Net Energy Balance
of
Tokamak Fusion Power Plants

R. Bünde

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ABSTRACT

The net energy balance for a tokamak fusion power plant was determined by
using a PWR power plant as reference system, replacing the fission-specific
components by fusion-specific components and adjusting the non-reactor-
-specific components to altered conditions. For determining the energy in-
put to the fusion plant a method was developed that combines the advantages
of the energetic input-output method with those of process chain analysis.
A comparison with PWR,HTR, FBR, and coal-fired power plants is made.

As a result the net energy balance of the fusion power plant turns
out to be more advantageous than that of an LWR, HTR or coal-fired power
plant and nearly in the same range as FBR power plants.

Contents

I. INTRODUCTION

At first glance the principle of power plant net energy balancing seems to be very plausible. On the one hand, one determines the total energy consumption which is caused by the construction of the plant and its operation over the whole lifetime. On the other, the energy which will probably be delivered by the plant during its lifetime is determined. The ratio of this energy output to the energy consumption should, of course, be as high as possible.

This kind of energy balance has been studied in detail since the middle of the last decade for nuclear and conventionally heated power plants. It can be seen from evaluation of the literature[1; with 21 References] that, in general, nuclear power plants are energetically worthwhile in spite of a slightly lower ratio of energy output to comsumption as compared with

conventional power plants.

However, to date very little work has been done on the net energy balance of fusion power plants. The rough assessments given in [2] and [3] indicate the trend that the considerably higher energy consumption expected for building a fusion reactor as compared with a fission reactor will only have a strongly reduced influence on the energy required for constructing the whole plant because of the important percentage of non--reactor-type-specific components. A study [4] which was published just as this work was nearing completion gave only some support to this trend. However, previously published paper [5] gives highly disastrous results for a fusion power plant: it claims that the power density within the fusion reactor has to be about one order of magnitude higher than that of the UWMAK-III [6] design in order to be competitive with a Light Water Reactor (LWR) power plant with respect to the net energy balance. The discrepancy between the above-described general trend and the results of [5] made it necessary to consider the fusion power plant net energy balance in much greater detail.

For this purpose a special method has been developed in order to cope with the problem of making this kind of energy balance for a type of reactor which still only exists in the form of designs. This method is described in detail in Sec. 2, which finally gives the energy input values for constructing and operating a tokamak fusion power plant. Section 3 presents a comparison between the energy input data for fusion and those for other types of power plants. In Sec. 4 it is attempted to evaluate the energy input with respect to the energy output. A comparison between the results of this work and [4] and [5] is contained in Sec. 5. Conclusions are given in Sec. 6.

2.   ENERGY INPUT FOR CONSTRUCTING AND OPERATING A FUSION POWER PLANT

2.1 Description of the method

As far as the way of calculating the energy necessary for constructing the power plant is concerned, there are two methods available in principle: In the one method the mass of all construction materials has to be determined and each value is then multiplied by the energy input per unit mass of ready assembled material. The energy intensities of the mass can be obtained by means of detailed analysis of the total chain of production

steps from the ore to the component ready for use, so-called process
chain analysis. The second method is based on a detailed component-wise cal-
culation of the costs, which consequently will be multiplied by the energy
intensity of the monetary unit, this depending on the industrial branch
which produces the particular plant component. These energy intensities
are determined by allocating a detailed input-output (I/O-) matrix of the
energy flows to a matching matrix of monetary flows of goods and services
in an economy, the so-called energetic I/O method. The advantage of the
I/O method compared with the process chain method is that the allocation
of all energy flows to all monetary flows ensures that all energies are in
fact included. A disadvantage is that the monetary values of goods and
services are subject to economic conditions such as the industrial structure
of a country, its energy supply system, the inflation rate or market
politics of the relevant producers. However, as this can be coped with to a
certain extent by fixing a certain country and a certain year as a basis,
there is a general tendency to prefer this method. Nevertheless the process
chain method is advantageous when new production processes are considered
that have not yet been introduced into the industry, so that no real market
price can be determined. This holds, for example, for nuclear fuel pro-
duction or for the production of a new type of nuclear reactor, e.g. the
fusion reactor.

