to choose incremental power steps at suitable periods so as to follow the load-growth as closely as possible in every region. The process for evaluating these steps has, of course, to take into consideration the load and any spare capacity which may exist on the transmission line system, as well as problems arising from the break-down of large units.

One of the items of data is a guessed initial pattern for future installations in the various areas, e.g. all coal-fired, or with some nuclear on coastal sites. If an increment in power is called for in a particular area at a particular time, within the study period, then this may be satisfied by any of a number of alternatives, depending on the geographical location. A nuclear or coal-fired power station may be built there, or consideration may be given to the construction of another transmission line to feed power to the area from a pit-head power station on a distant coal field (this, of course, presupposes that the area under consideration is remote from a coalfield). At this stage the retirement of existing plant, if plant of a suitable minimum age exists in the area, is also considered by establishing whether future costs will be reduced by this action.

The choice between the alternative actions is made by simulating the operation of each contender over a period of time which can be varied between one year and 25 years. The latter period is chosen for the study presented in this paper. The successful plant type then replaces the guessed, initial type and control is transferred to the next time interval where the process is repeated. When the end of the study period is reached the computer is directed to start the study again, but on this and subsequent interations the new pattern of installations is compared with that chosen on the previous occasion. Execution ceases when either two calculated installation patterns agree, or when a specified maximum number of iterations is exceeded.

For the calculations reported in this paper ESCOM's six undertakings have been condensed into five load-centres: numbers one and five are inland on the Reef and the Kimberley-Bloemfontein area, the other three being the coastal load-centres at Durban, the Port Elizabeth-East London area and Cape Town. The Reef area is the focal point of the transmission line system, the other load centres being between 350 km and 1 280 km distant from it.

DATA EMPLOYED

One of the physical characteristics of the energy economy of South Africa as a whole has been its rapid growth over the past 60 years. The growth rate has been even slightly greater than that in most economically mature Western countries. Whether this growth will be maintained is questionable. Thus, calculations have been made using two different growth rates for electricity demand; one which averages 7,5 per cent over the study period, and the other based on an 'S' curve analysis which averages only 5 per cent over the same time interval.

One of the great uncertainties which no amount of study can finally resolve is the future price of the competing fuels. At this juncture it is relevant to remark that the possibility of oil being used for the large-scale production of electricity has been excluded from this study. This course was taken because preliminary studies by ESCOM have shown this to be uneconomic in plant sizes of current interest. One can utilize historical price trends for forecasting coal costs, but it is recognised that this is by no means infallible and can lead to quite large errors. Nevertheless, by making use of data in the ESCOM Annual Reports from the early 1950's and fitting a compound interest type of law to these data, the cost of coal in 1978 is predicted to be approximately R2,10 per ton at the mine mouth, escalating at a rate slightly over, but close to, 3 per cent per annum. This will result in the future fuel costs for coal-fired pit-head power stations shown in Fig. 1. It should be noted that although collieries for pit-head power stations in this country usually contract for the supply of fuel on a fixed plus a tonnage-related cost, an average of the totals of these figures has been taken for the calculations in this paper.

