

Evaluation of the Energy Required
for Constructing and Operating
a Fusion Power Plant

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ABSTRACT

The energy required for constructing and operating a tokamak fusion power plant is appraised with respect to the energy output during the lifetime of the plant. A harvesting factor is deduced as a relevant figure of energetic merit and is used for a comparison between fusion, fission, and coal-fired power plants. Because fusion power plants involve considerable uncertainties the comparison is supplemented by a sensitivity analysis. In comparison with Light Water Reactor plants fusion power plants appear to be rather favourable in this respect. The energy required for providing the fuel is relatively low for fusion plants, thus overcompensating the considerably higher amount of energy necessary for constructing the fusion power plant.

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1. INTRODUCTION

In recent years the principle of net energy balancing has been applied not only to fission and conventional power plants but also to fusion power plants, the latter being represented only by designs. The principle of this kind of balancing comprises mainly three parts:

- determination of the energy input for constructing and operating the plant during its lifetime,
- determination of the energy output likely to be delivered by the plant during its lifetime,
- calculation of a figure of merit from the previously determined input and output energies.

However, this principle only seems to be very plausible. As can be seen from evaluation of the literature [1], differences in definitions and assumptions yield results that differ by more than one order of magnitude for the same type of power plant. These differences mainly refer to the method of accounting the energy input - process chain analysis or energetic input/output method - to the evaluation of the electric energy - as equivalent primary energy or as dissipated electric energy-, and to the kind of figure of energetic merit defined for relative evaluation of the input and output energies. Thus, in order to achieve reliable results, it was necessary to develop first of all such a figure of merit on the basis of commonly accepted criteria for the assessment of energy conversion systems. Definitions and assumptions are afterwards chosen in keeping with this figure of merit.

2. A CONSISTENT ASSESSMENT SCHEME

An energy conversion system comprises all installations necessary to convert an energy raw material from its natural state into a useful form of energy. An energy gain, of course, is only achieved by such a system if the total amount of useful energy delivered is larger than the sum of all energy expenditures necessary for installing and operating the system. The difference between these two energies, i.e. the net energy gain, is a measure of the gain obtained from an energy raw material by means of a certain conversion system. Relating this gain to the above-named sum of energy expenditures yields an energy gain factor. The estimated net gain and the gain factor characterize the energetic attractiveness of utilizing a certain energy raw material and therefore indicate whether it is energetically profitable to develop the adherent conversion system. It will be shown that both magnitudes can be expressed by a so-called harvesting factor.

2.1 The harvesting factor as a figure of energetic merit

Starting from the definition given above, one can calculate the potential net energy gain E_{GN} from an energy raw material:

$$E_{GN} = \eta_c \cdot e \cdot M_{FR} , \quad (1)$$

with M_{FR} = mass of fuel reserves or resources, e = specific gain of primary energy from the fuel (e.g. the calorific power of a fossil fuel or the burn-up of nuclear fuel), and η_c = overall efficiency of converting the primary energy into a required form of secondary energy, taking into account all energy expenditures from fuel prospecting to auxiliary supply of the conversion plant. In the following, consideration will be restricted to the conversion of primary energy from a fuel to electric energy. Figure 1 represents all energy flows of such a thermal-electric energy conversion system during the lifetime of the plant. It is assumed that the total conversion efficiency of this system is identical with efficiency η_c representing the mean value over all plants installed and operated to exploit the total fuel reserves or resources.

The energy flow diagram in Fig. 1 comprises the entire conversion from the fuel energy to the final energy gain, taking into account all energy expenditures for constructing and operating the system during its lifetime. (Index L in Fig. 1 designates integral values over the lifetime). The fuel energy $E_{F,L}$ is supplemented by the thermally dissipated auxiliary energy $E_{th,A,L}$ to the total thermal energy input $E_{th,L}$ of the power plant. This energy is converted to the electric gross energy $E_{g,L}$ with a certain thermal efficiency, the losses produced being designated as $E_{v,L}$. Reducing the gross energy by the energy requirements of the internal auxiliary supply systems of the power plant $E_{A,L}$ - only part of this ($E_{A,V,L}$) are real losses - yields the net electric energy output $E_{n,L}$ of the plant. However, in order to determine the real energy gain $E_{G,L}$ of the conversion, all additional energy expenditures $E_{E,L}$ have to be deduced. These expenditures occur in two different time regions: before commissioning of the plant energy is required for constructing the plant itself ($E_{CON P}$), for constructing the installations for fuel supply ($E_{CON F}$) and for producing the first fuel core ($E_{F FIRST}$); after commissioning of the plant a certain amount of energy is necessary for the operation of the plant (e.g. for maintenance and repairs) ($E_{OP P, L}$) and the fuel supply requires energy ($E_{OP F, L}$).

From Fig. 1 the above defined overall efficiency η_c reads

$$\eta_c = \frac{E_{G,L}}{E_{F,L}} \quad (2)$$

$$\text{with } E_{G,L} = E_{n,L} - E_{E,L} .$$

Defining the net efficiency of the power plant as

$$\eta_n = \frac{E_{n,L}}{E_{F,L}} \quad (3)$$

and expressing the fuel energy as the mass of fuel $M_{F,L}$ and the specific gain of primary energy from the fuel e as

$$E_{F,L} = e \cdot M_{F,L} \quad (4)$$

then yields from eq. (2)

$$\eta_c = \eta_n \left(1 - \frac{E_{E,L}}{\eta_n \cdot e \cdot M_{F,L}} \right) \quad (5)$$

With this expression the total net energy gain (eq. (1)) reads

$$E_{GN} = \eta_n \left(1 - \frac{E_{E,L}}{\eta_n \cdot e \cdot M_{F,L}} \right) \cdot e \cdot M_{FR} \quad (6)$$

From eqs. (3) and (4) one gets

$$E_{n,L} = \eta_n \cdot e \cdot M_{F,L} \quad (7)$$

Hence the quotient in the bracket of eq. (6) can be designated as the harvesting factor of the power plant at the end of its lifetime:

$$H_L = \frac{\eta_n \cdot e \cdot M_{F,L}}{E_{E,L}} \quad (8)$$

Equation (6) then reads

$$E_{GN} = \eta_n \left(1 - \frac{1}{H_L} \right) \cdot e \cdot M_{FR} \quad (9)$$

Besides this net energy gain, the ratio of this gain to the total sum of energy expenditures E_E was defined as a characterizing magnitude.

Rearranging eq. (6) yields

$$E_{GN} = \eta_n \cdot e \cdot M_{FR} - \frac{E_{E,L} \cdot M_{FR}}{M_{F,L}}, \quad (10)$$

where the first term represents the total net electric energy that can be produced from the total mass of fuel reserves or resources, and the second term represents the total sum of energy expenditures E_E required for exploiting the total fuel mass:

$$E_E = E_{E,L} \cdot \frac{M_{FR}}{M_{F,L}}. \quad (11)$$

The quotient of E_{GN} and E_E then reads

$$\frac{E_{GN}}{E_E} = \frac{\eta_n \cdot e \cdot M_{F,L}}{E_{E,L}} - 1. \quad (12)$$

With eq. (8) this yields

$$\frac{E_{GN}}{E_E} = H_L - 1. \quad (13)$$

Thus the influence of the energy expenditures for constructing and operating the conversion system on the absolute (eq. (9)) and relative (eq. (13)) energy gain can be represented by the influence of the lifetime harvesting factor H_L .

2.2 Sensitivity of the energy gain

For simplicity, the products $\eta_n \cdot e \cdot M_{F,L}$ and $\eta_n \cdot e \cdot M_{FR}$ will be kept constant in order to isolate the influence of energy expenditures expressed by the harvesting factor. Thus, the total net energy gain depends (see eq. (9)) on the harvesting factor as

$$E_{GN} \sim 1 - \frac{1}{H_L} \quad (14)$$

The expression $1 - \frac{1}{H_L}$ as a function of H_L is shown in Fig. 2. It represents the importance of H_L the absolute values of H_L . It is noteworthy that for the small value $H_L = 2.5$ already 60 % of the theoretical maximum of E_{GN} is achieved, and 80 % at $H_L = 5.0$. Additional doubling of H_L increases the percentage by only 10 % (additive). With respect to uncertainties of the fuel reserves M_{FR} a utilization of 80 % of the maximum energy reserve should be sufficient, corresponding to the lifetime harvesting factor of $H_L = 5$. Higher values are, of course, welcome but strong efforts to achieve them are scarcely worthwhile.

An advantageous effect of slightly higher H_L values (e.g. $H_L = 10$) is the reduced sensitivity of the net energy gain E_{GN} to deviations of H_L . This is shown in Fig. 3, where relative changes of E_{GN} are represented as functions of relative changes of H_L with a varying reference value of $H_{L Ref}$ as parameter. On the basis of eq. (14) the respective relation is

$$\frac{E_{GN}}{E_{GN Ref}} = \frac{1 - \frac{1}{H_L}}{1 - \frac{1}{H_{L Ref}}} \quad (15)$$

If the harvesting factor H_L is uncertain around the reference value $H_{L Ref}$ by $\pm 0.5 \cdot H_{L Ref}$ (see Fig. 3), this corresponds to a margin of E_{GN} between 75 % and 108 % at $H_{L Ref} = 5.0$, and a margin between 89 % and 104 % at $H_{L Ref} = 10.0$.

