Cost Sensitivity Analysis of Possible Fusion Power Plants

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Abstract

A reference design was used in preparing a mathematical model of a fusion power plant with a tokamak reactor to investigate the extent to which the uncertainty still inherent in the physical reactor parameters affects the power costs. While only limited reductions of the power costs are achieved by improvements of the reference values for the reactor burn time, power density in the torus and load on the first wall, the power costs rise in keeping with the extent to which these parameters fall short of the reference values. As the results obtained in present-day experiments are still well below the reference values, a great deal of effort is still required in the fields of plasma physics and materials research to achieve an economically operating fusion power plant.

CONTENTS

1. Introduction

The present state of the art of fusion research allows us to draw a tentative picture of what fusion power plants will possibly look like by extrapolating from present experimental facilities. This, of course, is also necessary because the allocation of funds to cover the soaring costs in fusion research will only be justified if it can be shown that any fusion power plants resulting from these extrapolations are, in fact, also attractive for the energy market. Besides the provision of a practically unlimited supply of primary energy, it is primarily the reduced hazard potential relative to fission reactors that makes the fusion reactor a worthwhile proposition [1]. One of the most important requirements for subsequent marketing, however, is that the costs of the power produced in fusion power plants be in the region of the prevailing values. It is therefore necessary to obtain an idea of the anticipated costs as soon as possible and to keep it abreast of current developments in fusion physics and technology. With due allowance for the factor of uncertainty involved, these costs should be enlisted as criteria for comparing the various types of fusion reactors emerging from the lines of research now being pursued.

2. Uncertainty of cost calculations

A major difficulty is that the present state of the art does not allow us to obtain reliable values for the costs of energy produced with fusion power plants.

It should be recognized that neither the material and production costs of the components specific to fusion nor their maintenance and repair costs can at present be given with certainty. Therefore, all that can be done for the time being is to determine the probable costs of such a design according to the present state of the art and include safety margins, which may differ in size for the individual components. In this way it is possible to determine the element of uncertainty in calculating the specific plant costs.
In addition, there is a second source of uncertainty, namely the physical design parameters of the reactor. These are unreliable over sometimes very wide ranges because the behaviour of fusion plasmas is not yet understood theoretically and experimentally and a great deal of work is still needed before an experiment for thermonuclear fusion with positive energy balance can be achieved. For the reactor that may emerge from a certain line of research and development, e.g. a tokamak reactor, it is thus only possible to specify with any degree of certainty the components required for realizing the principle involved; for the design data, on the other hand, it is only possible to give values which are considered as probably attainable at a certain time in keeping with the state of the art, and to superpose fluctuation ranges on these values. This allows for the physical uncertainty.

The probable values and the superposed fluctuation ranges due to the calculation or physics are used to determine power costs which can then also be specified with a certain range of fluctuations about the probable value. This calls first of all for a self-consistent fusion power plant design on the basis of the probable parameters and for the appropriate power cost calculation. After estimating the respective margins of uncertainty of single parameters, it is then a question of establishing how these uncertainties affect the power costs. In this way it is possible, despite the complexity of a complete power plant, to obtain an overall, although rough, idea of the relative importance of individual variables. This knowledge is necessary when formulating a mathematical model of the power plant, in order to know relatively soon the components which have to be treated in particular detail. The reference design taken as starting point for this study is described in the following.

3. Reference design and cost calculation

A detailed analysis [2] of published cost calculations for tokamak power plant designs yielded the cost structures shown in Fig. 1 for the designs of the University of Wisconsin, Madison, U.S.A. (UWMAK-I) [3] and Princeton Plasma Physics Laboratory, U.S.A. (PPPL) [4] and the study of Brookhaven National Laboratory, U.S.A. (BNL) [5]. Of these it is the UWMAK-I design that is chosen as reference case because its cost structure comes very close to the "mean" structure according to [2] (Fig. 1, right-hand column) and the corresponding cost calculation is largely complete and detailed and was made with considerable caution. This design can therefore be regarded as representative of the physical and calculative parameters which were considered to be probably attainable when it was performed (1972 - 74). There are, admittedly, more recent designs (e.g. UWMAK-II [6], UWMAK-III [7] and Fintor [8]) but these are less suited as reference cases because they have not been worked out or published in such detail.

Figure 2 shows the heat flow diagram of the plant. The mean thermal power of the reactor is 4,617 MW_{th}; it is cooled with lithium (12 parallel cooling cycles), the pressure of the Li being about 2.8 bar and a maximum coolant temperature of 489 °C being attained. When heat is transferred to an intermediate Na cycle the Li is cooled to 359 °C, while the Na is heated from 336 °C to 456 °C (pressure about 2.4 bar). The main purpose of the intermediate Na cycle is to impede the passage of tritium from the lithium cooling cycle to the subsequent steam turbine process; the Na cycle is therefore provided with a cleaning system for T_2 and H_2. A second function of the Na cycle is to bridge the idle time of the reactor between successive burns by means of a Na storage system so that a constant thermal power is transferred within the steam generator at the rated load. The steam turbine process has live steam data of 138 bar/404 °C, and at 15 bar there is a water separation followed by internal superheating by live steam. The exhaust steam pressure is 0.12 bar, and wet cooling towers with ventilators are used. Of the six feed water heaters (preheating to 281° C) the bottom low-pressure preheater is heated with the heat from the cooling of the divertor (system for extracting burn-up and impurities from the reactor). The power plant is equipped with two identical steam turbine units with 841 MW_e gross each. Each of them is connected to the reactor by 6 cooling and intermediate cooling cycles. The gross efficiency of the system is 36.4 %, this being mainly due to the modest live steam data. With allowance for the requirements of the power plant, this yields a net electric power of 1,473 MW_e and a net electrical efficiency of 31.9 %.

The various operation phases of the reactor are shown in Fig. 3, in which the mean output power and energy of the reactor are represented schematically versus time. The total (electric) heating energy transferred to the reactor during the heating time t_h is E_h, which then reappears as part of the energy output of the reactor (in the form of thermal energy). During the burn time t_b the total energy output is E_f, the mean power being P_{th}. After extinction of the fusion reactions - due either to the limitation of the flux swing of the transformer (in UWMAK-I) or possibly to excessive accumulation of burn-up (α particles) and impurities in the plasma - the reaction chamber has to be evacuated in the time t_{id} (idle time) and possibly flushed before a new cycle commences with heating of the newly added fuel. The power averaged over the total cycle time ($t_h + t_b + t_{id}$) is $\overline{P_{th}}$. For the reference case considered here the design values are $\overline{P_{th,N}}$ = 4,617 MW_{th} and $P_{th,N}$ = 4,990 MW_{th} (subscript N denotes nominal load conditions). The power surplus during the burn time is stored in the form of hot sodium in the manner already mentioned (see description of Fig. 2) and then used for bridging the idle time and part of the heating time. The cost calculation for this design is based on a scheme [9], devised by USAEC/USERDA* for calculating nuclear power plants, whose subdivision of the nuclear section was adapted to the structure of the fusion reactor [3]. The initial data for the calculation were obtained from [10]. Table 1 (I) presents the absolute installation costs, the specific investment costs (in relation to the net power) and the power production costs in both absolute and relative figures. The numerical values for the absolute installation costs (cash costs) were taken straight from [3], while the additional costs incurred during the construction phase and the operational costs were determined in the manner modified relative to [3] that is described in [11]. The cash costs of 1.22×10^9 $($ value approximately at end of 1974) correspond to specific investment costs (including additional costs during the construction phase) of 1,116 $/kWe and power costs of 23.32 mills/kWh. These values may be regarded as probable values (in accordance with Sec. 2); for the physical parameters this refers to the knowledge available in 1972, for the cost calculation to that available at the end of 1974.

4. Uncertainty of the reference cost calculation

This uncertainty was determined by analyzing the cost calculation for the individual components, which is described in more detail in [3]. It was found that a large part of the materials and production techniques that would be needed

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* USAEC ≙ United States Atomic Energy Commission
USERDA ≙ United States Energy Research and Development Administration

to accomplish this design are of quite a conventional nature. The calculations based on conventional technology may be assumed to be reliable, especially since they were made in collaboration with or completely by the manufacturing industry. With regard to the specific fusion components, however, calculations are sometimes highly unreliable. The degree of uncertainty may thereby differ, depending on whether such a component consists of mainly conventional elements or whether it requires completely new materials and production techniques. In the component cost analysis the detailed costs stated in [3] therefore include different deviations (mostly up). On the basis of [12], for example, it was assumed that the costs for superconductors in the toroidal magnets might be a factor of 5 higher. For the complete magnet system (including cooling) this incurs additional costs of slightly over 42 %, which, however, would lead to a power cost increase of only 6 % since, according to Fig. 1, the magnet costs are represented in the power costs by a factor of only 0.14. The uncertainties estimated for the individual components are listed in Table 1 (II). They are based on the following assumption: 10 % increase of costs for shielding despite the fact that materials familiar in nuclear engineering are used, this being due to design complications resulting from ducts, 20 % increase in the cost of the blanket since not only have the same design problems to be solved but also because there is still a lack of practical experience in handling large quantities of liquid lithium; double costs for neutral injectors since hardly any relevant production experience is available; fivefold costs for all components of the tritium cycle, threefold for handling replaced activated components and double costs for maintenance of the reactor, electric power supply of the coils for the heating transformer and divertor, for hoisting equipment in the power plant and for the initial lithium filling. Cost reductions might be achieved at most where the costs from [10] initially taken as a basis had already been increased 1.5 to 2 times for the "probable" cost calculation (see Table 1 (II)).

