CLM-R298

Parameters of a Reference Tokamak Reactor

P. I. H. Cooke
R. Hancox
W. R. Spears

CULHAM
LABORATORY

AEA TECHNOLOGY

CLM-R298

PARAMETERS OF A REFERENCE TOKAMAK REACTOR

P.I.H. Cooke, R. Hancox, W.R. Spears*

Culham Laboratory, Abingdon, Oxon. OX14 3DB, U.K.
(Euratom/UKAEA Fusion Association)

* The NET Team, c/o Max Planck Institut für Plasmaphysik,
D-8046 Garching bei München, Federal Republic of Germany.

December 1989

ABSTRACT

Several sets of parameters have been developed for tokamak reactors that might be available around the year 2050 as a result of the Commission's fusion research programme. One parameter set, based on modest improvements in physics and technology relative to present experience, has been adopted as a Reference Reactor for use in further studies including the environmental impact of fusion power. The Reference Reactor parameters have been compared with those of the Base Case reactor developed in the ESECOM study in the USA in 1987. The computer codes used in the two studies have both been used to generate parameter sets for these two reactors, and differences in resulting parameters and costs are discussed.

These studies were undertaken at the request of the Study Group on the Environmental, Safety related and Economic Potential of Fusion Power (the EEF Study Group), and formed part of the NET contracts 357/89-1/FU UK NET and 375/89-5/FU UK NET.

Contents

1 Introduction

The objective of this study was to develop several sets of parameters for tokamak reactors that might be available around the year 2050 as a result of the Commission's fusion research programme. In particular, one set of parameters is proposed for a "Reference Reactor" which can be used as the basis of further reactor studies. As in similar previous studies, these parameters were generated by making a number of assumptions about the physics and engineering performance of the reactor, and then calculating a set of self-consistent parameters optimised with respect to some figure-of-merit, in this case the cost of generating electricity. It should be emphasised that these parameter sets do not in themselves constitute reactor designs, but rather are frameworks around which the detailed design of the various components can be undertaken.

Since the extent of developments in the physics and engineering performance of tokamak reactors by the middle of the next century is not known, sets of parameters have also been generated on the basis of optimistic expectations. These advanced tokamak reactors indicate the extent to which generating cost reductions might be possible as the result of further significant advances in fusion research.

A comparison has been undertaken of the Reference Reactor parameter set with the results of similar work performed in the USA, as part of the ESECOM study (Senior Committee on Environmental, Safety and Economic Aspects of Magnetic Fusion Energy). In addition to a direct comparison of the modelling assumptions and results, the codes used for each study were used to model the parameter set generated in the other study, as an aid to understanding the different approaches.

Section 2 of this report contains an explanation of the tools used to model the reactor and optimise its performance, and a description and discussion of the results. The results of sensitivity studies for the electrical power output of the reactor and for the unit cost of the first wall and blanket structural material are also given. Section 3 contains the results for the advanced tokamak reactors. Section 4 contains a comparison of results from this work with those from the ESECOM Study.

2 Reference Tokamak Reactor Parameters

2.1 Models

When choosing the parameters of a tokamak reactor, there are a large number of variables which need to be optimised within given constraints. To ease this process, the SUPERCOIL code [1,2,3] has been used. This code has been extensively used for the NET design, and also for estimating power reactor parameters [4,5]. The figure-of-merit, which is used as the criterion for optimisation for power reactors is the cost of generating electricity, as estimated by the SCAN-2 cost model [6]. Full details of these models are given in the references cited, but brief descriptions are given here.

2.1.1 Parameter Optimisation

The SUPERCOIL model contains a large number of equations describing the components of the reactor (e.g., plasma, blanket, shield, coils, etc.) and their interactions. These equations can be solved explicitly only when a minimum set of independent parameters has been specified. The independent parameters can be subdivided into those which are given as input and fixed throughout a calculation (fixed parameters) and those which are self-consistently determined (grid variables). The fixed parameters include basic design characteristics (e.g., blanket and shield attenuation lengths, coil conductor characteristics), certain plasma parameters (e.g., safety factor, elongation, temperature), and other weak parameters which do not vary over a large range (e.g., scrape-off layer thickness, coil thermal insulation thickness).

The remaining independent parameters, the grid variables, are scanned over a user-specified range, within which it is expected that the optimum design point will lie. For the calculations reported here, five quantities were used as grid variables; the plasma minor radius, the plasma aspect ratio, the shield thickness, the radial thickness of the toroidal field coils and the magnetic field on axis.

For a given combination of grid variables, the resulting set of dependent parameters is checked to ensure that specified constraints have been satisfied. Most of the constraints relate to physical, technical or material limitations, such as the toroidal field ripple limit, stress and strain limits, maximum field in superconductors etc. For these calculations for a power-producing reactor, an important input parameter is the net electrical power. Since this is the result of a large number of calculations, it is not possible to fix its value at the outset in the SUPERCOIL/SCAN model. However, by careful design of the figure of merit, it is possible to restrict its value to well within 1% of that required.

Acceptable points are then costed using the SCAN-2 costing model described below. At the end of a set of calculations for all points in the five-dimensional grid, the point with the minimum cost of electricity is used as the centre of a new grid which has more closely-spaced points. The grid is then successively refined until the desired degree of accuracy for the optimum point has been obtained.

2.1.2 Costs

The costs of the reactor and its components were calculated with the SCAN-2 cost model, which has been extensively used for the parameter optimisation of NET and power-producing reactors. The algorithms used for estimating the costs of components, buildings etc., which are described in Reference 6, are based on a "first-of-a-kind" device, and hence do not take advantage of any "learning-curve" effects which will tend to reduce the costs of later plants with identical components. No attempt was made to include such effects because of the considerable effort required, and the large uncertainty associated with any such estimate. Other studies [7], however, suggest that the effect can be very significant.

All costs quoted in this report are in ECU using January 1984 prices. It is estimated that for conversion to 1990 ECU the total costs should be inflated by about 11%.

To determine the operating point for a reactor, the blanket can be characterised by a very small number of parameters, such as its radial thickness. However, a somewhat fuller description is necessary to estimate the cost of the device. Although the location of the optimum operating point is only very weakly dependent on the cost of the blanket, as demonstrated in Section 2.4, it is necessary to use a specific blanket design to serve as the basis for a cost estimate.

In the absence of a detailed blanket design for a commercial-sized reactor, the same blanket design as was previously used for the NET systems optimisation has been used for this study. This blanket employed a water cooled lithium-lead tritium breeding material, and used austenitic steel as the structural material [8,9]. For power-producing reactors the austenitic steel has been replaced by a lower-activation ferritic steel. As the same unit costs have been used, this change makes no difference to the reactor parameters or costs. The cost estimate is based on the masses of the different materials used, and the important parameters for this calculation are the volume fractions, densities and unit costs of all materials, and thicknesses of all regions. Table 1 shows these values, which were maintained constant for all calculations reported in this paper.

Indirect costs are split into two components; basic indirect costs, and launching costs. The former category includes costs incurred during the construction phase related to management and personnel, training, design, licensing and taxes, etc. Launching costs are connected with first-of-a-kind devices, and include extra design and cost studies, extra engineering and design, higher quality control and quality assurance costs, higher risk of delay, slower than normal commissioning, etc. The basic indirect costs total 14%, and the launching costs 15% of the total direct costs.

Interest during construction is calculated on the basis of an "S-shaped" expenditure profile with time during the construction phase. For the assumptions of an eight-year long construction phase and a real annual interest rate of 5%, the total interest is about 18% of the sum of the direct and indirect costs.

Costs during an operational lifetime of 25 years are based on estimates of expenditure as a function of time for project manpower requirements, spares and replacement parts, waste disposal, insurance, taxes, etc. Fuel costs are based on the amounts of deuterium and lithium used, and include a penalty for decaying tritium stored in the plant components. Decommissioning costs are assumed to be 20% of the total direct costs.

Table 1

BLANKET DESIGN PARAMETERS

Component	Material	Volume Fraction	Density (t/m^3)	Unit Cost (ECU/kg)
First Wall	Ferritic steel structure	0.667	7.9	75
	Lead multiplier	0.176	9.4	8
	Water coolant	0.157	1.0	0
Main Blanket Zone	Ferritic steel structure	0.117	7.9	75
	Lithium-lead breeder*	0.487	9.4	22
	Water coolant	0.081	1.0	0
	Void	0.315	0.0	0
Blanket Flange Zone	Ferritic steel structure/	0.03	7.9	75
	shield	0.25	7.9	20
	Lithium-lead breeder*	0.12	9.4	22
	Water coolant	0.12	1.0	0
	Void	0.48	0.0	0
Shield	Austenitic steel structure	0.79	7.9	20
	Water coolant	0.21	1.0	0

*The breeder contains 90% enriched lithium.

All these operational and maintenance, fuel and decomissioning costs are discounted from the date they occur to the date of commissioning using a discount rate (or required rate of return on capital) of 5%. The discounted costs are added to the direct costs, the indirect costs and the interest charges incurred during construction to give the total project costs. The generation cost of electricity is obtained by dividing this cost by the total electricity sales during the lifetime of the plant, assuming 75% availability, again discounted to the date of commissioning.

This cost of electricity is used as the figure-of-merit in the parameter optimisation. One feature of the optimisation which should be noted is that the generation cost is a very weak function in the vicinity of the optimum, so that there is a relatively wide range of possible solutions whose cost is extremely close to the minimum. The problem of optimising within this flat region is compounded by slight discontinuities in the generation cost. For example, a very small change in the dimensions may lead to a slight increase in the neutron wall loading and a jump in the integral number of replacement blankets required during the plant life, and hence a slight increase in cost. The focus for optimisation can therefore move around the grid in a discontinuous manner, making sensitivity analysis somewhat difficult.

2.2 Basic Reactor Parameters

Two sets of consistent reactor parameters are developed in this section, and are referred to as Reactor 1 and Reactor 2. These are compared with the reactor PCSR-E, whose parameters were also developed using the SUPERCOIL and SCAN codes for an earlier study [4,5]. The assumptions used to generate the parameters are described below.

The general aim was to employ assumptions typical of those used in the present ITER study for the first reactor, while improved values were used for various input parameters for the second reactor. The input parameters for all three reactors are shown in Table 2.

Both Reactors 1 and 2 have the same magnetic configuration as ITER, with a double-null divertor, in contrast to the earlier single-null configuration of PCSR-E. Reactor 1, being essentially an extrapolation of ITER, has the same null-point elongation of 2.2. For Reactor 2, the elongation is increased to 2.5, which allows a higher value of β to be obtained, but increases the problems posed by vertical instabilities of the plasma.

The Troyon coefficient, which defines β in terms of other physical parameters, is assumed to be 3.0 %Tm/MA for Reactor 1, with 33% of the total β being taken up by impurities and fast particles, compared with figures of 3.5 and 26% for PCSR-E. The Troyon coefficient is assumed to be 4.0 %Tm/MA for Reactor 2, which slightly exceeds the present theoretical expectations and experimental observations for the so-called first-stability régime of operation, but is the value used for the Base-case Reactor in the ESECOM study [10,11].