On the basis of these considerations a method has been developed that
combines the advantages of the two principles. First the energy input for
constructing an LWR power plant is calculated by means of the I/O method.
In a second step the masses of construction materials for this plant and
for an equivalent fusion power plant are determined. However, as the fusion
reactor needs a greater mass of materials and even different types of ma-
terials than the fission plant, the differences varying from component to
component, it is necessary to take into account the different energy in-
tensities per unit mass of material. These energy intensities are determined
by the process chain analysis method. The multiplication of the masses of
materials by the energy intensities yields the energy inputs for construct-
ing the fission and the fusion plants. As these input data are consequently
based on process chain analysis, their value is too low according to the
previous remarks. Only the ratio of fusion to fission plant energy inputs
is therefore used to scale up that values of the fission plant energy input
which had been determined in the first step by the I/O method. This yields

a value for fusion plant construction which is based indirectly on the more reliable I/O method.

2.2 Energy input for a fission power plant.

In this study the application of the I/O method is based on the flows of energy [7] and monetary values [8] within the economy of the Federal Republic of Germany in 1974. The BIBLIS-A nuclear power plant, which is equipped with a Pressurized Water Reactor (PWR), was chosen as reference plant; however, in order to take into account present-day requirements of regulatory licensing, the data valid for BIBLIS-A were scaled up to BIBLIS-C, the latest block, which is now in the process of being licensed (the alterations from block A to C are only slightly relevant for the construction energy). Figure 1 gives an impression of the BIBLIS-C plant arrangement (1230 MWe,net), the dimensions of which are characterized by the lower diameter d = 180 m of the natural draught wet cooling tower [9].

Energy accounting for a BIBLIS-type power plant has already been made [10] together with a consideration of power plants with High Temperature Reactor (HTR), Fast Breeder Reactor (FBR) and coal-fired boiler. However, that study is based on preliminary economic data for 1974 and only the primary energy input was calculated, whereas this study requires the secondary energy input to be separated into thermal and electric energy because of the later relative evaluation of energy input and output (see Sec. 4). The I/O method was thus applied in somewhat modified form compared with [10]: the electric and thermal energies were dealt with separately, but the economic sectors in the energy matrix, in the monetary value matrix, and consequently in the resulting energy intensity matrix (the so-called Leontief matrix) were much more aggregated, and the exports and imports were treated in a very rough manner. In spite of these simplifications the energy intensities of the monetary values of the goods produced in the civil, mechanical and electrical engineering sectors and services are in rather good agreement with the data given in [10].

In addition to these energy intensity values, the determination of the energy input for construction of the power plant requires the cost calculation for the power plant to be such that for each component the distribution of costs for civil, mechanical, and electrical engineering is known. Fortunately, the secretiveness of German power plant suppliers and electric utilities as far as plant costs are concerned could be compensated by the American practice of making de-

tailed cost calculations on the basis of officially defined conditions that are summarized under the definition of "Middletown". Such a cost calculation [11] has been published for the Seabrook power plant, just being commissioned, which is very similar to the BIBLIS-A power plant. The costs of each component of this plant have been broken down according to civil, mechanical, and electrical engineering and the services sector, and then converted from $\$_{1976}$ values to DM_{1974} values at an exchange rate of 2.5 DM_{1976} to 1 $\$_{1976}$ and an inflation factor of 0.9 from DM_{1976} to DM_{1974} in order to be consistent in time with the energy intensities calculated on the basis of 1974 data.