The overall result is that because of these margins of uncertainty the investment costs might be up to approx. 23 % higher but hardly lower, which is also approximately true of the power costs. The cost structure, i.e. the percentage costs for individual components, is thereby not altered significantly in the sense that fusion specific components assume greater importance. This, of course, only affords a measure of the uncertainty of the cost calculation made for the physical parameters on which the design is based. The manner in which and the extent to which deviations of these physical parameters would act on the costs are shown in the following sections.

5. Influence of the uncertainty of physical parameters on costs

The costs of a power plant component are mainly governed by the power and the power density as well as the types of materials needed for the various functions involved together with the necessary production outlay; in the case of energy storing components the amount of energy that has to be stored also plays a role. In the following estimates it is assumed that the types of materials and the production costs per unit quantity of material remain unchanged. In addition, the net electric power of the power plant should not be changed relative to the reference design. Under these conditions the essential parameters governing the investment costs that remain are the respective powers for which the individual components have to be designed and the specific costs (in relation to these powers). In estimating the influence of variations of physical parameters a distinction is therefore made between those parameters affecting the absolute magnitude of a component power, the specific costs thereby remaining constant, and those parameters that modify the specific costs of a component at constant power.

5.1 Cost factors governing the component powers

Table 1 (III) states which of the components are essentially influenced by which of the powers occurring in the power plant. Item 20 (land and land rights) and item 21 (structures and site facilities) may be regarded as predominantly dependent on the net electric power of the power plant; this also applies to item 25 (miscellaneous plant equipment), to item 91 (construction facilities, equipment, services), to item 92 (engineering services) and to item 93 (other costs). The costs of the turbine plant equipment (item 23) are proportional to the gross power of the power plant, while in the case of electric plant equipment (item 24) this only applies to about half the costs; the other half is proportional to the thermal reactor power P_{th} averaged over the burn time (see Fig. 3). Also proportional to this power are the costs for special materials (item 26) and those for the complete reactor plant equipment (item 22) except for the costs for the main heat transfer and transport equipment (item 222), which are mainly governed by the thermal power $\overline{P_{th}}$ averaged over one cycle (see Fig. 3).

As the net electric power $P_{e,N}$ of the power plant should be constant, the gross electric power $P_{e,b}$ will only be subject to change when the electric power requirements of the power plant vary.

As the mean thermal power $\overline{P_{th}}$ of the reactor is coupled with the gross electric power through the gross efficiency of the thermal energy system, $\overline{P_{th}}$ can only change via the power requirements of the auxiliary systems and the gross efficiency. The mean power of the reactor P_{th} required during the burn time to attain a certain value of $\overline{P_{th}}$ depends not only on the magnitude of $\overline{P_{th}}$ but also, as can be seen from Fig. 3, on the heating and burn times and on the idle time. As the power requirements of conventional auxiliary systems for power plants are essentially fixed and the mean power requirements for plasma heating may be regarded as approximately proportional to the mean power P_{th} during the burn time*, the only essential parameters still to be con-

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* It is thereby assumed that the thermal power P_{th} is proportional to the plasma volume, i.e. the plasma state and heating methods are not changed.

sidered are the heating, burn and idle times and the gross efficiency of the thermal energy conversion.

In the reference design a value of $t_b = t_{b,N} = 5400$ s is assumed for the burn time. More recent work on the behaviour of α particles and impurities in plasmas indicate, however, that the attainable burn times may be up to two orders of magnitude lower. If in reducing the burn time it is assumed first that the heating and idle times of the reactor are constant, the thermal power P_{th} during the burn time and, owing to the higher energy required for heating, also the mean thermal power $\overline{P_{th}}$ have to increase, as shown in Fig. 4. Details of the calculations made in this respect are described in [11]. The effects of these power increases, and hence shortening of the burn time, on the power costs can be calculated from Fig. 4 with the data in Table 1. A reduction of the burn time to $t_b = 540$ s, for example, leads to a power cost increase of 18 %, whereas a reduction to $t_b = 54$ s already results in quadrupling of the power costs relative to the design value.

A reduction of the thermal power P_{th} during the burn time could be achieved by shortening the heating and idle times (reference design $t_{h,N} = 110$ s, $t_{id,N} = 280$ s). The influence of the idle time on the thermal power during the burn time, with constant heating time and different values for the burn time t_b, is shown in Fig. 5. The shorter the burn time the more effective is the reduction of the idle time. For example, the thermal power P_{th} required for half the idle time (relative to the reference value) drops to 85 %

of the reference value $P_{th,N}$ for t_b = 540 s and to slightly less than 70 % for t_b = 54 s. A reduction of the idle time to 20 % of the reference value would reduce this thermal power to ≈ 75 % (t_b = 540 s) or 50 % (t_b = 54 s). This reduction of the thermal power curtails costs via the size of the reactor: The stated quadrupling of the power costs by shortening the burn time from 5400 s to 54 s could be reduced to only tripling the costs by decreasing the idle time from 280 s to 140 s. Whether further shortening of the idle time, e.g. to times shorter than the heating time, leads to a further decrease in costs is open to question since the flux reversal of the transformer then has to happen more quickly, this being accompanied by an increase in costs owing to the higher power. Furthermore, it was not taken into account that shortening the idle time leads to higher construction costs for the vacuum pump system of the reaction chamber; since, however, the thermal energy storage system for bridging the idle time may also be smaller with decreasing idle time, it could be assumed that these two cost factors approximately compensate one another. A reduction of the heating time, which was not further considered above, would tend to reduce the necessary thermal reactor power P_{th} but, on the other hand, leads to higher specific investment costs for the heating system since the same heating energy would have to be supplied in a shorter time.

It can be seen from this estimate that the power costs rise more sharply with the reduction of the burn time, and that the possibilities of reducing this rise are rather limited;

here the reduction of the idle time would presumable do more good than shortening the heating time if the idle time started by being much longer than the heating time. The possible prospect of extracting ash (α particles) and impurities from the plasma during the burning period with a divertor would also tend to extend the burn time, but it would also considerably complicate the reactor. As an optimum reactor design(including the decision on incorporating a divertor) can only be arrived at from the point of view of minimum power costs, it is necessary to interrelate and investigate the function and costs of all the components involved.

For the later design of the reactor it will be necessary to make allowance for the uncertainty concerning the burn time by choosing a correspondingly higher thermal power during the burn time in order to achieve guaranteed values for the power and availability of the power plant. Figure 6 shows the influence of the relative burn time on the load factor (definition according to VDEW [13]; base load operation being assumed). The load factor is largely insensitive to deviations of the burn time from the design value ($t_{b,N}$ = 5400 s). Halving the burn time at the same thermal power during this burn time would only lead to a reduction of the load factor by about 7 % (additive), based on the reference point for the reference design. Such a deviation is hardly to be expected, of course, since such a long burn time can only be achieved with a control system, with which it is then possible to suppress deviations. If, however, only short burn times are achieved for the design point as well, the influence of deviations is much stronger. In Fig. 6 the fact that the curves drop more steeply with decreasing burn time shows that the load factor reacts with increasing sensitivity to variations of the burn time when the burn time is made shorter. An estimate showed that halving a design burn time of 540 s already leads almost to a halving of the load factor. In this case the necessity of acutally attaining the guaranteed values for the net power and load factor would call for appreciable overdimensioning of the reactor, with correspondingly higher installation costs. In addition, Fig. 6 shows the connection between the annual outage times of the power plant and the load factor; this will be dealt with in the next section.

In Figs. 4 and 5 it had been found that a sharp reduction of the burn time despite certain improvements in the idle time would presumably lead to an increase in the power costs relative to the reference design. This therefore raises the question whether improvements might not be possible in the conventional area of the power plant, e.g. in the gross efficiency of the energy conversion system (see Fig. 1). The simplest possibility would be to raise the live steam pressure at constant live steam temperature and carry out a second internal intermediate overheating of the steam. It is also conceivable to raise the live steam temperature by reducing the temperature differences (Li/Na) of the intermediate heat exchanger and of the steam generator so that direct intermediate superheating with sodium is possible while raising the live steam pressure at the same time. It should also be investigated whether the intermediate sodium cycle is actually required as a tritium barrier, or whether there are other possibilities of reducing the tritium permeation which are not accompanied by temperature loss, e.g. the formation of oxide layers on steam generator materials, by which the T permeation could be reduced by several orders of magnitude [14]. An improvement of the gross efficiency can also be achieved by raising the upper coolant temperature in the blanket, which, of course would lead to major changes in the blanket structure owing to the higher stress then exerted on the materials and the enhanced tritium permeation; with helium as coolant and with a maximum coolant temperature of about 600 ^{o}C it might be possible (without a further intermediate cooling cycle) to connect a high-grade steam turbine process; a helium temperature of > 750 ^{o}C would allow the use of a helium turbine cycle, which according to recent proposals [15] could be coupled in the low-temperature regime with a NH_3 steam turbine cycle. On the whole, it seems quite possible to improve the efficiency of the energy conversion system from the reference value of 36.4 % to something over 40 %, which, of course, would involve an increase in construction costs. The extent to which this is justified in relation to the power cost minimum can only be determined by considering this jointly with the time behaviour of the reactor operation already treated. The optimum design of the power plant may therefore appreciably differ from the reference design owing to the reduction of the burn time and may also have a correspondingly different cost structure.