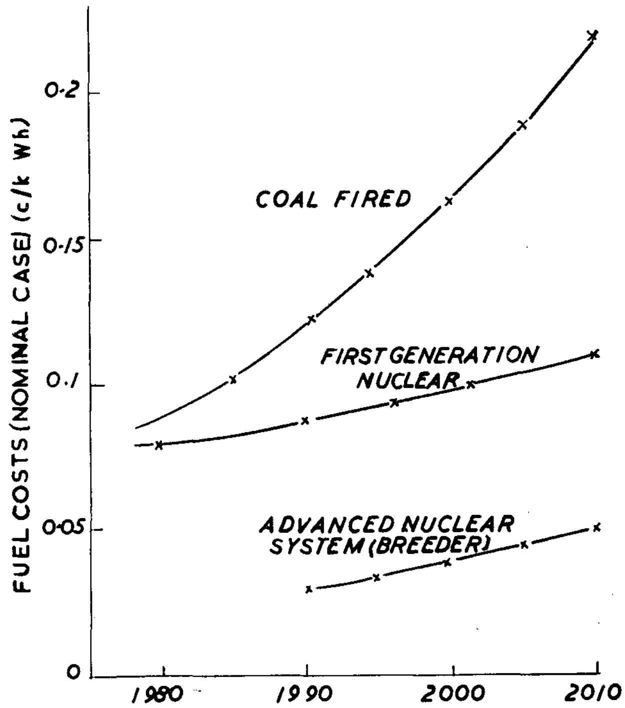

Fig. 1—Fuel component of power costs from the alternatives considered

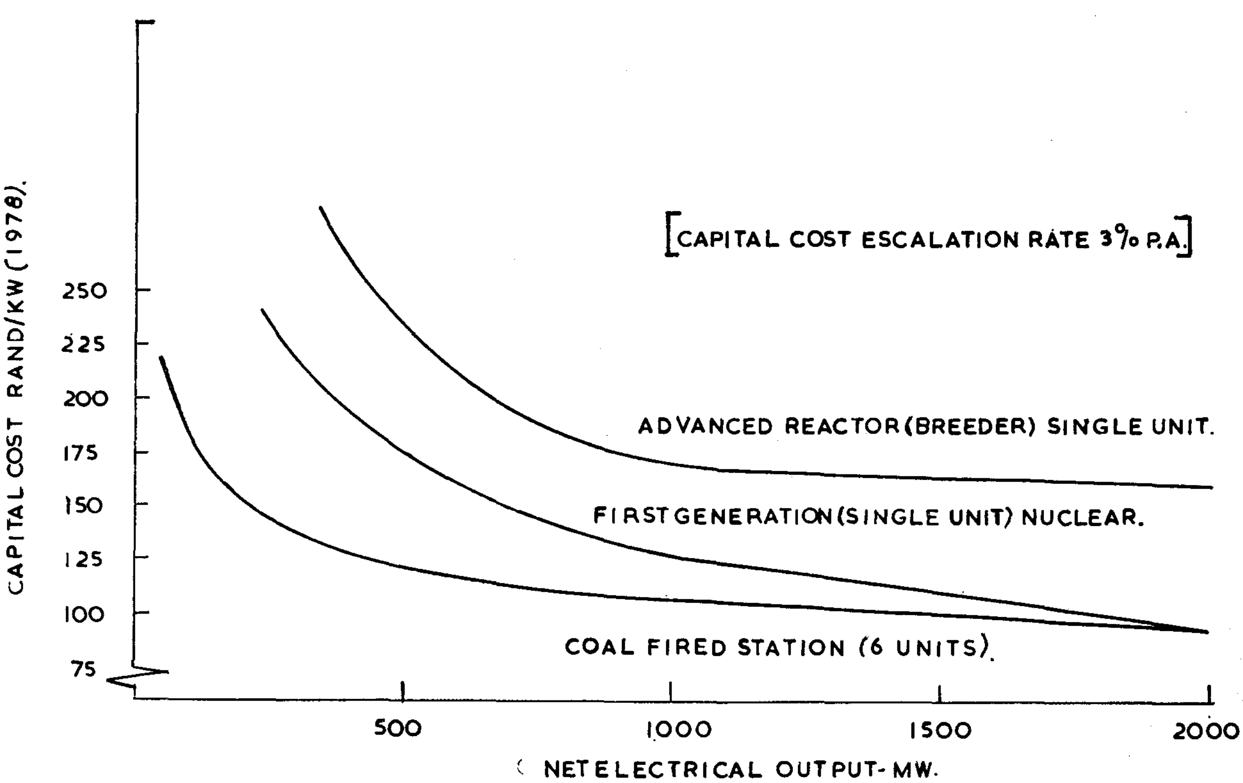

Fig. 2—Variation of the total capital cost of wet-cooled power stations with output

The nuclear fuel industry is very young, so that historical data on costs are not only difficult to obtain but very sparse. In addition, calculating the cost of electricity derived from nuclear fuel is incomparably more difficult than evaluating that derived from coal, because of the complexity of the nuclear fuel cycle. However, using the best available methods and data, the future fuel costs for nuclear power from one of the reactor types likely to be installed in the country are taken to be as shown in Fig. 1. Note that its rate of escalation is predicted to be lower than for coal-derived power but that the initial cost, in 1978, will be very similar.