Thus, as far as the absolute net energy gain is concerned, lifetime harvesting factors of $H_{L \text{ Ref}} \approx 10$ would be sufficient and even values of $H_{L \text{ Ref}} \geq 5.0$ would be acceptable.

The relative energy gain as given by eq. (13) is simply linearly dependent on this harvesting factor. The sensitivity of this gain therefore depends on the magnitude of the reference harvesting factor $H_{L \text{ Ref}}$ according to

$$\frac{E_{GN}/E_E}{(E_{GN}/E_E)_{\text{Ref}}} = \frac{H_L - 1}{H_{L \text{ Ref}} - 1} \quad (16)$$

This expression is illustrated in Fig. 4 with $H_{L \text{ Ref}}$ as parameter. The sensitivity is the lower the higher the reference value $H_{L \text{ Ref}}$. If again the harvesting factor H_L is uncertain around the reference value $H_{L \text{ Ref}}$ by $\pm 0.5 \cdot H_{L \text{ Ref}}$, this corresponds to a margin of E_{GN}/E_E between 38 % and 163 % at $H_{L \text{ Ref}} = 5.0$, and a margin between 44 % and 156 % at $H_{L \text{ Ref}} = 10.0$. So the relative energy gain is much more sensitive to changes of H_L than the absolute energy gain. However, the theoretical minimum of sensitivity is achieved for $H_{L \text{ Ref}} \rightarrow \infty$; in this case the respective margin is between 50 % and 150 %. It can therefore be concluded that - again - a value of $H_{L \text{ Ref}} \approx 10$ would already be sufficient and values of $H_{L \text{ Ref}} \geq 5.0$ could be tolerated. This statement can be taken as a general result of the sensitivity consideration. Values of $H_{L \text{ Ref}} > 10$ are, of course, welcome, but serious efforts to achieve them are not worthwhile.

2.3 The harvesting factor as a function of time

Until now only the harvesting factor at the end of the lifetime of the conversion system has been considered. However, it might be of some interest to extend the consideration to the time dependence of this factor. Starting from zero at the time of commissioning of the plant, it increases after a certain time to the value unity when the output just equalizes the expenditures, and finally it achieves its maximum value at the end of the lifetime of the system.

An expression for calculating the time-dependent harvesting factor can be derived from eq. (8) with eqs. (3) and (4) and from Fig. 1,

$$H_L = \frac{E_{n,L}}{E_{CON} + E_{F \text{ FIRST}} + E_{OP,L}}, \quad (17)$$

by assuming that the energy output $E_{n,L}$ and the operational expenditures $E_{OP,L}$ are equally distributed over the lifetime t_L , thus yielding lifetime averaged powers E/t_L . Equation (17) can then be transformed to

$$H(t) = \frac{(E_{n,L}/t_L) \cdot t}{E_{CON} + E_{F \text{ FIRST}} + (E_{OP,L}/t_L) \cdot t}. \quad (18)$$

With the mean net electric power output

$$P_n = \frac{E_{n,L}}{t_L}, \quad (19)$$

the mean expenditure of operational power

$$P_{OP} = \frac{E_{OP,L}}{t_L}, \quad (20)$$

and the sum of energy expenditures before commissioning of the system

$$E_{BC} = E_{CON} + E_{F \text{ FIRST}}$$

eq. (18) can be written as

$$H(t) = \frac{P_n \cdot t}{E_{BC} + P_{OP} \cdot t}. \quad (21)$$

This equation is illustrated in principle in Fig. 5. Here $t = 0$ designates the time of commissioning the system where $H(t=0) = 0$. The inclination of the $H(t)$ curve at this point is given by the tangent

$$H_0(t) = \frac{P_n}{E_{BC}} \cdot t. \quad (22)$$

For large values of t the $H(t)$ curve approaches the asymptotic line of

$$H_a(t) = \frac{P_n}{P_{OP}}. \quad (23)$$

Thus, at a given value for the net power output P_n of the conversion plant the inclination of $H(t)$ at $t = 0$ is the higher the lower the energy expenditures E_{BC} before commissioning of the plant. The asymptotic line is the higher the lower the power expenditure P_{OP} during operation.

In comparing two different conversion systems constructed for the same net power output and with the same total sum of energy expenditures (\cong same H_L -value), the curves $H(t)$ may be quite different if the distributions of these expenditures between "before commissioning"

$$E_{BC} = n \cdot E_{E,L} \quad (24)$$

and "during operation"

$$P_{OP} \cdot t_L = (1 - n)E_{E,L} \quad (25)$$

are different. (According to eq. (24) n is defined as the quotient of energy expenditures before commissioning to total energy expenditures).

The influence of n on the $H(t)$ curves can be shown in a general way by expressing the normalized harvesting factor $H(t)/H_L$ as a function of t/t_L . Equation (21) for t and for $t = t_L$ yields

$$\frac{H(t)}{H_L} = \frac{E_{BC} + P_{OP} \cdot t_L}{E_{BC} + P_{OP} \cdot t} \cdot \frac{t}{t_L}, \quad (26)$$

which can be transformed by using eqs. (24) and (25) to

$$\frac{H(t)}{H_L} = \frac{1}{1 + n(t_L/t - 1)}. \quad (27)$$

This equation is illustrated in Fig. 6. If all energy is required before commissioning ($n = 1$), the harvesting factor is proportional to the time. If, on the contrary, no energy is required before commissioning ($n = 0$), the harvesting factor achieves its maximum value just after commissioning,

remaining constant, however, until the end of the lifetime of the plant. These two limiting cases are only of theoretical interest. In reality, n may vary between approximately 0.1 and 0.9.

On the assumption that two power plants to be compared have the same lifetime harvesting factor H_L but different n -values, the energy "break-even" point ($H = 1$) will be achieved after time spans of operation which are the longer the higher the n -values are. These time spans are generally called "pay-back times". Thus, even in the case where two conversion systems are energetically equally profitable (same H_L) the pay-back times may vary drastically because of the different distribution of energy expenditures between "before commissioning" and "during operation". Solving eq. (27) for this case, which is represented by

$$H = 1 \quad \text{at} \quad t = t_{pb} \quad ,$$

yields

$$\frac{t_{pb}}{t_L} = \frac{1}{1 + 1/n (H_L - 1)} \quad . \quad (28)$$

This equation is illustrated in Fig. 7, where t_{pb}/t_L is shown as a function of n with H_L as parameter. For low H_L -values t_{pb}/t_L drastically increases with n . For higher values of H_L this dependence diminishes considerably, but even at high H_L -values the pay-back time increases linearly with n . Whereas the energy gain of an energy conversion system is entirely represented by the lifetime harvesting factor H_L (see Sec. 2.1) the pay-back time can be extremely misleading about the energy gain e.g. if n is small. Thus, it must be clearly stated that the pay-back time is not at all an adequate figure of merit to judge the energetic profitability of an energy conversion system. The pay-back time might have a certain importance only if two systems to be compared show the same H_L -value: in this case the shorter pay-back time signals an earlier energy break-even point, which could be advantageous with respect to market introduction strategies.

As far as fusion power plants are concerned, determination of the harvesting factor $H(t)$ requires - according to eq. (18) - determination of the net energy output of the plant during its lifetime, the energy expenditures for constructing the plant and providing the first fuel, and the expenditures for operating the plant during its lifetime. This, however, makes it necessary to discuss first the methods available for energy accounting and to decide on the method best suited for fusion power plants.

3. ENERGY ACCOUNTING FOR A FUSION POWER PLANT

In view of the fact that fusion power plants only exist in the design state a special way of energy accounting has been developed. Its deduction and application are described in [2], so that it is sufficient here to describe the basic idea and the results.

In principle, two methods are used for energy accounting of goods, the input/output (I/O) method and the process chain analysis (PCA) method. The I/O method is based on multiplying the cost of a commodity by the average energy load of a monetary unit produced in the respective economic sector. The PCA method is based on multiplying the mass of materials by the energy load of the unit of mass which has been determined by summing up all energy input in the course of processing that material. In general, the first method is preferred because the energy load values of the monetary unit completely include all indirect energy expenditures, whereas the completeness of the determination of these is doubtful with the process chain analysis. However, the more sophisticated the produced commodity the larger the percentage of weakly energy-relevant or non-energy-relevant costs, such as for services (engineering), complexity of assembly, quality assurance, and contingencies for licensing and market risks. Thus, the I/O method yields too high energy input values for the construction of nuclear power plants, especially for the nuclear-specific components. This is even more true of fusion reactors because the fusion-specific components are probably more complicated than the fission-specific components, the estimated costs of a fusion power plant thus being even less relevant for energy input calculations.