Table 2

INPUT PARAMETERS

Parameter	PCSR-E	Reactor 1	Reactor 2
Plasma configuration	SN	DN	DN
Effective plasma elongation	1.7	2.0	2.25
Null-point elongation (upper/lower)	1.57/1.85	2.2/2.2	2.5/2.5
Plasma triangularity (upper/lower)	0.2/0.6	0.6/0.6	0.6/0.6
Scrape-off layer thickness (inner/ outer) (m)	0.2/0.12	0.15/0.15	0.15/0.15
Average plasma temperature (keV)	10	20	20
Alpha density fraction (relative to DT)	0.05	0.053	0.053
Z_{eff}	1.14	1.54	1.54
Troyon coefficient (% Tm/Ma)	3.5	3.0	4.0
Ratio of useful to total β	0.74	0.67	0.67
Plasma safety factor q_I	2.22	2.17	2.17
Current drive method	Inductive	NBI	NBI
Normalised current-drive efficiency (10^{20} m^{-2} A/W)	-	Calculated	0.7
Current-drive "wall plug" efficiency	-	0.7	0.7
Bootstrap current fraction	0.0	0.3	0.5
Burn time (s)	5000	10^6	10^6
Number of TF coils	22	22	22
Maximum tensile stress in TF coil (MPa)	160	200	250
Thermal conversion efficiency (%)	35	35	40
Blanket neutron energy multiplication	1.22	1.25	1.25
First wall/blanket thickness (inboard/outboard) (m)	0.55/0.85	0.55/0.85	0.55/0.85
Blanket radiation lifetime (MWy/m^2)	10	10	10
Divertor neutron fluence limit (MWy/m^2)	2	2	2
Net electrical power output (MW)	~1200	~1200	~1200
Reactor design lifetime (y)	25	25	25
Availability (%)	75	75	75
Construction time (y)	8	8	8
Required rate of return on capital (%)	5	5	5

Steady-state current drive by neutral beam injection is assumed for both Reactors 1 and 2. The selection of steady-state operation reflects the desire to avoid pulsed operation to minimise cyclic stresses and obviate the need for high thermal inertia in the cooling circuits; there is also now an increased confidence in the projections for steady-state current drive from present experiments. Neutral-beam current drive was chosen in preference to radio-frequency methods because of its potentially higher efficiency compared with the realistic alternatives, although the possibly more severe geometric impact on building design was not included.

For Reactor 1, the normalised current-drive efficiency ($\gamma = n_e IR/P_{cd}$) was calculated from a prescription used in the ITER design [12], (which gives a value ~0.5 for typical reactor parameters) while a higher value of 0.7 was fixed for Reactor 2; such higher efficiencies have been predicted for certain plasma régimes and for more advanced methods of current drive. A "wall-plug" efficiency (power absorbed by plasma compared with electrical power input) of 70% was used for both cases, taken from projections from Oak Ridge for systems based on radio-frequency quadrupoles (RFQs) [13]. A density-weighted plasma temperature of 20 keV was assumed, compared with 10 keV for PCSR-E, to improve the current-drive efficiency. The bootstrap current fraction was set at 0.3 for Reactor 1, which is typical of results from detailed calculations for reactors with similar parameters, and at 0.5 for Reactor 2.

The maximum toroidal field strength attainable is usually determined by the allowable tensile stress in the toroidal field coil rather than any limit on the peak field per se. For Reactor 1, the allowable tensile stress was set at 200 MPa, in line with detailed modelling of the toroidal field coils for NET/ITER, while this value was increased to 250 MPa for Reactor 2. In addition, the constraints being applied in NET and ITER on forced-flow conductor cooling were removed and substituted with weaker requirements on bath cooling, in the expectation that further experience will permit conductor operation with peak field values greater than 12 T. The number of toroidal field coils was fixed at 22 for all cases, this number having been determined to be the optimum for PCSR-E. A number of test calculations showed that the costs are relatively insensitive in the present analysis to this number, which was held constant to simplify the calculations.

The thermal conversion efficiency (ratio of gross electrical power to total thermal power) was set at 35% for Reactor 1, as estimated for a power-producing water-cooled, lithium-lead breeder, steel structure blanket. A value of 40% was used for Reactor 2, which is probably higher than could be achieved with the assumed blanket, but could be obtained with a different combination of coolant, breeder and structure. Since the detailed design of the blanket makes very little difference to the reactor parameters, the higher efficiency represents an attempt to model the effect of using a more "advanced" blanket design, without intending to be fully self-consistent.

The net electrical power output of the station was set at close to 1200 MW (although the optimisation procedure of SUPERCOIL does not allow an exact level to be set) for both Reactors 1 and 2. This level is close to that of PCSR-E, facilitating a comparison of results, and is typical of the power

Table 3

OUTPUT PARAMETERS

Parameter	PCSR-E	Reactor 1	Reactor 2
Plasma major radius (m)	9.30	7.07	5.31
Plasma half width (m)	2.39	2.03	1.40
Aspect ratio	3.89	3.49	3.78
Plasma current (MA)	16.6	22.4	16.6
Total volume-averaged plasma β (%)	3.83	5.14	7.62
Toroidal field on axis (T)	6.36	6.44	6.22
Peak toroidal field on TF coil (T)	11.3	13.5	14.9
Peak-to-peak toroidal field ripple (%)	1.73	1.60	0.25
Average electron density (10^{20} m^{-3})	1.57	1.05	1.45
Average ion density (10^{20} m^{-3})	1.43	0.89	1.23
Required enhancement factors:			
Rebut-Lallia	0.57	0.39	0.65
Kaye-Big	2.39	1.78	2.27
Kaye-Goldston	1.39	1.13	1.27
JAERI	1.42	1.08	1.54
Current-drive power to plasma (MW)	0	217	91
Normalised current-drive efficiency (10^{20} $m^{-2}A/W$)	-	0.54	0.7 (input)
Mean first wall neutron wall loading (MW/m^2)	2.22	3.10	4.15
Shield thickness (inboard/outboard) (m)	0.79/0.69	0.81/0.72	0.83/0.74
TF coil thickness (radial/axial) (m)	1.15/1.49	1.12/0.96	1.01/0.63
Stored energy in TF coils (GJ)	115	97	58
Vertical bore of TF coil (m)	12.5	14.2	12.4
Fusion power (MW)	3580	3900	3050
Total thermal power (MW)	4170	4920	3780
Gross electrical power output (MW)	1460	1730	1510
Net electrical power output (MW)	1250	1200	1200
Recirculating power fraction	0.14	0.30	0.20
Total plant costs (MECU)	9820	9340	6820
Cost of electricity (cECU/kWh) (January 1984 costs)	10.9	10.5	7.8

level proposed for future large-scale nuclear and fossil-fuelled power plants.

Table 2 indicates several differences in the assumptions for PCSR-E (which reflected the state of the development of the NET design in 1985) and for Reactor 1, although the philosophy for both machines is similar, that is, to take the present-day database in plasma physics. Some of the differences reflect improved estimates for certain parameters and others occur because different approaches were used for various reactor sub-systems, in particular, operation in the pulsed or steady-state mode.

The output parameters from the systems code optimisation for the three cases are shown in Table 3. Reactor 1 has a somewhat larger major radius than ITER (7.1 m compared with 6.0 m for ITER), although the minor radii are similar. The increased size arises from the provision of extra shielding and the higher power output of Reactor 1. The difference is relatively small because ITER is sized to give a high probability of obtaining ignition, even if the plasma performance is below the present estimates.

Reactor 2 is significantly smaller than Reactor 1, with a reduction of 25% in the major radius, and a plasma radius which is smaller than that of ITER. Compared with Reactor 1, the higher thermal conversion efficiency means that a lower fusion power is required to produce the specified net electrical power output. This effect is amplified by the higher values for the current-drive efficiency and the bootstrap current fraction, both of which lead to a lower power input necessary to maintain the plasma current (91 MW compared with 217 MW). The higher values for the Troyon coefficient and for the plasma elongation both help in yielding an improvement in the plasma β value, which nearly doubles the plasma power density. Finally, the higher allowable stress in the toroidal field coils results in a higher magnetic field in the coils. This does not lead to a higher field in the plasma, because the aspect ratio increases to maintain adequate shielding of the smaller plasma.

No constraint on achieving an energy balance in the plasma is applied during the optimisation procedure because of the wide spread in energy confinement times predicted by the presently-favoured scalings, which arise from different functional dependences on the major parameters and on whether operation is in the L or H-mode. Instead of applying any constraint, the optimum operating point is examined after its parameters have been calculated to determine what energy confinement time is necessary to provide a plasma power balance. The required enhancement factors, which are quoted in Table 3, are the factors by which the L-mode predictions for energy confinement time for the various scalings indicated have to be multiplied to provide a power balance. The definitions for these factors are taken from Reference 14, ignoring the atomic mass correction in the Rebut-Lallia scaling. A factor of about 2 is often considered achievable for H-mode operation, so there do not appear to be severe problems for any of the scalings for either Reactor 1 or Reactor 2, with the possible exception of the Kaye-Big scaling for Reactor 2. Note that better confinement is required for Reactor 2 than for Reactor 1 because of its smaller size and lower current. If the available energy confinement turns out to be greater than is required for a power balance, other energy loss mechanisms (such as increased radiation or some other means of burn control) would have to be provided to maintain the desired operating point.

The mean neutron wall loading rises from 3.1 MW/m^2 for Reactor 1 to 4.15 MW/m^2 for Reactor 2, because of the higher fusion power density in the latter case. The loading for Reactor 2 is almost twice that of the larger, less optimistically-based PCSR-E reactor. The peak neutron wall loading on the first wall (which occurs on the outboard equatorial midplane) will be substantially greater than the mean value because of toroidal effects, the high plasma elongation and the outward shift of the magnetic axis of the plasma where the plasma power production is centred.

One potential area of concern for all three reactors is the heat loading and erosion of the divertor plates. This is a crucial problem even for next-step machines, such as NET [8,9] and ITER [14] and the higher power density of the power-producing reactors coupled with their relatively low plasma densities may require considerable design innovation to accommodate the high loadings.

The recirculating power fraction is high for both Reactors 1 and 2, because of the high power requirement for steady-state current drive. The lower plasma current, higher current-drive efficiency and higher bootstrap fraction lower the power required for Reactor 2 compared with Reactor 1, but even Reactor 2 has a significantly higher recirculating power than the pulsed PCSR-E.

As would be expected from the foregoing discussion, Reactor 2 proves cheaper, in both capital cost and generating cost terms, than either Reactor 1 or PCSR-E. The cost ratio between Reactors 1 and 2 is very close to the size ratio as given by the major radius of the devices, while Reactor 1 is only slightly cheaper than PCSR-E, despite the considerable difference in their sizes. This arises chiefly from the cost penalty paid by Reactor 1 for the steady-state current drive system and its associated recirculating power, which is none-the-less regarded as desirable owing to the perceived unattractiveness to utilities of pulsed operation.

Since this study is aimed at reactor parameters that might be achieved by the middle of the next century, it seems reasonable to assume some improvement in plasma and reactor performance above those which could be obtained (or directly extrapolated) from today's results. Since such improvements have been incorporated in the assumptions used for Reactor 2, this reactor is used as the "Reference Reactor" for which more detailed results are presented, and as the central case for other sensitivity studies.