The next most important parameter to consider is the capital cost of the various alternative types of power stationwhich feature in this study. Extensive studies carried out by the ESCOM-AEB long-term study team show that not only do the various types of power station have different capital costs for a given unit size, but that the costs also obey different capital cost scaling laws. These costs are summarised in Fig. 2 for the year 1978, and are assumed to escalate at 3 per cent per annum. Because of observations made in an earlier study (Atomic Energy Board, 1968) any power-generating equipment installed inland during the study period is assumed to employ dry cooling, and this is estimated by ESCOM to increase the capital cost of the plant by a factor of 1,006.

Any additions to the transmission line system, as it will exist at the beginning of the study period, will be assumed to be in the form of fully compensated, 400-kV lines at an assumed cost of approximately R38 000 per kilometre in 1978, escalating at 3 per cent per annum. The cost of one kilometre of transmission line varies, of course, with its total length, but above distances of about 300 km the dependence is very weak.

The fixed annual charge rate on the capital outlay involved in the various alternative ways of satisfying the demand for electricity in the five demand areas is assumed to be 9,6 per cent for the basic case, but higher figures have also been used in the sensitivity analysis presented below.

RESULTS FROM THE BASIC CALCULATION

Optimizing system operating costs over the period under consideration using the data summarised in the preceding section, and with the higher value for growth in electricity demand, leads to the prediction that a further 59 000 MW(e) of coal-burning plant will be installed between 1978 and the end of the century. All this generating capacity is predicted to be sited on the inland coal-fields. Unless something is done to improve water supplies to this area, or unless some of the planned, but as yet unconstructed, units are converted to dry-cooling prior to 1978, cooling-water limitations may modify this prediction. The cumulative basic fuel requirements for a programme of this size are shown in Fig. 3. If nuclear power were not allowed to feature in the study at all, the cumulative coal requirement by the year 2000 would have been 2 040 million tons with the high electricity demand growth rate. The basic study therefore shows that the introduction of nuclear power into South Africa has the potential to cut coal requirements for electric-power production by at least 20 per cent by the year 2000.

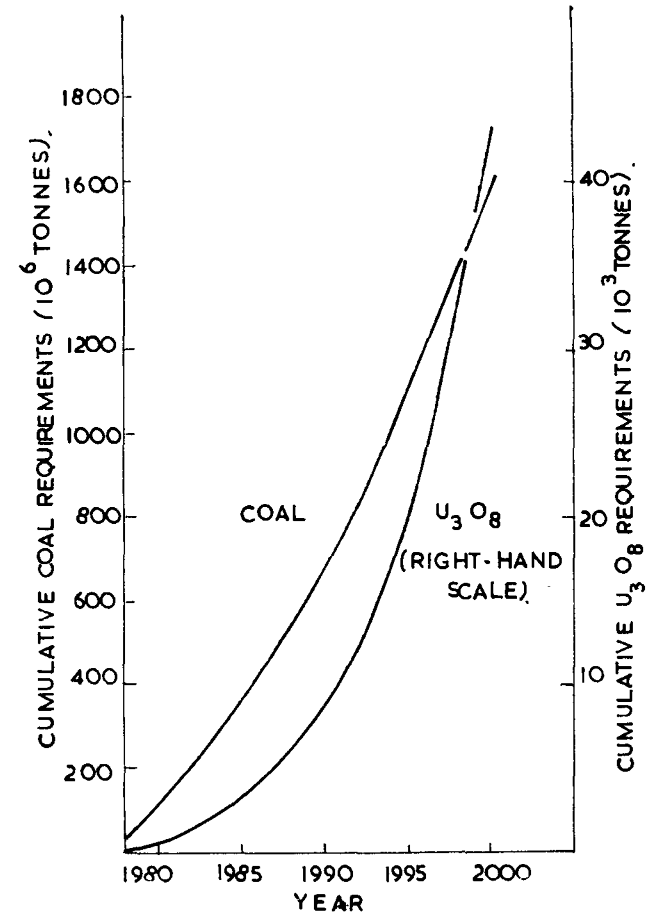

Fig. 3—Cumulative coal and uranium requirements (basic case)