This takes care of the essential physical parameters which influence the power costs primarily via the power values of the individual components. The following section deals with those quantities which affect the power costs primarily via the power density of the components, and hence via the specific component costs.

5.2 Factors governing costs via the specific component costs

As regards specific costs, the reactor itself involves the greatest uncertainty since it is still not clear what power density will be achieved in the plasma. It should therefore be estimated, again on the basis of the reference design described in Section 3, how strong the influence of this power density is on the specific reactor costs and hence on the power costs.

A measure of the power density in the toroidal reaction chamber is the quantity ß, i.e. the ratio of the pressure in the plasma to the pressure of the confining magnetic field. The solid lines in Fig. 7 show the connection between ß and the plasma volume V_p required to yield a constant thermal power (averaged over the burn time), in relation to the plasma volume $V_{P,N}$ of the reference design of various values of the maximum magnetic induction B_{max}. The dashed lines give the respective profiles of the fictitious wall load q, i.e. the thermal reactor power per unit surface area of the first wall; this wall load is also referred to the design value q_N of the reference design. Increasing ß for a given thermal power reduces the necessary plasma volume, but increases the wall load. When the plasma volume is reduced the volume of the blanket and the space that has to be filled with magnetic field also become smaller, thus reducing costs. Increasing the wall load while retaining the same wall properties leads to a shorter lifetime of the first wall and therefore calls for more frequent replacement with correspondingly high outlay and longer shutdown times or else a higher-grade material. Both alternatives involve increased costs, which are paralleled by reduced costs due to the smaller volume. The decrease of the plasma volume thus reduces costs, while the increase of the wall load leads to a rise in costs. The reduction of the magnetic field, starting from the reference value $B_{max,N} = 8$ T produces (see Fig. 7) for the same ß an increase of the necessary plasma volume and a corresponding decrease of the wall load. To determine whether for increased ß it is the cost reduction due to the decreasing plasma volume or the cost increase due to the higher wall load that is dominant, the effects of variations of ß on the costs of the essential reactor components are estimated.

These components are listed under item 22 (reactor plant equipment) in Table 1. The heat transfer costs are largely independent of the volume of the reactor. The notation explained in Fig. 8 was used to derive relations for calculating the costs of the other reactor components, in relation to the costs in the reference case (subscript "N").

This yielded for the magnets (item 221.1)

$$\frac{K_M}{K_{MN}} = \frac{r_p}{r_{pN}} \cdot \frac{(\varepsilon \cdot r_p + d_B + d_M)^2}{(\varepsilon \cdot r_{pN} + d_B + d_M)^2} \cdot \frac{B_{max}^2}{B_{max,N}^2} \qquad (1)$$

on the following assumptions: The costs are proportional to the stored magnetic energy, which, in turn, grows as the square of the maximum magnetic induction permitted in the conductor; the relations $A = R/r_p$ and $\varepsilon = r_w/r_p$ are constant, as also are the thickness d_B of the blanket and shielding and the thickness $2 \cdot d_M$ of the magnet. As only relative costs are considered, the shape of the coil is of no consequence as long as the relation of the horizontal and vertical half-axes does not vary.

The relative costs for the blanket and shielding (items 221.2 and 221.3, but without the first wall) are calculated with

$$\frac{K_B}{K_{BN}} = \frac{2 \cdot \varepsilon \cdot r_p^2 + d_B \ (2-\alpha) \cdot r_p}{2 \cdot \varepsilon \cdot r_{pN}^2 + d_B \ (2-\alpha) \cdot r_{pN}} \tag{2}$$

on the assumptions that the costs per unit volume of the blanket as well as the relations A, ε, α, and d_B are constant.

The first wall for the cost calculation is defined as the region of the blanket (with a thickness of $(1 - \alpha) \cdot d_B$; $\alpha = 0.75$) which, as a function of the wall load q, has a lifetime shorter than that of the power plant, and which thus has to be replaced at certain intervals. Characterizing the quality of the first wall by the product of the wall load and the lifetime t_W of the wall at this load,

$$D_L \ [\frac{MW}{m^2} \cdot a] = q \ [\frac{MW}{m^2}] \cdot t_w \ [a], \tag{3}$$

it is possible, depending on any change in the wall load, to determine the number of first walls required during the lifetime of the power plant. If it is assumed for simplicity that these walls are acquired at the time of the installation of the power plant, the relative costs of the sum of the first walls are

$$\frac{K_W}{K_{WN}} = \frac{D_{LN}}{D_L} \; \frac{1 + \left[\frac{(1-\alpha) \cdot d_B}{2 \cdot \varepsilon \cdot r_p}\right]}{1 + \left[\frac{(1-\alpha) \cdot d_B}{2 \cdot \varepsilon \cdot r_{pN}}\right]} , \qquad (4)$$

where it has also been assumed that the costs per unit volume of the first wall and the thickness of the first wall are constant. These costs should include the total extra costs incurred for wall replacement, a simplification which is only permissible as long as the lifetime of the first wall is not less than approximately six months.

The influence of the power density on the other components of the reactor (items 221.4-6 and 223 to 227), for want of more detailed data, is taken into account with the ansatz

$$\frac{K_{Re}}{K_{Re,N}} = \frac{r_p^3}{r_{pN}^3} , \qquad (5)$$

i.e. costs proportional to the plasma volume. By means of eqs. (1), (2), (4) and (5) and the values from Table 1 for K_{MN}, K_{BN}, K_{WN} and $K_{Re,N}$ it is then possible to calculate the dependence of the relative reactor costs K_R/K_{RN} on the plasma radius and hence on ß (see Fig. 7).

There it is assumed that the value of the maximum magnetic induction B_{max} for variable ß is kept constant, so that an increase of ß is accompanied by a decrease of the plasma volume and a corresponding increase of the wall load (at constant thermal power); cf. the lines for B_{max} = const in Fig. 7. Such an approach is possible because the size of the wall load does not constitute a constraint since the first wall can be replaced. The cost calculation makes allowance for the higher wall load by including the higher costs due to more frequent wall replacement. The difference between this approach and that in which the plasma volume, and hence the wall load, is kept constant, i.e. $\beta \cdot B_{max}{}^2$ = const, will be fully treated in a later publication.

In Fig. 9 the relative reactor costs K_R/K_{RN} are shown as a function of ß, where the data of the reference design ($\beta = \beta_N = 5.2$ %, $B_{max} = B_{max,N} = 8$ T and $D_L = D_{LN} = 2.5$ MWa/m^2) yield $K_R/K_{RN} = 1$. On the curves for which D_L is parameter the lifetimes of the first wall, which decrease with increasing wall load (see Fig. 7), are marked by points. For lifetimes below 1/2 a the validity of the curves is restricted according to the explanations for eq. (4). The cost curve for $D_L = D_{LN}$ is essentially only a slightly displaced image of the corresponding volume curve shown in Fig. 7. The reactor costs react with increasing sensitivity to a reduction of D_L, whereas any increase of D_L (at constant costs per unit volume of the first wall) results in hardly any saving. The foregoing initially applies just to the reactor costs. It is, however, also true of the power costs since more frequent replacement of the first wall also leads to longer shutdown times, and hence to smaller load factors in keeping with Fig. 6. If the power costs c for the work--independent part are roughly put at

$$c = \frac{K_A}{P_{e,N} \cdot t_{Betr}} \qquad (6)$$

(K_A = total investment costs for the power plant, $P_{e,N}$ = the net electric power of the power plant, t_{Betr} = number of operating hours per annum at the rated power), the power costs are

$$\frac{c}{c_N} = \frac{K_R + (K_{AN} - K_{RN})}{K_{AN}} \cdot \frac{8760 - t_{S,TN} - t_{1.W.} \cdot \frac{q_N}{D_{LN}}}{8760 - t_{S,TN} - t_{1.W.} \cdot \frac{q}{D_L}} \qquad (7)$$