In order to keep the level of overestimation of the energy input to that for fission plants, it has been assumed that the energy input, as calculated by the I/O method, divided by the energy input calculated by the PCA method is the same for fission (LWR) and fusion (FR) plants:

$$\left(\frac{E_{I/O}}{E_{PCA}} \right)_{FR} = \left(\frac{E_{I/O}}{E_{PCA}} \right)_{LWR} \quad (29)$$

This is true in good approximation because the percentages of the industrial sectors participating in the construction of plants do not differ considerably. According to the above definition of the PCA method the respectively calculated energy input is given by

$$E_{PCA} = \sum_{j=1}^k (m_j \cdot e_{mj}) \quad (30)$$

with k = number of materials used,
 m_j = mass of installed material j ,
 e_{mj} = energy load of unit mass of material j .

Equations (29) and (30) can be transformed to

$$\left(\frac{E_{I/O}}{E_{PCA}} \right)_{FR} = \left(\frac{E_{I/O}}{E_{PCA}} \right)_{LWR} \frac{\sum_{j=1}^{k_{FR}} (m_{j,FR} \cdot e_{mj})}{\sum_{j=1}^{k_{LWR}} (m_{j,LWR} \cdot e_{mj})} \quad (31)$$

Thus, calculating the energy input for a fusion power plant $(E_{I/O})_{FR}$ requires the energy input calculated for a LWR plant $(E_{I/O})_{LWR}$ and the masses m_j of materials for constructing both plants together with the respective energy loads e_{mj} per unit mass.

The reference value $(E_{I/O})_{LWR}$ was taken from [3], the masses of materials for the LWR plant were collected from the extensive literature and from industry, and the masses of materials for the fusion plant were calculated by means of the so-called SISYFUS code [4] developed at IPP and various plant designs published. All data are given in [2], from which the final result shown in Fig. 8 is also taken. The left-hand scale in this figure gives E_{PCA} values (see eq. (30)), the right-hand scale shows $E_{I/O}$ values (according to eq. (31)). Cases (A) and (B) designate LWR plant data differing between suppliers, cases (1) and (2) designate different coolants of the fusion reactor blanket (see Fig. 8). The maximum energy input factor for plant construction of fusion and LWR power plant is 1.9. Thus, with allowance for some uncertainties, the energy input for constructing a fusion plant can be regarded roughly as double that necessary to construct a LWR plant with the same net power output.

4. COMPARISON OF FUSION, FISSION, AND COAL-FIRED POWER PLANTS

As was shown in Sec. 2.1, the lifetime harvesting factor H_L is an adequate figure of merit for characterizing a certain power plant with respect to its energetic gain. It is therefore suited as a magnitude for comparing different power plants in this respect. According to eqs. (7) and (8) H_L is the quotient of the lifetime net energy output $E_{n,L}$ and the sum of all energy expenditures $E_{E,L}$ occurring during construction of the plant throughout its lifetime:

$$H_L = \frac{E_{n,L}}{E_{E,L}} \quad (31)$$

(for explanation see also Fig. 1). Thus, it makes sense to compare various types of power plants by representing $E_{E,L}$ on the one hand and $E_{n,L}$ on the other.

4.1 Comparison of energy input and output

A comparison between the various types of power plants has to include in the input not only the energy for constructing the plant itself but also a certain percentage for constructing the fuel supply installations, and the energy for providing the fuel and for general maintenance and repair (see Fig. 1). Figure 9a shows the respective data as already given in [2], in which the fission and coal plant data were taken from [3]. As can easily be seen, the total energy input for construction and operation of the Fusion Reactor (FR) plant is much less than that for the LWR, High Temperature Reactor (HTR), and coal-fired plants and is nearly the same as for Fast Breeder Reactor (FBR) plants. The magnitude of the differences between FR on the one hand and LWR and HTR plants on the other depends on the conditions of fission fuel supply, i.e. the U content of the ore and the kind of the enrichment process. Since the provision of the fusion fuel requires very low energy input. Considering only the energy input before commissioning of the plant (for construction and first fuel core), the LWR values for diffusion enrichment at 0.2 % U content in ore and for centrifuge enrichment at 0.02 % U content in ore do not significantly differ from the respective values of the fusion plant. The HTR values for the respective cases are slightly higher than the LWR data, the coal-fired plant being that with the lowest energy input before commissioning.

The bars of Fig. 9a are shown on a drastically reduced scale at the bottom of Fig. 9b, in which the energy output during the lifetime of the plant is represented by the bars at the top. This output energy, too, is given as the thermal equivalent of the electric energy, the load factor f being varied between 0.6 and 1.0. The general impression is that the output far exceeds the input even in the worst LWR case. The fusion power plant compares quite favourably with the other plant types. The ratio of the

length of the bars is - according to eq. (31) - a measure of the lifetime harvesting factor H_L . However, in order to show the influence of the time span in which the energy input is required - before or after commissioning - the time dependent harvesting factor $H(t)$ has to be considered.

4.2 Comparison of harvesting factors as a function of time

For simplicity, this comparison is restricted to the LWR cases and the fusion plant. It is intended to include FBR-plants in this comparison at a later time when the respective data are available in a sufficiently detailed form. For the five sets of LWR and FR data which are given in Table 1 (data taken or calculated from [2] and [3]) the harvesting factor $H(t)$ as given in eq. (18) is represented in Fig. 10 as a function of the full-load operation time which ends at 24 years (lifetime 30 years at load factor 0.8). Because the LWR case "Centrifuge enrichment, 0.2 % U content in ore" is unrealistic (the ore of that U content will be depleted when the centrifuge process is fully introduced, if ever), an optimistic LWR case was constructed by averaging the U content between 0.2 and 0.02 % for fully introduced centrifuge process (see also Table I). Even in this case there is no crossing of the FR and LWR lines since E_{BC} (Table 1) for LWR remains slightly higher than for FR plants. In addition, one has to bear in mind that no reserves of enriched fuel have been taken into account. According to [5], however, such reserves for 2 to 4 years of operation are generally stored by the electric utility, occasioning once again an energy input before commissioning of the order of that required for the first fuel core. The value of E_{BC} would thereby be increased, e.g. in the LWR (C, average) case by 30 %, the respective curve in Fig. 10 would be flatter but would nevertheless end at the same H_L value because only part of the total unchanged energy input has been shifted to the time span before commissioning. As the fuel supply for fusion power plant requires so much less energy, the same amount of fuel reserve would practically not alter the FR curve. Thus, the energetic superiority of the fusion power plant as expressed by Fig. 10 could be even higher.

However, one has to take into account that the LWR cases are calculated with a considerable amount of certainty, whereas the fusion data are based on designs representing only the state-of-the-art in fusion research and development. It is therefore necessary to analyse the influence of fusion uncertainties on the above results.

4.3 Sensitivity of results to fusion uncertainties

As far as the energy input for constructing and operating a fusion power plant is concerned, the uncertainties in fusion may be taken into account in three areas:

- Physical and technical problems of the reactor could result in an even higher increase of reactor masses of material as compared with the LWR than by the factor 32.2, which was calculated in [2]. An additional increase of this value is expressed by multiplying it by a factor n_{MR} (index M for masses, R for reactor), an upper limit of which has been estimated to be $n_{MR} = 2.0$.
- The fusion reactor requires more non-ferrous and non-copper materials than a fission reactor. Thus, mistakes in the specific energy input e_{mj} (see eq. (30)), which include the energy until the respective component is assembled and incorporated ready for operation, may have a considerable bearing on the total energy input. In spite of the fact that these values have been calculated very carefully [2], an additional increase of them is expressed by a factor of $n_E = 4.0$. However, the choice of just this factor was merely academic in order to be safer against imponderables in this area, e.g. for certain production processes of components from rarely used materials.
- The operational energy requirement results from fuel supply, maintenance and repairs. As lithium has been included in the construction materials, there remains only the deuterium supply, the production energy of which is known with certainty. Mainly uncertain, however, is the energy requirement for repairs, especially for new first walls in the reactor. Originally, 900 Mg of respective materials

(10 new walls at 90 Mg each) had been assumed for the whole lifetime of the plant [2]. The considerable uncertainty in this area is expressed by increasing this value by one order of magnitude: $\eta_F = 10$.

The influence of the above factors on the harvesting factor is represented in Fig. 11. The reference curve is the upper line designated by all factors equal to one; this line is identical with the FR line in Fig. 10. Increasing in each case only one of the factors of the values given above leads to a decrease of the $H(t)$ curve. For $\eta_{MR} = 2.0$ and $\eta_E = 4.0$ the inclination of the curves is lower than in the reference case because only the energy expenditure before commissioning is increased. For $\eta_F = 10$ the inclination at $t = 0$ is unchanged, but it decreases with t because only the operational energy is affected by η_F . At the end of the lifetime the harvesting factor H_L is roughly the same in all three cases, being about 15 to 20 % lower than in the reference case.

If the three factors are all increased at the same time, the lowest curve in Fig. 11 represents the harvesting factor, this now being reduced to slightly less than 60 % of the reference curve. The comparison with the LWR (centrifuge; average U content) now shows a crossing of the lines: until a time of about 4 years of operation at full load the harvesting factor of the LWR plant is slightly higher than that of the FR plant. At the end of the lifetime, however, the FR plant harvesting factor H_L is a factor of 2.8 higher than that of the LWR plant. Even if all energy expenditures of the FR plant were doubled or - what would be equivalent - the load factor of this plant were reduced to half its value, the H_L value would remain higher than that of the LWR plant, this idea, however, being of only academic value because already the original calculation in [2] was made very cautiously.