The radial build of components in the midplane of the Reference Reactor from the inboard poloidal-field coils through the plasma and out to the outboard poloidal field coils is given in Appendix I. The masses of various components around the torus are given in Appendix II; these results will be useful for further studies related to the quantities of waste arising from the reactor.

Tables 4 and 5 show the direct, indirect and operational cost breakdowns for the Reference Reactor, in January 1984 ECUs.

2.3 Variation of Costs with Power Output

The sensitivity of the reactor parameters and costs to the electrical power output of the reactor was examined. All the main input parameters were kept fixed at the values for Reactor 2 during the study, with the exception of the net electrical power output; Figures 1 to 3 show the trends of costs and key output parameters.

Figure 1 shows the change in the cost of generating electricity with net electrical power output. The capital cost increases slowly with increasing power output, partly because of the slow increase of size but more importantly because the costs of many components associated with the balance of plant scale with some exponent, which is less than unity, of the thermal or electrical power output. The slow increase of capital cost with increasing power output leads to a steep fall of the cost of electricity as the power level is raised. This economy of scale provides a strong incentive to examine high power output devices for tokamak reactor power stations.

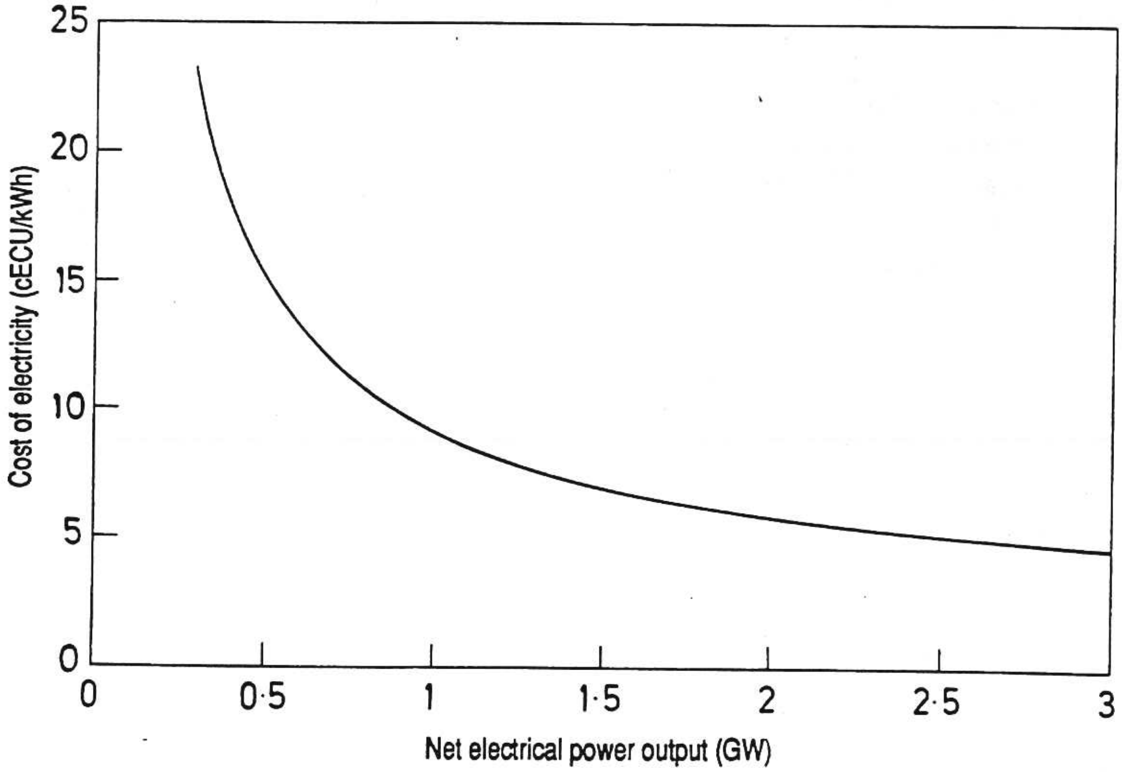

Figure 1 Variation of cost of electricity with net electrical power output

Table 4

DIRECT COST BREAKDOWN FOR THE REFERENCE REACTOR
(in January 1984 MECU)

Site and Improvements		40
Nuclear Buildings	629	
Heat Transport Buildings	44	
Cooling System Buildings	41	
Electric System Buildings	10	
Plant Protection, Instrumentation and Contol Buildings	46	
Plant Auxiliary Buildings	8	
Additional Buildings	16	
Site Services Buildings	32	
Buildings		826
First Wall	8	
Divertor	6	
Blanket	89	
Shield	332	
Toroidal Field Magnet System	477	
Poloidal Field Magnet System	98	
Overall Cryostat	35	
Tokamak		1045
Vacuum Pumping	190	
Central Cryoplant	41	
Heating and Current Drive	286	
Fuelling	10	
Fuel Handling	215	
Heat Transport	234	
Power Supplies	120	
Plant Protection, Instrumentation and Control Systems	362	
Maintenance Equipment	152	
Tokamak Auxiliaries		1610
Electrical Power Distribution	90	
Waste Handling	43	
Cooling Water Systems	273	
Fluid Supply Systems	66	
Plant Auxiliaries		472
Spares		94
Contingencies		400
TOTAL DIRECT COSTS		4487

Table 5

COST BREAKDOWN FOR THE REFERENCE REACTOR
(in January 1984 MECU)

TOTAL DIRECT COSTS (from Table 4)			4487
Project management Personnel	224		
Project management Material and Expenses	134		
Design and Engineering Services	36		
Licensing	18		
Taxes, Fees and Insurance	90		
Energy and Services	45		
Personnel Training	81		
Basic Indirect Costs		628	
Launching Costs		673	
TOTAL INDIRECT COSTS			1301
INTEREST DURING CONSTRUCTION			1030
Project Personnel		438	
Project Adminstration, Material and Expenses		108	
Energy Costs during Operation		75	
General Spares, Consumables and Services	577		
Blanket Replacements	168		
First Wall Replacements	33		
Divertor Replacements	137		
Spares, Consumables and Services		915	
Waste Disposal		68	
Insurance, Taxes and Fees during Operation		202	
OPERATION AND MAINTENANCE COSTS			1806
Deuterium		2	
Tritium		94	
Lithium		8	
FUEL COSTS			104
Planning and Project Management		21	
Decontamination and Dismantling		224	
Waste Disposal and Treatment		20	
DECOMMISSIONING			265
TOTAL PROJECT COSTS			8993

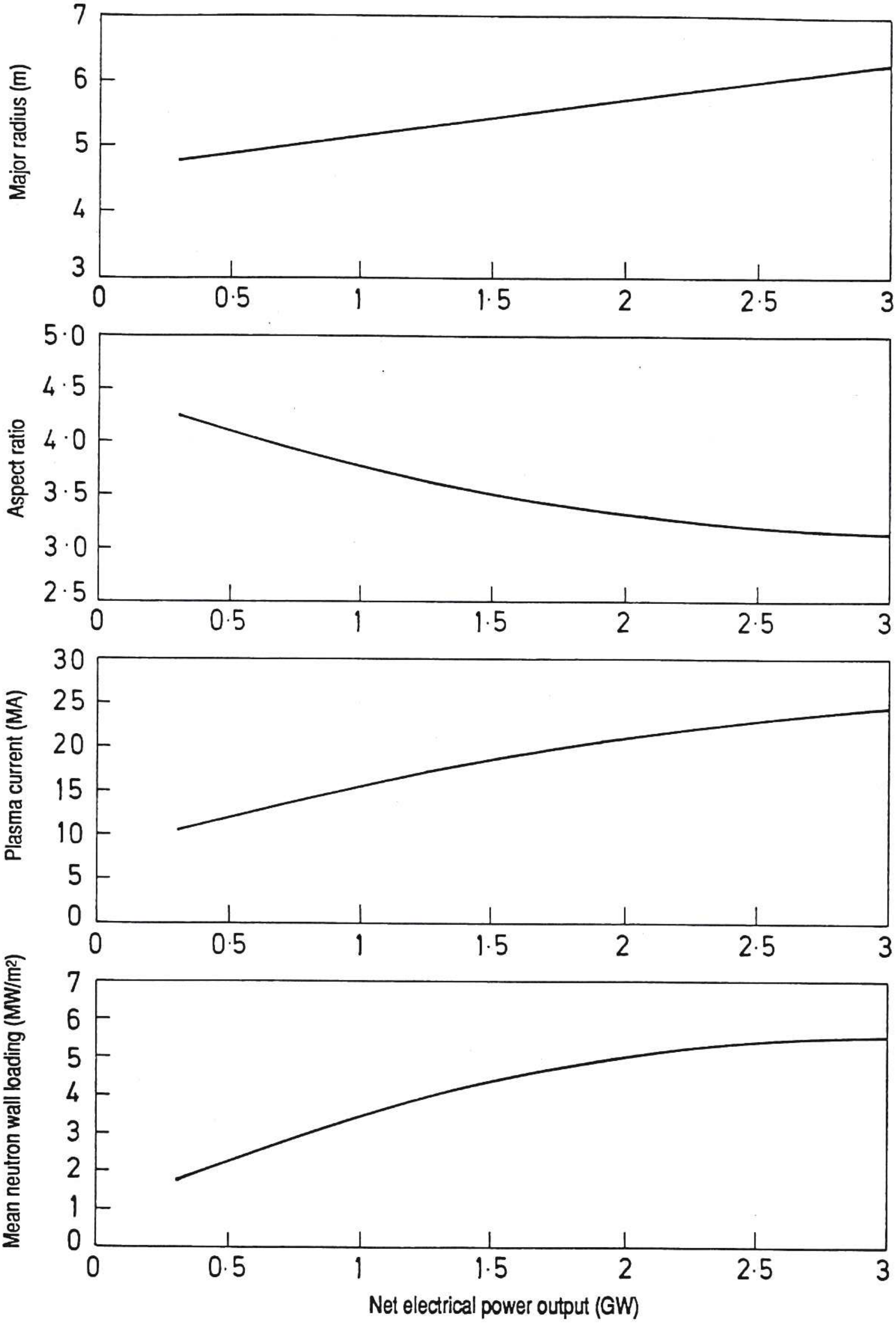

Figure 2 Variation of major radius, aspect ratio, plasma current and neutron wall loading with net electrical power output.

Figure 2 shows the variation of major radius, aspect ratio, plasma current and neutron wall loading. As expected the size of the device increases with increasing power output, although the increase in plasma volume is rather less than linear. The reason for this slow increase is that some of the more significant power drains which contribute to the recirculating power in the plant only increase slowly with increasing power output. The recirculating power fraction, therefore, falls quite significantly with increasing net electrical power output, from 32% at 300 MW to about 20% at the standard case of 1200 MW.

The aspect ratio tends to decrease as the power output is increased, which has the effect of increasing the plasma current, and also the current drive power. This is favoured by the cost optimisation because current drive power has a more significant cost impact at the lower power output levels and is a greater influence on the overall plant power balance.