As is evident in Fig. 3 the curve for predicted cumulative uranium oxide requirements changes its gradient during the year 1984, corresponding to the predicted introduction of nuclear power into the Eastern Cape. A further change of gradient takes place towards the mid-1990's at which time, with the data used, nuclear power is predicted to be economic in the Republic's second largest load centre, namely, Natal. At this point in time there is a point of inflexion in the cumulative coal-requirement curve as the rate of growth of demand for coal becomes correspondingly reduced. The installed nuclear capacity by the year 2000 is predicted to be 25 000 MW(e) compared with approximately 75 000 MW(e) of coal-fired generating capacity, and as predicted in earlier studies (Atomic Energy Board, 1968) the first nuclear installations in the country appear on the coast, in the Western Cape, in this system simulation.

With this set of assumptions it is predicted that almost 16 per cent of the currently quoted coal and low-cost uranium reserves of the country will have been used by the year 2000. A further considerable percentage will also, of course, have been committed for use in power stations then existing. Cooling water considerations could increase the amount of uranium required relative to coal, but as shown in the next section, the early introduction of one of the more advanced reactor types could reduce the requirement for both coal and uranium.

SENSITIVITY STUDIES

Of more interest than the basic calculation itself is the the way in which its predictions alter with variations in the initial assumptions. This aspect is examined briefly in the following paragraphs.

Higher fuel costs

The results of the sensitivity studies as well as those from the basic case are shown in Table II. For the initial sensitivity studies the nominal fuel cost data sets displayed in Fig. 1 are first escalated individually in price by an additional 1 per cent, then escalated collectively by this factor to produce Cases 2, 3 and 4 in Table II. It is clear from this table that although predictions of the amount of coal required, either by 1990 or the year 2000, are relatively insensitive to these data changes, uranium requirements after the year 1990 prove to be extremely sensitive to the relative prices of the competing fuels. Further scrutiny of the results reveals that the key to this behaviour lies in the date of introduction of nuclear power into Natal. This fluctuates wildly with changes in the assumed prices for coal and uranium.

TABLE II

Case No.	Cumulative requirements for electricity generation (tons)			
	Coal by the year 1990	Coal by the year 2000	Uranium by the year 1990 as U_3O_8	Uranium by the year 2000 as U_3O_8
1	691×10^6	$1\,630 \times 10^6$	8 890	43 800
2	690×10^6	$1\,340 \times 10^6$	11 300	78 700
3	702×10^6	$1\,760 \times 10^6$	7 050	24 600
4	691×10^6	$1\,540 \times 10^6$	8 890	63 600
5	690×10^6	$1\,700 \times 10^6$	8 890	28 800
6	690×10^6	$1\,430 \times 10^6$	10 000	72 800
7	703×10^6	$1\,760 \times 10^6$	7 020	24 300
8	690×10^6	$1\,630 \times 10^6$	8 890	42 900
9	690×10^6	$1\,630 \times 10^6$	8 890	42 800
10	691×10^6	$1\,610 \times 10^6$	8 890	43 300
11	666×10^6	$1\,010 \times 10^6$	7 550)	13 600
12	690×10^6	$1\,740 \times 10^6$	8 890	25 800
13	690×10^6	$1\,800 \times 10^6$	8 890	22 000
14	682×10^6	$1\,520 \times 10^6$	6 700	26 900

Key to Table II.

