MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

GARCHING BEI MÜNCHEN

On the Economic Prospects of Nuclear Fusion with Tokamaks*

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IPP 6/271 December 1987

*revised version December 1988,

Title of the original version:

"On the Economic Prospects of Nuclear Fusion
with Magnetically Confined Plasmas"

Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

Abstract

This paper describes a method of cost and construction energy estimation for tokamak fusion power stations conforming to the present, early stage of fusion development. The method is based on first-wall heat load constraints rather than β limitations, which, however, might eventually be the more critical of the two. It is used to discuss the economic efficiency of pure fusion, with particular reference to the European study entitled "Environmental Impact and Economic Prospects of Nuclear Fusion" [1]. It is shown that the claims made therein for the economic prospects of pure fusion with tokamaks, when discussed on the basis of the present-day technology, do not stand up to critical examination. A fusion-fission hybrid, however, could afford more positive prospects. Support for the stated method is even derived when it is properly applied for cost estimation of advanced gas-cooled and Magnox reactors, the two very examples presented by the European study to "disprove" it.

1. Introduction

Since the beginning of fusion research the economic efficiency of energy production by pure fusion has been assessed by the fusion community as largely positive. The tenor of the times between 1955 and 1975 was that the fusion energy expected to become available in 20 years would be clean, inexhaustible and inexpensive [2, 3]. Later the message became more specific, with the kWh prices of electricity generated by fusion being predicted to within four decimal places [4, 5, 6]. A paper published in 1984 then pointed out methodic errors in previous cost analyses and gave rough estimates based on power density comparisons for pure fusion which yielded electricity costs about ten times as high as those for the pressurized water reactor [7,8]. A publication of the Commission of the European Community [1], predicts, like [7], higher fusion electricity costs, albeit by a factor of "just" 2 to 3 in relation to those of a fission reactor scheduled for 1995. In addition to the cost analyses, Ref. [1] also compares the energy balances of fusion and fission power plants with one another, giving the advantage to fusion.

Notwithstanding, it is stated that "an understanding of the technical and economic feasibility of fusion will not exist until at least the next generation of experiments have been operated"!

The following critical discussion of the points in Ref. [1] relating to the economic efficiency of pure fusion is strictly based on present-day technology, unlike [38]. Section 2 starts by treating the logic of energy accounting. In Sect. 3 we present plasma physics constraints on the engineering power density which are obtained from the maximum plasma beta values considered possible at present. Section 4 discusses the methods of absolute energy and cost accounting of fusion reactors on which the statements in Ref. [1] are based, and confronts them with a method of relative accounting. Section 5 provides numerical material thus obtained, on the basis of thermal wall load constraints rather than on β limitations, which might, however, eventually turn out to be the more critical of the two.

2. Logic of energy accounting

In this section we show how the widely used quantities, payback time and harvesting factor, are to be rationally defined and how inappropriate definitions such as those in Ref. [10] - including that of the quantity energy expenditure appearing there - are used to arrive at arbitrary assertions, e.g. ones particularly favourable to pure fusion. The remarks made here are very closely linked with Ref. [7].

Let us start with the basic definition of a harvesting factor. In order to have a power P freely available, certain installations have to be built: power plants with such high electric power output that the power P still remains available after deduction of the power P_0 (0 = operation) permanently needed in the power plant itself (auxiliary power P_{aux}) or in external facilities (e.g. P_{FW} for fuel production and waste disposal), see Fig. 1a; first core; fuel factory; steel works; machine tool factories; etc. Let the energy needed to construct all these installations be E_C, which is a function of the power $P + P_0$, i.e. $E_C = E_C(P + P_0)$. This energy E_C is, so to speak, the seed grain which allows the energy $P \cdot t$ to be harvested up to the time t. This yields a - time-dependent - harvesting factor:

$$H(t) = P \cdot t / E_C(P + P_0). \tag{1}$$

With regard to inappropriate definitions to be discussed later, a necessary property of a harvesting factor is presented and proved for the present definition:

The harvesting factor $H(t)$ must be independent of whether the power P_0 is provided by the power plant in question or partly or wholly by another power plant of equal performance, i.e. with equal harvesting factor. If P_0 is divided in this sense into an internal component P_{0i}, which would usually be identical with P_{aux}, and an external component P_{0e}, which would usually be identical with P_{FW}, the power $P + P_{0e}$ is now freely available from the power plant in question (see Fig. 1b). This calls, however, for an additional construction energy $E_{Ce} = P_{0e} \cdot t/H(t)$, which is obtained from $H(t) = P_{0e} \cdot t/E_{Ce}$. This yields a new harvesting factor $\hat{H}(t)$ for our power plant:

$$\hat{H}(t) = (P+P_{0e}) \cdot t / \left[E_C(P+P_0) + P_{0e} \cdot t/H(t) \right]. \tag{2}$$

$E_C(P+P_0)$ can be expressed according to the first relation by $E_C(P+P_0) = P \cdot t/H(t)$. It thus follows that $\hat{H}(t) = H(t)$.

The definition chosen for the harvesting factor thus has the necessary invariance to arbitrary division of the permanently required power P_0 into an external and an internal component.

With the time-dependent harvesting factor $H(t)$ an energy payback time t_{pb} can be defined by means of

$$H(t_{pb}) = 1, \tag{3}$$

i.e.

$$t_{pb} = \frac{E_C(P+P_0)}{P} \quad . \tag{4}$$

This quantity thus gives the time taken to pay back in the form of electric energy the energy E_C originally expended. Only then does the whole installation pay off. With this payback time, H(t) is written as

$H(t) = t/t_{pb}$.

(The discussion could also have been conducted by having a time-varying division of the total power of the power plant into P(t) and $P_0(t)$.)

The following are examples of false definitions of H(t) and t_{pb}: The statement mentioned in Ref. (10), namely that the net energy balance in fusion would be better than that in fission, has partly to do with the definition

$$\tilde{H}(t) = (P+P_{0e})\cdot t/\left[E_C(P+P_0)+P_{0e}\cdot t\right] \quad , \tag{5}$$

its inverse for $t = t_L$, the lifetime of the complete installation, being the quantity "energy expenditure" defined in Refs. [11-13] and used in Ref. [10]. Here the denominator features the sum term $P_{0e}\cdot t$ instead of $P_{0e}\cdot t/H(t)$, which previously appeared. This definition is not invariant to arbitrary splitting of P_0 into $P_{0i}+P_{0e}$. In comparing fusion and fission one can therefore obtain all kinds of results, depending on the particular splitting chosen, as can readily be seen by letting t or t_L go to infinity, in which case $\tilde{H}(t)$ becomes $(P+P_{0e})/P_{0e}$. . Thus, for different P_{0e} but fixed $P_0 = P_{0e} + P_{0i}$ all values between $(P+P_0)/P_0$ and infinity can be obtained:

$$1 + P/P_0 \leq \tilde{H}(\infty) < \infty. \qquad (6)$$

Only the latter would be correct. This goes without saying, because the harvesting continues till the plant is shut down. This is a period that is not related to the formal splitting of P_0 into P_{0e} and P_{0i}.

The foregoing discussion may appear somewhat academic. The following examples show, however, that the definition of a harvesting factor not fulfilling the invariance property as in Refs. [11], [13], leads to a completely wrong relative rating of PWRs and tokamak reactors. One obtains with Chapman's [16] energy input data without first core harvesting factors of about $H_{PWR} = 35$ for PWR's after 30 years of operation and a load factor of 0.75. Assuming $E_{CTOK} \approx 10\ E_{CPWR}$ as in Fig. 5b of the present paper for a wall life of 2.5 years one finds $H_{TOK} = 3.5$. An external power of $P_{0e} = 70\ MW_{el}$ for both a PWR and a tokamak reactor of electric power output of $P+P_{0e} = 1300\ MW_{el}$ as in Sect. 4.1.2 yields, however, $\tilde{H}_{PWR} = 12.4$ and $\tilde{H}_{TOK} \approx 3.1$. For $E_{CTOK} = 2\ E_{CPWR}$ as claimed by Ref. [1] one finds $H_{TOK} = 17.5$ and $\tilde{H}_{TOK} = 9.3$. A tokamak reactor could, therefore, be found to be better than a PWR only, when $\tilde{H}$ is taken as a harvesting factor in conjunction with the values for E_{CTOK} chosen by Ref. [1] and $P_{0e\ TOK} = 0$, in which case $\tilde{H}_{TOK} = H_{TOK}$. Taking $P_{0e\ TOK} = 0$ means that the power needed for waste disposal in the tokamak case is neglected.

For the energy payback time the definition

$$\frac{(P+P_{0e})\cdot\tilde{t}_{pb}}{E_C(P+P_0)+P_{0e}\cdot t_L} = 1 \qquad (7)$$

is used. In the original definition the payback time t_{pb} appears instead of t_L. The new definition has the absurd consequence that the payback time grows arbitrarily with the lifetime. This can be expressed in the form that, in actual fact, $\tilde{t}_{pb}$ partly constitutes a pay-in-advance time.

3. Plasma physics constraints on the engineering power density

The fusion power density in a DT plasma with particle densities n_D and n_T is given by

$$p_f = n_D \cdot n_T \cdot \langle\sigma v\rangle \cdot E_{DT} \ , \qquad (8)$$

where σ is the reaction cross-section, v is the relative velocity of a deuterium to a tritium ion, on which σ also depends, $\langle\ \rangle$ denotes averaging over the relative velocities, and $E_{DT} \approx 20$ MeV is the reaction energy in the DT process, including exothermic reactions involved in tritium breeding. With approximate thermal equilibrium, $\langle\sigma v\rangle$ becomes a function of the temperature T. For the case $n_D = n_T$ one can write

$$n_D = n_T = 0.25 \cdot p/T \ , \qquad (9)$$

where p is the plasma pressure, which is composed of the ion and electron pressures. This yields

$$p_f = f(T) \cdot p^2 = 0.25 \cdot \mu_0^{-2} \cdot f(T) \cdot \beta^2 \cdot B^4. \qquad (10)$$

The function f(T) has a maximum at $T \approx 15$ keV. For this temperature one has

$$p_f = p_{f,max} = 1.5 \cdot \beta^2 \cdot B^4 \ MW/m^3, \qquad B[T] . \tag{11}$$

A favourite parameter combination is $\beta = 0.07$, $B = 5$ T, which results in $p_{f,max} = 4.6$ MW/m³, a value which, though much too low for an economical reactor, is usually considered sufficient.

With a minor plasma radius a of a circular plasma cross-section and with a wall radius of 1.2 a, and with positive profile effects and the negative dilution effects due to α particles and impurities being assumed to approximately compensate each other, $p_{f,max}$ leads to an effective total wall load of

$$f_w = 0.6 \cdot a \cdot \beta^2 \cdot B^4 \ MW/m^2 , \qquad a\,[m] \; ; \; B\,[T] \; . \tag{12}$$

The maximum $\bar{\beta}$ values expected at present with tokamaks are given by the relation

$$\bar{\beta}_{max} = g \cdot I/(a \cdot B) \qquad ; \quad I\,[MA] \, , \; a\,[m] \, , \; B[T] \, , \tag{13}$$

where I [MA] is the total plasma current in megamperes, a [m] the horizontal half-width of the plasma cross-section in metres, and B [T] the toroidal field strength in the plasma in teslas. The constant factor g is not exactly known. According to [14] g = 2.4 can be considered to be really safe and attainable and g = 3 may be attainable and possible for reactors. (At the XV European Conference on Controlled Fusion and Plasma Heating held recently in Dubrovnik (Cavtat), F. Troyon in his invited paper even argues for g = 2 in spite of g = 3.5 obtained for short times in D III

D. An approximate form of eq. (13) is obtained by introducing the current q, q_I, and the horizontal and vertical half-widths of the plasma cross-section a and b:

$$q_I \approx \frac{5B}{I} \cdot \frac{a^2+b^2}{2\,R} , \qquad (14)$$

which yields

$$\bar{\beta}_{max}\,\% = 5g\cdot\left[1+(b^2/a^2\right]/(2\cdot q_I\cdot A); \quad A = R/a . \qquad (15)$$

In this formula it can be assumed that $12 < 5\,g < 15$.
In the above-mentioned discussion it was concluded that $q_I \approx 2.3$ might be possible. For technical reasons it is unlikely that lower values of A than 4.5 can be achieved. One should therefore expect

$$\bar{\beta}_{max} = (1.16 \text{ to } 1.45)\cdot(1 + b^2/a^2)/2 \quad \% . \qquad (16)$$

For b/a = 2 - a rather optimistic value - this yields

$$\bar{\beta}_{max} \cong 2.9 \text{ to } 3.6\ \% \qquad (17)$$

with corresponding wall loads of f_w = 0.63 MW/m^2 to 0.97 MW/m^2 for a = 2 m.

These values are much too low even by ordinary standards. Improvements could be envisaged by using more complicated configurations, such as a bean-shaped cross-section. This would mean, however, that the cost assumed hitherto would have to be corrected upwards. Furthermore, all noncircular plasma cross-sections are subject to anisotropic energy losses, which impose further constraints on the thermal wall loads, discussed in Sect. 4.1.1. Another way out would be to use higher magnetic fields: 6 T instead of 5 T would increase f_w to values between 1.3 MW/m^2 and 2.0 MW/m^2, which are still very low. The latter comes close to the value of 3 MW/m^2 obtained in Sect. 4.1.1 from thermal wall load constraints. Higher fields would, of course, again increase the cost. Some people hope that there might be a way of reaching the so-called second stability regime at high β, which ideal linear MHD theory predicts to exist. It would further complicate the tokamak reactor. On the other hand, the finite resistivity of the plasma makes this hope at best a very vague one. Some optimistic results in this respect are only found with approximate formulae not valid in the regimes of interest. Since thermal wall load constraints alone, as discussed in Sect. 4.1.1, turn out to be almost as severe as present-day β limitations, we base our discussion in the following solely on thermal wall load constraints.