The neutron wall loading increases with power output, reflecting the higher ratio of plasma volume to surface area and the slow rate of increase of reactor size. However, despite the increased difficulty of handling the higher heat fluxes, the unit costs of the first wall, divertor and blanket in the SCAN-2 model are not directly affected by power loading. The only influence of the higher wall loading is in the more frequent replacement required, which appears in the operating costs.

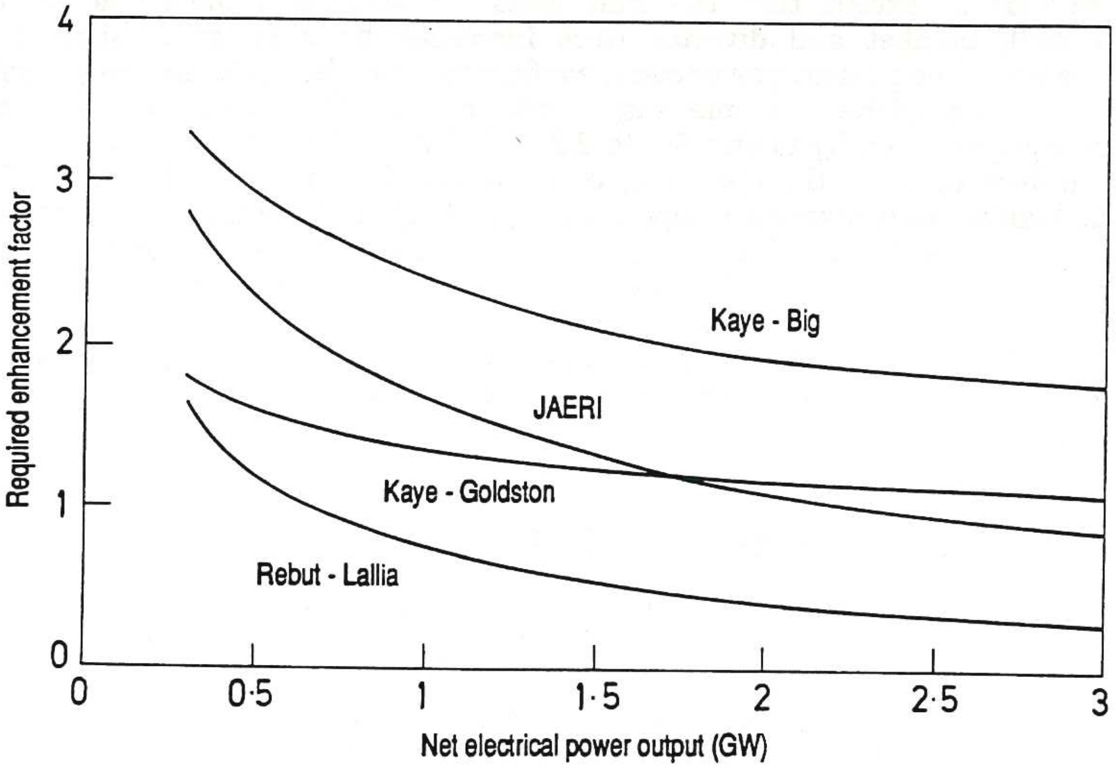

Figure 3 Variation of required enhancement factors for four different energy confinement scalings with net electrical power output.

The larger size and plasma current at higher power output increases the energy confinement time as predicted by most of the presently favoured models. This is reflected by Figure 3, which shows that the required enhancement factors fall with increasing power output for all four scalings illustrated, although there is a large degree of scatter between the different scalings because of different dependences on the important parameters. The Kaye-Big and JAERI scalings both indicate that enhancement factors greater than 3 are necessary for a net electrical power output of 300 MW, implying that operating such low-power devices may prove difficult without continuous plasma heating beyond that delivered through the steady-state current drive system.

2.4 Sensitivity to Structural Material Costs

A potential advantage of fusion reactors is their reduced impact on the environment, and in particular the possibility of minimising the radioactivity of the waste generated by the use of low-activation structural materials. Since these more environmentally benign materials are likely to be more expensive than the conventional materials currently available, an important consideration is the extent to which their use affects the economics of the plant and the optimum design point. Without a detailed design for the whole reactor it is difficult to assess these effects quantitatively but an indication of the likely effects has been obtained by increasing the unit cost of structural materials for the first wall, blanket and divertor (the components which are in the most severe radiation environment) and re-optimising the reactor parameters.

The results for a reactor which had identical assumptions and constraints to Reactor 2, except that the unit costs for structural materials for the first wall, blanket and divertor were increased by a factor 2, showed no difference in the reactor parameters; confirming that the optimum design point is very insensitive to material unit costs. The cost of electricity increased, however, by nearly 5% to 8.2 cECU/kWh. The largest component of this difference is in the operating costs, where the cost of replacement first wall, blanket and divertor components rises from 340 MECU to 680 MECU. Under the direct capital costs the cost of these components increases from 100 MECU to 160 MECU. Further increases, such as contingency and spares, indirect costs and decommissioning costs arise from their treatment as certain fractions of the direct costs. If the unit costs for structural materials increased by more than a factor 2, the above increases would continue pro rata.

3 Advanced Tokamak Reactor Parameters

Although the main objective of this study was to develop a set of parameters for a "Reference Reactor" which might reasonably result from the Commission's fusion research programme, further parameters have been generated for "Advanced" reactors which might result from significant improvements in the physics and engineering performance of tokamak reactors [15].

3.1 Single Parameter Variation

To aid understanding of the effects of different assumptions on reactor parameters and costs, key input parameters were individually varied from their Reactor 2 values. Table 6 shows the cost of electricity resulting from variations in five of the most important input parameters to SUPERCOIL; the plasma elongation, the normalised current-drive efficiency, the Troyon β-scaling coefficient, the maximum tensile stress in the toroidal field coils, and the thermal conversion efficiency. In all these cases it was assumed that the improvements were "free", i.e., the unit costs of materials and components were held fixed.

The cost is most sensitive to the Troyon coefficient, where an increase from the Reactor 2 value of 4.0 %Tm/MA to 10.0 %Tm/MA reduces the cost of electricity by over 13%. Such high values of the Troyon coefficient might be attainable by operation in the so-called "second-stability régime". An improvement in the structural materials of the toroidal field coil allowing a doubling of the maximum allowable tensile stress to 500 MPa could reduce costs by about 5%. An advanced scheme for thermal conversion with a thermal conversion efficiency of 50%, compared with the standard Reactor 2 value of 40%, would cut the cost of electricity by 6% if the unit costs remained the same. It might be expected that this reduction would be greater, as the same fusion power core would yield a 25% higher gross electrical power output with a thermal conversion efficiency of 50% compared with a 40% efficiency. However, when the net electrical output is maintained constant, at 1200 MW in this case, the generating costs are much less sensitive to changes in thermal efficiency, because of economies of scale. A reactor with an increased thermal conversion efficiency needs to produce a lower thermal power, but the cost per unit thermal power is higher.

Improvements in the other two parameters studied, the plasma elongation and the normalised current-drive efficiency, do not lead to significant reductions in costs. Even if there is no power required to drive the plasma current the cost of electricity falls by only about 3% compared with Reactor 2, where the normalised current drive efficiency was set at 0.7 x 10^{20} $m^{-2}A/W$. This lack of sensitivity is largely because the Reactor 2 efficiency is already at a high enough level that the impact of the current-drive system on costs is not great. A further point is that there is no reduction in capital costs with increasing current-drive efficiency beyond a certain point because it is assumed that 100 MW of auxiliary heating power will be required to heat the plasma to ignition. A much stronger sensitivity of costs to current-drive efficiency would be apparent, however, if the efficiency were reduced significantly from the Reactor 2 value.

3.2 Reactor Parameters

The main parameters of three possible advanced model tokamak reactors, referred to as AMTR 1, 2 and 3, are shown in Table 7. The input parameters are given in the first block of data, and show that AMTR 2 is a more advanced reactor than AMTR 1 with a higher Troyon coefficient, higher toroidal field coil tensile stress, and perfectly efficient current drive. AMTR 3 is identical in assumptions to AMTR 2 except in the thermal conversion

Table 6

SINGLE PARAMETER VARIATION ABOUT REACTOR 2

Parameter	Cost of electricity cECU/kWh
Reactor 2	7.84
Effective plasma elongation	
$\kappa = 2.5$	7.71
Troyon coefficient	
$g = 6.0$ % Tm/MA	7.34
$g = 10.0$ % Tm/MA	6.80
Normalised current-drive efficiency	
$\gamma = 2.0 \times 10^{20}$ $m^{-2}A/W$	7.71
$\gamma = \infty$ $m^{-2}A/W$	7.60
Maximum tensile stress in TF coil	
$\sigma = 500$ MPa	7.42
Thermal conversion efficiency	
$\eta_{th} = 50\%$	7.34

efficiency, which is the same as for Reactor 2. These advanced reactors are significantly smaller than Reactor 2. The neutron wall loadings are correspondingly higher, with the mean value for AMTR 3 approaching 8 MW/m^2; the peak loading on the outboard equatorial plane would be considerably higher.

The toroidal field on axis for AMTR 2 is much lower than in Reactor 2, despite the higher value of the peak field on the toroidal field coil. This is because the thickness of the inboard first wall, blanket and shield remains approximately constant (it actually increases slightly to attenuate the higher neutron flux to an acceptable level), which reduces the ratio of the on-axis field to the peak field on the coil because of the smaller major radius of AMTR 2. The same effect occurs to a lesser extent in AMTR 1 and 3.

The lower current-drive power for the advanced reactors, which is due to the improved efficiency and the lower plasma current, reduces the recirculating power fraction. An additional factor in AMTR 1 and 2 leading to a lower recirculating power fraction is the lower thermal power output, which arises because of the higher thermal conversion efficiency. This reduces many of the power drains, such as blanket cooling power, which are assumed to scale with the thermal power.

The advanced reactors require higher enhancement factors on the main energy confinement scalings in order to provide plasma power balance. For AMTR 2 and 3 an enhancement factor of nearly 4 on the Kaye-Big scaling is required, which is greater than the factors of ~2 which have been seen in H-mode discharges of present experiments. However, an improvement of a factor of 2 in confinement is not inconsistent with other improvements assumed in this study.

3.3 Costs

The capital and generating costs of the advanced reactors are given in Table 8. The overall effect of the changes in input parameters is a reduction of the cost of electricity compared with Reactor 2 of 17% for AMTR 1, 25% for AMTR 2 and 20% for AMTR 3. The capital cost of the fusion power core of AMTR 2, the "Tokamak" account, is less than half that of Reactor 2. The total plant costs are only 28% lower, because other costs, especially the auxiliaries, scale much more slowly with the size of the reactor, or have some component which scales in some way with the thermal or electrical power output. Indirect costs, the cost of spares and contingencies, and interest during construction all scale directly with the total direct costs.

In the generating cost components, the cost of replacement blankets is rather insensitive to the size of the reactor. This is largely due to the higher neutron wall loading for the smaller advanced machines, which leads to a need for more frequent replacement.