The component-wise multiplication separated into the three above-named goods production sectors and the services sector finally yields a secondary energy input of 191.5 MWh_{el}/MWe and 1008.8 MWh_{th}/MWe. With a 25 % efficiency in producing and distributing electricity from thermal energy and a general efficiency of 90 % in liberating thermal energy from fuels, these two values are equivalent to a primary energy input of 1/0.9 (1008.8 + 191.5/0.25) = 1972 $MWh_{th\ equiv}$/MWe. This value is less than 10 % lower than the value of 2160 $MWh_{th\ equiv}$/MWe given in [10]. With respect to the numerous uncertainties and the high aggregation of the energy intensity calculation in this study this slight deviation may be regarded as rather good agreement. However, to be on the safe side, the values from [10] have been used for the purpose of comparison and especially the above-cited value of 2160 $MWh_{th\ equiv}$/MWe for a PWR power plant has been used as reference value for upscaling the energy input to build a fusion power plant. The construction energy input values given in [10] for various types of power plants are represented by the upper ranges of the bars shown in Fig. 2, the PWR value being designated by REF as the later used reference value. This figure contains in addition the primary energy input for the fuel supply, separated into the energy inputs for providing the first core and for refuelling during the lifetime of the plant, assuming a plant availability of f = 80 %. This availability is defined as the ratio of actually delivered output energy to that energy output which could have been delivered when operating the plant at nominal load during its total lifetime. The energy input for the fuel supplies of PWR and HTR are given for two methods of uranium(U) -enrichment and for two values of the U content in the ore. The energy input for refuelling includes a certain amount for refabrication and waste disposal. The influence of the U content in the ore on the primary energy re-

quired for fuel supply is represented in more detail in Fig. 3, where it can be seen that reduction of the U content by a factor of 10 requires nearly ten fold the amount of energy to produce the "yellow cake" U_3O_8.

Having fixed a PWR power plant as a reference system for the transition to a fusion power plant, one can now proceed to the next step according to the method described in Sec. 2.1.

2.3 Materials accounting for the fission power plant

In general, the mass of materials for a power plant has only been published in the case of some particularly heavy reactor components. However, this is not at all sufficient in order to sum up all those masses of materials that are relevant for energy accounting. Therefore, besides detailed evaluation of publications it was necessary to cultivate a great deal of personal contacts with power plant suppliers, plant component producers, and civil engineering companies in order to set up a list of component masses and their separation into the different materials used. From this list Tab. 1 was derived by summing up the masses of equal or similar materials of the plant components for the four items of account "Structure and Site Facilities", "Reactor Plant Equipment", "Turbine Plant Equipment", and "Electric Plant Equipment". (This classification was chosen in accordance with [12]). As the information on the necessary amounts of concrete differed considerably, two cases A and B were introduced; case B corresponds approximately to the BIBLIS-C plant.

2.4 Materials accounting for the fusion power plant

As a first step layout calculations for a fusion power plant with tokamak reactor were performed for a given electric net power output of 1230 MWe$_{net}$, this value being the same as for the PWR plant. For these calculations the SISYFUS-TE systems code ($\hat{=}$ SImulation model for SYstematic analyses of FUSion power plants - Tokamak, Energy balance) developed at Max-Planck-Institut für Plasmaphysik, Garching, during the past years [13] was applied. The characteristic data of the layout are summarized in Tab.2 ; several of the free parameters were chosen in accordance with the layout calculations for INTOR [14, 15]. Geometric dimensioning and mass determination were developed on the basis of [16], in which a first version of scaling laws for all components had been established. The mass calculation

for blanket, shielding and toroidal magnets had already been added to
the dimensioning of the tokamak in the SISYFUS code. For dimensioning and
mass determination of the other fusion-specific components scaling laws
were derived from the commonly known reactor designs. The masses of the
non-fusion-specific components were calculated on the basis of, for ex-
ample, power-specific mass values derived from the PWR power plant. Thus,
as an example, the mass of the saturated steam turboset was scaled up from
the PWR gross electric power to the fusion gross electric power, which
is higher because of the higher auxiliary requirements of the fusion plant.
The results of the mass determination for the fusion plant are finally
summarized in Tab. 3, where the masses of the various materials are given
according to the classification of [17], which was derived from [12].