4. Content of energy accounting

In the European study [1] it is stated that the results of comparative studies on the energy required for constructing and operating pressurized water reactor and tokamak reactor power plants were in favour of fusion. The main references are three papers by Bünde [10,11,12]. The direct and indirect energy requirements, the so-called gross energy requirement (ger) [15], for constructing complex systems such as power plants are determined predominantly by the input-output (I/O) method [16, 17] using inverted input-output tables, known as the Leontief inverse [15]. The more differentiated method of determining the energy requirements by process chain analyses (PCA) fails in the case of nuclear power plants because the individual production processs, with the exception of the fuel cycle, cannot yet be sufficiently well analyzed. The fusion reactor is mainly composed of products which have not hitherto been manufactured and which, moreover, are not typical of the branches of industry which provide input-output tables. The I/O method is therefore not applicable to the fusion reactor at present. As regards the PCA method, what has been said about nuclear power plants applies to the fusion reactor to a much greater extent: in the latter case all the requirements for analyzing the production process are still lacking because the fusion reactor is far from having reached the stage of being technically documentable. This also becomes clear on closer inspection of available reactor design studies: on decisive issues knowledge is replaced by assumptions (e.g. physics, materials technology, components). Notwithstanding, the sources used in the European study employ the PCA method for absolute energy accounting of the fusion reactor and, what is more, they do so without documenting a detailed fusion reactor model as a basis for this energy accounting! Reference [10] does cite a paper of 1981 [18] as basis of the "geometric dimensioning and mass determination" of the tokamak power plant. However, this unpublished work, marked "confidential", does not even contain a reactor design study, let alone a detailed design with component description, mass calculation, etc., which are basic requirements for applying PCA. The construction energy calculations in [10], which were done on the basis of uncheckable mass tables, are consequently worthless. Finally, also the ger values used there for the most important fusion reactor materials do not stand up to critical appraisal. For high-alloyed steels (stainless steel in the case of the fusion reactor), for example, a ger value of just 15,758 is given, the "main source of information" for this figure being a book by D.G. Altenpohl [19]. The source quoted contains, however, neither this figure nor data leading to it. In actual fact, a value twice as high must be expected [15, 20]. This, however, has an extremely unfavourble effect on the energy balance of the tokamak reactor (TR) in relation to that of the pressurized water reactor (PWR) owing to the inherently high mass component of this material in the TR. For this reason alone the TR energy input stated in [10] would increase from 355 to 510 $MW_{th}h/MW_{el}$. Furthermore, the power and power density values in that study are based on a thermal wall load which, according to the results in Sect. 4.1.1, is a factor of 3 too large. Elimination of these two shortcomings would thus already result in a fourfold increase of the PCA value of the TR plant.

To get more reliable construction energy values of a TR plant, the PCA results were scaled up in Refs. [10,11] by a factor of about 2, which corresponds to the ratio between the PWR construction energy value gained by I/O measurements and that obtained by PCA accounting. This could improve the result, provided that:

1) the net energy requirements for PWR plants are properly determined by I/O measurements, but are underestimated by PCA;
2) the ratios between I/O values and PCA values of TR and PWR plants are equal.

But it is to be taken from the foregoing that the second assumption is not fulfilled in this case and therefore the results of that scaling [10,11] are unusable.

Other shortcomings in [10, 11, 12] are that the auxiliary energy requirement of the TR is underestimated [21] and the availability assumed for it is too high [22], as well as the fact that the logic of the energy accounting is false (see Sect. 2) and the energy required for radwaste disposal is neglected at the same time. According to a Japanese study [23] the latter is higher than the energy required in a PWR of equal net power for producing fuel by the diffusion method and for radwaste disposal.

As already explained, neither the absolute energy requirement nor the construction cost of fusion reactors can yet be directly determined. All that is possible at present is to estimate them in relation to, for example, those of the PWR. An appropriate state-of-the-art method was described for the first time in Ref. [24], an improved version of which was later used in Ref. [7] to estimate investment costs as well. The following sub-sections are closely linked with these studies. As the limiting factor we take only the thermal wall load constraint for reasons discussed in Sect. 3.

4.1 Investment cost ratio R_C and construction energy ratio R_E between tokamak and PWR power plants

The above discussion leads us to base cost and construction energy investigations on experience made very generally in industry. This experience shows that the cost and hence also the construction energy expenditure for producing technical commodities and equipment of technically identical or similar type and equal complexity are approximately proportional to their weight or volume. In the context of nuclear heat generators this means that the cost incurred and the construction energy required to produce nuclear boilers of equal complexity, equal overall energy intensity of the construction materials and equal unit power size scale roughly linearly with the power density. By assuming tokamak nuclear boilers and PWR nuclear boilers to possess similar masses per unit volume (PWR Biblis B: 2.26 to/m^3 without fuel; 2.59 to/m^3 with fuel; Starfire 2,06 to/m^3) and to be of equal complexity and to consist of construction materials with equal overall energy intensities - the latter two assumptions being very generous to the tokamak - one can compare their production costs and production energy requirements per unit net electric output power on the basis of their relative power densities with respect to both volume and mass. The volumes represent the safer basis if there is not sufficiently detailed knowledge of a system, in which case weights are often underestimated. The net electric output power P_{net} is the electric power averaged over the lifetime of the reactor that remains after deducting the auxiliary energy requirement of the power plant and the energy consumed for fuel supply and waste management.

The investment costs for a 1.2 GWel PWR plant (1982) break down as in Table I and the construction energy expenditures as in Table II.

For a rough estimate of the total cost ratio or construction energy ratio between a tokamak power plant and a PWR power plant it can be assumed that the absolute balance of plant of the two for equal power will be the same. This is not the case with the nuclear island: For one thing, it has to be assumed, in keeping with what has just been said, that the cost and construction energy ratios for the nuclear boilers are about inversely proportional to the power density ratio. But the other components of the nuclear island, except for the primary loop 1.b and reactor electrical equipment 1.d, are also dependent on - besides the system - the power density. The extent of their dependence will also be governed by the details of the particular reactor concept. The relation between the ratio R_C of the costs as well as the ratio R_E of the construction energies for the complete power plant and the power density ratio of the nuclear boilers can be expressed approximately as follows [7]:

$$R_C = \{ 1 + 1.06 \cdot \alpha \cdot [(p_{PWR}/p_{TOK}) - 1] \} \cdot (\eta_{rel} \cdot K_{rel})^{-1} , \qquad (18)$$

$$R_E = \{ 1 + 1.19 \cdot \alpha \cdot [(p_{PWR}/p_{TOK}) - 1] \} \cdot (\eta_{rel} \cdot K_{rel})^{-1} . \qquad (19)$$

The ratios refer to the construction cost and energy expenditure of PWRs, excluding the first core. The notation is as follows:

p_{PWR} = power density in the PWR nuclear boiler (pressure vessel)

p_{TOK} = power density in the tokamak reactor nuclear boiler (engineering power density)

α = power-density-dependent plant fraction

K_{rel} = TOKAMAK-to-PWR plant availability ratio

η_{rel} = TOKAMAK-to-PWR total efficiency ratio.

As opposed to [7], the plant availability ratio and efficiency ratio were introduced to afford a uniform evaluation of the net electric output power.

The relation between power density and construction cost or construction energy is placed in doubt by the European study [1]. It is stated there: "That solely power-density-based comparisons are not very reasonable can be seen by examining fission itself, where typical power densities in a PWR, AGR and Magnox reactor are around 15, 3 and 0.4 MW_{th}/m^3 respectively, whereas the construction and operation cost differences are within a factor of 2." The PWR Biblis-B, cited in our study as reference PWR, yields a power density of just under 12 $MWth/m^3$ in the reactor pressure vessel. The cost factors then calculated with eq. (18), the differences in the efficiencies and availabilities being neglected as in [7], are RC = 1.25 for the AGR and about 3 for the Magnox reactor, these values being in very good agreement with the above-quoted factor of 2. In view of these figures it is therefore incomprehensible why the authors of the European study [1] were prompted to make the above statement. In this context they also enlist a coal power plant for comparison. This comparison is absurd, in our opinion, because that part of such a plant corresponding to the nuclear island is simple, and the materials used in it are conventional and relatively cheap. Furthermore, the data used for this comparison are absolutely inappropriate, e.g. in calculating the power densities in the combustion chamber and typical fusion power core. The former value was too low by a factor of approximately 2, because the steam generator volume was included, and the latter value was too high by a factor of 3.

4.1.1 Thermally prescribed power density ratio limits between the PWR and tokamak

The ratio R_{SV} of the surface area of the first wall to the reaction volume enclosed governs the heat transport through the wall. For fundamental reasons this ratio is low in the case of toroidal magnetic plasma confinement: the R_{SV} values attainable in tokamaks are at most 1.2 m^{-1}. In comparison, R_{SV} values of 380 m^{-1} are obtained in PWRs because the core volume is spread over a large number of slender fuel elements (Table III).

A second important geometrical parameter is R_V, the ratio of the reaction volume to the total reactor volume. Its theoretical upper limit in the case of tokamaks without divertor is about $R_V = 25 \times 10^{-2}$ [27]. For tokamaks with divertor $R_V < 6 \times 10^{-2}$ seems to be realistic, and for PWRs (Biblis B) the value is $R_V = 5 \times 10^{-2}$ [28]. The product $G = R_{SV} \cdot R_V$ is a geometrical quality figure determining the ratio of the mean reactor power density to the thermal flux density f_{th} to the walls and should thus be as high as possible. It is 300 times higher in PWR's than in tokamaks (Table III).

To protect the first wall of tokamak reactors against bombardment by plasma particles, it is intended to use limiters or divertors. The latter facility deflects these particles to collector plates by means of appropriately shaped magnetic fields which are located outside the reaction volume and are thus easier to replace, but which have a smaller surface than the first wall of the vacuum vessel. The problems thus arising will be dealt with below.

The engineering power densities p of PWRs and tokamak reactors are described by the following equations:

$$p_{PWR} = (R_{SV} \cdot R_V \cdot f_{th})_{PWR} \quad , \tag{20}$$

$$p_{TOK} = (R_{SV} \cdot R_V \cdot f_{th})_{TOK} \cdot \varepsilon_\alpha \cdot [1 - \eta_D \cdot (1 - \varepsilon_{rad})]^{-1} \quad . \tag{21}$$

In keeping with the INTOR study let it now be assumed that it would be possible to build divertors of such high efficiency that up to $\eta_D = 95\ \%$ of the alpha particle energy not transported by radiation is kept away from the walls and is deposited on collectors, and that the radiation component ε_{rad} is not more than 30%. In this case, the power density ratio would still be almost 17 if equal thermal flux densities to the wall were assumed. A tokamak reactor would thus have a much higher volume even than present-day types of PWR with equal output.

This still leaves the question of the thermal flux density f_{th} to the wall that is permissible in DT reactors. It is limited by the permissible wall temperature and thermal wall stresses. The temperature gradient in the first wall causes compressive thermal stresses to be generated in the surface facing the plasma and corresponding tensile stress to be generated on the coolant side. Additional primary stresses result from the coolant pressure and, if ferritic material is used, also from magnetic forces. The upper limit of the thermal flux density to the wall is thus approximately inversely proportional to the thickness d of the first wall and also depends on the properties of the wall material used:

$$f_{th} \leqq 2 \cdot \sigma_{0.2} \cdot \lambda \cdot (1-\nu) \cdot [d \cdot \alpha \cdot E]^{-1} \quad , \tag{22}$$

λ = therm. conductivity, ν = Poisson's ratio,

α = thermal expansion, E = Young's modulus,

$\sigma_{0.2}$ = yield strength d = wall thickness

(no volumetric heat generation by neutrons, free expansion, no bending).

While the fuel cans in the PWR have wall thicknesses of less than 1 mm, the first wall in a tokamak has to be thicker, probably by more than an order of magnitude for reasons yet to be discussed. In the case of austenitic steel, type SS 316, which is selected in most tokamak reactor designs as wall and structure material, eq. (22) yields for a wall thickness of 10 mm, a permissible thermal flux density to the wall of f_{th} = 0.14 MW/m². The mean flux density to the wall in the case of the Biblis PWR, on the other hand, is 0.61 MW/m². It thus follows from eq. (22) that, alone in view of thermal constraint, a divertor tokamak reactor with a 10 mm thick first wall made of SS 316 would have to have a volume about 80 times that of a PWR of present-day design with equal output (Table III). It is pointed out, that these values are obtained when adverse effects of non-circular cross-sections and other inhomogeneities, e.g. high local wall load due to ripple-lost fast α particles, and also fatigue failure are neglected. Wall protection, which is considered necessary for several reasons and which would also improve the heat removal situation, by means of carbon or tungsten tiles is not very likely to be possible in a reactor. However, a proposal by G. Coast [37] to use a chocolate structure first wall might perhaps allow double the thermal load.