Table 7

PARAMETERS OF ADVANCED REACTORS

Parameter	AMTR 1	AMTR 2	AMTR 3
Effective plasma elongation	2.25	2.5	2.50
Troyon coefficient (% Tm/MA)	6.0	10.0	10.0
Normalised current-drive efficiency (10^{20} m^{-2}A/W)	2.0	∞	∞
Maximum tensile stress in TF coil (MPa)	250	500	500
Thermal conversion efficiency (%)	50	50	40
Plasma major radius (m)	4.51	3.53	3.81
Plasma half width (m)	0.98	0.84	0.83
Aspect ratio	4.60	4.21	4.58
Plasma current (MA)	8.96	7.53	7.49
Total volume-averaged plasma β (%)	9.39	20.2	18.59
Toroidal field on axis (T)	5.84	4.44	4.84
Peak toroidal field on TF coil (T)	14.4	16.0	14.74
Peak-to-peak toroidal field ripple (%)	0.08	0.06	0.05
Average electrom density (10^{20} m^{-3})	1.58	1.96	2.14
Required enhancement factors:			
Rebut-Lallia	1.19	1.47	1.32
Kaye-Big	3.05	3.79	3.67
Kaye-Goldston	1.55	1.93	1.76
JAERI	2.04	2.16	2.02
Current-drive heating power (MW)	16	0	0
Mean neutron wall loading (MW/m^2)	5.04	6.72	7.99
Shield thickness (inboard/outboard) (m)	0.84/0.75	0.86/0.7	0.88/0.78
Stored energy in TF coils (GJ)	34	15	20
Vertical bore of TF coil (m)	10.3	10.1	10.1
Fusion power (MW)	2250	2210	2815
Total thermal power (MW)	2730	2670	3402
Gross electrical power output (MW)	1370	1340	1360
Net electrical power output (MW)	1200	1200	1200
Recirculating power fraction	0.115	0.096	0.111

Table 8

ADVANCED REACTOR COST ESTIMATES
(January 1984 price levels.)

	AMTR 1	AMTR 2	AMTR 3
CAPITAL COSTS (MECU)			
Site and Improvements	33	29	31
Buildings	689	583	602
Tokamak	705	482	528
Tokamak Auxiliaries	1436	1401	1488
Plant Auxiliaries	397	379	419
Spares and Contingencies	402	356	380
Indirect Costs	1063	937	1000
Interest during Construction	840	741	791
TOTAL PLANT COSTS	5565	4908	5239
GENERATING COSTS (cECU/kWh)			
Capital Return	4.85	4.28	4.56
Basic Operation and Maintenance	1.15	1.09	1.12
Fuel and Replacement Blankets	0.33	0.31	0.37
Decommissioning	0.19	0.17	0.18
COST OF ELECTRICITY	6.52	5.85	6.24

4 Comparison with Other Studies

The reactor parameters and costs of the Reference Reactor developed in Section 2 have been compared with those generated in other studies, and in particular the Base Case reactor in the American ESECOM study [10].

The ESECOM study was organised in late 1985 to provide an up-to-date assessment of whether magnetic fusion reactors will be competitive with other energy sources available in the same time frame in terms of economic, safety and environmental characteristics. A component of this study was the development of several sets of reactor parameters, which were used as the basis of the assessment. These parameter sets included both tokamaks and reversed-field pinches, and allowed a variety of materials, power conversion schemes, fuel cycles and power densities to be considered. The parameters were produced using the GENEROMAK generic magnetic fusion costing model developed at Oak Ridge [11,16,17,18]. The base-case, or "point-of-departure", ESECOM case (referred to as V-Li-TOK), incorporated a vanadium-alloy structure with liquid lithium as the coolant and breeder.

An additional analysis has been made using the ARIES systems code [19], for a case very similar to the Reference Reactor. This represents a point of comparison for parameters and costs with a more recent code than GENEROMAK, and is reported in Appendix III.

4.1 GENEROMAK Models

The GENEROMAK code used for the ESECOM studies is written in BASIC and designed for use on an IBM-PC. The only iteration involved is in the solution of a non-linear algebraic equation for the on-axis toroidal field and the plasma minor radius for fixed input values of net electrical power output, total plasma β, aspect ratio, plasma elongation, and peak field on the toroidal field coil. This is in contrast to the more complex SUPERCOIL/SCAN code, which runs on a CRAY to perform reactor cost minimisation over a multi-dimensional group of variables. Such variation would have to be done manually with GENEROMAK, together with extensive checks to ensure that constraints on stress levels, dose rates, ripple limits etc., which are monitored continuously in SUPERCOIL, were not exceeded.

The following subsections describe the models used in the GENEROMAK calculations and compare them with those used in SUPERCOIL; Table 9 lists the physics, engineering and economic input parameters used for the ESECOM base case V-Li-TOK.

4.1.1 Physics and Engineering Models

The physics models of GENEROMAK and SUPERCOIL are basically similar, although, as mentioned above, GENEROMAK operates on a "once-through" basis, whereas SUPERCOIL carries out plasma calculations for many possible operating points. Both models use a Troyon scaling for β, the V-Li-TOK value of 4.0 %Tm/MA for the coefficient being identical to the value used for the Reference Reactor.

To allow the plasma operating point to be determined uniquely, the plasma aspect ratio is fixed in GENEROMAK, whereas it is a free parameter for SUPERCOIL. In addition to fixing the aspect ratio and the Troyon coefficient, the absolute value of the plasma β is also fixed in GENEROMAK. At first sight this may seem strange but, by considering the equations for the plasma safety factor and the Troyon β scaling, it can be seen that the same result could have been achieved if the safety factor at this fixed aspect ratio had been specified instead of the β value.

The fusion power density in GENEROMAK is calculated as being proportional to the value of $\beta_u^2 B_0^4$, where β_u is the useful β and B_0 is the magnetic field on axis, with the constant of proportionality being 1.62 MW/m^3T^4, compared with 1.50 MW/m^3T^4 for the Reference Reactor. The ratio of useful β to total β is 0.91 for GENEROMAK, compared with a much lower value of 0.67 for the Reference Reactor. This lower value reflects a much higher allowance for impurities and non-thermal particles. For given values of total β and plasma toroidal field, the fusion power density calculated by GENEROMAK is approximately twice that for the Reference Reactor.

Steady-state current drive is assumed in GENEROMAK, although the absolute rather than the normalised efficiency is generally used. For V-Li-TOK the absolute efficiency is taken to be 0.2 A/W, corresponding to a high normalised current-drive efficiency of 2.7 x 10^{20} $m^{-2}A/W$; this compares with a value of 1.4 x 10^{20} $m^{-2}A/W$ used for the Reference Reactor, based on the total current. No contribution to current drive from the bootstrap current is included in GENEROMAK.

The impurity control mechanism assumed in GENEROMAK is a pumped limiter, with the corresponding difference in magnetic configuration of the plasma. This has little bearing on the final parameters, although a slightly lower allowance for poloidal field coil costs would be appropriate.

It is implicitly assumed in the GENEROMAK model that 30% of the α-heating and current-drive power is lost as low-grade heat and is not usable in the thermal conversion cycle. In SUPERCOIL, all of the α-heating and current-drive power is recovered in the main thermal cycle.

The toroidal-field strength in GENEROMAK is fixed by the peak value on the toroidal field coil, which was set at 10 T for the base case. This value was chosen from a point variation study to minimise the cost of electricity. In SUPERCOIL the toroidal field is determined either by this constraint or, more often, by the tensile stress in the inboard leg of the toroidal field coil.

Differences in assumptions for the important engineering parameters are summarised in Table 9.

Table 9

INPUT PARAMETERS FOR ESECOM BASE CASE
AND THE REFERENCE REACTOR

Parameter	ESECOM	Reference Reactor
Plasma configuration	Limiter	Double null
Aspect ratio	4.0	(3.78)
Effective plasma elongation	2.5	2.25
Troyon coefficient (% Tm/MA)	4.0	4.0
Total β value (%)	10	(7.62)
Ratio of useful to total β	0.91	0.67
Plasma safety factor q_I	1.81	2.17
Average plasma temperature (keV)	10	20
Current-drive efficiency (A/W)	0.2	(0.18)
Bootstrap fraction	0.0	0.5
First-wall/plasma radius	1.1	(1.11)
Number of TF coils	20	22
Peak toroidal field on TF coil (T)	10	(14.9)
Thermal conversion efficiency (%)	40.4	40
Blanket thickness (inboard/outboard) (m)	0.71/0.71	0.55/0.85
Shield thickness (inboard/outboard) (m)	0.83/0.83	(0.83/0.74)
Blanket energy multiplication factor	1.27	1.25
Blanket fluence lifetime (MWy/m^2)	20	10
Limiter fluence lifetime (MWy/m^2)	10	2
Basic recirculating power fraction (excluding current drive)	0.06	(0.114)
Net electrical power output (MW)	1200	~1200
Reactor design lifetime (y)	30	25
Availability (%)	65	75
Construction time (y)	6	8
Indirect cost factor	0.375	0.32
Contingency factor	0.21	0.1
Interest during construction factor	0.086	0.178

Values in parentheses for the Reference Reactor are output from the optimisation rather than being specified, as in the GENEROMAK model.

4.1.2 Costing Models

The costing models used in GENEROMAK and SUPERCOIL are substantially different, making comparisons between the two difficult. The currencies used are different and apply to different years. Different cost-scaling algorithms are used for the reactor components, the treatment of return on capital invested differs, and the methodologies used to arrive at a cost of generating electricity are different. Table 9 gives the differences in assumptions for indirect costs, contingencies and interest during construction. A comparison of these costs in terms of direct costs is given in reference [20].

The basis for most of the costs estimated in the GENEROMAK model is the STARFIRE study [7], with costs updated to January 1986 price levels. Some unit costs (e.g., magnets) were increased significantly from those of STARFIRE. The costs are thus based on a "tenth-of-a-kind" plant, with appropriate allowances incorporated for learning-curve effects. However, the SCAN model is based on a "first-of-a-kind" reactor with many costs estimated from studies for NET, and includes launching and development costs which would be excluded in GENEROMAK.

The costs of the first wall, blanket, shield, coils systems and primary structure in GENEROMAK are calculated from the volumes and densities of the components, with a cost per unit mass of the appropriate materials. Other direct costs are scaled with some power (between 0 and 1) of the value of an appropriate parameter (e.g, reactor thermal power for heat transfer equipment, volume of the fusion power core for the reactor buildings, etc). The approach adopted in SCAN is basically similar, although SCAN is a much more detailed model, with a greater subdivision of costs for each major component and implicit assumptions on plant layout, for example. Other elements of the capital cost in both models are estimated as percentages of the direct costs.

One important difference between the two models relates to the estimates of component volumes. The fusion power core volume calculated in GENEROMAK is typically about half the SCAN value for a similar case. This discrepancy arises from the inclusion of ducts and ports, duct shielding and additional support structure in SCAN, and the modelling of volumes as nested toroids in GENEROMAK.

Calculations of generating costs proceed differently. In SCAN, the expenditure over the entire plant lifetime is estimated. These costs are then converted to the date of commissioning by applying interest charges to costs incurred during the construction phase, or by discounting future costs. The total lifetime costs are then divided by the total lifetime electricity generation, also discounted to the date of commissioning, to give the cost of electricity.