Thus, it can be concluded that the energetic superiority of the fusion power plant in comparison with the LWR power plant even holds with drastic deterioration of the fusion plant.

5. CONCLUSIONS

The lifetime harvesting factor was deduced as a relevant figure of energetic merit for evaluating the energy expenditures for the construction and operation of an energy conversion system. With respect to this factor a fusion power plant based on a tokamak reactor is energetically superior to a fission power plant equipped with a Light Water Reactor, bearing in mind that fusion power plants today only exist as designs based on an extrapolation from present day tokamak experiments.

The energy input just for constructing a fusion power plant is roughly twice that for constructing the fission plant compared. However, the energy expenditures before commissioning the power plants do not differ very much because the energy requirement for providing the fission fuel first core may reach values which are as high as those for constructing the power plant, depending on the process of U enrichment and on the U content in the ore. The energy expenditures after commissioning are extremely different for the two types of power plants since the fission fuel supply requires up to more than two orders of magnitude more energy than the fuel supply, maintenance and repair of fusion plants. With respect to the lifetime harvesting factor this considerably overcompensates the higher energy input for construction. Even a drastic increase of energy expenditures for the fusion case does not change this result in principle.

Thus, the net energy balance of the fusion power plant considered is sufficiently favourable. However, the high percentage of weakly-or non-energy-relevant costs in nuclear power plant technology forbids conclusions on the economics to be drawn from the net energy balance.

6. ACKNOWLEDGEMENTS

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Table 1 Energy expenditures for constructing and operating power plants with Light Water Reactor (LWR) and Fusion Reactor (FR) in $MWh_{th} \text{ equiv}/(MWe \cdot 30 \text{ a})$

U in ore	LWR					FR
	0.2 %		0.02 %		0.11 % (average)	
U enr. proc.	D	C	D	C	C	
$E_{CON P}$	2160	2160	2160	2160	2160	4082
$E_{CON F}$	789	789	789	789	789	16
$E_{F FIRST}$	2281	399	4005	2123	1261	3
E_{BC}	5230	3348	6954	5072	4210	4101
$E_{OP,L}$	32290	5554	53738	27002	16278	87
$E_{E,L}$	37520	8902	60692	32074	20488	4188

(for explanation of designations see Fig. 1)

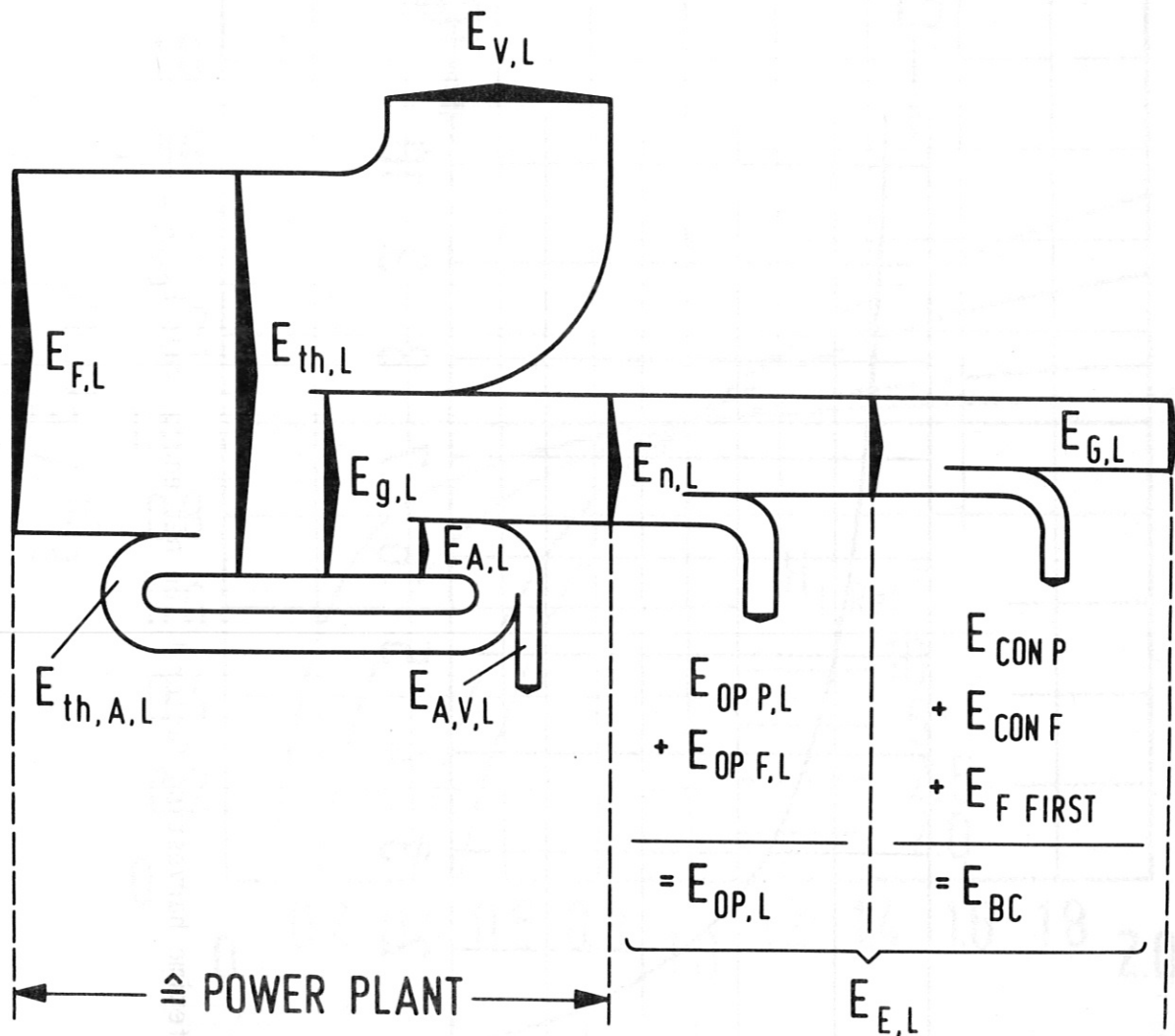


Fig. 1 Energy flows of a thermal - electric energy conversion system

(E = energy; E as index = expenditure; other indices: A = auxiliary; BC = before commissioning; CON = construction; F = fuel; FIRST = first core; G = gain; g = gross; L = integrated over lifetime; n = net; OP = operation; P = power plant; th = thermal; V = losses)

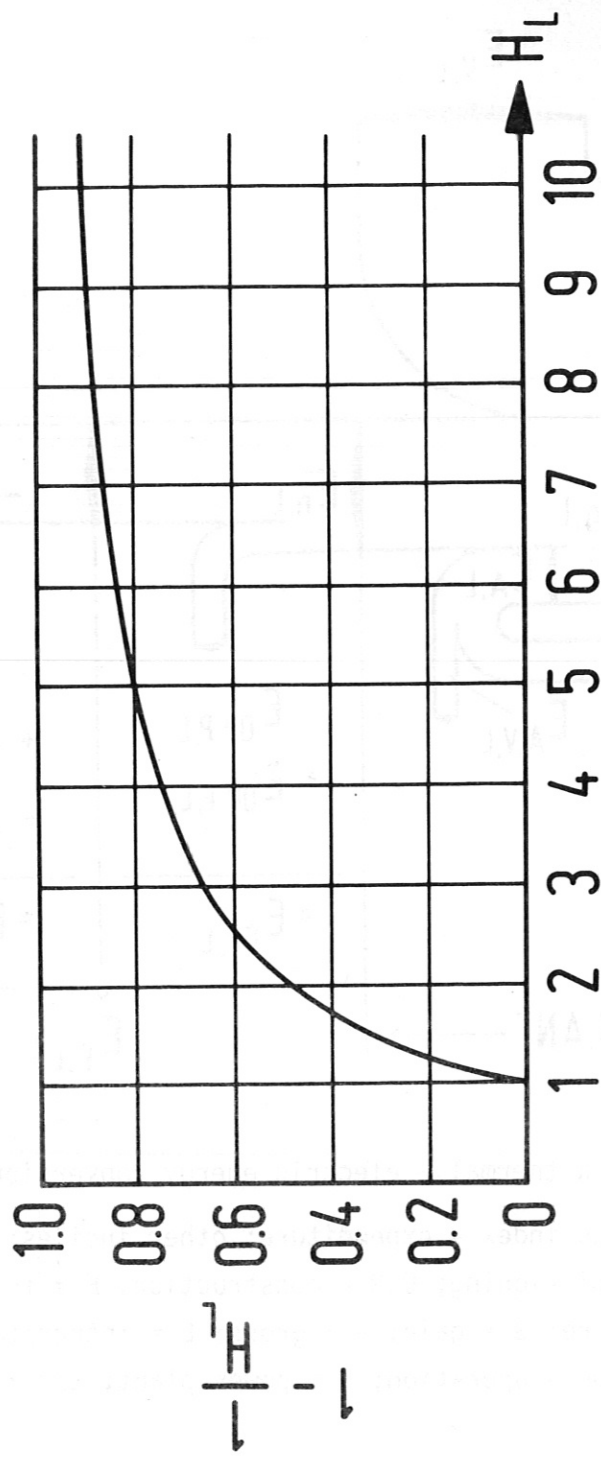


Fig. 2 Influence of lifetime harvesting factor H_L on net energy gain $E_{GN} \sim 1 - \frac{1}{H_L}$