Reducing the thickness of the first wall is one of the main possibilities under discussion for attaining higher power densities by increasing the permissible thermal flux density to the wall. The lower limit of the wall thickness is governed by the primary load which the wall has to withstand (coolant pressure, force of gravity, electromagnetic forces) and by the mechanical properties of the wall material. When put into operation, the wall has to be thicker, however, by the amount that will be sputtered by particle bombardment etc. in the course of its service life. In other words, the longer the service life required, the thicker the wall has to be, but also the lower the thermal load capacity of the wall and hence the reactor power density will be. In Fig. 2 the power density ratio between the PWR and tokamak as a function of the service life of the tokamak first wall is given. This curve is based on the values listed in Table 3. For comparison, the corresponding value for INTOR is marked [29]. Considering that the power density in INTOR is too high, since it does not constitute a complete power reactor, the agreement is not bad. To get an idea of the proportions, the envelopes of a tokamak and of a PWR are illustrated true to scale in Fig. 2. Both nuclear boilers are for a power output of 3.7 GW_{th}. The tokamak first wall service life is 10 years.

In a divertor the conditions are more critical. For the values assumed the collector plates there would have to let about twice as much heat through as the main vessel wall. Their surface areas will certainly not exceed 1/3 of that of the vessel wall. This would result in a thermal wall flux density six times as high. Material erosion due to sputtering possibly need not be taken into account for a "cold gas blanket" in front of the collector plates. (This is not true of presently discussed next-generation tokamaks such as ITER, where one is confronted with extremely severe erosion problems. Erosion rates of the order of several meters per year are envisaged, which might be reduced to some degree by sweeping the plasma hitting the divertor plates over a larger area.) However, they would have to be about 3 mm thick for mechanical reasons, whereas 1.5 mm would be the maximum permissible thickness to allow the thermal flux.

4.1.2 Relative total plant efficiency

As already stated in Sect. 4.1, the net electric power is defined as the freely available electric power. This is the power available after deducting the auxiliary power required inside the power plant and the power required outside the power plant for fuel supply and waste management. Comparative assessments of the tokamak in respect of economic efficiency and energy often disregard, like [10, 11, 12], differences in the internal operating power requirements to the PWR. This results in overly favourable assessment of the tokamak, in view of its typically higher auxiliary consumption. As regards the external operating energy requirements, a study by A. Miyahara et al. [23] is of particular interest. It is shown there that the energy required for radwaste disposal and fuel preparation in the tokamak reactor is not several orders of magnitude lower than in the PWR [10, 11, 12] but is roughly comparable.

Below, breakdowns of the total internal and external operating power requirements of 1300 MW_{el} power plants are given [21, 23]:

PWR plant

- main coolant pumps. . . . . .
- feed water pumps. . . . . . .
- cooling water pumps . . . . . P_{aux} = 60 MW_{el}
- cooling tower operation . . .
- fuel supply . . . . P_{fuel} = 70 MW_{el}
- waste disposal. . . . . P_{waste} = 1 MW_{el}

Total operating power requirements . . . . 131 MW_{el}

Tokamak plant

- auxiliary power as in PWR (pumps etc.) . . . . . 60 MW_{el}. . .
- magnet operation. . . . . $P_{aux,TOK}$
- vacuum system operation . . . . $P_{op,TOK}$ = 180 MW_{el}. .
- plasma heating. . . . .
- waste disposal. . . . . .P_{waste} = 70 MW_{el}
- fuel supply . . . . .P_{fuel} ≈ 0 MW_{el}

Total tokamak operating power requirements 310 MW_{el}.

The above definition of P_{net} means

$$P_{net} = P_{th} \cdot \eta_{th} - (P_{aux} + P_{fuel} + P_{waste}) \qquad (23)$$

$$= P_{th} \cdot \eta_{total} ,$$

where $\eta_{total} = \eta_{th} - (P_{aux} + P_{fuel} + P_{waste})/P_{th}$. (24)

The above values yield for η_{th} = 0.348 the following total efficiencies: :

PWR : $\eta_{PWR} = 0.316$,

Tokamak : $\eta_{TOK} = 0.280$,

and hence

$$\eta_{rel} = \eta_{to_{TOK}} / \eta_{to_{PWR}} = 0.89 \qquad (25)$$

4.1.3 Relative tokamak plant availability K_{rel}

The availability is one of the most important criteria of the economic efficiency of a power plant, because it has a direct influence on both the specific investment costs and the specific construction energy expenditure.

The availability of a power plant during its lifetime is governed by the number and duration of scheduled outages for inspection and maintenance work and of unscheduled outages due to failures and their repair. In nuclear power plants, furthermore, a distinction is made between outages due to the nuclear island (NI) and those originating in the balance of plant (BOP).

In PWR power plants scheduled maintenance in the BOP sector is generally carried out in the time shadow of the more time-consuming NI inspection and maintenance. We assume that this would also be the case in tokamak power plants. We can then write

$$K_{rel} = K_{TOK}/K_{PWR} = (K_u/K_{PWR}) \cdot (1+t_{rw}/t_L)/(1+K_u \cdot t_{rw}/t_w), \qquad (26)$$

where K_u is the availability relating to unscheduled outages,

$$K_u = t_{bu}/(t_{bu} + t_{ru}) \quad , \qquad (27)$$

and t_L = reactor lifetime,

t_w = wall lifetime,

t_{rw} = time required to replace the first wall,

t_{bu} = mean operating time between unscheduled outages,

t_{ru} = mean down time required to eliminate failures.

It should be noted here that $t_L > t_w/K_u$ has to be satisfied.

For tokamak power plants [30, 31]:

$$t_L = 30 \text{ years},$$
$$K_{PWR} = 0.75.$$

This together with the approximation

$$1 + t_{rw}/t_L \approx 1 \quad (28)$$

yields

$$K_{rel} \approx \left[(1/K_u) + (t_{rw}/t_w)\right]^{-1} \cdot 4/3 . \quad (29)$$

This formula is valid without constraint on t_w.

The estimation of t_{rw}, t_{bu} and t_{ru} is based on the following:

The theoretical minimum outage for replacement of fuel elements and inspection of the 1300 MW_{el} PWR Biblis-B is 0.093 y/y. The shortest time required with a staff peak of 880 (!) was 0.12 y/y. If these figures are taken to scale the time t_{rw} required for the periodic, incomparably more difficult and more time-consuming replacement or partial replacement of the first tokamak wall, in keeping with the operations described in reactor design studies, the following estimates are obtained as lower limits in the most optimistic case:

t_{rw} = 0.5 to 1.0 y, depending on the maintenance concept.

The main reference on the question of unscheduled outages of nuclear origin is a study by Musicki and Maynard [22]. Using the logic diagram of a mirror machine power plant, they calculate an availability of 2 to 3.4 % for this fusion power plant by simulating the failures in the subsystems by the Monte Carlo method. This value presupposes that no extraordinary action is taken to reduce unscheduled outages. Being a highly complex serial system of components essential for operation, a fusion reactor with PWR-comparable component reliability and redundancy must of necessity have a much higher total failure rate. The above result therefore did not come as a surprise to the authors "since failures in almost any subsystem will shut down the plant", this being of course typical of serially complex systems. In order to achieve a higher availability, they recommend among other things "on-line redundancy" for major subsystems, which would be equivalent to enhancing the parallel complexity. In this context the reader is referred to comments such as "For comparison, today's aircraft have many more systems and are much more complex, yet they are now much more reliable than in earlier times" [1] stem from lumping together the two complexities, which have opposite effects on system availability.

A reliability study for the NET tokamak [32] uses comparatively simple methods (not Monte Carlo methods) to clarify the question whether the objective of demonstrating a 25 % availability over one year is realistic. With subsystem failure data not very much different from those in [22], the author arrives at the surprising conclusion that "the target to demonstrate a plant availability of 25 % over one year is a realistic one". This result can probably be attributed to the fact that the author of [32] replaced the average of a function of statistical quantities by that function of the averages of these quantities.

In summary, thermonuclear heat systems, e.g. of the tokamak type, require a relatively long time for regular wall replacement, and would have to afford unusually high redundancy and component reliability if they are ever to achieve the availability necessary for base load power plants.

Assuming this possibility, remote though it be, we also made calculations with correspondingly high K_u values, but of course without taking into account the still unclarified increase in investment costs that would be entailed. The results obtained are therefore very optimistic.

5. Results

The formulae (18, 19) for the cost ratio R_C and the construction energy ratio R_E between the tokamak and PWR power plants were evaluated as functions of the wall lifetime t_w for the following parameter values:

- scheduled down time for one first-wall replacement operation (see 4.1.3):

$$t_{rw} = 0.5\ y;\ 1.0\ y;$$

- availability, considering unscheduled down time only:

$$K_u = 0.25;\ 0.5;\ 0.75;$$

- power-density-dependent plant fraction (see Sect. 4.1, Tables 1, 2, [7]):

for R_C : $\alpha = 0.075; 0.10; 0.15;$

for R_E : $\alpha = 0.085; 0.12; 0.15.$

The results are displayed for R_C and R_E together with the total availability ratio K_{rel} between the tokamak and PWR plants in Figs. 4 and 5. All curves for R_C and R_E show minima in the vicinity of a wall lifetime of just one year. This is due to the adverse effect of the wall thickness on the wall lifetime and the power density. Such a minimum is useless for base load operation owing to the small value of t_w associated with it. Notwithstanding, the curves obtained are discussed first on the basis of these minima: as an example, we choose the rather optimistic parameter values $t_{rw} = 0.5$ y and $K_u = 0.5$. Here even the minima of the unrealistically optimistic curves for $\alpha = 0.075$ and 0.085 are located at 10 and 12, respectively. For base load operation the wall lifetime should be $t_w \geqq 5$ y, for which the values $R_C \geqq 14$ and $R_E \geqq 17$ are found. As shown in [7], $\alpha = 0.15$ with $R_C = 26$ and $R_E = 29$ presumably conforms more to the actual conditions. When a chocolate structure first wall such as recently proposed by G. Coast [37] is assumed, these cost and energy ratios might have to be reduced by a factor of 2.

6. Conclusions

The estimates made in this study on the basis of present-day technology have shown that the costs incurred and the energy expended in constructing tokamak reactor power plants will necessarily exceed the values for fission PWR power plants by a factor of at least 10, or perhaps 5 when a chocolate structure wall is assumed. (A similar result (factor 13) would be arrived at if a cost analysis made at Harwell in 1981 on the basis of the Culham IIB reactor design [33] were modified in accordance with the present-day β-limits, which would at the same time bring down the thermal wall load to a realistic regime. This analysis uses the account numbers defined by the IAEA as a guide in the economic evaluation of bids for nuclear power plants.) As stated by Robert Carruthers, former Head of the Applied Physics and Technology Division, Culham, "the factors which led to these disappointing results are nothing to do with any physics uncertainties or problems in the (European) Technology Programme but due to well-established engineering constraints".

Particularly misleading, according to our estimates, are the energy balance data for tokamak power plants that are taken from [10, 11, 12] by the European study [1]. Contrary to what the European study claims, these data certainly cannot be better than those of a PWR power plant of present-day design; rather they must be much more unfavourable. Properly defining the harvesting factor (see Section 2) - which is not properly defined in the European study, where it is called "energy gain" - one obtains with Chapman's energy input data [16] a value of about 35 for PWRs after 30 years of operation with a load factor of 0.75. This means that, at the end of its lifetime, the reactor has yielded 35 times as much net electric energy as construction energy was invested in it, whereas a tokamak power plant, according to our estimate, has only provided at most five (or ten) times this energy, but very probably not much more than it (or twice this energy), where the parentheses refer to chocolate structure walls. An illustration of the relation between a tokamak reactor and a PWR is given in Fig. 3, which shows, on the same scale, the nuclear boilers of the two systems for the same output power without allowance for the differences in total efficiency and availability. At this point it should be noted that the tokamak reactor designs enlisted in [1] to justify the claim that this concept has favourable economic properties - the last of which, namely Starfire, dates from 1980 - do not conform to the present state of the art. One case in point is the quite universally observed β-limits, which are represented here by eq. (13) and which yield for Starfire a β of 2.7 % instead of the assumed 6.7 %. This would mean, that the gross electric power of that station as it is would be reduced by the factor of $(6.7/2.7)^2 = 6.2$ resulting in about zero net power output. Conforming to this finding would certainly necessitate rather drastic modifications of the design. Another case in point is the thermal wall load constraint discussed in this paper and earlier in Ref. [1]. Our investigation [7] was, of course, not considered for these designs, because it was published later. One would, however, have expected a study such as Ref. [1] to include a discussion of these problems when referring to such designs.

Are ways of somehow improving the economic prospects of fusion conceivable? As concerns the β problem, one possibility would be to improve β by, for example, further increasing the elongation of the plasma cross-section beyond the rather optimistic value of 2 used in this study. Quite apart from the attendant difficulties (see also Sect. 3), this would not bring about any fundamental change, owing to the thermal and neutronic load limits. Other proposals [34, 35] aim at reducing the cost and unit size by working with very much thinner breeding blankets. Any reduction in cost thereby achieved, however, would not basically improve the overall situation. In any case, such a procedure would only be capable of supplying energy worldwide for less than 50 years, since the beryllium and lead needed to compensate the large neutron losses from the thin breeding blankets are very limited resources [36]. - Furthermore, even if the new high-temperature superconductors could ever be applied for fusion, a doubtful prospect at the moment, this would not essentially reduce the costs. We believe that it is of paramount importance to find new materials which would allow much higher power densities than those known at present.

Despite all these negative aspects affecting so-called pure fusion, a major role could be played by D-T fusion in supplying power based on nuclear energy if it were used for breeding fissile material in a hybrid reactor. The effective energy multiplication factors associated with this application might possibly allow energy production at a cost competitive with that of fast breeders. This would also afford a number of advantages over fast breeders, but discussion of these would exceed the scope of this study. In addition, the fusion-fission hybrid reactor might be a near-term goal that could provide us with sufficient time to gain experience and develop new schemes and technologies which might eventually allow us to build economic pure fusion reactors.