In GENEROMAK, annual costs are calculated, either from estimates of operating, maintenance and fuel costs, or by applying the appropriate fixed-charge rate (or required rate of return) to the capital investment. Taxation (local and federal) is then included. These total annual costs are divided by the annual electricity generated to arrive at a levelised cost of electricity. These procedures, although fundamentally different, will give the same results under appropriate assumptions. However, the different assumptions used by the two models make direct comparison difficult.

Certain general observations can be made, however. As shown in Table 9, contingency and indirect costs are somewhat higher in GENEROMAK than in SCAN, but this is partially compensated by higher interest costs in SCAN. The factor of 0.178 for interest during construction applied in SCAN is based on an S-shaped expenditure profile during the 8 year construction period, and a 5% real net interest rate. A shorter 6 year construction period is assumed for the ESECOM base case, and, assuming the same expenditure profile, the quoted factor for interest during construction corresponds to a lower real interest rate of 3.35%.

Operating and maintenance costs tend to be estimated as absolute annual costs, which are assumed to scale with the square root of the net electrical power output in GENEROMAK and are unrelated to the power in SCAN. For a typical reactor, the lifetime sum of these basic operating and maintenance costs is 35-45% of the direct costs in GENEROMAK, but only 20-30% of the direct costs in SCAN. Fuel costs, which, using the GENEROMAK definition, include replacement first walls, blankets and divertor/limiters, are highly design dependent, and will vary according to the fluence limit assumed for the

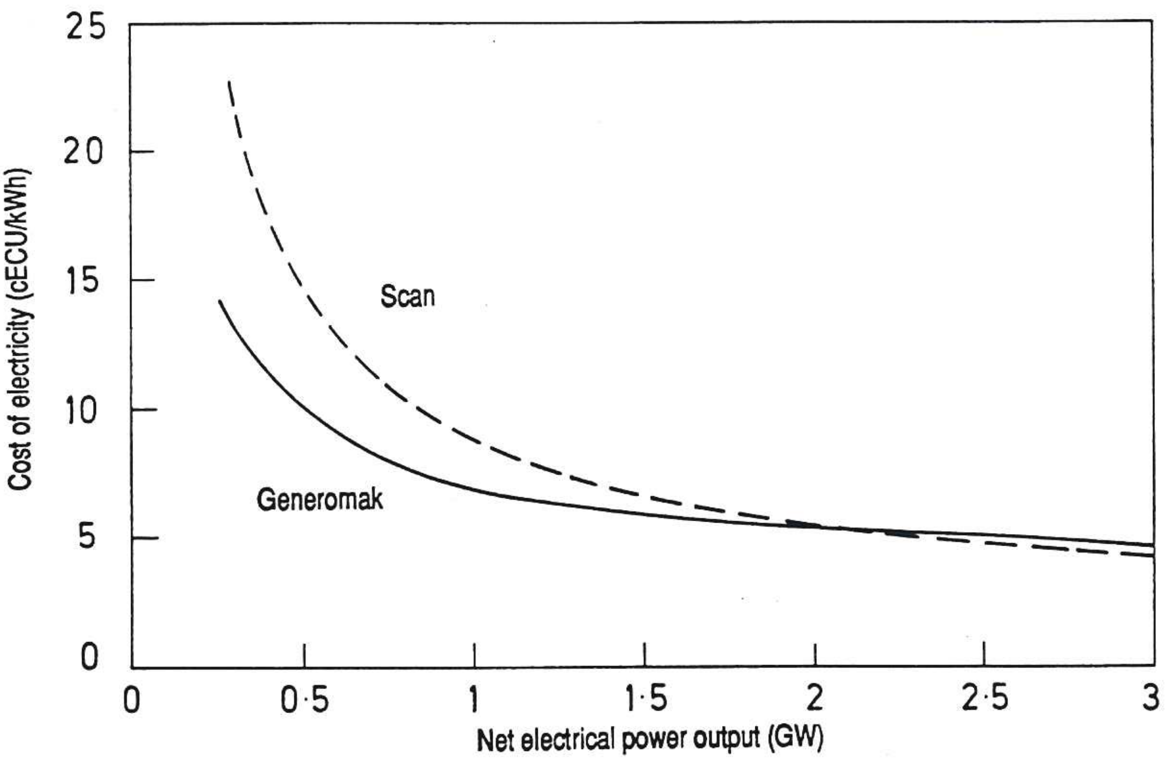

Figure 4 Variation of cost of generating electricity with net electrical power output, using the SCAN and GENEROMAK codes.

component and the neutron wall loading. Estimates for these costs tend to be higher in GENEROMAK than in SCAN. An additional factor accentuating this difference is that the cost of the initial first wall, blanket and divertor or limiter is taken as a capital cost in SCAN, but is converted to a fuel cost in GENEROMAK.

As mentioned above, different methods are used to estimate the capital component of the generating cost. In GENEROMAK, the fixed charge rate applied to capital costs is 0.0844 per year. The discount rate of 5% per year applied to SCAN costs, taken with a 25 year design lifetime, can be converted to an equivalent fixed charge rate for comparison of 0.0692.

The above differences somewhat affect the scaling with power output derived in section 2.3. The result for GENEROMAK is compared to the SCAN result in figure 4, for the same reactor parameters, using the $/ECU conversion rate described in the next section. The outcome is that the SCAN model has a stronger tendency to favour larger devices than GENEROMAK.

To summarise, the costing models used by the two codes are rather different. Related to the direct costs, the indirect and operating costs tend to be higher in GENEROMAK than in SCAN, with the exception of interest costs. A comparison of the direct costs and absolute generation costs will be made in the next section.

4.2 Comparison of Results

4.2.1 ESECOM Base Case and The Reference Reactor

Tables 10 and 11 compare the major parameters and costs, respectively, of the ESECOM base case, V-Li-TOK, calculated with GENEROMAK, and the Reference Reactor, calculated with SUPERCOIL/SCAN. To facilitate comparison with SCAN, GENEROMAK costs were converted to January 1984 ECU. This was achieved [20] by deflating 1986 $ to 1984 $ by multiplying by 0.975 (this factor being derived from the US wholesale goods index), and then converting to 1984 ECU, using the exchange rate of 1 ECU = $ 0.8274; these two conversions imply that $ 1 (January 1986) = 1.1784 ECU (January 1984).

The general size of the two reactors is quite similar, with the Reference Reactor being about 10% smaller in terms of the major radius. The higher fusion power density in the Reference Reactor, implied by its smaller size, requires a considerably higher value of the product $\beta^2 B^4$, because of the assumptions about the ratio of the useful to total β value referred to in the previous section. This is achieved by the large increase in the toroidal field strength of the Reference Reactor relative to V-Li-TOK; values of both the on-axis and the peak field are nearly 50% higher in the Reference Reactor than in V-Li-TOK. The toroidal field coil current density scaling used in GENEROMAK strongly penalises the use of higher peak field levels, which leads to massive and expensive coils, so that the optimum operating point is at a lower field strength.

Table 10

MAJOR PARAMETERS OF V-Li-TOK AND THE REFERENCE REACTOR

Parameter	V-Li-TOK	Reference Reactor
Plasma major radius (m)	5.89	5.31
Plasma half width (m)	1.47	1.40
Aspect ratio	(4.0)	3.78
Effective plasma elongation	(2.5)	(2.25)
Plasma current (MA)	15.8	16.6
Total β value (%)	(10)	7.62
Toroidal field on axis (T)	4.29	6.22
Peak toroidal field on TF coil (T)	(10)	14.9
Average plasma temperature (keV)	(10)	(20)
Average electron density (10^{20} m^{-3})	2.29	1.45
Current-drive heating power (MW)	79	91
Mean first wall neutron wall loading (MW/m^2)	3.20	4.15
Fusion power (MW)	2860	3050
Total thermal power (MW)	3560	3780
Gross electrical power output (MW)	1360	1510
Net electrical power output (MW)	(1200)	1200
Recirculating power fraction	0.12	0.20

Values in parentheses are specified as input parameters.

Table 11

COST COMPARISON OF V-Li-TOK AND THE REFERENCE REACTOR
(January 1984 price levels.)

	V-Li-TOK	Reference Reactor
CAPITAL COSTS (MECU)		
Site and Improvements	6	40
Buildings	374	826
Tokamak	374	1045
Tokamak Auxiliaries	619	1610
Plant Auxiliaries	520	472
Spares and Contingencies	457	494
Indirect Costs	730	1301
Interest during Construction	264	1030
TOTAL PLANT COSTS	3344	6818
GENERATING COSTS (cECU/kWh)		
Capital Return	4.13	5.94
Basic Operation and Maintenance	1.04	1.28
Fuel and Replacement Blankets	0.97	0.39
Decommissioning	0.12	0.23
COST OF ELECTRICITY	6.26	7.84

Although both reactors have the same Troyon coefficient, the β value for V-Li-TOK is higher than for the Reference Reactor. This is achieved by a slightly higher plasma elongation, and a lower safety factor; these two factors more than offset the slightly higher aspect ratio of V-Li-TOK.

The recirculating power fraction of 0.20 for the Reference Reactor is rather greater than the corresponding value of 0.12 for V-Li-TOK. This is partly due to the higher current-drive power for the Reference Reactor, an effect which is increased by the assumption of a 100% "wall-plug" efficiency in V-Li-TOK, compared with 70% in the Reference Reactor. The other main contributor to the lower recirculating power in V-Li-TOK is the assumption of a lower power requirement for the balance of plant; a fraction of 0.06 is used for V-Li-TOK compared with about 0.11 for the Reference Reactor.

Table 11 compares the costs of the two reactors. It should be emphasised that the accounting methods used in the two models do not permit an exact comparison to be made, and that there remain certain inconsistencies between the two columns in the table. However the degree of correspondence is good enough to show the main features of the two costing models.

Two changes were made to the V-Li-TOK costs to improve the correspondence between the two sets of costs. The costs of spares were removed from the individual cost accounts and lumped together into the "Spares and Contingencies" account, and the capital cost of auxiliary heating and current-drive power was moved from the "Tokamak" account to the "Tokamak Auxiliaries" account to accord with SCAN accounting.

One clear observation from the table is that the SCAN model for Reactor 2 predicts much higher costs for the "nuclear island" components and buildings than GENEROMAK does for V-Li-TOK. The good agreement in the costs of the conventional plant items in the account "Plant Auxiliaries" is probably coincidental.

Several contributing factors can be identified as explanations for the cost differences. Firstly, the SCAN model estimates costs for a "first-of-a-kind" device, whereas GENEROMAK, which bases its costs on STARFIRE data, is for a "tenth-of-a-kind" reactor. Learning-curve effects, and launching and development costs can therefore increase SCAN costs relative to GENEROMAK. As an example, Instrumentation and Control costs are a large contributor to costs in the "Tokamak Auxiliaries" account in the SCAN estimate for the Reference Reactor. As these costs are scaled from estimates for NET, it is expected that they would be larger than for the STARFIRE-based GENEROMAK model.

One major component of the "Tokamak" account is the magnet costs, which are considerably higher for the Reference Reactor than for V-Li-TOK. As the peak field on the coil is nearly 50% higher for The Reference Reactor than for V-Li-TOK, the cost difference is indicative of a difference in the design rather than in the cost model itself.