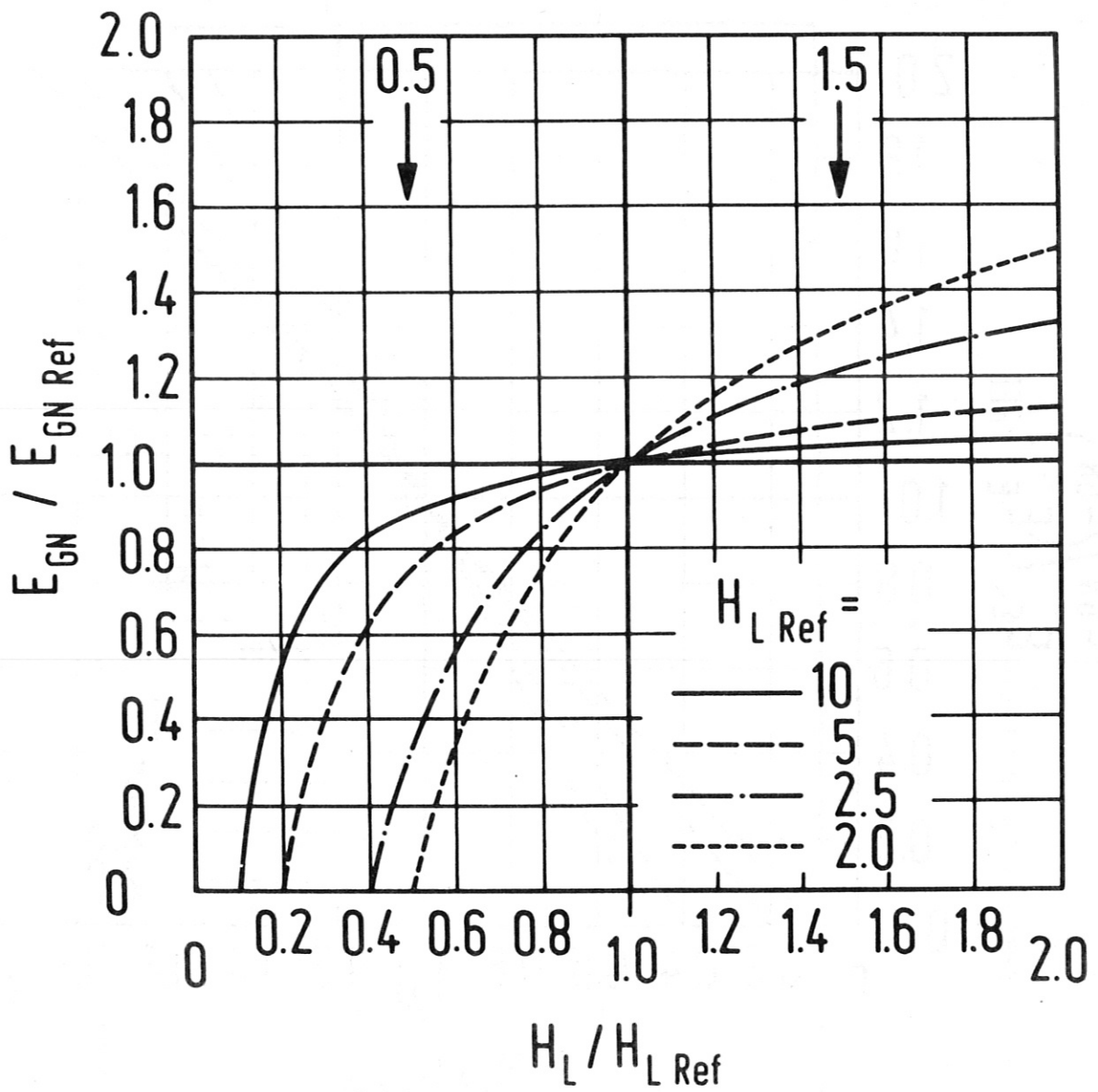


Fig.3 Sensitivity of absolute net energy gain E_{GN} to uncertainties of lifetime harvesting factor H_L

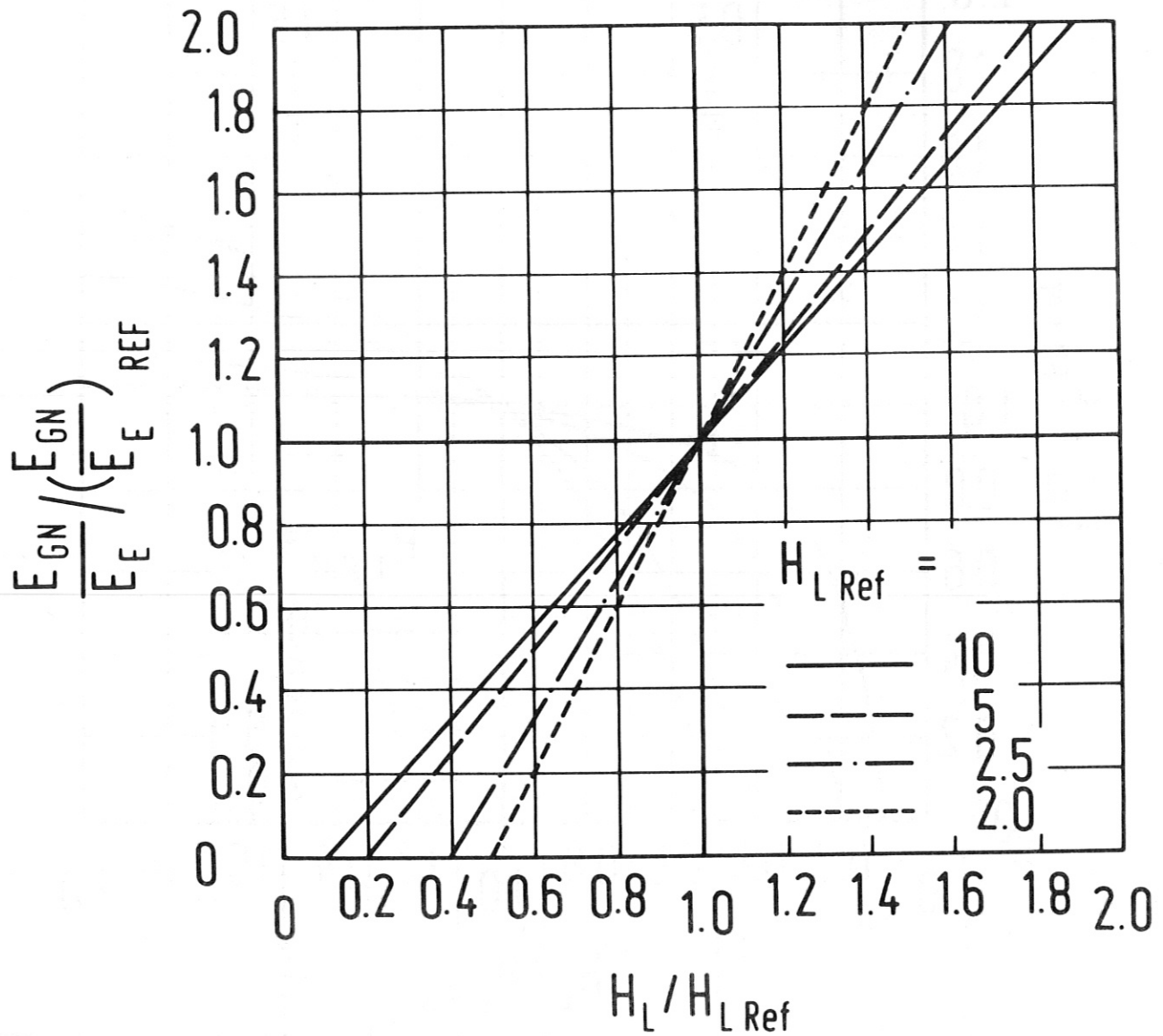


Fig. 4 Sensitivity of relative net energy gain E_{GN}/E_E to uncertainties of lifetime harvesting factor H_L