Acknowledgements

We are grateful to F. Pohl for his help in numerically evaluating the final formulae.

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Plant component		Investment costs
1.	Nuclear island	
.a	- nuclear boiler	7.5 %
.b	- primary loop	18.5 %
.c	- reactor building	8.0 %
.d	- reactor electrical equipment and control	6.0 %
.e	- reactor site installation	6.0 %
.f	- reactor project management	2.0 %
	Subtotal nuclear island	48.0 %
2.	Balance of plant	46.0 %
3.	First core	6.0 %
		100 %

(see Refs. [16, 17, 25, 26]).

Table I: PWR investment cost breakdown

Plant component:		Construction energy
1.	Nuclear island	
.a	- nuclear boiler	8.5 %
.b	- primary loop	16.5 %
.c	- reactor building	7.0 %
.d	- reactor electrical equipment and control	5.5 %
.e	- reactor site installation	5.5 %
	Subtotal nuclear island	43.0 %
2.	Balance of plant	41.0 %
3.	First core (centrifuge enrichment)	16.0 %
		100 %

(see Ref. [7]).

Table II: PWR construction energy breakdown

Table III: Power density relevant quantities of typical PWRs and tokamak reactors

	PWR (Biblis)	TOKAMAK
Surface to volume ratio of fuel rods or plasma R_{SV} $[m^{-1}]$	380	~ 1
Fuel rod or plasma to reactor volume ratio R_V	$5 \cdot 10^{-2}$	$< 6 \cdot 10^{-2}$
Geom. quality Fig.G $[m^{-1}]$	19	≤ 0.06
Quality Fig. ratio G/G_{PWR}	1	$< 1/300$
Ratio of total to α-particle energy ε_α	-	6
Divertor efficiency η_D	-	0.95
Radiated fraction of α-particle energy ε_{rad}	-	0.3
Wall life [year]	3	~ 5
Wall material	Zircaloy	SS 316
Wall temperature °C	400	400
Sputtering rate $[\frac{mm}{a} \cdot \frac{m^2}{MW_{th}}]$	-	11
Average particle energy at the first wall [eV]	-	200
Wall thickness required:		
a) at the end of life [mm]	0.7	3
b) initially [mm]	0.7	10
Thermal wall flux density f_{th} $[MW_{th}/m^2]$	0.61 [1)]	< 0.14 [2)]
Engineering power density ratio p/p_{PWR}	1	$< 1/80$ [2)]

1) Operating value

2) Thermal stress limitation

Figure Captions

Fig. 1a Power flow diagram with the total operating power taken from the power plant in question

P_{th}: Reactor thermal output; P_0: gross electric power output;
P_O: total operating power; P_{aux}: auxiliary operating power;
P_{FW}: operating power for fuel production and waste disposal.

Fig. 1b Power flow diagram with external operating power $P_{Oe} = P_{FW}$ for fuel production and waste disposal, provided by an outside power plant, and with an internal operating power $P_{Oi} = P_{aux}$, taken from the power plant in question.

Fig. 2 Engineering power density ratio between PWR and tokamak nuclear boilers with equal thermal powers.

Fig. 3 Envelopes of 3.7 GW_{th} nuclear boilers.

Fig. 4 Estimated capital cost ratio between PWR and tokamak power plants with equal thermal powers.

Fig. 5 Estimated construction energy ratio between PWR and tokamak power plants with equal thermal powers.

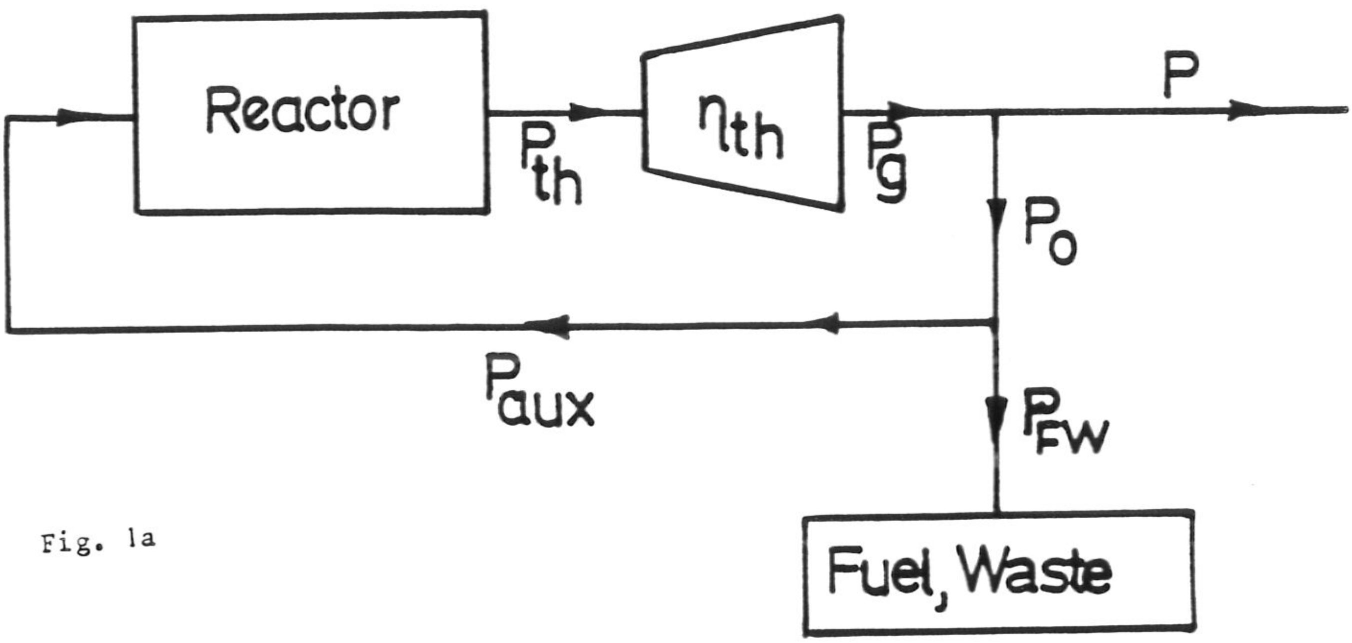

Reactor
P_{th}
η_{th}
P_g
P
P_o
P_{aux}
P_{FW}
Fuel, Waste

Fig. 1a

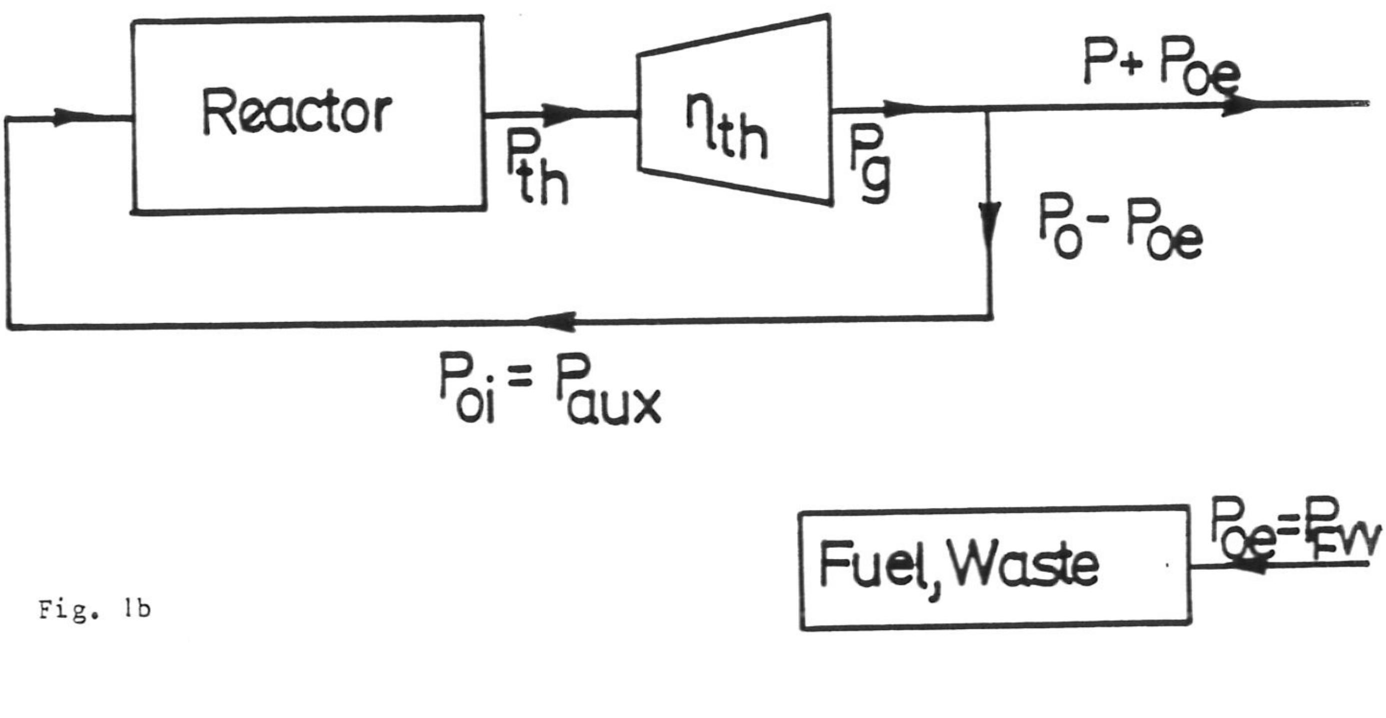
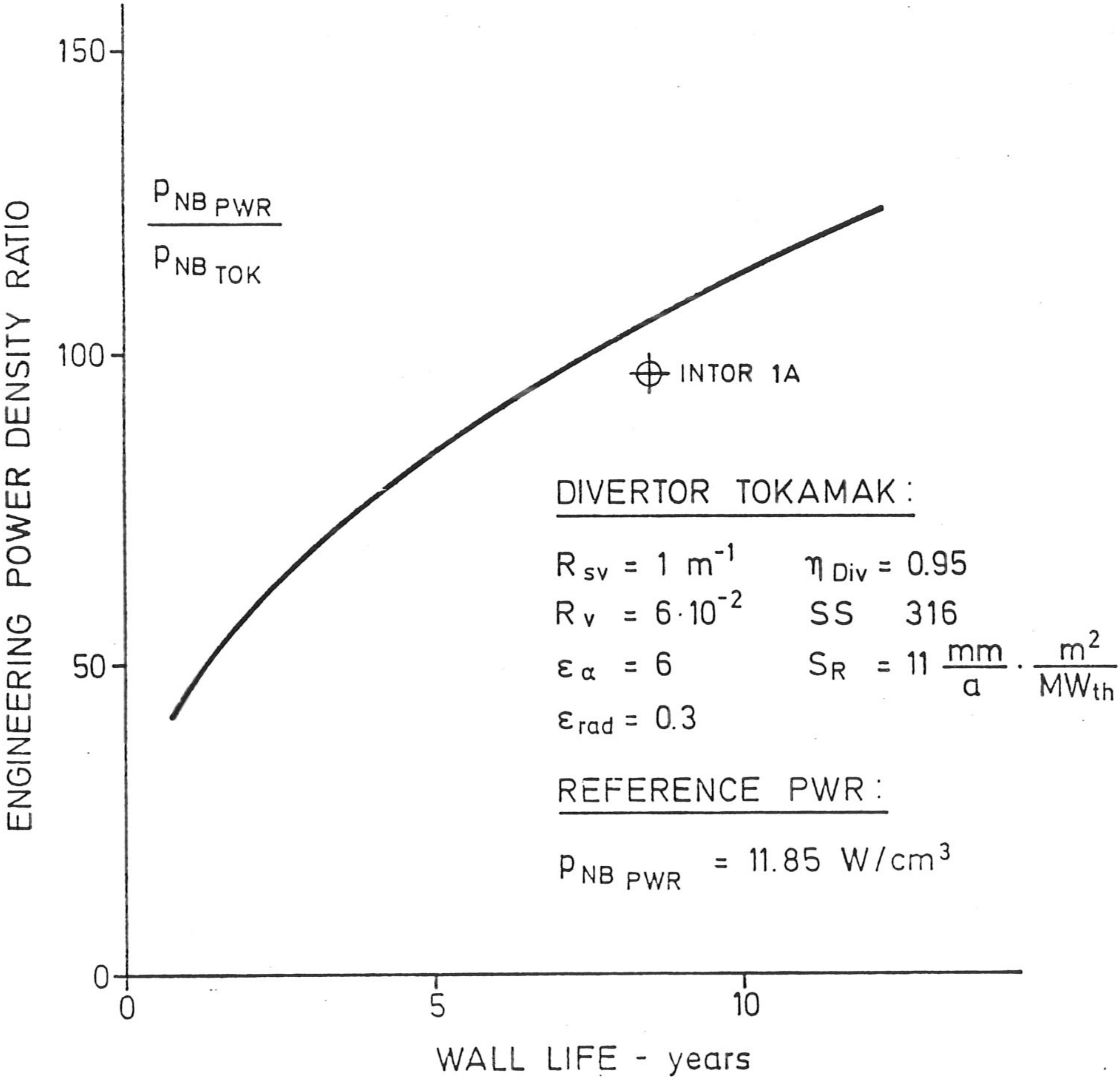
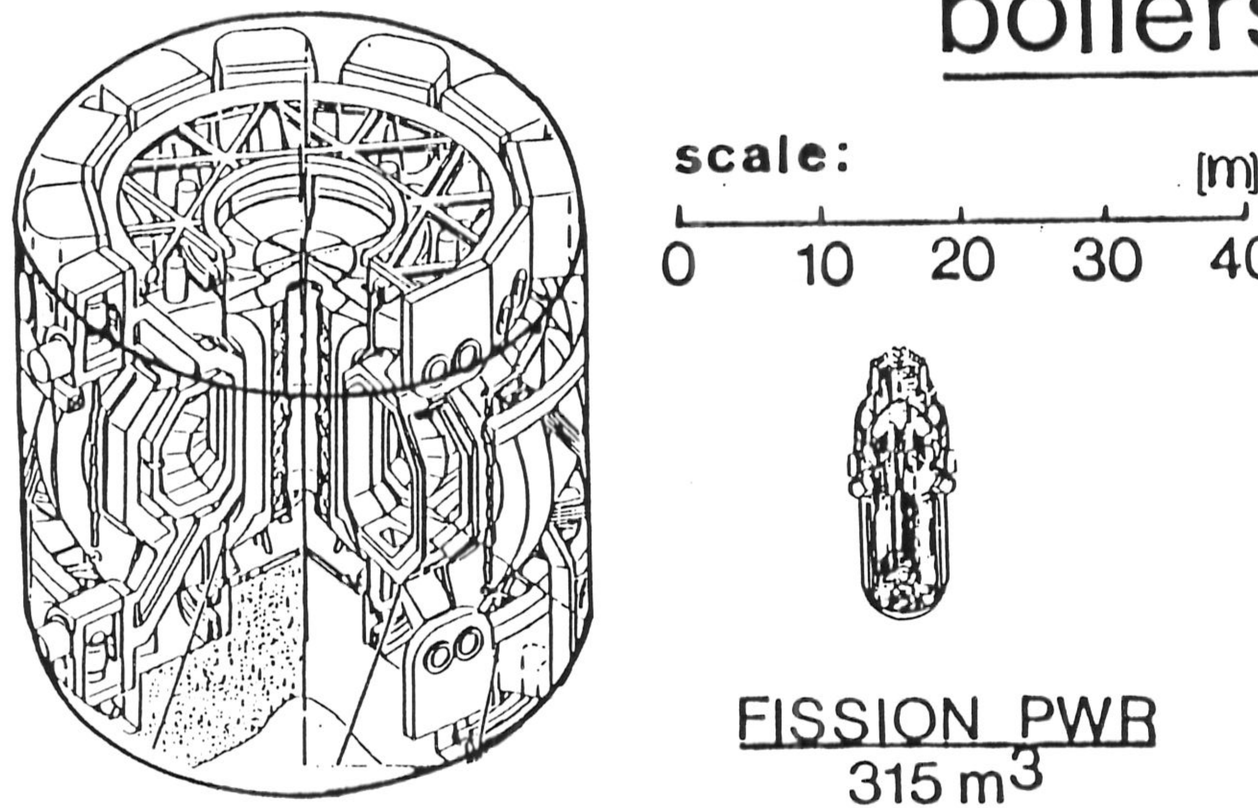