Other disparities in the costs arise from different approaches adopted in the cost modelling, as referred to above. For example, the initial blanket cost is included as a capital cost in SCAN, but as an operating cost in GENEROMAK. Differences in the indirect and generating costs can largely be attributed to modelling differences such as these. A point worthy of note, however, is that although the the Reference Reactor capital costs are predicted to be over twice those of V-Li-TOK, the difference in the cost of generating electricity is only 25%.

4.2.2 ESECOM Base Case using SUPERCOIL

As a further step in the comparison of the ESECOM results with those from this study, SUPERCOIL and SCAN were used to model the ESECOM base case, V-Li-TOK. This was performed by adjusting several assumptions and input parameters to the SUPERCOIL model, although no attempt was made to change the cost model SCAN. Table 12 shows the changes made to the model, and also compares the output parameters. Gaps in the table for GENEROMAK indicate parameters for which no value was given or was deducible from the reports.

Most of the changes made to the SUPERCOIL assumptions reflect the differences between the two models outlined earlier. The ratio of useful to total β was increased, as was the plasma reactivity. The current-drive efficiency was increased, although this difference was offset by the removal of any bootstrap current drive. The wall-plug efficiency of the current-drive system was set at 44%, indicative of what would be expected from a RF-based system, and also to compensate for the GENEROMAK assumption of discarding 30% of the current-drive and α-heating powers in the thermal conversion system. The toroidal field coil tensile stress limit was reduced in line with the reduced peak field for V-Li-TOK. The base recirculating power fraction (for power drains other than heating and current drive) was cut from 0.114 to 0.06, while the availability was reduced from 75% to 65%.

There is satisfactory agreement in the output parameters from SUPERCOIL and GENEROMAK in modelling V-Li-TOK. The only clear differences are in the thermal power and the recirculating power, which arise from the inherent modelling differences discussed above. The cost estimates are substantially different, although it is interesting to note that the SCAN cost estimate for V-Li-TOK is almost identical to that for the Reference Reactor.

4.2.3 Reference Reactor using GENEROMAK

A copy of the GENEROMAK program was obtained and used to model the Reference Reactor. Table 13 shows the changes made to the GENEROMAK model and compares the results with the SUPERCOIL results. In order to match the fusion power estimated from SUPERCOIL and to allow for the loss of some thermal power in the conversion cycle assumed by GENEROMAK, the ratio of useful to total β and the blanket energy multiplication factor had to be set to values different from those used in the SUPERCOIL analysis. As GENEROMAK used the current-drive efficiency to estimate the total power supplied to the current-drive system rather than just to the plasma, the efficiency was set to a value of 0.13 A/W instead of the 0.18 A/W which would be appropriate for the plasma power, in the absence of any contribution from the bootstrap effect.

Table 12

V-Li-TOK CALCULATED WITH SUPERCOIL/SCAN AND GENEROMAK

Parameter	SUPERCOIL	GENEROMAK
Null point plasma elongation	2.50	2.50
Plasma safety factor q_I	1.81	1.81
Troyon coefficient (% Tm/MA)	4.0	4.0
Ratio of useful to total β	0.91	0.91
Ratio of fast particle to total β	0.04	
Average plasma temperature (keV)	10	10
Plasma reactivity ($\beta_u^2 B^4/p_{fus}$)	1.62	1.62
Current-drive efficiency (A/W)	0.20	0.20
Normalised current-drive efficiency (10^{20}) m^{-2}A/W)	2.7	2.7
Bootstrap fraction	0.0	0.0
Wall plug efficiency (%)	44	100
Number of TF coils	20	20
TF coil tensile stress (MPa)	107	
Thermal conversion efficiency (%)	40.4	40.4
Blanket energy multiplication	1.27	1.27
Base recirculating power fraction	0.06	0.06
Availability (%)	65	65
Plasma major radius (m)	5.89	5.89
Plasma minor radius (m)	1.47	1.47
Plasma current (MA)	15.8	15.8
Toroidal field on axis (T)	4.29	4.29
Peak field on TF coil (T)	10.0	10.0
Total β value (%)	10.0	10.0
Average electron density (10^{20} m^{-3})	2.27	2.29
Current-drive power (MW)	78	79
Mean neutron wall loading (MW/m^2)	3.36	3.20
Fusion power (MW)	2870	2860
Total thermal power (MW)	3620	3560
Recirculating power fraction	0.18	0.12
Net electrical power (MW)	1197	1200
Cost of electricity (cECU/kWh) (January 1984 price levels.)	7.85	6.26

Table 13

REFERENCE REACTOR CALCULATED WITH SUPERCOIL/SCAN AND GENEROMAK

Parameter	SUPERCOIL	GENEROMAK
Effective plasma elongation	2.25	2.25
Aspect ratio	3.78	3.78
Troyon coefficient (% Tm/MA)	4.0	4.0
Ratio of useful to total β	0.67	0.68
Total β value (%)	7.62	7.62
First wall/plasma radius	1.11	1.11
Average plasma temperature (keV)	20	20
Current-drive efficiency (A/W)	0.09	0.13
Peak field on TF coil (T)	14.9	14.9
Blanket thickness (in/out) (m)	0.55/0.85	0.55/0.85
Shield thickness (in/out) (m)	0.83/0.74	0.83/0.74
Thermal conversion efficiency (%)	40	40
Blanket energy multiplication	1.25	1.35
Base recirculating power fraction	0.114	0.114
Blanket lifetime (MWy/M^2)	10	10
Availability (%)	75	75
Reactor design lifetime (y)	25	25
Plasma major radius (m)	5.31	5.31
Plasma minor radius (m)	1.40	1.40
Plasma current (MA)	16.6	16.6
Toroidal field on axis (T)	6.22	6.22
Plasma density (10^{20} m^{-3})	1.45	1.83
Current-drive power (MW)	91	130
Mean neutron wall loading (MW/m^2)	4.15	4.31
Fusion power (MW)	3050	3050
Total thermal power (MW)	3780	3780
Recirculating power fraction	0.20	0.20
Net electrical power (MW)	1200	1200
Cost of electricity (cECU/kWh) (January 1984 costs)	7.84	7.30

Table 14

GENEROMAK AND SCAN COST ESTIMATES FOR THE REFERENCE REACTOR
(January 1984 price levels.)

	GENEROMAK	SCAN
CAPTIAL COSTS (MECU)		
Site and Improvements	6	40
Buildings	383	826
Tokamak	600	1045
Tokamak Auxiliaries	749	1610
Plant Auxiliaries	522	472
Spares and Contingencies	595	494
Indirect Costs	888	1301
Interest during Construction	321	1030
TOTAL PLANT COSTS	4064	6818
GENERATING COSTS (cECU/kWh)		
Capital Return	4.32	5.94
Basic Operation and Maintenance	0.90	1.28
Fuel and Replacement Blankets	1.96	0.39
Decommissioning	0.12	0.23
COST OF ELECTRICITY	7.30	7.84

The results show good agreement in all the major parameters. The only significant discrepancy lies in the current-drive power, which arises from the different definition mentioned above. The cost of electricity is estimated to be lower than that predicted by SUPERCOIL/SCAN, but higher than that of V-Li-TOK. Table 14 compares in more detail the capital and generating costs predicted by GENEROMAK and SCAN for the Reference Reactor on the same basis as used in Table 11.

The main differences between the two columns are as described in Section 4.2.1. The GENEROMAK costs for the "Tokamak" account for the Reference Reactor is significantly higher than for V-Li-TOK, largely due to the more expensive coils. This is a result of the higher peak field of the Reference Reactor, and the added costs associated with the lower current density and the more massive structure.

5 Conclusions

Several sets of parameters for steady-state tokamak reactors that might be available midway during the next century have been developed. The first parameter set (Reactor 1) is based upon conservative plasma physics assumptions typical of those presently being used to design the ITER device, while the second (Reactor 2) includes several possible improvements in the input parameters. These improvements include an increase in the Troyon coefficient from 3.0 %Tm/MA to 4.0 %Tm/MA, an increase in the null-point plasma elongation from 2.2 to 2.5, an increase in the bootstrap current fraction from 0.3 to 0.5, an increase in the normalised current-drive efficiency from 0.5 to 0.7, an increase in the allowable tensile stress in the toroidal field coils from 200 MPa to 250 MPa, and an increase in the thermal conversion efficiency of the power cycle from 35% to 40%. The cost of electricity for these reactors is estimated at 10.5 cECU/kWh and 7.8 cECU/kWh, respectively, indicating the potential benefit in reactor economics if such improvements in performance can be obtained.

These two new sets of parameters have been compared with the parameters of the pulsed reactor PCSR-E, which was developed for an earlier study. The estimated cost of PCSR-E is only slightly higher than that for the steady-state ITER-based Reactor 1, although the size of PCSR-E is rather greater, 30% larger in terms of the major radius.

The main objective of this study was to develop a set of parameters for a Reference Reactor, for use in further studies. As the focus is on reactors during the next century it appears reasonable to assume some improvement over the performance of present-day experiments, and therefore the parameters of Reactor 2 have been adopted for the Reference Reactor.

The economy of scale for tokamak reactors has been assessed by varying the net electrical power output of a reactor with the input parameters of the Reference Reactor around the central value of 1200 MW. There is a strong variation in the cost of electricity, from over 20 cECU/kWh for a 300 MW output to about 4.5 cECU/kWh for a 3000 MW reactor.

To simulate the effect of using advanced low-activation structural materials in the blanket the unit cost of these materials in the first wall, blanket and divertor were varied, on the assumption that such materials are likely to be more expensive than conventional materials. For a two-fold increase in these unit costs the change in reactor parameters is very slight, while the cost of electricity increased by about 5%.

Parameters and costs for three advanced reactors have also been developed. Improved values compared with Reactor 2 were used for the Troyon coefficient, the current-drive efficiency, the plasma elongation, the maximum stress in the toroidal field coils, and the thermal conversion efficiency. These improvements give rise to smaller, higher power density reactors, with higher wall loadings. The capital costs of the small reactors are lower, although not in proportion to the dimensions, because of the many fixed, or slowly varying, components of the cost. The cost of generating electricity for the most advanced reactor, AMTR 2, where very significant improvements in performance were assumed, falls by 25% compared with Reactor 2.

These reactor parameters and costs have also been compared with those generated in the American ESECOM study using the GENEROMAK code. Despite many differences in assumptions for a wide range of input parameters, the general size of the ESECOM base case, V-Li-TOK, is quite similar to that of the Reference Reactor, although there are significant variations in many individual parameters, such as toroidal field strength, current drive power, etc. The costing model used by GENEROMAK is very different from SCAN, so that the costs of many components vary widely between the two cases. As GENEROMAK takes credit for "learning-curve" effects, whereas the SCAN model estimates costs for a "first-of-a-kind" device, capital cost estimates of the "nuclear island" components tend to be higher with SCAN. This is partially offset by generally higher estimates for the indirect and generating costs with GENEROMAK. However, the GENEROMAK estimate of the cost of electricity of the ESECOM base case is about 25% less than the SCAN estimate for the Reference Reactor.

Additional comparisons between the two studies were performed by modelling V-Li-TOK with SUPERCOIL/SCAN, and using the GENEROMAK code to model the Reference Reactor. Suitable adjustments to the input parameters could be made to reproduce the reactor parameters of either case, although differences remained in the cost estimates. For each case the SCAN estimate of cost was higher than the GENEROMAK estimate.