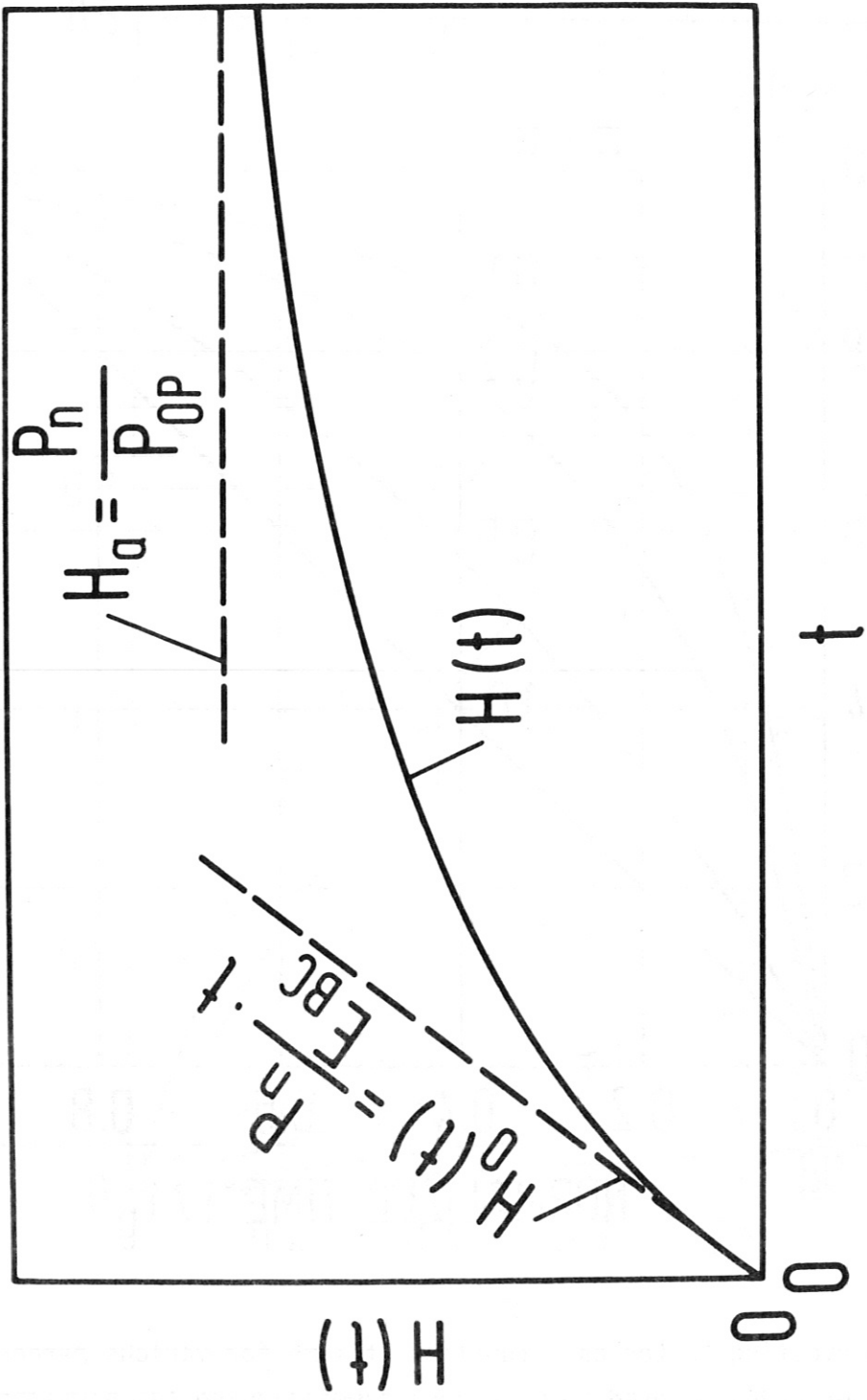


Fig. 5 Illustration of time - dependent harvesting factor

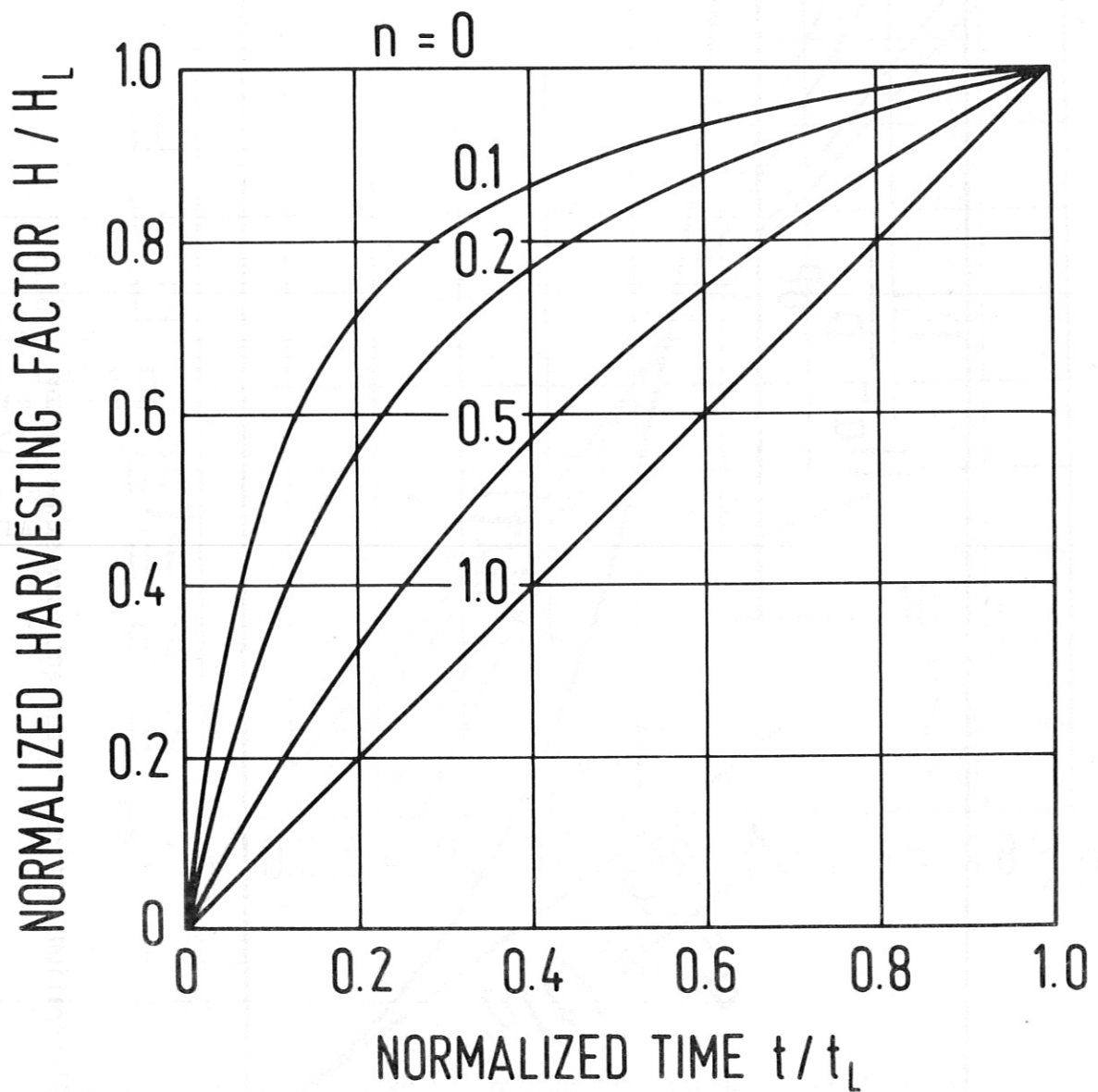


Fig. 6 Harvesting factor as a function of time for various percentages n of energy expenditures before commissioning (in normalized representation; $n = E_{BC}/E_{E,L}$; see Fig. 1)