Reactor
P_{th}
η_{th}
P_g
$P + P_{oe}$
$P_o - P_{oe}$
$P_{oi} = P_{aux}$
Fuel, Waste
$P_{oe} = P_{FW}$

Fig. 1b



150
100
50
0
ENGINEERING POWER DENSITY RATIO
$p_{NB\,PWR} / p_{NB\,TOK}$
INTOR 1A
DIVERTOR TOKAMAK:
R_{sv} = 1 m^{-1}
η_{Div} = 0.95
R_v = $6 \cdot 10^{-2}$
SS 316
ε_α = 6
$S_R = 11 \frac{mm}{a} \cdot \frac{m^2}{MW_{th}}$
ε_{rad} = 0.3
REFERENCE PWR:
$p_{NB\,PWR}$ = 11.85 W/cm^3
0
5
10
WALL LIFE - years

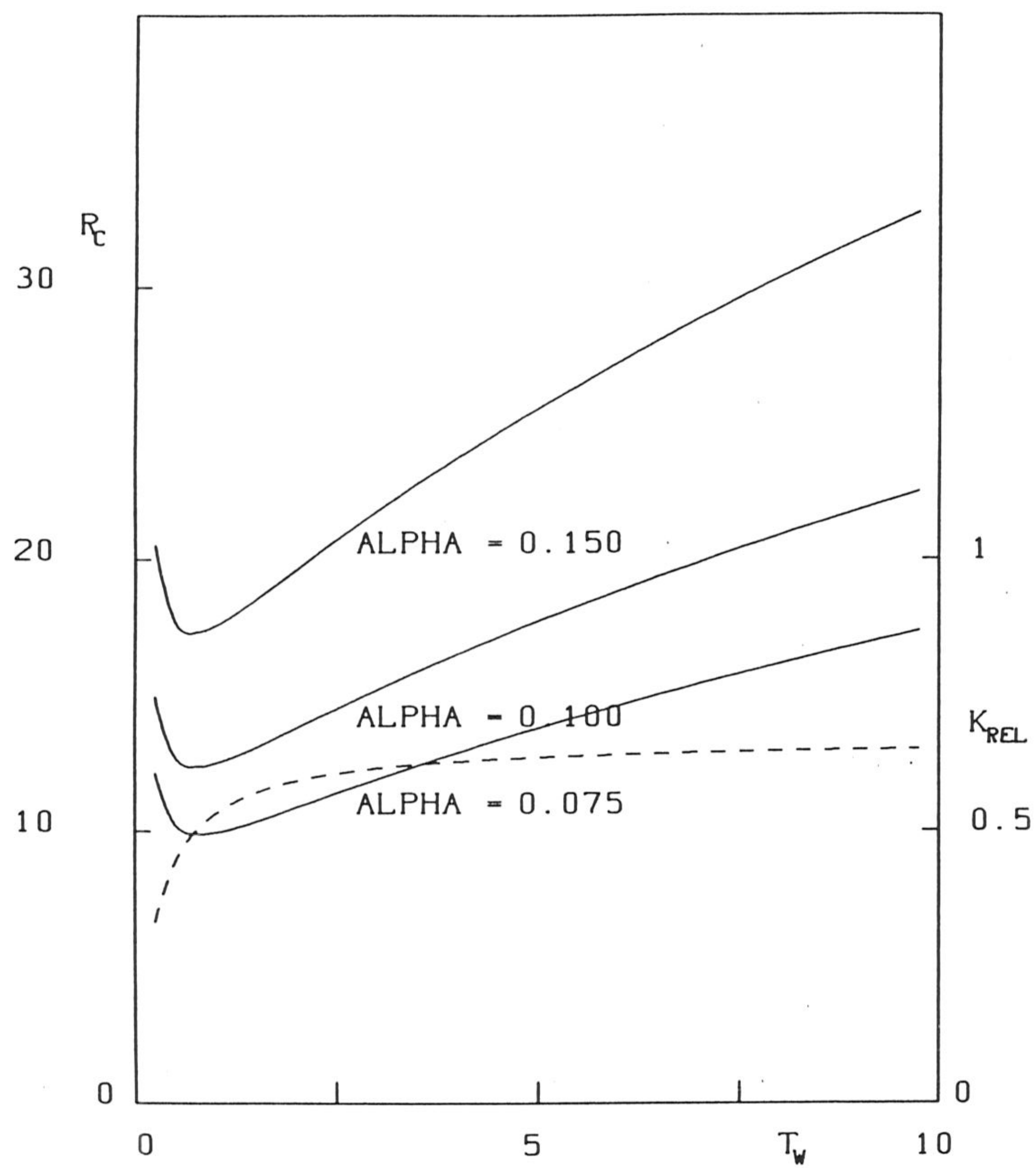
Envelopes of 3.7 GW_{th} nuclear boilers



FUSION TOKAMAK
~35.000 m^3
First Wall Life: 10 years

FISSION PWR
315 m^3

Fig. 3



R_C ————

K_{REL} - - - - - - - - -

T_{RW} (YEARS) = 0.500

K_U = 0.500

REFERENCE PWR: BIBLIS-B

T_W – FIRST WALL LIFE (YEARS)

R_C – CAPITAL COST RATIO BETWEEN TOK AND PWR

K_{REL} = AVAILABILITY RATIO BETWEEN TOK AND PWR

Fig. 4a

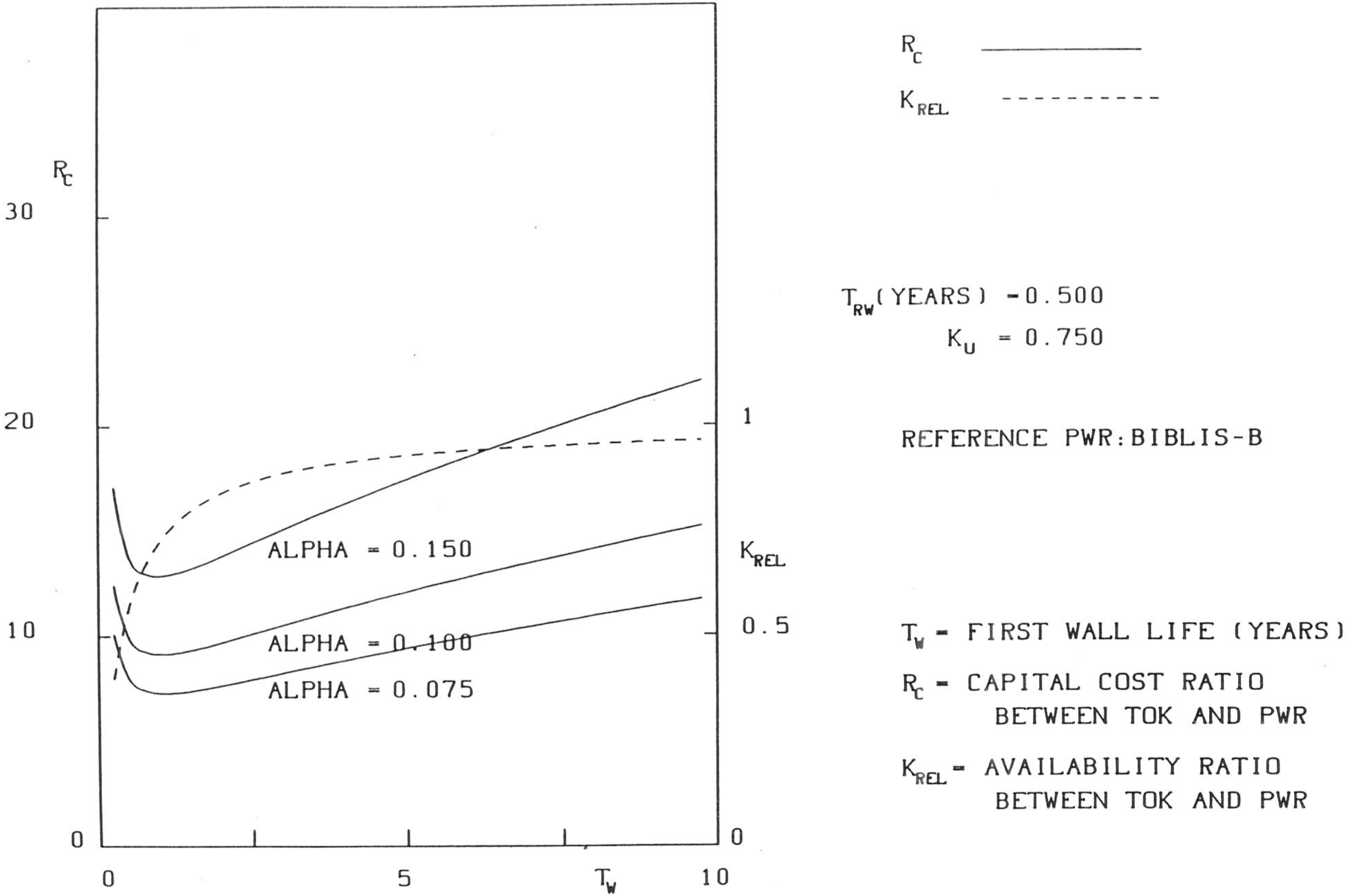
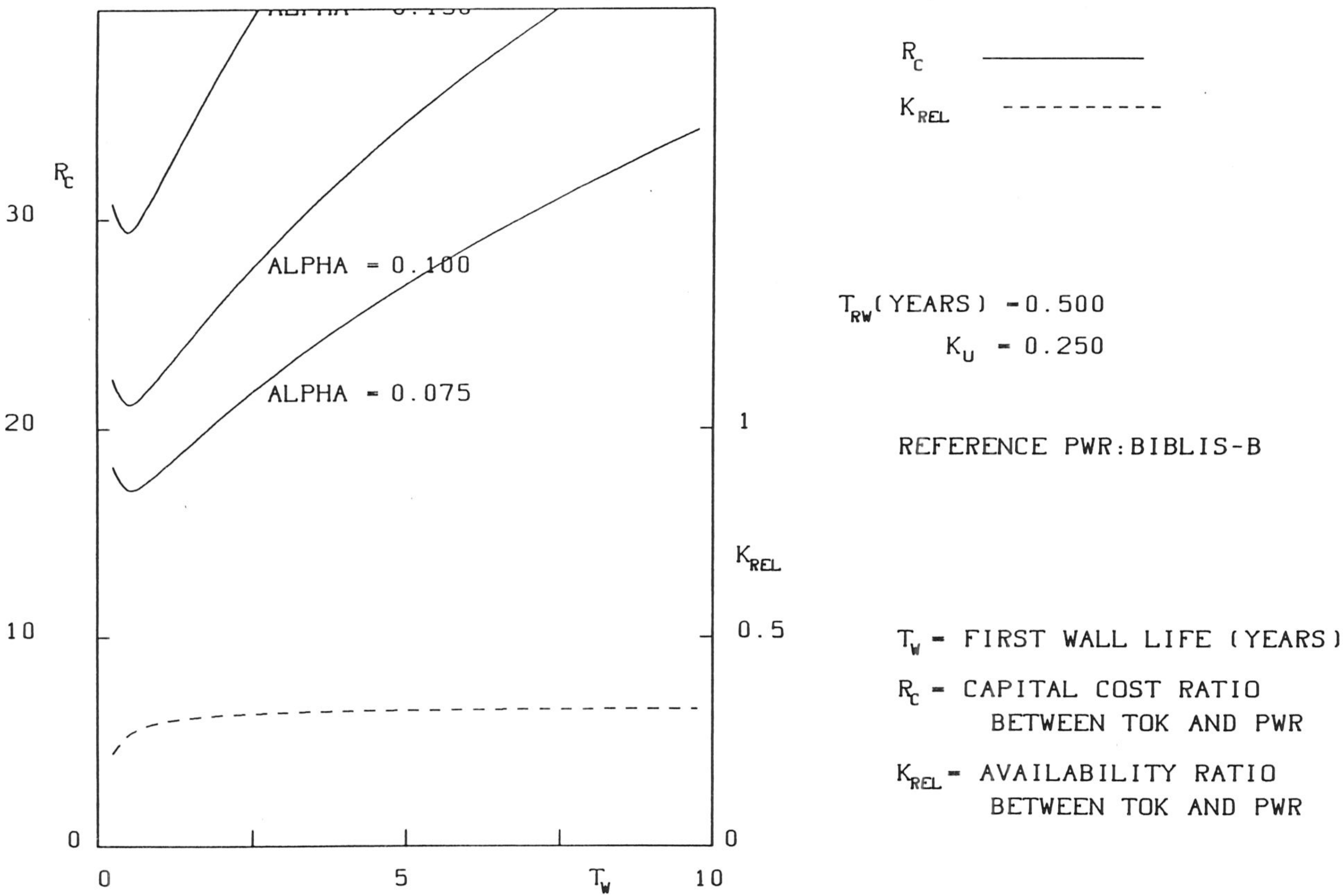