(subscript "N" ≙ reference design; $t_{S,TN}$ = shutdown time per annum to allow for malfunctioning and operation at partial load, according to the reference design 672 h/a; $t_{1.W.}$ = shutdown time required for complete replacement of the first wall, according to the reference design 1344 h; q_N = 1.25 MW/m^2; D_{LN} = 2.5 MWa/m^2; cost data according to Table 1). The relative power costs according to eq. (7) are shown in Fig. 10. Compared with Fig. 9, it can be seen that the shutdown times necessary for replacing the wall have a strong influence. The effects of increasing the wall load, i.e. increasing ß, are more serious the smaller the values D_L (maximum integral wall load). On the other hand, increasing D_L even to values of over 40 MWa/m^2 hardly results in any appreciable reduction in costs (it being assumed that the costs per unit volume of the first wall are constant in spite of this increase). It can be seen that it is scarcely worthwhile to try for D_L values of > 10 MWa/m^2 if there are no other arguments for longer lifetimes of the first wall, such as, for example, a reduction of the integral radiation hazard to the personnel concerned with replacing the wall or limitation of the quantities of activated wall material replaced. From the economic viewpoint alone, it might even be sufficient to attain the value of D_L = 2.5 MWa/m^2 used in the reference design. Lower values, however, appreciably raise the power costs. In addition, Fig. 10 shows that failure to reach the reference value of β_N = 5.2 % also leads to considerably higher power costs; if only 2.6 % is obtained (for D_L = 2.5 MWa/m^2), the power costs rise to 1.35 times, and if only β = 1.3 % is achieved, the power costs are a factor of 2.3 as high as in the reference case. It is obvious that with such a small β value the reactor costs constitute a very large share of the power cost structure and hence become much more sensitive to, for example, variations such as discussed in Sections 4 and 5.1. It is also obvious from Fig. 10 that any increase of β beyond the reference value can only provide a limited reduction of the power costs. For D_L = 2.5 MWa/m^2 the reduction in costs obtained by doubling β to 10.4 % - this is just about the cost minimum - is almost infinitesimally small, very much smaller than, for example, the calculation uncertainty of 23 %. It is thus hardly worthwhile aiming at β values of over approx. 5 % if the D_L values are not higher than 2.5 MWa/m^2; and even if these values were higher, it seems desirable from the viewpoint of cost to aim at β values up to the region of at most 10 - 12 %*. In the limiting case

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* This is also mentioned in [16].

of equally long lifetimes of the first wall and reactor the relative reactor costs would be a somewhat distorted representation of the volume curve in Fig. 7 (e.g. for B_{max} = 8 T), which becomes increasingly flatter with rising ß. The reduction of the reactor costs has less effect on the power costs the smaller the contribution of the reactor costs to the total installation costs.

The foregoing points are still valid if any decrease in the maximum magnetic induction B_{max} is taken into account. Equation (1) shows that the magnet costs vary in proportion with B_{max}^2, so this decrease might be very effective. On the other hand, it can be seen from eq. (1) that the magnet costs rise more strongly than the cube of the plasma radius and hence more strongly than with the plasma volume. From Fig. 7 it can be seen that the decrease of B_{max} leads to an increase of the plasma volume which is the greater the smaller ß is. The resulting variations of the reactor costs are plotted in Fig. 11 versus ß, where it is seen that these costs rise more strongly at lower ß as B_{max} is reduced. Figure 12 shows the power cost variations that result when the maximum integral wall load D_L is varied as in Fig. 10, but in this case for B_{max} = 6 T. It can be seen that the shapes of the curves are similar to those for B_{max} = 8 T. It continues to remain true that ß values below the reference value of 5.2 % cause drastic increases in costs, but that ß values of over 10 - 12 % have in this case only a weak cost reducing effect.

Figure 13 shows a comparison of the results obtained here with those of other authors. For this purpose the relative costs for β_N = 5.2 % from Fig. 10 are plotted against the integral wall load. A reference curve was obtained from [17] by conversion, and a reference point from [18]; both of these studies deal in detail with the influence of the wall load on the power costs and arrive at basically the same results. The numerical deviations of max. 5 % obtained from Fig. 13 have to be assessed in comparison with the rest of the uncertainties (e.g. in calculation).

6. Summary and conclusions

This study has shown that failure to reach the values assumed in the reference design for the burn time of the reactor, for the power density in the reaction chamber and for the load on the first wall may involve drastic increases in the calculated power costs. As the burn time of the reactor affects the power costs via the absolute magnitude of the thermal reactor power to be installed, whereas the power density acts via the specific installation costs of the reactor, the two influences are supplementary. A reduction of the burn time is stronger in its effect the lower the power density of the reactor; conversely, the costs are more sensitive to variations of the power density the shorter the burn time, since reduction of one parameter at a time is alone sufficient to change the power cost structure to such an extent that the reactor costs assume greater weight. It might be possible to reduce the sensitivity by shortening the idle time and possibly the heating time as well or to improve the energy conversion efficiency; both of these procedures, of course, entail major construction outlay.

The parameters treated here should be accorded special emphasis in further fusion work. This has in fact been done more or less in previous development work with the exception of that on the permissible fictitious wall load. It is, however, also indispensable that the material problem of the first wall be tackled with greater effort since a physically possible high power density can only be utilized technically and economically when sufficiently high values are also permissible for the wall load, with sufficiently long lifetimes of the wall material. As material tests are known to be very time-consuming, a start has to be made as soon as possible on the task of testing materials under realistic radiation load conditions.

Under the conditions on which this study is based it has also been shown, however, that from the economic point of view alone it is not absolutely necessary to considerably exceed values of $\beta \approx 10 - 12$ % since the economic gain decreases with increasing β. In the same way it can be said of the maximum integral wall load that from the economic point of view alone it is true that values of $D_L > 2.5$ MWa/m^2 are desirable, but the economic gain decreases with increasing D_L. In keeping with the present state of the art, which still yields values of $\beta < 1$ % and does not yet afford any data on the lifetimes of wall materials under fusion reactor conditions, attaining the above values alone still calls for an immense amount of effort.

The results of this study are subject to the restriction, not with respect to the trends indicated, but with respect to the numerical values stated, since they are based on relatively simple estimates and only roughly take into account the inter-relations of all parameters. More reliable data will not be possible until the highly intricate internal couplings of all power plant components have been treated in a computer model so that the influence of parameter variations on the power costs can be traced.

The author is indebted to K. Borrass, W. Dänner and M. Söll for valuable suggestions and also to H. Herold, G. Müller and J. Raeder for most stimulating discussions as well, and to H. Gorenflo for performing the calculations.

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Table 1 Cost structure of the UWMAK-I fusion power plant design

Account No. and Title	I: Inst. Costs (abs.) 10^3 \$	I: Inst. Costs (abs.) %	I: Spec. Investment costs %	I: Spec. Investment costs \$/kW$_{(P_{e,N})}$	I: Power Production costs mills/kWh	I: Power Production costs %	II: max.	II: min.	III: $f(P_{e,N})$	III: $f(P_{e,b})$	III: $f(\overline{P_{th}})$	III: $f(P_{th})$
20 Land and Land Rights	1200	0,10	0,07	1,10	0,02	0,04	1200		X			
21 Structures and Site Fac.	139807	11,51	8,50	128,40	2,40	10,29	139 807		X			
22 Reactor Plant Equipmt.	(573636)	(47,21)	(34,89)	(526,86)	(9,85)	(42,24)						
221 Nuclear Island	(313043)	(25,76)	(19,04)	(287,52)	(5,37)	(23,01)						
221.1 Magnets	189900	15,63	11,55	174,42	3,26	13,98	267900	189900				X
.2 Shield	41333	3,4	2,51	37,96	0,71	3,04	45466	41333				X
.3 Blanket	74160	6,1	4,51	68,11	1,27	5,45	81576	74160				X
.4 Neutral Beam Injectors	6000	0,5	0,37	5,51	0,10	0,43	12000	6000				X
.5 Equipment Found.	250	0,02	0,01	0,23	0,004	0,02	250					X
.6 Reactor Seals	1400	0,12	0,09	1,29	0,02	0,09	1400					X
222 Heat Transf.Equip.	214885	17,68	13,07	197,36	3,69	15,82	217885	214885			X	
223 Aux.Heating Syst.	10442	0,86	0,64	9,59	0,18	0,77	13082	10442				X
224 Rad. Waste Treatment & Disp.	330	0,03	0,02	0,30	0,01	0,04	990	330				X
225 Fuel System	1870	0,15	0,11	1,72	0,03	0,13	2110	1870				X
226 Other Plant Equip.	21366	1,76	1,30	19,62	0,37	1,59	30718	21366				X
227 Instruments & Contr.	11700	0,96	0,71	10,75	0,20	0,86	11700	5850				X
23 Turbine Plant Equipment	170580	14,04	10,38	156,67	2,93	12,57	170 580			X		
24 Electric Plant Equipmt.	142859	11,76	8,68	131,22	2,45	10,51	208195	142859		≈50 %		≈50 %
25 Miscell. Plant Equipmt.	9410	0,77	0,57	8,65	0,16	0,69	10935	7356	X			
26 Special Materials	28290	2,33	1,72	25,99	0,49	2,10	45290	28290				X
91 Constr. Fac., Equipmt., Services	24300	2,00	1,48	22,32	0,42	1,80	48600	16200	X			
92 Engineering Services	48500	3,99	2,95	44,55	0,83	3,56	93450	28480	X			
93 Other Costs	76600	6,30	4,66	70,35	1,32	5,66	86600	76600	X			
Total	1215182	100	73,92				1489698	1178158				
Additional costs during Construction	428834	35,29	26,08				525714	416124				
TOTAL INVESTMENT COSTS	1644016	135,29	100	1116,11	20,87	89,5	2015412	1595283				
TOTAL OPERATIONAL COSTS					2,45	10,50						
POWER PRODUCTION COSTS					23,32	100,00						
UNCERTAINTY							+ 22,6%	- 3 %				