Case 1—Basic case
Case 2—Higher coal costs with basic nuclear fuel costs
Case 3—Higher nuclear fuel costs with basic coal costs
Case 4—Both fuel costs high
Case 5—Both fuel costs low
Case 6—Lower nuclear fuel costs with basic coal costs
Case 7—Lower coal costs with basic nuclear fuel costs
Case 8—Capital charge rate increased to 11,6 per cent
Case 9—Capital charge rate increased to 13,6 per cent
Case 10—Advanced type of reactor introduced when fuel available in R.S.A.
Case 11—Advanced type of reactor introduced with imported fuel
Case 12—Cost differential between coal and nuclear stations increased by R10 per kilowatt
Case 13—Cost differential between coal and nuclear stations increased by R20 per kilowatt
Case 14—Lower growth rate in electricity demand.

Lower fuel costs

At first sight it might seem that reducing the escalation rate of one of the fuels should produce the same calculated result as increasing the escalation rate of the alternative fuel by the same amount. However, another parameter has to be taken into consideration, and that is the fuel-cost merit-order of the plants concerned in the electricity system as a whole. This can change in a way which is not immediately obvious as fuel prices vary. Reducing fuel costs in a manner similar to that in which they were increased earlier leads to the results summarised in Cases 5, 6 and 7 in Table II. The same remarks may be made about these results as for those reflecting the price increases, with the exception that the predictions of uranium demand are not quite so sensitive to data changes in this case.

Increased capital charges

Table II shows that predictions of future fuel requirements are extremely insensitive to changes in this parameter. Increasing the fixed annual charges by 40 per cent produces an almost insignificant change in fuel requirement predictions. The reason for this becomes apparent if the cost data used in the calculation are examined closely. Comparing the capital cost of a nuclear power station in the Eastern or Western Cape with that of a coal-fired power station inland, plus the transmission line that would then be needed, reveals that the nuclear alternative is the cheaper and will, of course, remain so whatever the capital charge rate. Repeating this exercise for Natal shows that the alternatives from which the choice may be made are almost exactly equal in cost. Under these conditions, as has been shown earlier, fuel costs dominate the economic decision analysis.

Introduction of an advanced type of reactor

The type of reactor considered under this heading is a breeder, that is, one that produces more fuel than it consumes.

The fuel is plutonium which is also a by-product of the first generation of reactors which will be introduced to South Africa. If the introduction of the advanced type of reactor is delayed until sufficient plutonium has been accumulated from the Republic's initial reactor installation programme, then the breeder is introduced so late on the study period that it makes little or no impact on coal or uranium requirements by the year 2000 (Case 10). If, however, the importation of several inventories of fuel for the early breeders is considered, starting in 1987, Table II shows that the requirements for coal and uranium are heavily reduced by the year 2000, but not affected much by the year 1990. This is clearly an aspect to study further.

Capital cost differential

The important parameter in this case is not the absolute value of the capital costs of the alternatives, but their ratio. For Case 12 in Table II the capital cost of the first generation nuclear station, the LWR, was allowed to increase by R10 per kilowatt. This results in a 40 per cent drop in the predicted uranium requirements by the year 2000, but very little change in the other three estimates. Increasing this cost differential further to R20 per kilowatt decreases the amount of uranium required by the year 2000 further to 50 per cent of that predicted in the basic calculation. Again the other three predictions change only by 10 per cent or less.

Lower growth in electricity demand

Case 14 in Table II gives the cumulative coal and uranium requirements for a 5 per cent growth in electricity demand from 1978 to the end of the century. Once again the results show that predictions of the amount of coal required by 1990 are insensitive to this change in the data. Slightly more sensitive are the predictions of coal requirements up to the year 2000 and uranium requirements up to the year 1990, while, as before, uranium requirements to the year 2000 remain most sensitive to this data change.

DISCUSSION

If Case 11 in Table II is ignored because of the even greater uncertainties involved with this reactor type, then the maximum and minimum predicted cumulative requirements for coal and uranium are as summarised in Fig. 4. The minimum uranium prediction is a composite curve employing data from the low electrical demand growth case and the high capital cost differential between the competing plants. A feature of this graph is that up to the year 1990 predictions of the amount of coal and uranium that will be needed for electricity production are relatively firm, but with the uranium requirements being more in doubt than the estimate of the amount of coal required. Throughout the 1990's both predictions become progressively more uncertain, but the comparison remains the same: uranium requirements more uncertain than coal requirements. It may be thought strange that if a given amount of energy has to be produced, uncertainties in the amount of one type of fuel required do not reflect equally on the alternative fuel. There are two explanations for this.