R_C
K_REL
R_C
30
20
10
0
1
K_REL
0.5
0
0
5
T_W
10
ALPHA = 0.150
ALPHA = 0.100
ALPHA = 0.075
T_RW (YEARS) -0.500
K_U = 0.750
REFERENCE PWR:BIBLIS-B
T_W - FIRST WALL LIFE (YEARS)
R_C - CAPITAL COST RATIO BETWEEN TOK AND PWR
K_REL - AVAILABILITY RATIO BETWEEN TOK AND PWR

Fig. 4b



R_C
30
20
10
0
ALPHA = 0.100
ALPHA = 0.075
1
K_{REL}
0.5
0
0
5
T_W
10
R_C
K_{REL}
T_{RW}(YEARS) = 0.500
K_U = 0.250
REFERENCE PWR:BIBLIS-B
T_W = FIRST WALL LIFE (YEARS)
R_C = CAPITAL COST RATIO BETWEEN TOK AND PWR
K_{REL} = AVAILABILITY RATIO BETWEEN TOK AND PWR

Fig. 4c

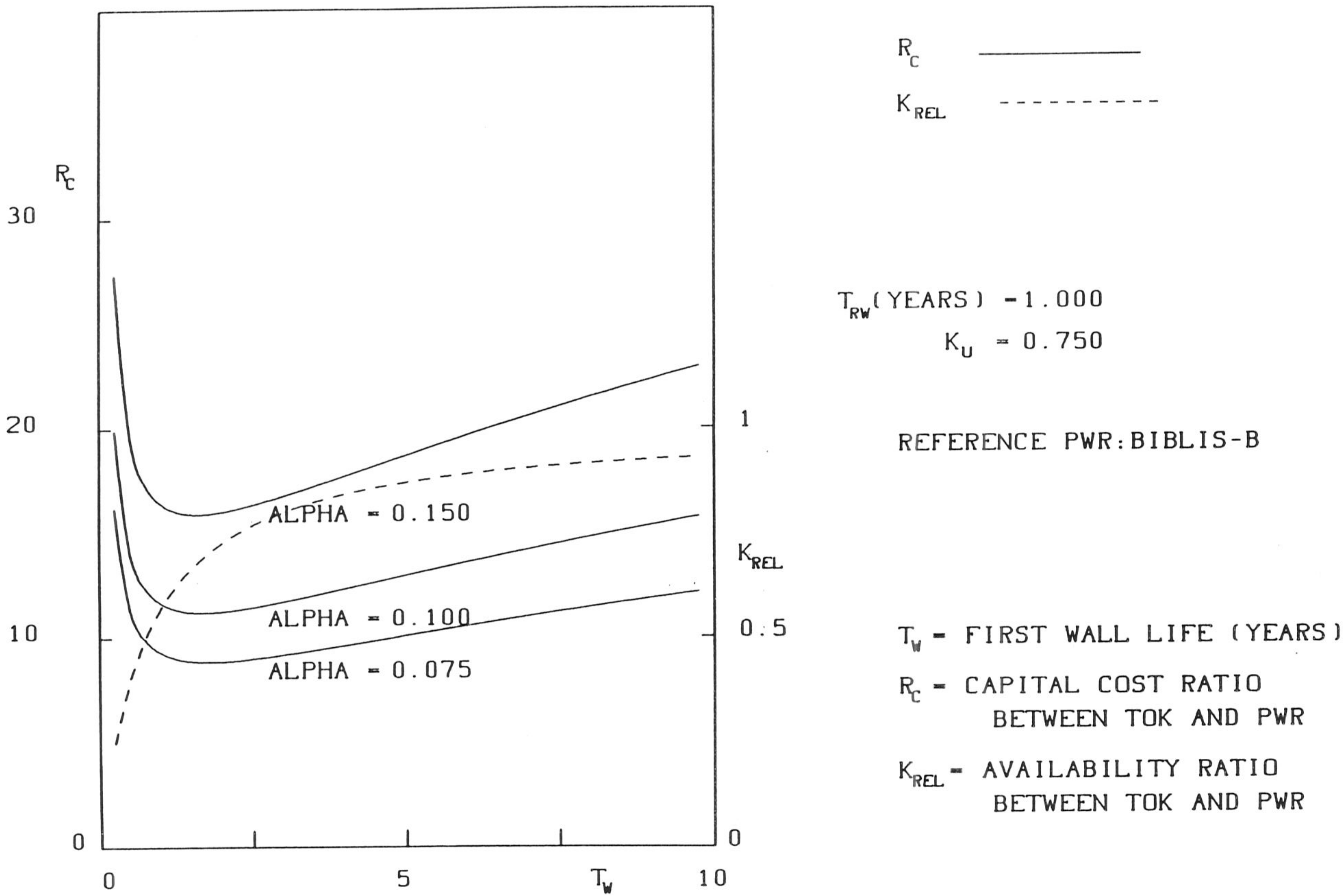

R_C
K_{REL}
R_C
30
20
10
0
0
5
T_W
10
1
K_{REL}
0.5
0
ALPHA = 0.150
ALPHA = 0.100
ALPHA = 0.075
T_{RW} (YEARS) = 1.000
K_U = 0.750
REFERENCE PWR:BIBLIS-B
T_W - FIRST WALL LIFE (YEARS)
R_C - CAPITAL COST RATIO BETWEEN TOK AND PWR
K_{REL} - AVAILABILITY RATIO BETWEEN TOK AND PWR

Fig. 4d

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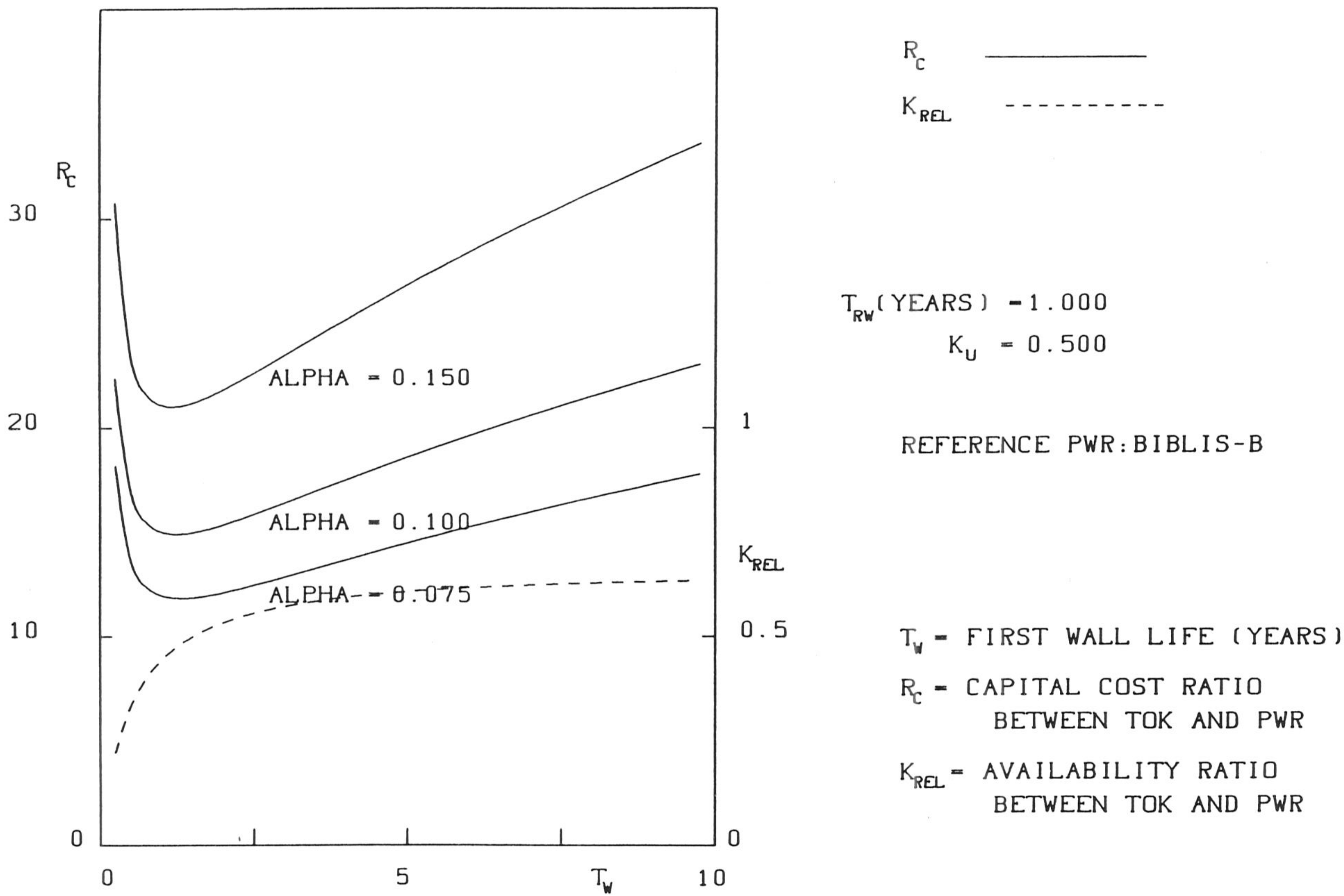
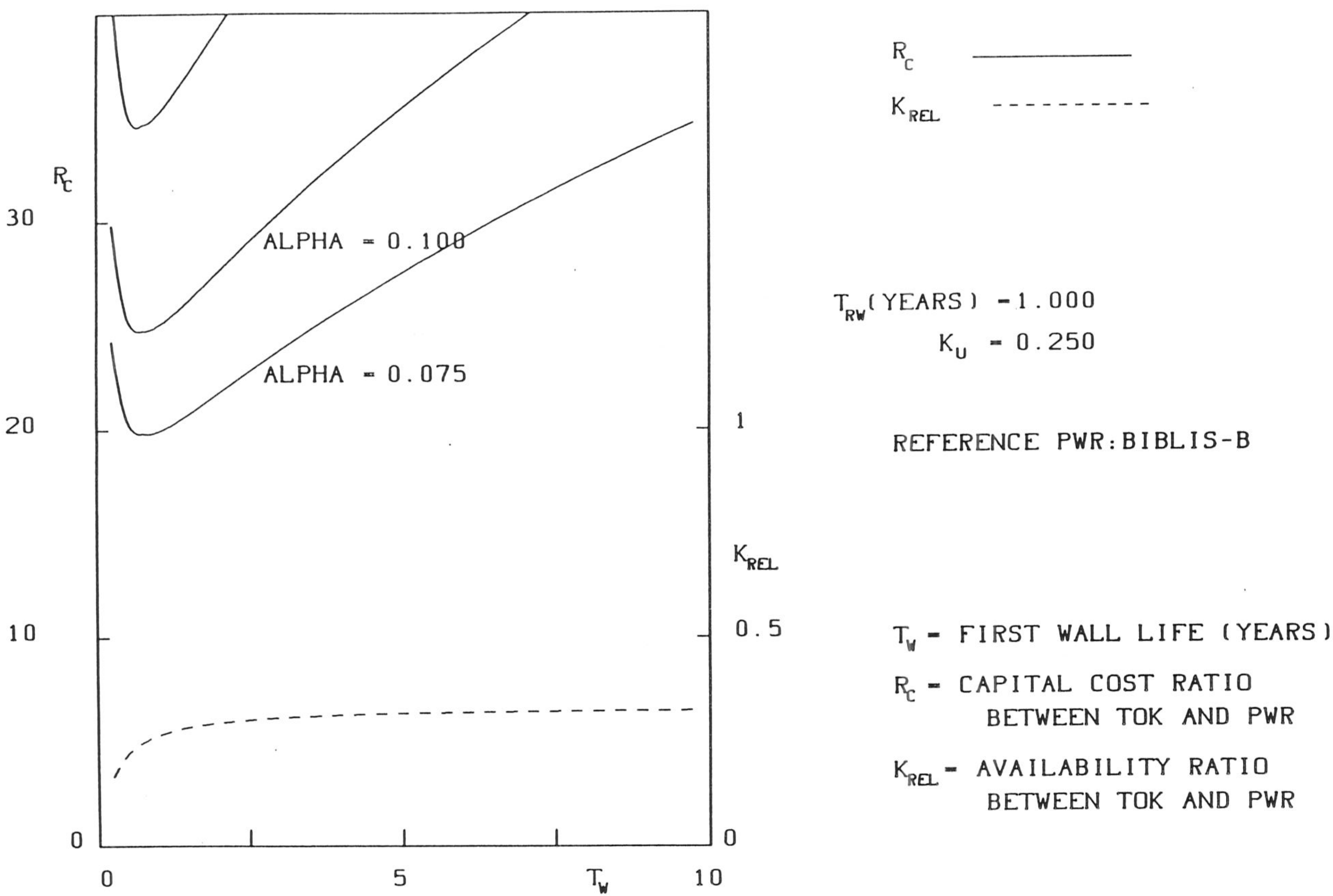