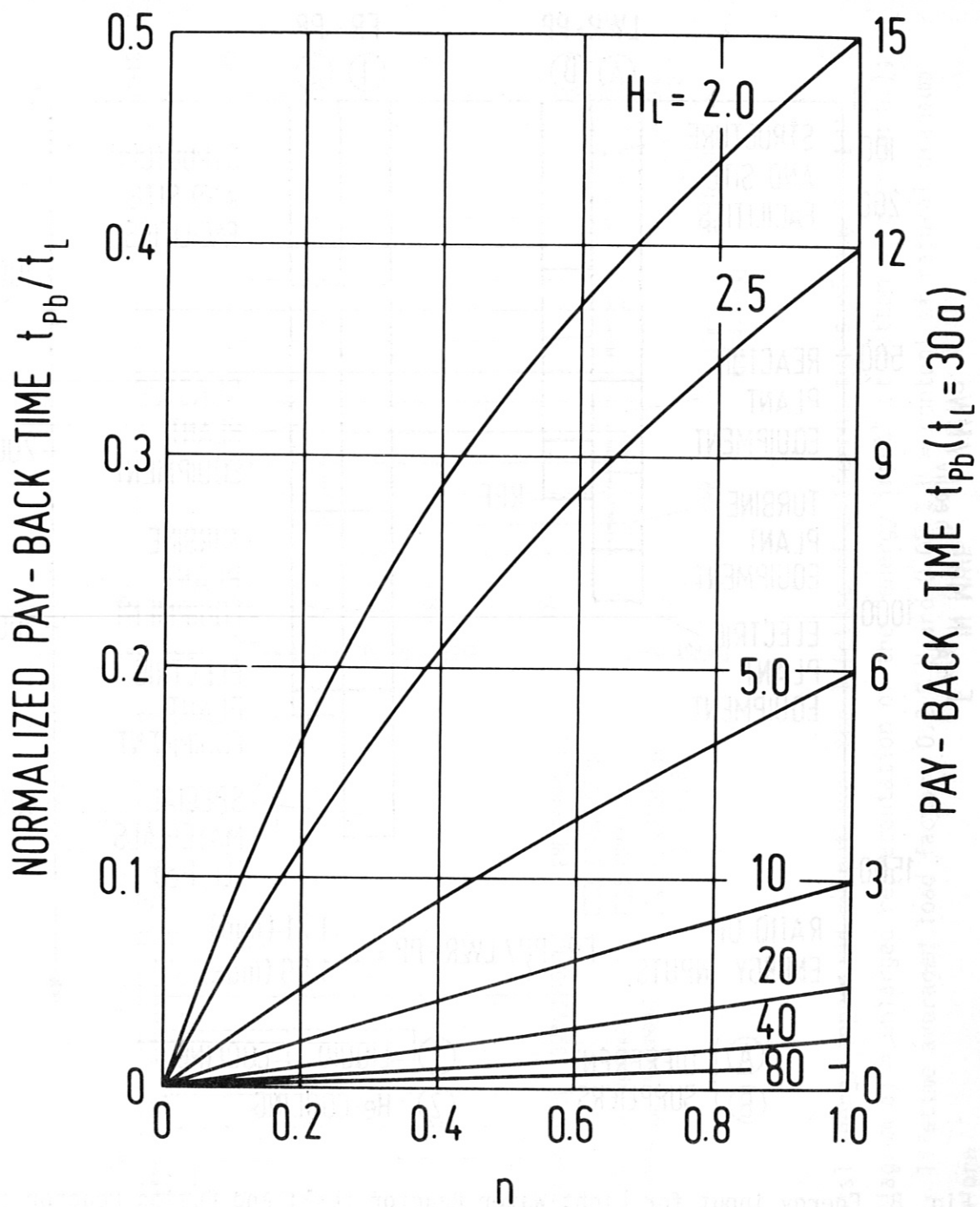


Fig. 7 Dependence of pay-back time on distribution of energy expenditures between "before commissioning" (n) and "during operation" ($1-n$) ($n = E_{BC}/E_{E,L}$; see Fig. 1)

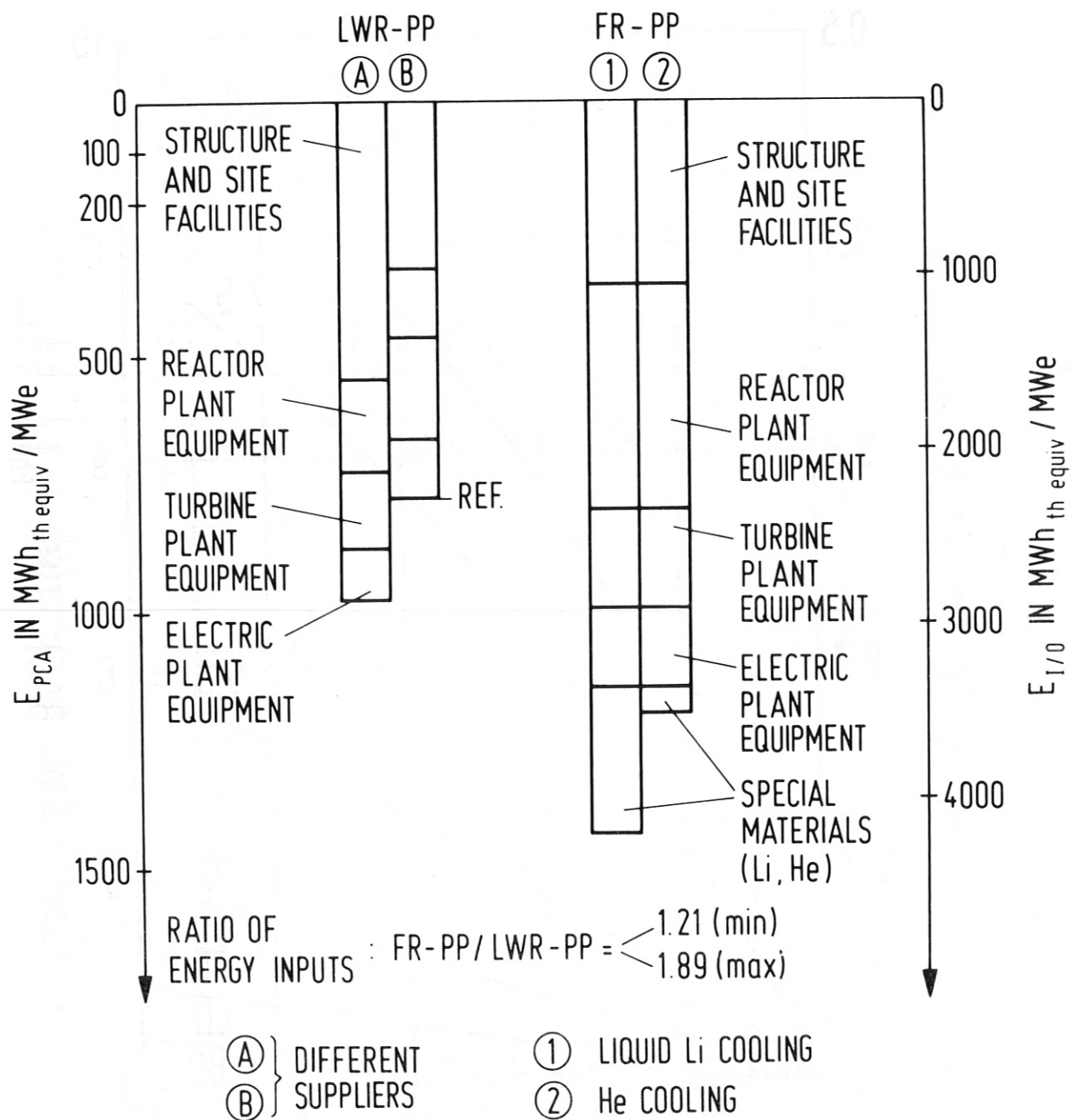


Fig. 8 Energy input for Light Water Reactor (LWR) and Fusion Reactor (FR) Power Plant (PP) construction

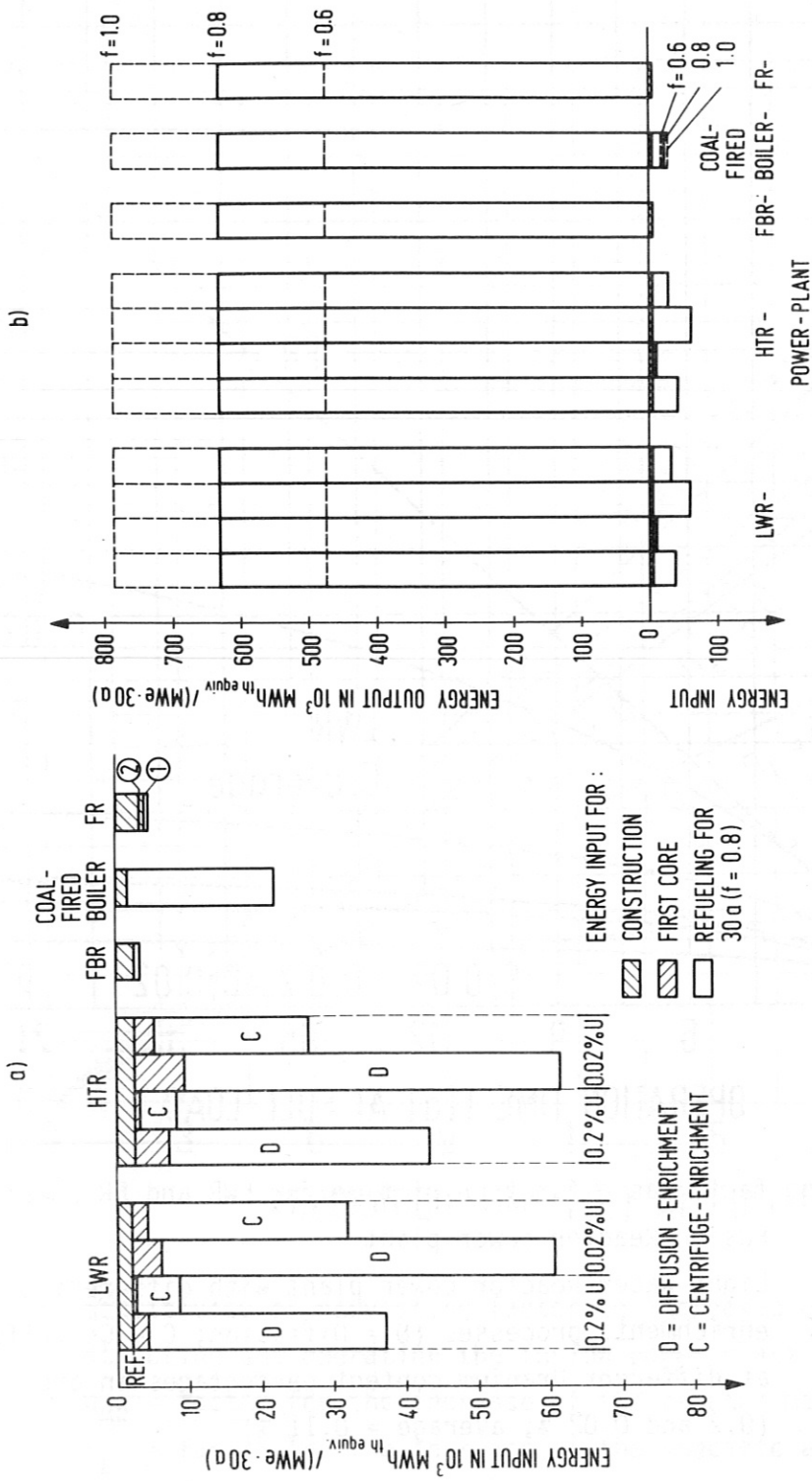


Fig. 9 Total energy input and output over the lifetime of different types of power plants
 Diagram a) = enlarged representation of the "energy input" at bottom of diagram b.);
 f = lifetime averaged load factor; 0.2 % U and 0.02 % U = content of natural uranium
 in ore