$P_{e,N}$ = net electric output of the power plant

$P_{e,b}$ = gross electric output of turbine set

$\overline{P_{th}}$ = thermal reactor output power averaged over one cycle

P_{th} = thermal reactor output power averaged over the burn time

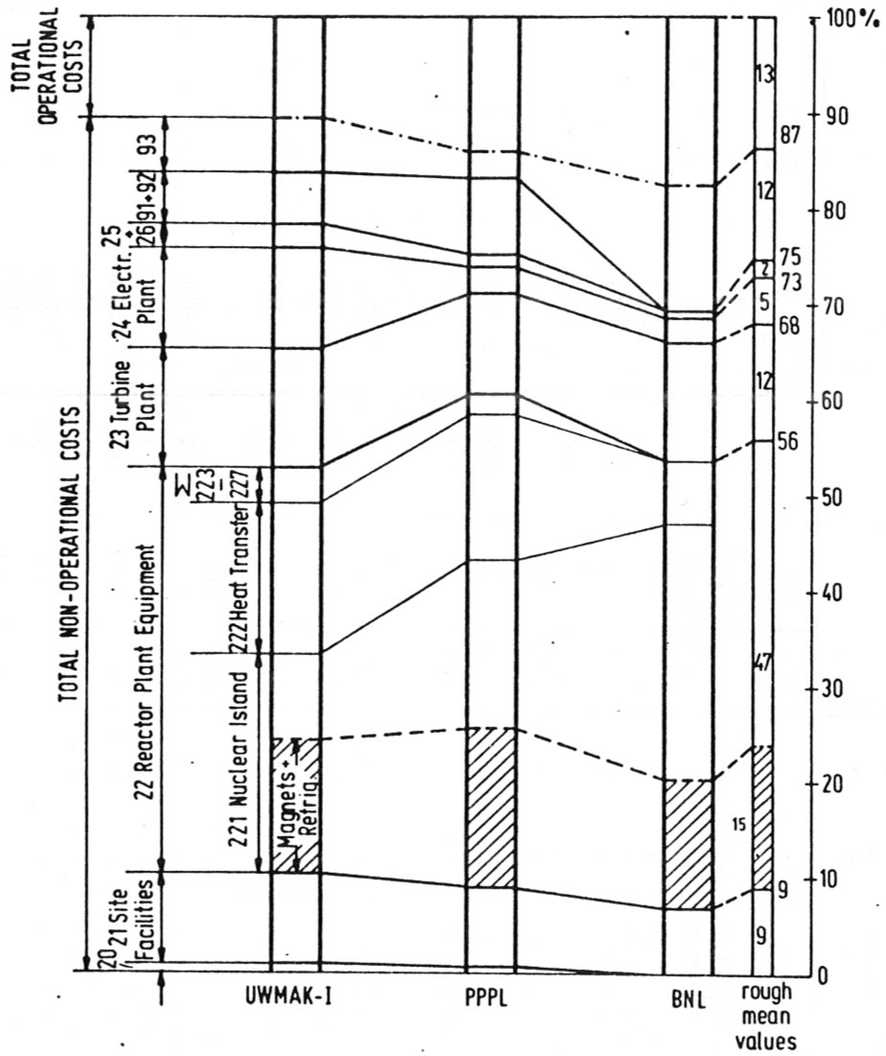

Fig. 1 Percentage division of power production costs (data according to [2]; the missing item names are given in Table 1)

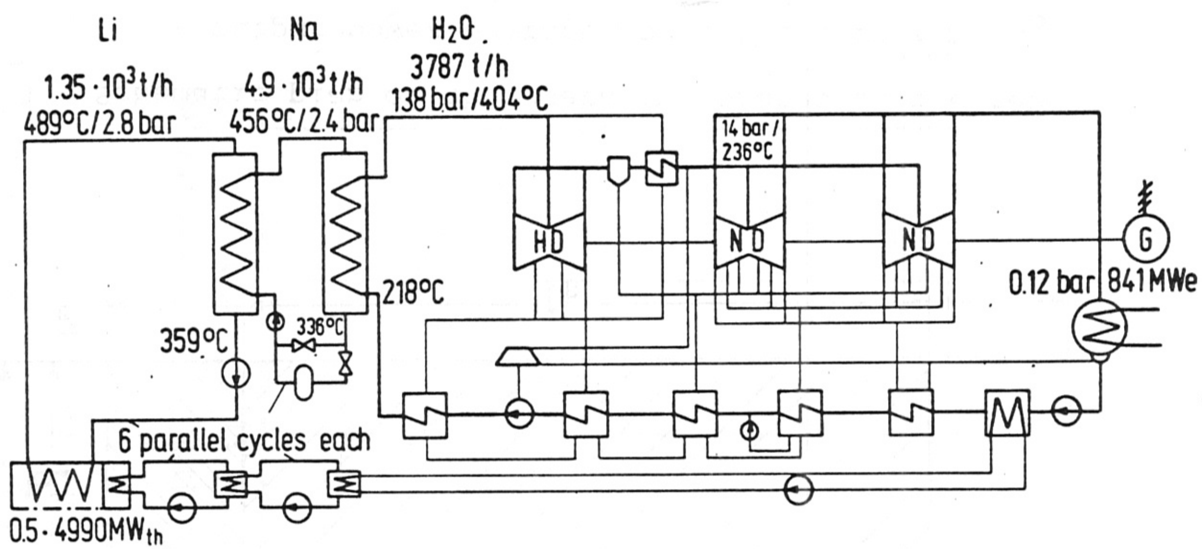

Fig. 2 UWMAK-I heat flow diagram (according to [3])
(two identical turbine sets)

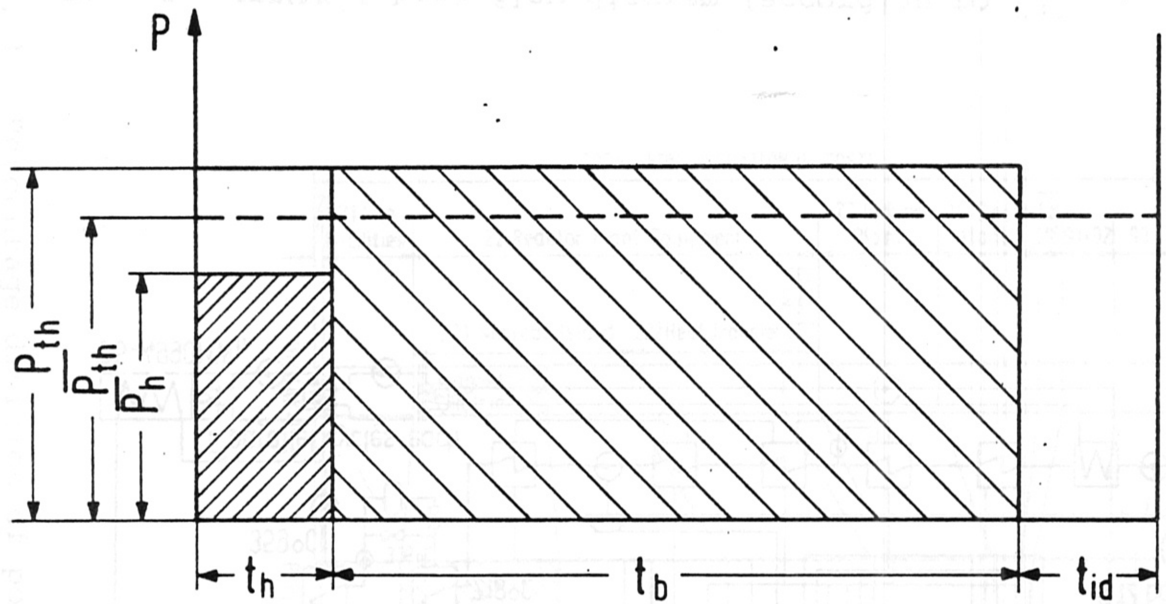

Fig. 3 Schematic plan of the operation phases of the reactor

P_{th} = output power averaged over the burn time t_b

$\overline{P_{th}}$ = output power averaged over the cycle time ($t_h + t_b + t_{id}$)