6 Acknowledgement

The authors gratefully acknowledge the help of J G Delene of the Oak Ridge National Laboratory and R A Krakowski of the Los Alamos National Laboratory in making available the GENEROMAK and ARIES codes used for the code comparison. They also acknowledge the advice of M Cox in the choice of input parameters for the Advanced Model Tokamak Reactors.

7 References

[1] K Borrass, "SUPERCOIL: A Model for the Computational Design of Tokamaks", Nucl. Eng. Des./Fusion, 4 (1986) 21.

[2] K Borrass and M Söll, "Normal Conducting Steady-State Toroidal Magnet Systems for Ignited Tokamaks", IPP Garching Report IPP 4/203, July 1981.

[3] K Borrass and M Söll, "SUPERCOIL, "A Layout Model for Tokamaks with Superconducting TF Coils", IPP Garching Report IPP 4/207, June 1982.

[4] W R Spears, "Prototype Commercial-Sized Reactor PCSR-E", NET Report No 67, December 1986.

[5] W R Spears, "Reactors beyond NET", Proc. Fusion Reactor Design and Technology, Yalta, USSR, May 1986, Vol. I, 285, International Atomic Energy Agency, Vienna.

[6] W R Spears, "The SCAN-2 Cost Model", NET Report No. 62, July 1986.

[7] C C Baker et al., "STARFIRE - A Commercial Tokamak Fusion Power Plant Study", Argonne National Laboratory Report ANL/FPP-80-1, September 1980.

[8] "NET Status Report", NET Report No. 51, EU-FU/XII-80/86/51, December 1985.

[9] "Next European Torus", Fusion Technology, 14, No. 1, July 1988.

[10] J P Holdren et al., "Report of the Senior Committee on Environmental, Safety and Economic Aspects of Magnetic Fusion Energy", Lawrence Livermore National Laboratory Report, UCRL-53766, June 1989.

[11] R A Krakowski and J G Delene, "Connections Between Physics and Economics for Tokamak Fusion Power Plants", J. Fusion Energy, 7 (1988) 49.

[12] R S Devoto, "Fitting Recent ACCOME Neutral-Beam Current Drive Results with a Scaling Relation", Lawrence Livermore National Laboratory Memorandum LLNL-ITER-88-056, December 1988.

[13] W R Becraft, Oak Ridge National Laboratory, private communication, February 1989.

[14] ITER Concept Definition, ITER-Documentation Series, No 3, , IAEA, Vienna, 1989.

[15] D C Robinson et al, "Tokamak Advances Expected and Needed and Advances in Exhaust Technology for Commercial Fusion Power in 21st Century", Culham report, CLM-P862, April 1989.

[16] J Sheffield, R A Dory, S M Cohn, J G Delene, L F Parsly, D E T F Ashby and W T Reiersen, "Cost Assessment of a Generic Magnetic Fusion Reactor", Oak Ridge National Laboratory Report ORNL/TM-9311 (1986).

[17] J Sheffield, R A Dory, S M Cohn, J G Delene, L F Parsly, D E T F Ashby and W T Reiersen, "Cost Assessment of a Generic Magnetic Fusion Reactor", Fusion Technology, 9 (1986) 199.

[18] J G Delene, R A Krakowski, J Sheffield and R A Dory, "GENEROMAK: Fusion Physics, Engineering and Costing Model", Oak Ridge National Laboratory Report, ORNL/TM-10728 (1988).

[19] R L Miller and the ARIES Team, "The ARIES-I High-Field Tokamak Reactor: Design-Point Determination and Parameter Studies", presented at the IEEE 13th Symposium on Fusion Engineering, Knoxville, Tennessee, October 1989.

[20] W R Spears, "Cost Analysis of Next-Step Devices and the Implications for Reactors", presented at the Seminar on "Safety, Environmental Impact and Economic Prospects of Nuclear Fusion", Erice, August 1989, Plenum Press (to be published).

Appendix I Radial build through midplane of the Reference Reactor

Radius (m)	
	1.109
Cryostat (0.05 m)	
	1.159
Poloidal-field coil (0.05 m)	
	1.209
Toroidal-field coil (1.013 m)	
	2.222
Cryostat (0.05 m)	
	2.272
Inboard shield (0.831 m)	
	3.103
Gap (0.10 m)	
	3.203
Inboard blanket (0.515 m)	
	3.718
First wall (0.035 m)	
	3.753
Scrape-off layer (0.15 m)	
	3.903
Plasma (1.403 m)	
	5.306
Plasma (1.403 m)	
	6.709
Scrape-off layer (0.15 m)	
	6.859
First wall (0.035 m)	
	6.894
Outboard blanket (0.815 m)	
	7.709
Gap (0.10 m)	
	7.809
Outboard shield (0.736 m)	
	8.545
Empty space (1.419 m)	
	9.964
Cryostat (0.05 m)	
	10.014
Toroidal-field coil (1.013 m)	
	11.027
Cryostat (0.05 m)	
	11.077
Poloidal-field coil (smeared thickness 0.12 m)	
	11.197

Appendix II Component Masses for the Reference Reactor

This appendix gives the masses and volumes of various components of the Reference Reactor, as estimated by the SUPERCOIL and SCAN-2 codes. The flange zones under the blanket and shield headings refer to the access region near the top of the machine through which blanket components are moved, which have different material fractions. The blanket and shield zones themselves refer only to the "onion-skin" toroidal layers surrounding the plasma.

First Wall Volume 20.7 m^3.

	Fraction	Density (t/m^3)	Mass (t)
Structure (ferritic steel)	0.667	7.9	109
Multiplier (lead)	0.176	9.4	34
Coolant (water)	0.157	1.0	3

Blanket

Blanket zone Volume 398 m^3.

	Fraction	Density (t/m^3)	Mass (t)
Structure (ferritic steel)	0.117	7.9	366
Breeder (Lithium-lead)	0.487	9.4	1821
Coolant (water)	0.081	1.0	32
Void	0.315		

Flange zone Volume 271 m^3.

	Fraction	Density (t/m^3)	Mass (t)
Structure (ferritic steel)	0.28	7.9	600
Breeder (Lithium-lead)	0.12	9.4	306
Coolant (water)	0.12	1.0	32
Void	0.48		

Shield

Shield zone Volume 766 m^3.

	Fraction	Density (t/m^3)	Mass (t)
Structure (austenitic steel)	0.79	7.9	4780
Coolant (Water)	0.21	1.0	161

Flange zone Volume 904 m^3.

	Fraction	Density (t/m^3)	Mass (t)
Structure (austenitic steel)	0.79	7.9	5640
Coolant (water)	0.21	1.0	190

Cryostat

	Fraction	Density (t/m^3)	Mass (t)
Austenitic steel structure	1.00	7.9	772

Toroidal Field Coil

	Mass (t)
Niobium-tin superconductor	44
Copper stabiliser	2420
Casing (austenitic steel)	1740
Support structure (austenitic steel)	2120

Poloidal Field Coil

	Mass (t)
Niobium Titanium superconductor	6
Copper stabiliser	333
Casing and support structure (austenitic steel)	310

Torus support structure

	Mass (t)
Austenitic steel structure	1350

Divertor   Volume 3.3 m^3.

	Fraction	Density (t/m^3)	Mass (t)
Structure (W-5Re)	0.71	19.3	44
Coolant (water)	0.29	1.0	1

Appendix III ARIES Systems Code applied to the Reference Reactor

The ARIES systems code [19] was used to model the Reference Reactor, to provide a further comparison of the results obtained in this study. This code is being used in the ARIES tokamak reactor study to choose parameters for the various designs proposed. It contains a greater level of detail than GENEROMAK, but is not as deep as SUPERCOIL. This comparison was not as rigorous as that between GENEROMAK and SUPERCOIL, and there remain differences in assumptions in plasma reactivity, auxiliary power requirements and blanket/shield thicknesses.

The aspect ratio and β-value were fixed in the code at the Reference Reactor values, and the toroidal field and plasma dimensions allowed to converge to the values required to give the specified net electrical power output.

Costs in the ARIES systems code are reported in 1988 $. These have been converted back to the GENEROMAK level of 1986 $ (using a factor of 0.947) and then to 1984 ECU for comparison with SCAN values. The cost basis of the ARIES code is rather different from that of GENEROMAK, because of different assumptions about indirect costs, contingency, interest etc., and changes in US tax laws in recent years. Indirect costs are generally lower than those used in GENEROMAK.

Table A-III 1 compares the input parameters used in and the output parameters obtained from the ARIES code with similar values from SUPERCOIL/SCAN. The major and minor radii predicted by the ARIES code are somewhat larger than the values obtained with SUPERCOIL but, considering the differences in assumptions, the agreement is good.

Table AIII 1

ARIES SYSTEMS CODE CALCULATION OF THE REFERENCE REACTOR
(January 1984 price levels.)

Parameter	ARIES	SUPERCOIL
Null-point elongation	2.50	2.25
Aspect ratio	3.78	3.78
Troyon coefficient (% Tm/MA)	4.0	4.0
Total β value (%)	7.63	7.62
First wall/plasma radius	1.10	1.11
Average plasma temperature (keV)	20	20
Normalised current-drive efficiency (10^{20} $m^{-2}A/W$)	0.7	0.7
Wall plug efficiency (%)	70	70
Blanket thickness (in/out) (m)	0.55/0.85	0.55/0.85
Shield thickness (in/out) (m)	0.83/0.74	0.83/0.74
Thermal conversion efficiency (%)	40	40
Blanket energy multiplication	1.25	1.25
Base recirculating power fraction	0.15	0.114
Availability (%)	76	75
Plasma major radius (m)	5.46	5.31
Plasma minor radius (m)	1.44	1.40
Plasma current (MA)	17.0	16.6
Toroidal field on axis (T)	6.18	6.22
Peak field on TF coil (T)	14.6	14.9
Plasma density (10^{20} m^{-3})	1.62	1.45
Current-drive power (MW)	107	91
Mean neutron wall loading (MW/m^2)	3.95	4.15
Fusion power (MW)	3073	3050
Total thermal power (MW)	3830	3780
Recirculating power fraction	0.22	0.20
Net electrical power (MW)	1200	1200
Cost of electricity (cECU/kWh)	7.98	7.84

Available, price £10.00 from:

HMSO Publications Centre
(Mail and telephone orders only)

PO Box 276, London SW8 5DT
Telephone orders 01-873 9090
General enquiries 01-873 0011
Enquiries about previously placed orders 01-873 0022
(queuing system in operation for all numbers)

HMSO Bookshops
49 High Holborn, London WC1V 6HB 01-873 0011 *(Counter service only)*
258 Broad Street, Birmingham B1 2HE 021-643 3740
Southey House, 33 Wine Street, Bristol BS1 2BQ 0272-264306
9-21 Princess Street, Manchester M60 8AS 061-834 7201
80 Chichester Street, Belfast BT1 4JY 0232-238451
71 Lothian Road, Edinburgh EH3 9AZ 031-228 4181

HMSO's Accredited Agents

ISBN: 085311 1820
C.18