Fig. 4e



R_C
30
20
10
0
ALPHA = 0.100
ALPHA = 0.075
1
K_{REL}
0.5
0
0
5
T_W
10
R_C
K_{REL}
T_{RW} (YEARS) = 1.000
K_U = 0.250
REFERENCE PWR:BIBLIS-B
T_W - FIRST WALL LIFE (YEARS)
R_C - CAPITAL COST RATIO BETWEEN TOK AND PWR
K_{REL} - AVAILABILITY RATIO BETWEEN TOK AND PWR

Fig. 4f

IPP--CMS FRP 2 F2-05 23.11.87 16.21:27

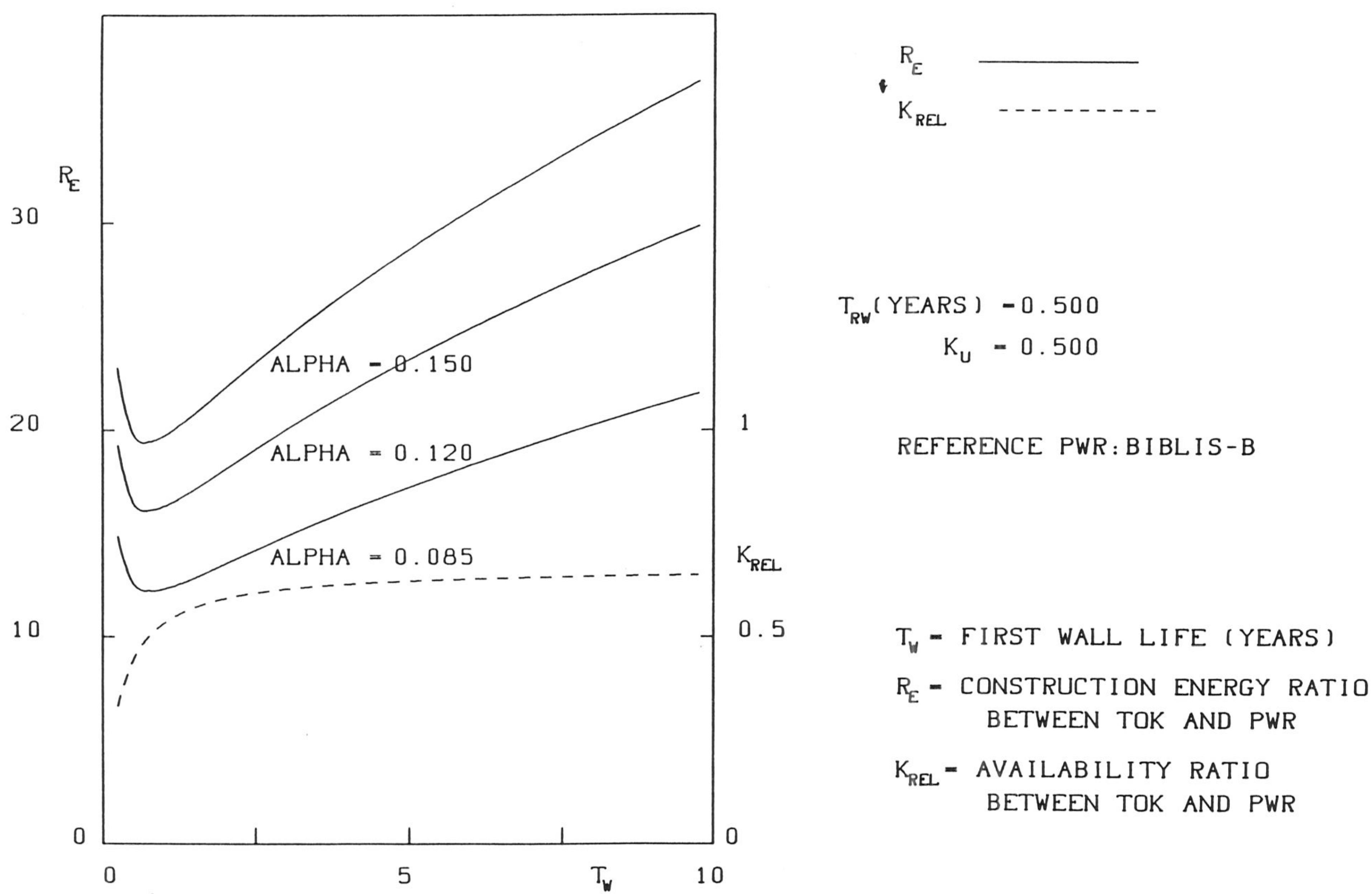


Fig. 5a

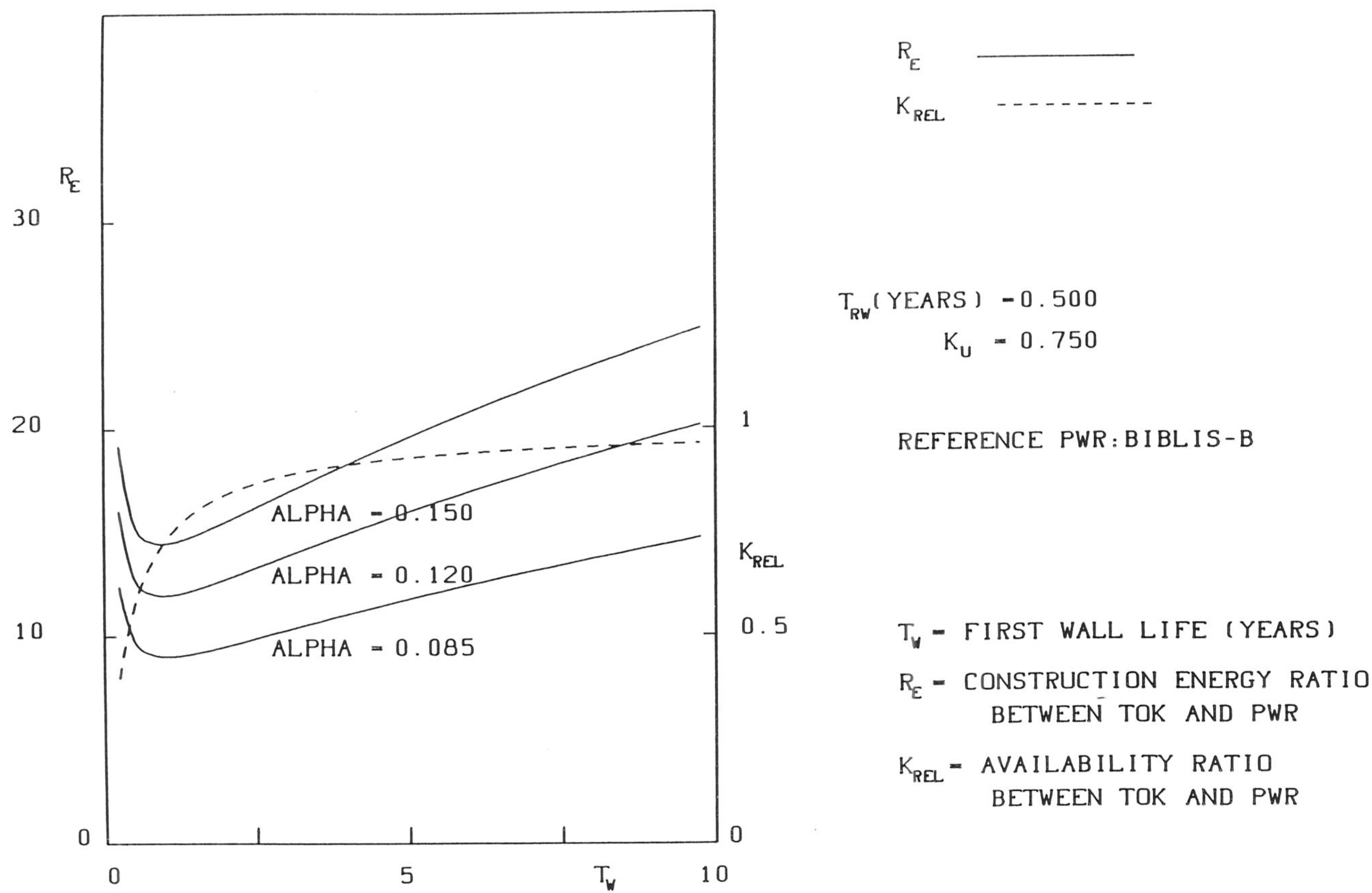

R_E
K_{REL}
T_{RW} (YEARS) -0.500
K_U = 0.750
REFERENCE PWR:BIBLIS-B
T_W - FIRST WALL LIFE (YEARS)
R_E - CONSTRUCTION ENERGY RATIO BETWEEN TOK AND PWR
K_{REL} - AVAILABILITY RATIO BETWEEN TOK AND PWR
ALPHA = 0.150
ALPHA = 0.120
ALPHA = 0.085
30
20
10
0
1
0.5
0
5
10
T_W

Fig. 5b

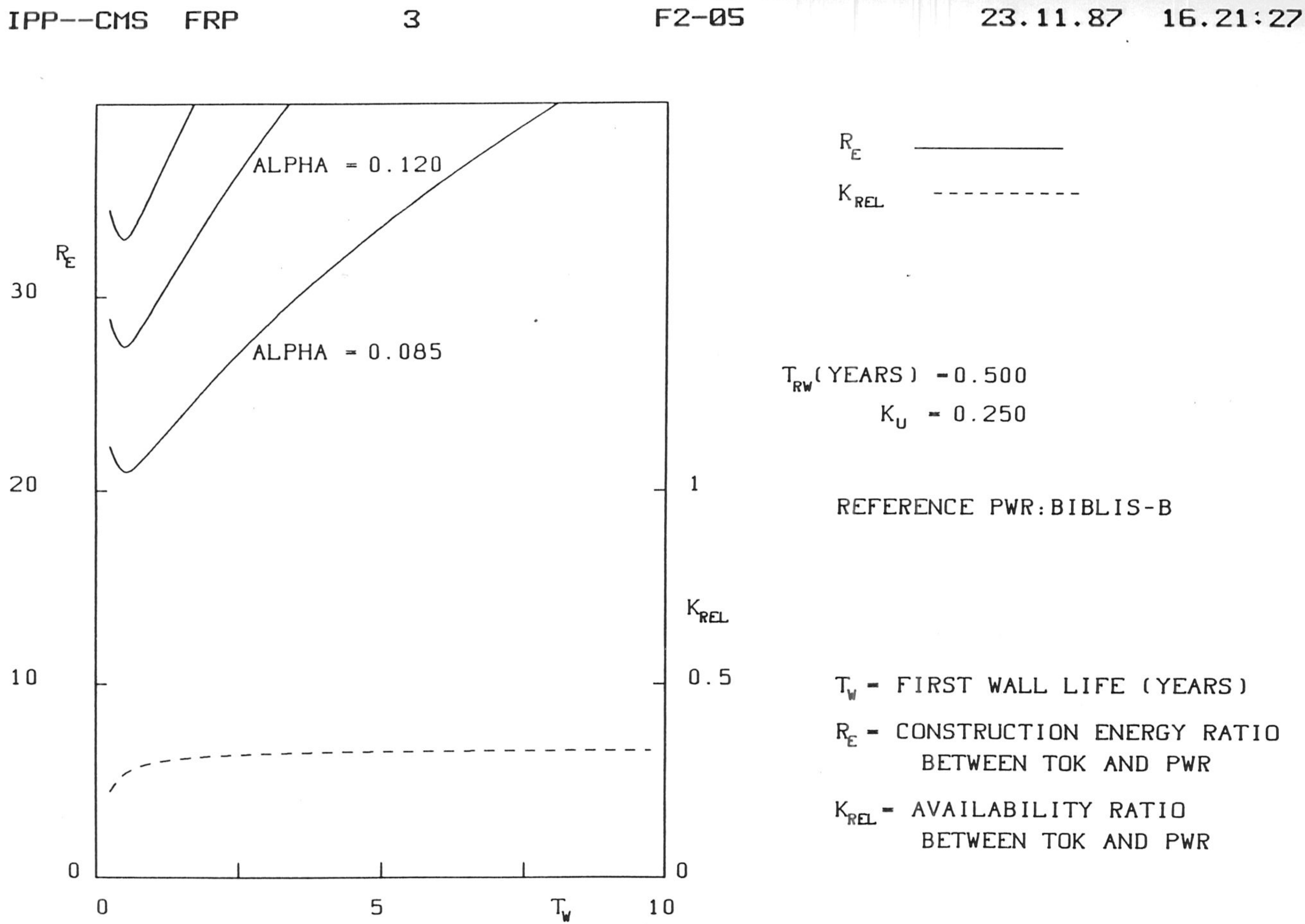

IPP--CMS FRP 3 F2-05 23.11.87 16.21:27
ALPHA = 0.120
ALPHA = 0.085
R_E
30
20
10
0
0
5
T_W
10
1
K_{REL}
0.5
0
R_E
K_{REL}
T_{RW}(YEARS) = 0.500
K_U = 0.250
REFERENCE PWR:BIBLIS-B
T_W - FIRST WALL LIFE (YEARS)
R_E - CONSTRUCTION ENERGY RATIO BETWEEN TOK AND PWR
K_{REL} - AVAILABILITY RATIO BETWEEN TOK AND PWR