$\overline{P_h}$ = heating power averaged over the heating time t_h

t_{id} = idle time

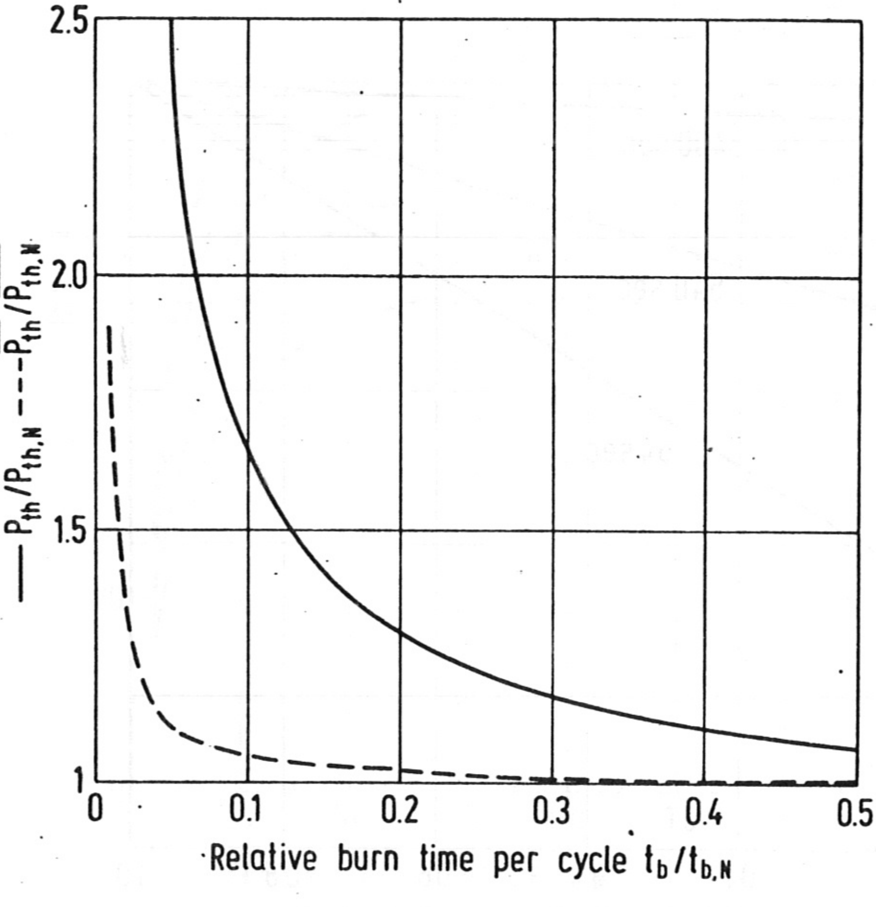

Fig. 4 Influence of the relative burn time per cycle on the thermal power during the burn time and on the mean thermal power of the reactor at constant net electric power of the power plant

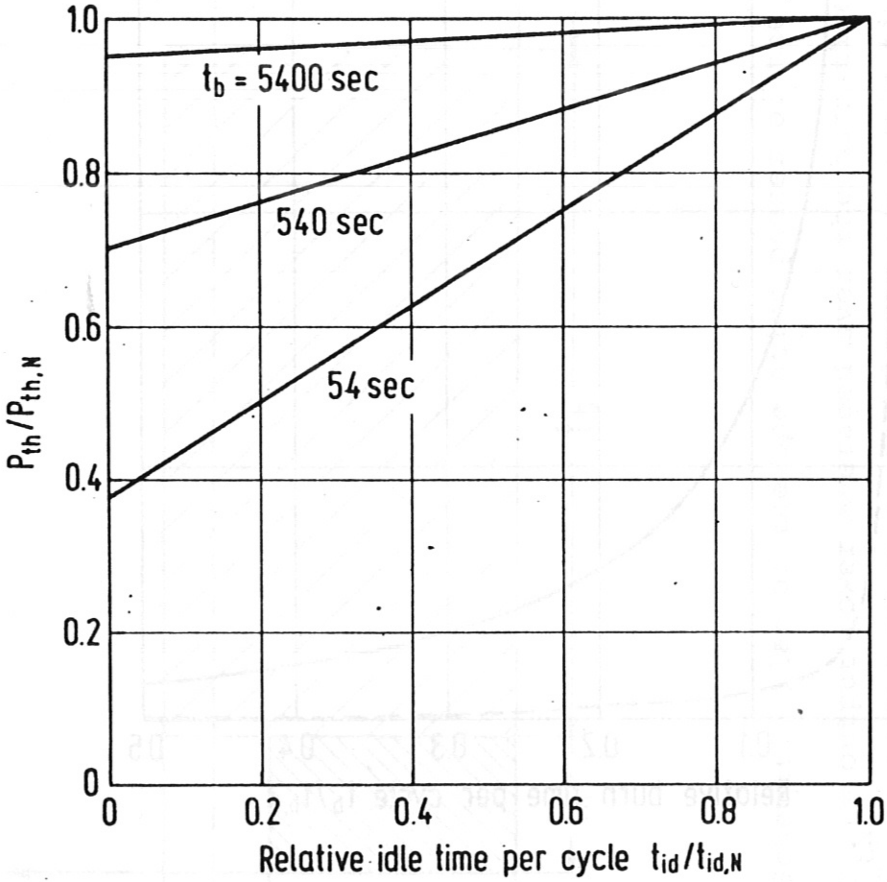

Fig. 5 Influence of the relative idle time per cycle on the required thermal reactor power during the burn time at constant mean thermal reactor power $\overline{P_{th}}$

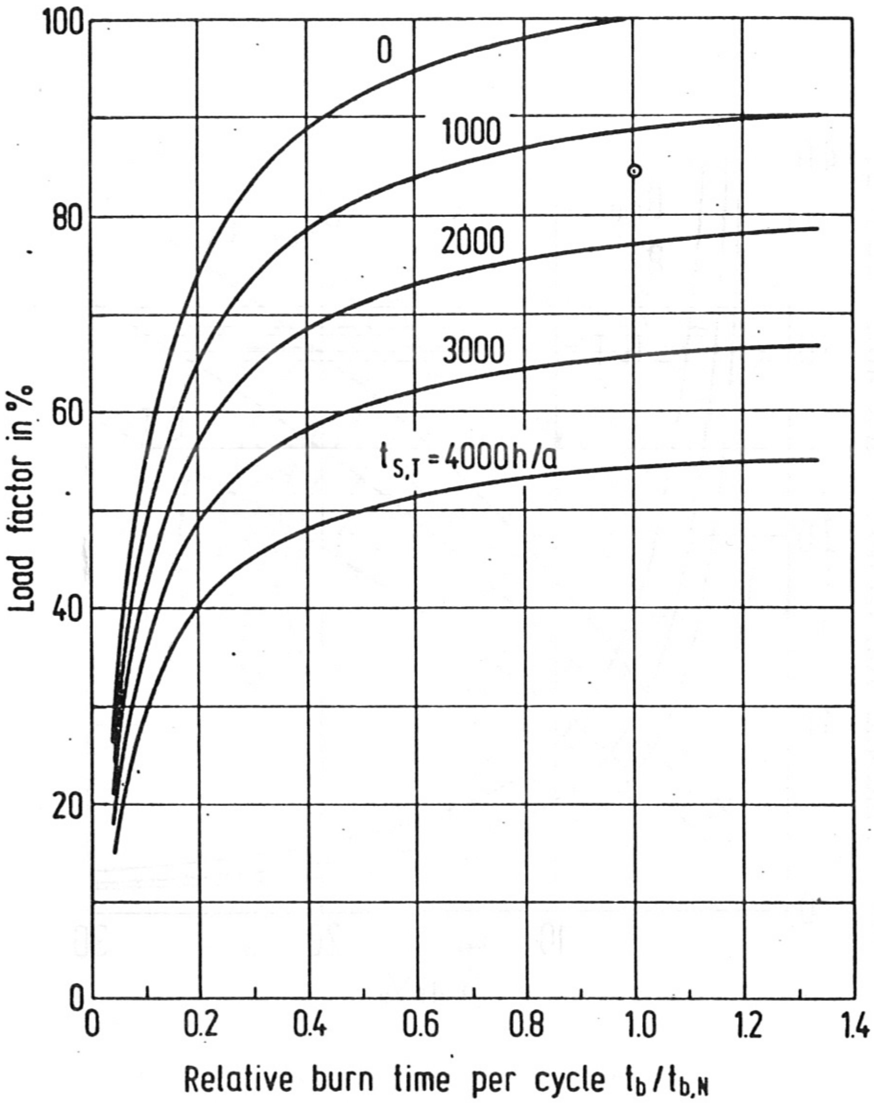

Fig. 6 Load factor versus the relative burn time per cycle for various annual shutdown times $t_{S,T}$, $t_{S,TN}$ = 1344 h/a