The major cause stems from the fact that predictions of the amount of coal required start to become more uncertain during the 1990's. This automatically introduces a degree of uncertainty in the uranium predictions. The program is written in such a way that coal burned by a power station in any three-month period is assumed to have been mined in that period. With nuclear fuel, a very complex series of operations takes place on the uranium after it leaves the mine. These can occupy up to two years for the first core loading, and this point is catered for in the computer program. In addition, the first fuel loading for a typical LWR could last for up to a further two years before refuelling takes place. Thus, when looking at the uncertainty in uranium requirements in the year 2000, it is found that this is strongly influenced by the uncertainty in the nuclear installed capacity in the year 2004. This point is also allowed to figure in the calculations, and this explains why the uncertainty in the uranium predictions appears earlier than that for coal.

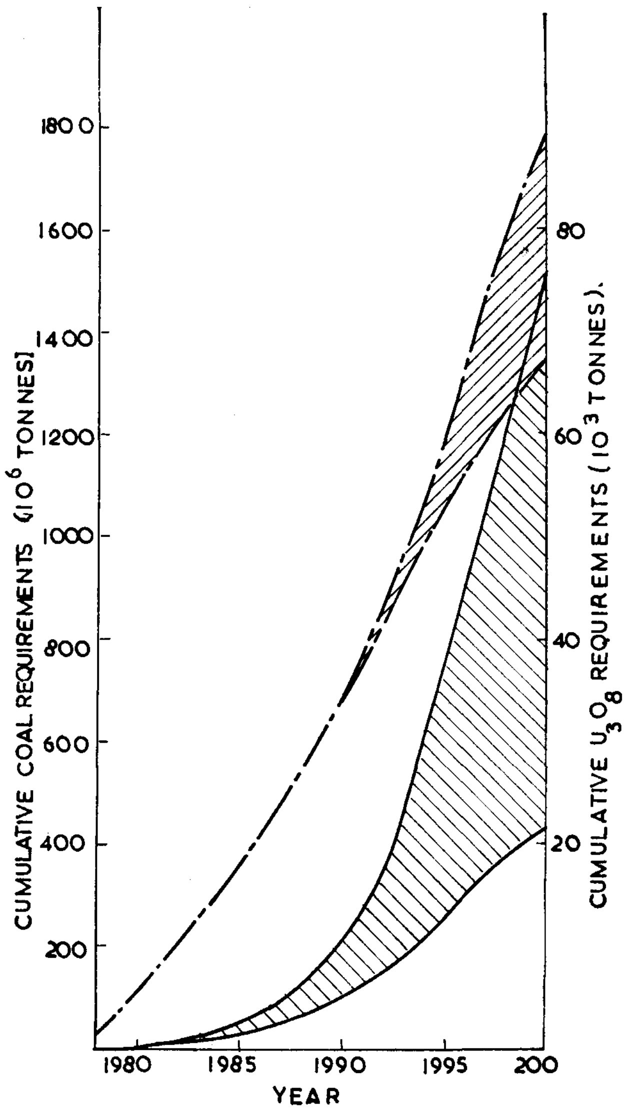

Fig. 4—Maximum and minimum predictions for cumulative coal and uranium requirements

The second, minor, reason is that as fuel costs are allowed to vary in the sensitivity studies, the amount of electricity supplied by the three hydro schemes, which also feature in the calculations, will itself vary, thus further helping to destroy the correlation between the amounts of coal and uranium used for the production of what is apparently a fixed amount of electrical power.

CONCLUSIONS

From the calculations presented in this paper it would appear likely that by the year 1990 between 680 and 700 million tons of coal will have been used for the generation of electric power, together with between 7 000 to 10 000 tons of uranium.

Beyond this point in time predictions of the requirements for these fuels become sensitive to the data used in the calculations, especially in the case of uranium requirements. Thus, it is only possible to predict that by the year 2000 between 1 300 and 1 800 million tons of