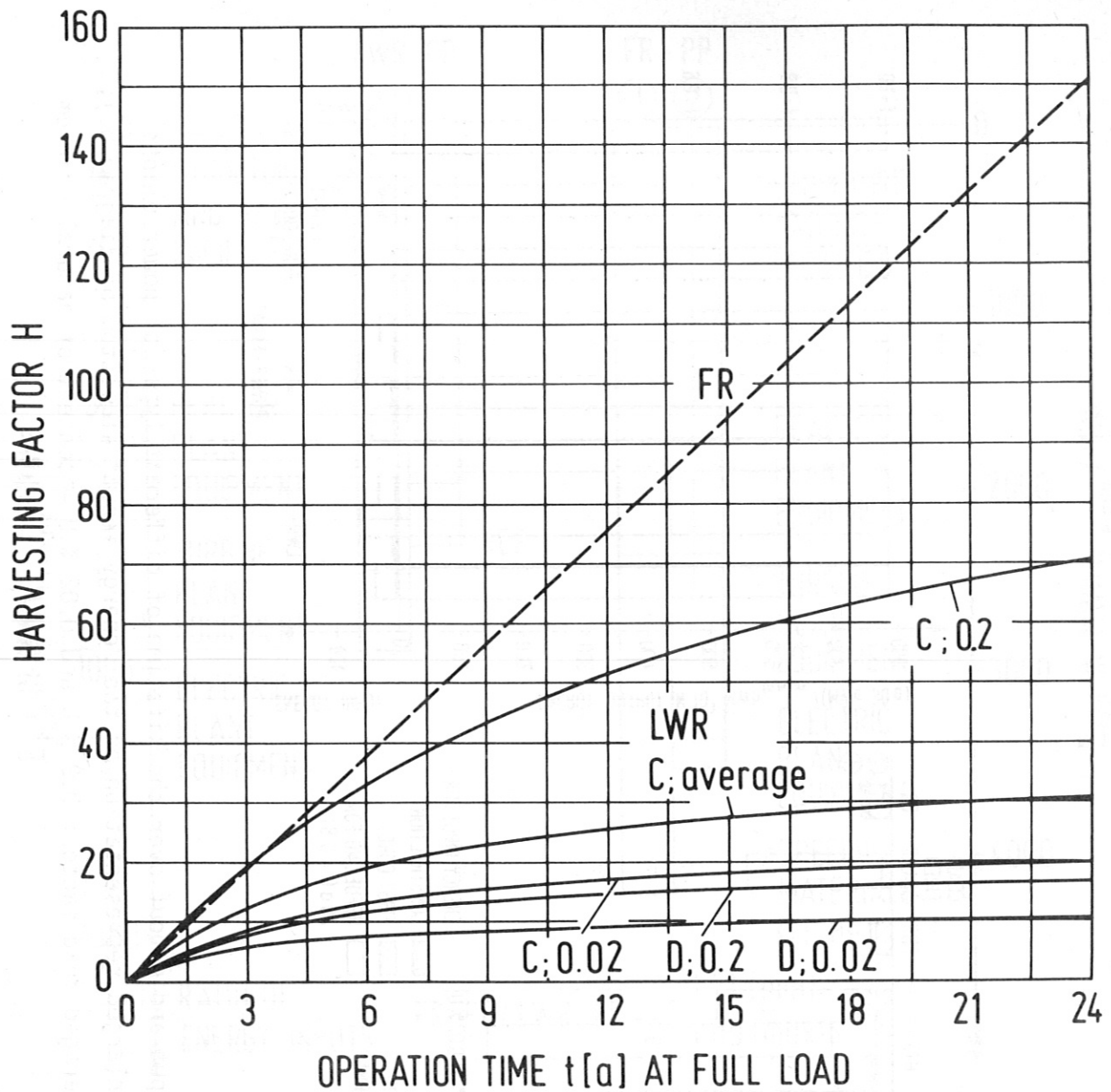


Fig. 10 Harvesting factor as a function of time for LWR and FR power plants

- Fusion Reactor power plant
- Light Water Reactor power plant with different Uranium enrichment processes (D = Diffusion; C = Centrifuge) at different Uranium content percentages in ore (0.2 and 0.02 %; average = 0.11 %)

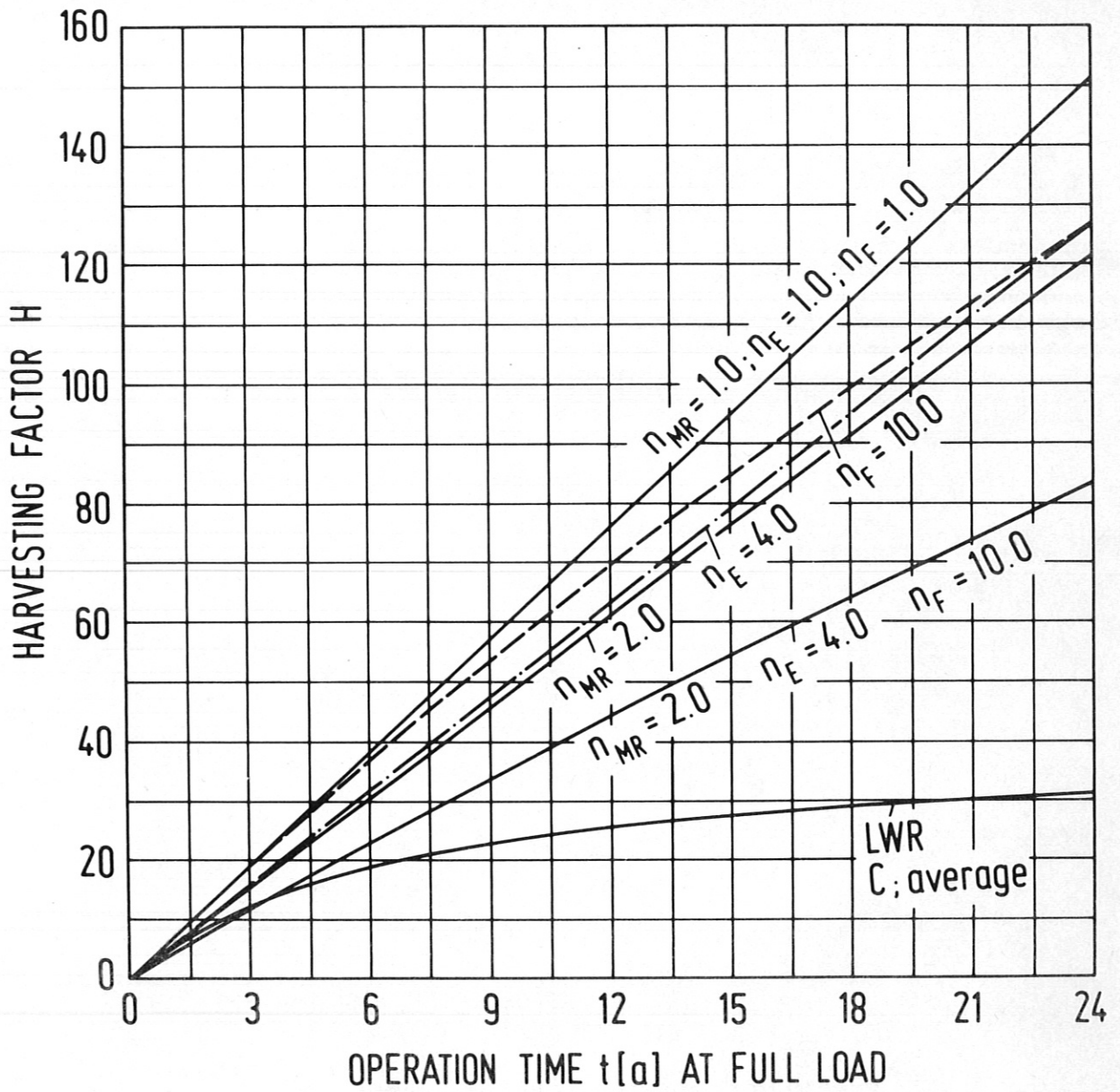


Fig. 11 Sensitivity of harvesting factor to increased energy input for constructing and operating the fusion power plant

n_{MR} = factor for the increase of the reactor masses,

n_E = factor for the increase of the specific energy input for non-ferrous and non-copper materials,

n_F = factor for the increase of the energy expenditures for fuel, maintenance, and repairs,

for LWR (c; average) see Fig. 10