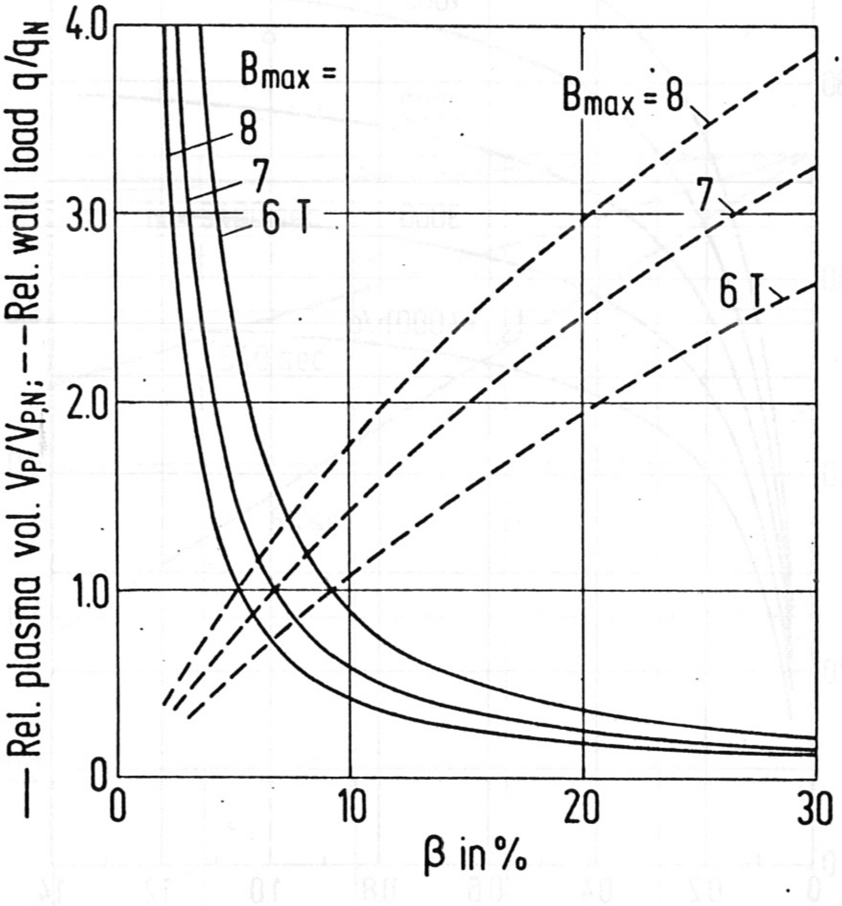

Fig. 7 Relative plasma volume and relative wall load versus β for various values of B_{max}

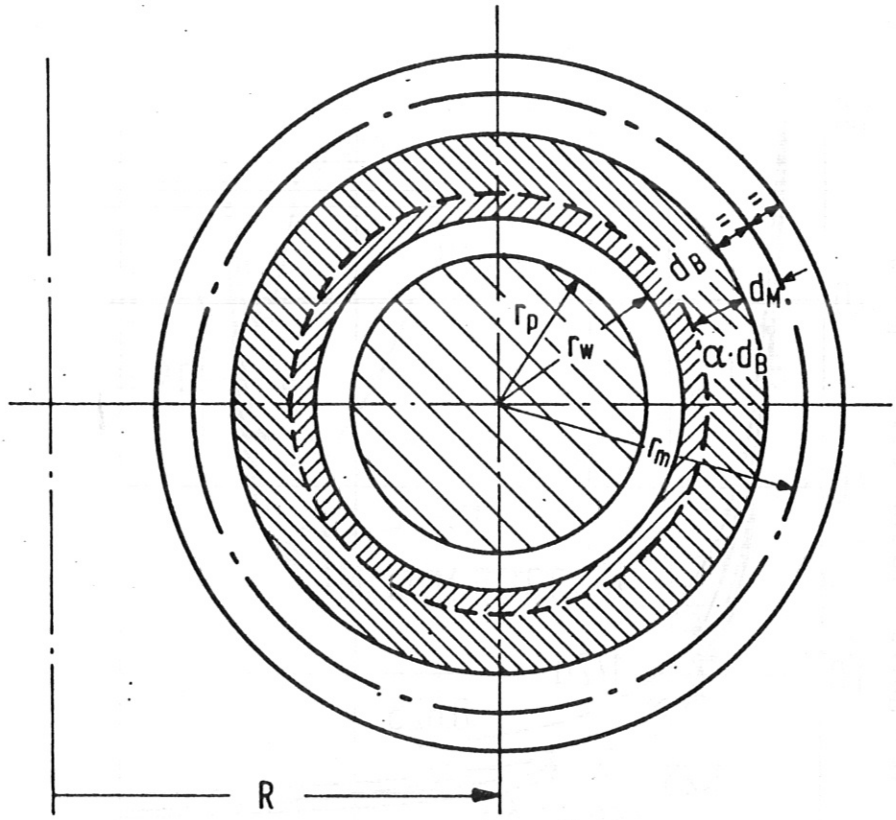

Fig. 8 Schematic of the toroidal configuration

R = major torus radius

r_p = plasma radius

r_w = wall radius; $r_w = \varepsilon \cdot r_p$

d_B = thickness of the 1st wall, blanket and shielding

$(1-\alpha)$ = contribution of 1st wall to d_B

d_M = half-thickness of the magnet

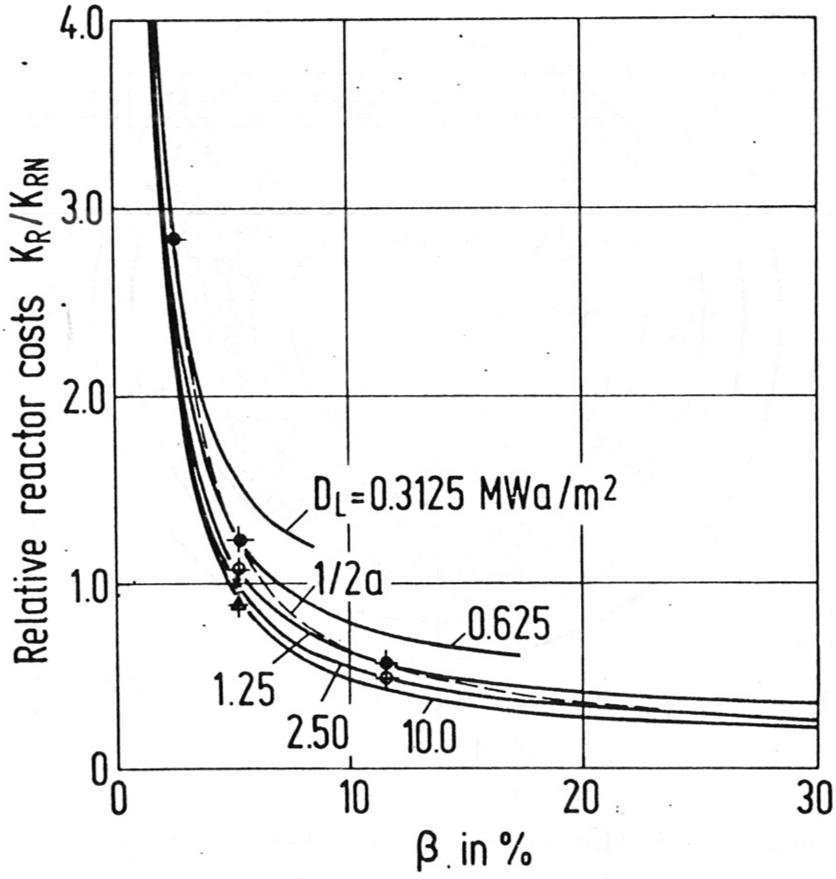

Fig. 9 Relative reactor costs versus ß for various values of the maximum integral wall load D_L

(B_{max} = 8 T, α = 0.75; minimum of a curve ≙ optimum wall load)

Lifetime of the 1st wall ◆ 1/2 a

⊕ 1 a

* 2 a (reference design)

Δ 8 a

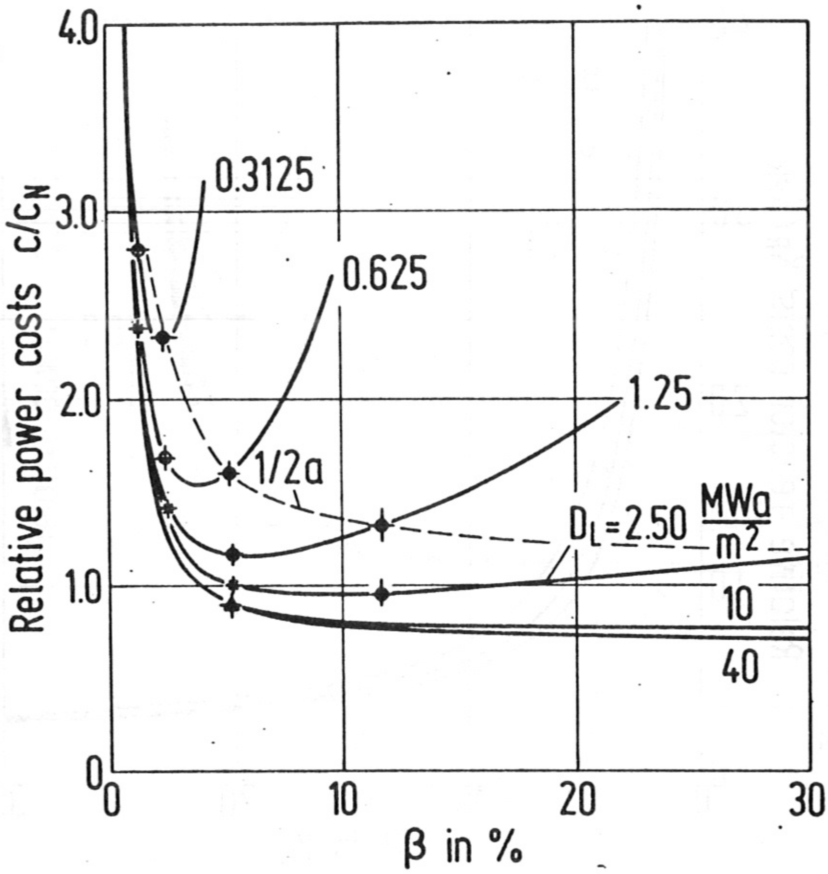

Fig. 10 Relative power costs versus ß for various values of the maximum integral wall load D_L