Fig. 5c

IPP--CMS FRP 4 F2-05 23.11.87 16.21.28

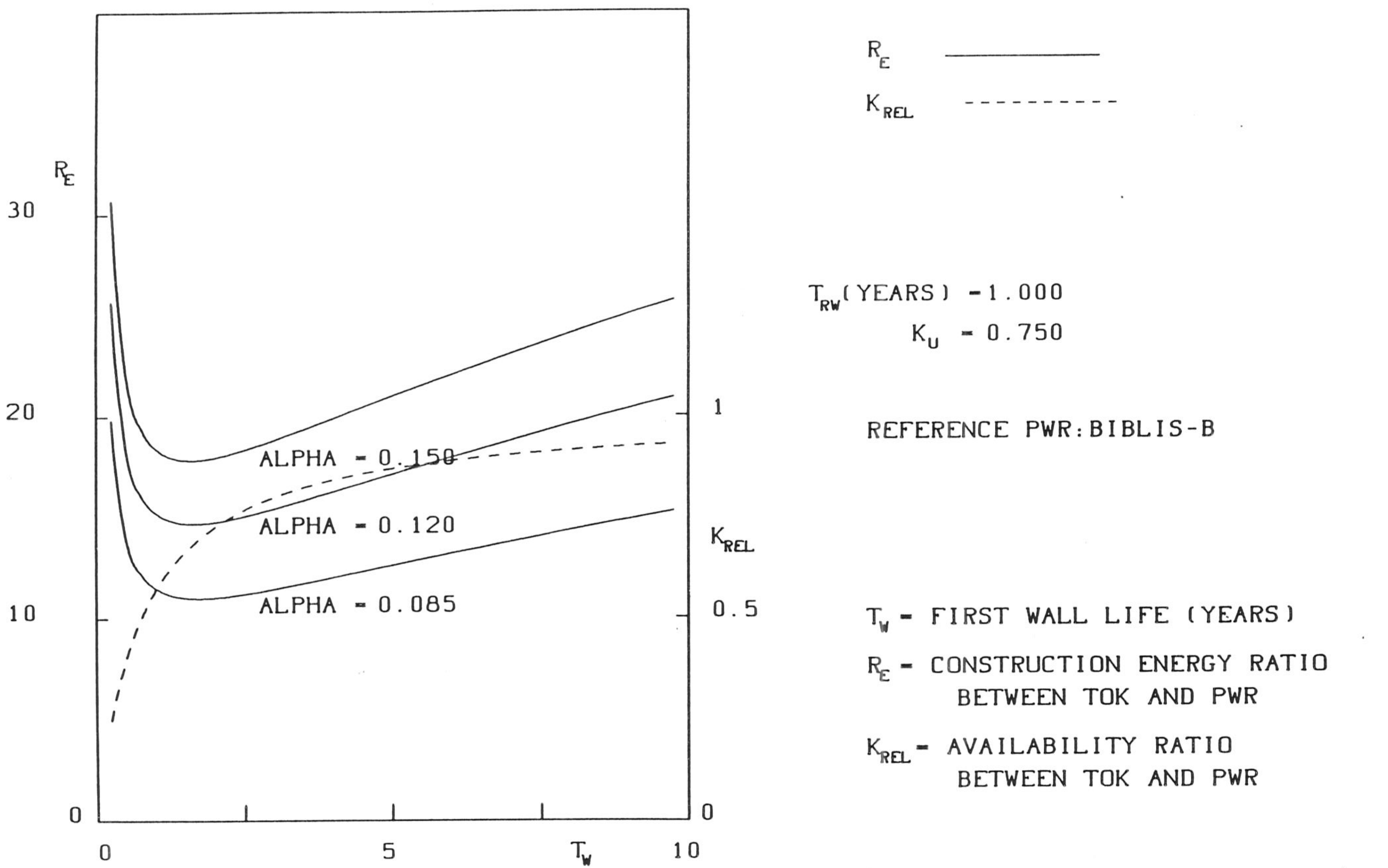


Fig. 5d

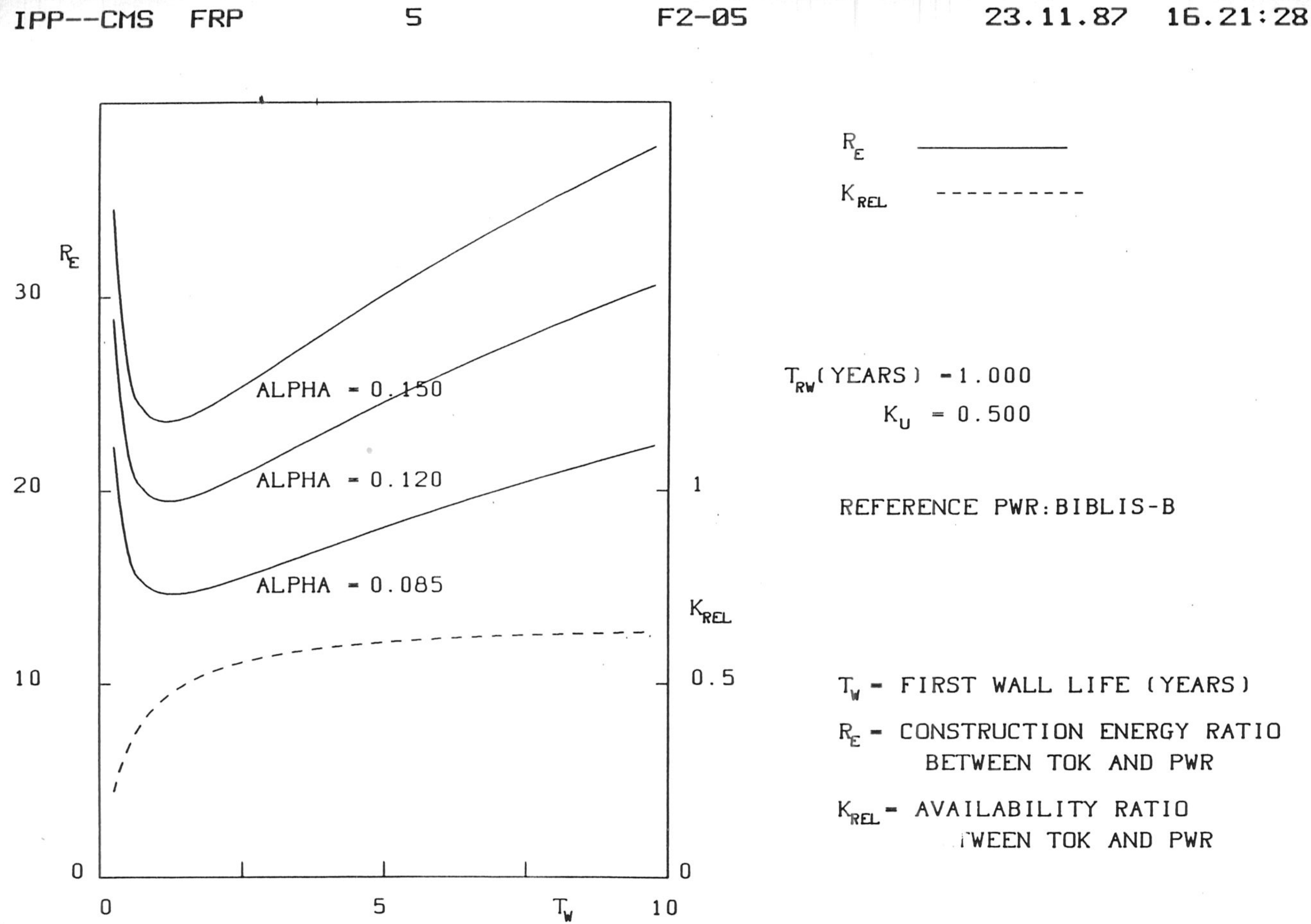
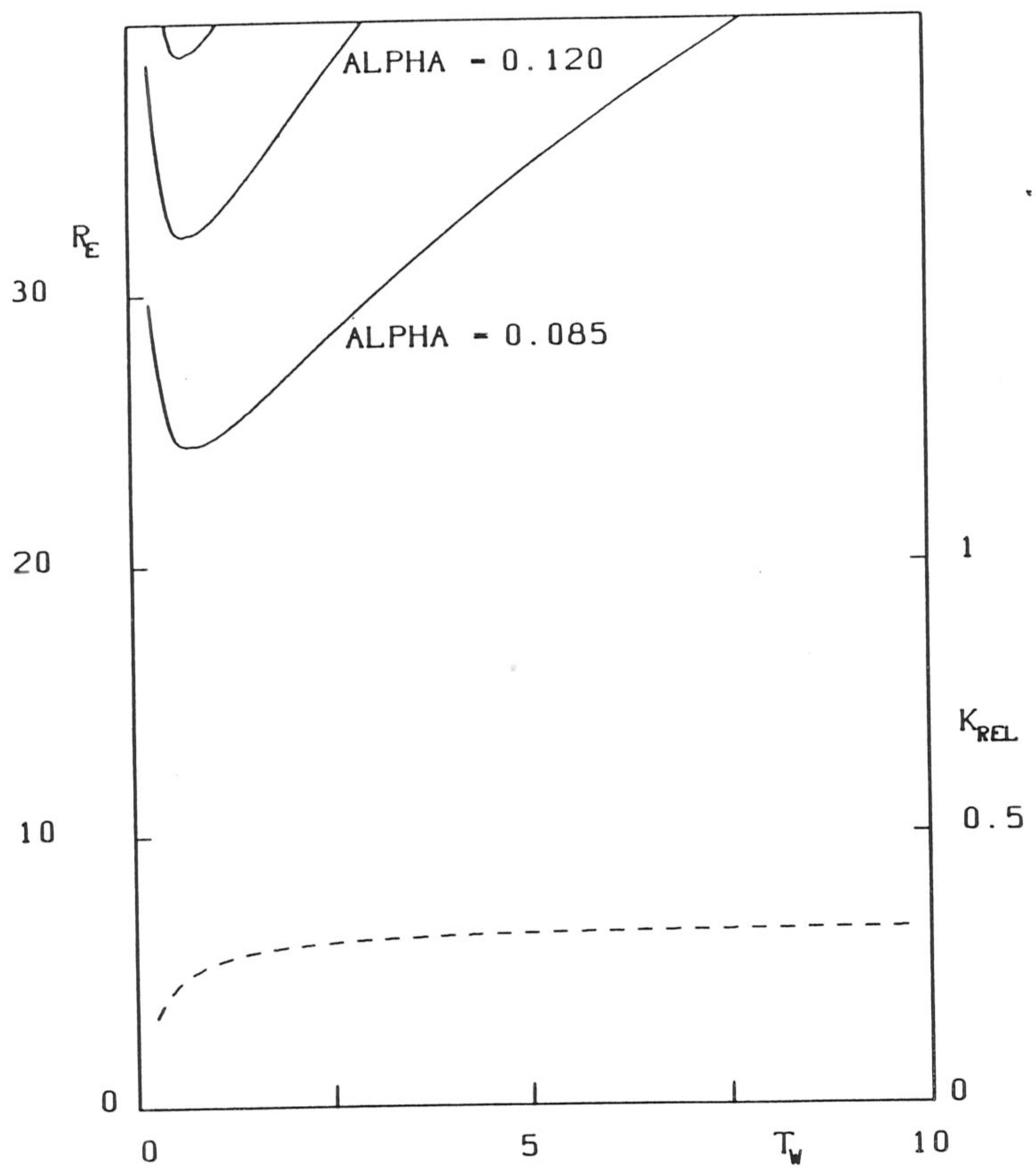

IPP--CMS FRP 5 F2-05 23.11.87 16.21:28
R_E
30
20
10
0
0
5
T_W
10
1
K_REL
0.5
0
ALPHA = 0.150
ALPHA = 0.120
ALPHA = 0.085
R_E
K_REL
T_RW (YEARS) = 1.000
K_U = 0.500
REFERENCE PWR: BIBLIS-B
T_W = FIRST WALL LIFE (YEARS)
R_E = CONSTRUCTION ENERGY RATIO
BETWEEN TOK AND PWR
K_REL = AVAILABILITY RATIO
TWEEN TOK AND PWR

Fig. 5e



R_E ————
K_{REL} - - - - - -

T_{RW}(YEARS) - 1.000
K_U - 0.250

REFERENCE PWR: BIBLIS-B

T_W - FIRST WALL LIFE (YEARS)

R_E - CONSTRUCTION ENERGY RATIO BETWEEN TOK AND PWR

K_{REL} - AVAILABILITY RATIO BETWEEN TOK AND PWR

Fig. 5f