(B_{max} = 8 T, α = 0.75; minimum of a curve ≙ optimum wall load)

Lifetime of the 1st wall ✦ 1/2 a

⊕ 1 a

* 2 a (reference design)

Δ 8 a

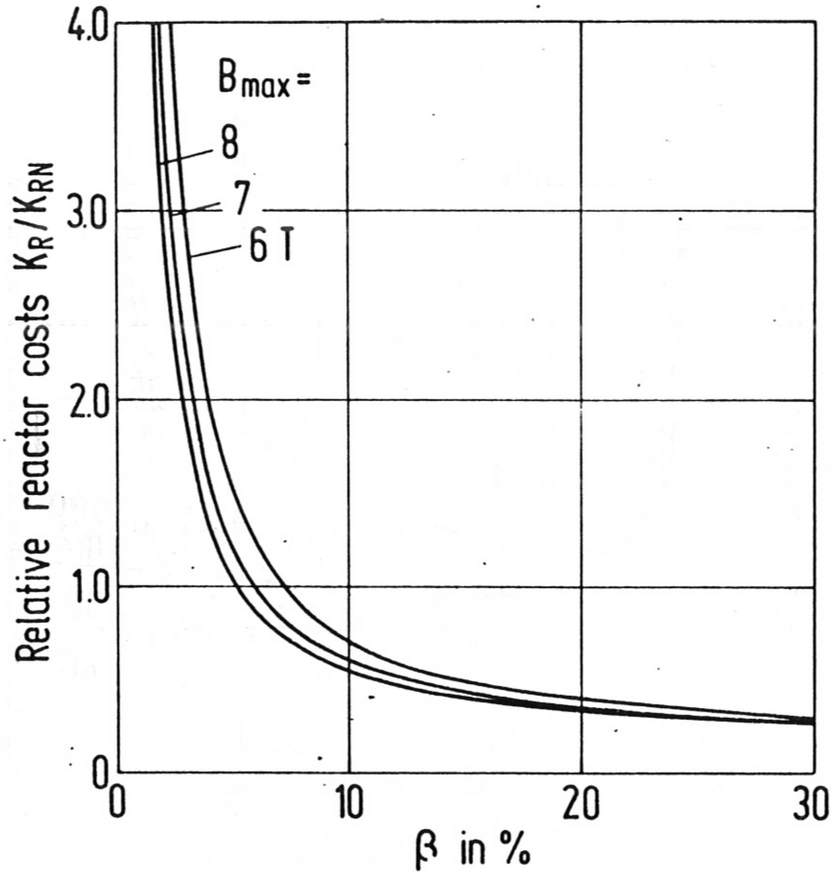

Fig. 11 Relative reactor costs versus ß for various values of B_{max} (D_L = 2.5 MWa/m^2)

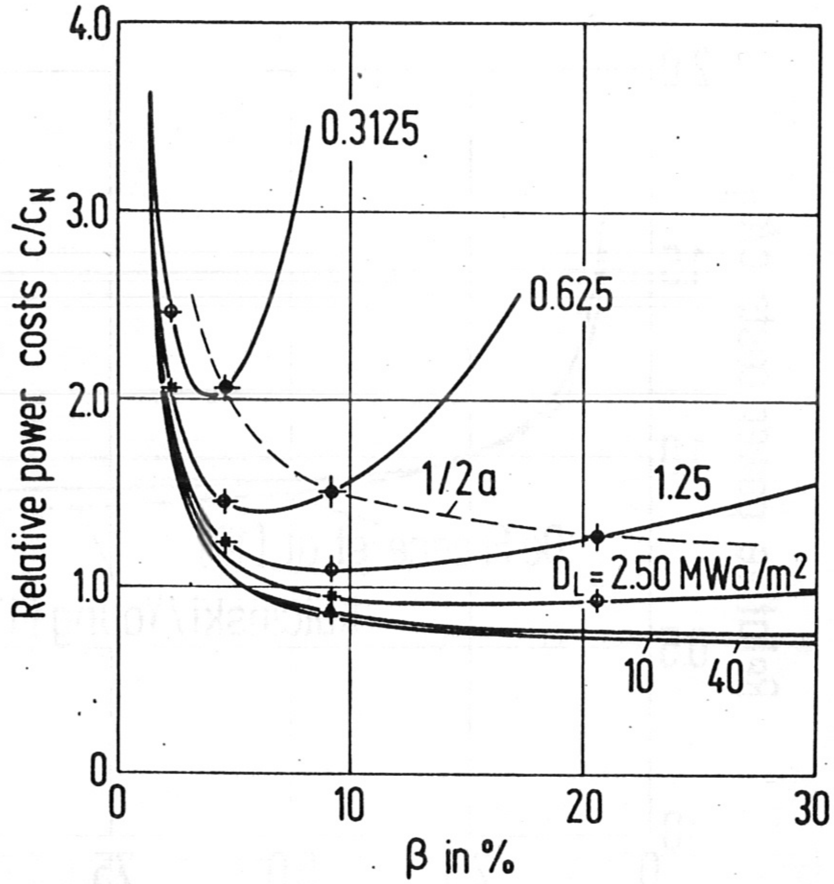

Fig. 12 Relative power costs versus ß for various values of the maximum integral wall load D_L
(B_{max} = 6 T, α = 0.75; minimum of a curve ≙ optimum wall load)

Lifetime of the 1st wall ✦ 1/2 a

⌖ 1 a

* 2 a

Δ 8 a

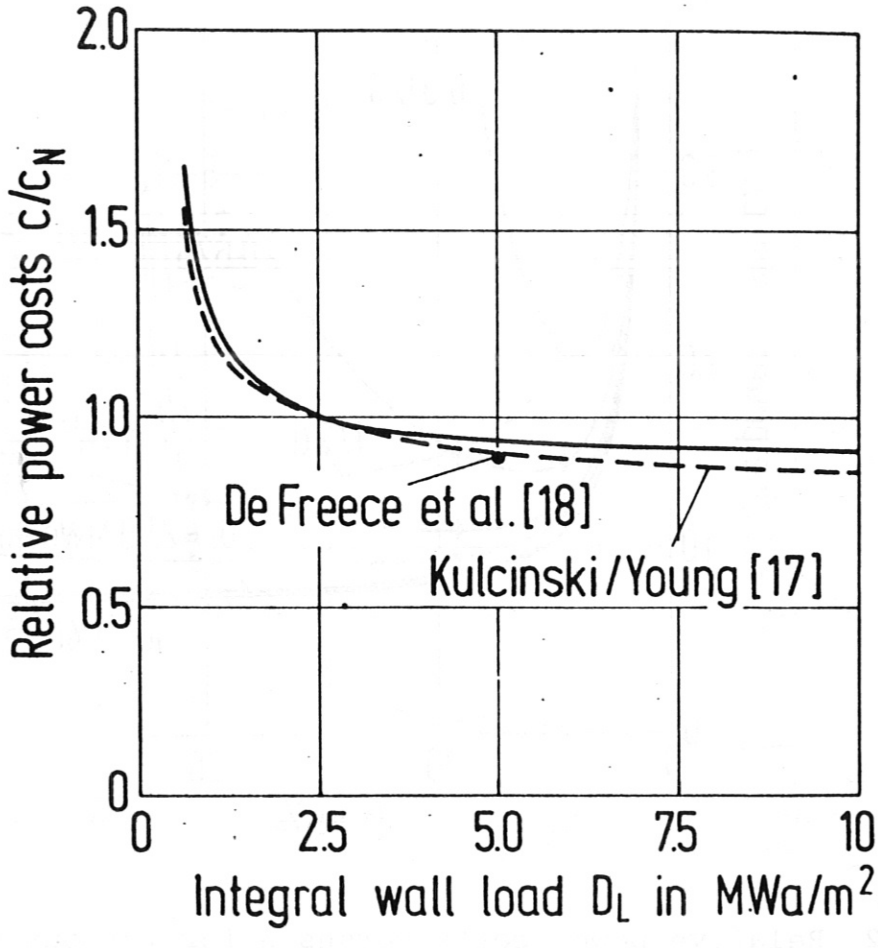

Fig. 13 Relative power costs versus the integral wall load D_L (comparison of the results of this paper with those of Kulcinski and Young [17] and of De Freece et al. [18])