2.5   Energy intensities as determined by process chain analysis

Detailed data on energy intensities, separated into electrical and
thermal inputs, were provided by evaluating the widely scattered literature
on energy requirements for producing materials and by asking relevant
companies and producer associations. These data referring to semi-finished
products are listed in Tab. 4 together with the respective sources. In
order to complete the chain of manufacturing processes up to the assembled
product, the direct energy inputs of the civil, mechanical and electrical
engineering industries have been added. The respective contingency factors
were taken from the earlier I/O calculations (see Sec. 2.2) as 1.18 for the
electrical energy input and 1.12 for the thermal input, thus reflecting the
higher sophistication of the final manufacturing steps. So the last row in
Tab. 4 contains the values to be used for energetically weighting the
masses of materials. However, it has to be emphasized that these values
were obtained by process chain analysis, which generally yields lower
values than the overall I/O method (see Sec. 2.1.). The values of Tab. 4
must thus not be seen as absolute data but only as a means of relative
weighting of the masses of materials.

2.6   Energetic weighting of the masses of materials

The difference between fission and fusion mostly effects the masses of
materials required for building the reactor. The mass of the PWR pressure
vessel and that of the fusion reactor up to the outer boundary of the

toroidal magnets (see Tables 1 and 3) are represented as bars in Fig. 4. The fusion reactor requires an approximately 28-fold mass of materials. The percentage of the non-ferrous metals is considerably higher for the fusion reactor than for the fission reactor pressure vessel, where it can be neglected. This has a certain bearing on the construction energy requirements, which are shown in Fig. 5 to be a factor of more than 32 higher in the fusion case. The reason for the increase of the energy ratio compared with the mass ratio is that the energy intensity of the non-ferrous metals is higher than that of the high-alloyed steels (see Table 4).

However, this large increase has to be considered in the perspective of the materials requirements for the total plant. Figure 6 shows the data of Tables 1 and 3 as bars.In spite of the 28-fold increase in reactor mass, which is again marked in this figure, the rather low increase in materials for non-fusion-specific components reduces the overall mass increase to approximately 40 % when the maximum difference between PWR plant (B) and fusion plant (1) is considered. Multiplying these masses by the energy intensities (see Table 4) yields energy input values, which are represented as bars in Fig. 7 but are now arranged in the order of the classification of components. Recomparison of fission plant (B) with fusion plant (1) yields an increase in energy input of nearly 90 %. The fact that the energy input increases considerably more than the total mass of materials is again due to the higher energy intensity of fusion reactor materials, which gives the 32-fold energy input increase (see Fig.5) a stronger weight.

As already pointed out in Sec. 2.5, the energy input values calculated here are based on process chain analysis and ought therefore not be taken as absolute values. They will only be used for scaling purposes.

2.7 Energy input for a fusion power plant

The energy input for PWR plant (B) is designated as 100 % (see Fig. 7 "REF"), a value to which the energy input of 2160 MWh$_{th\ equiv}$/MWe calculated by means of the energetic I/O method will now be allocated. This leads to a new scale for the energy input in Fig. 7 yielding a value of 4082 MWh$_{th\ equiv}$/MWe for fusion case (1), and 3314 MWh$_{th\ equiv}$/MWe for fusion case (2). This procedure implicitly assumes the deviation between the I/O method and process chain method to be the same for fission and fusion power plants. From the component-wise multiplication of mass data

from Tables 1 and 3 and electric and thermal energy intensities from Table 4 it can additionally be seen that the share of electric energy input for fusion plant construction is higher than for fission plant construction owing to the fact that the production of non-ferrous fusion reactor materials requires mostly electricity.

As far as the sensitivity is concerned, an increase of the fusion reactor energy input by 100 % increases the total energy input by about 25% (see Fig. 7, case 1). However, the energy intensities have been determined in a rather cautious way and their upscaling by the ratio of the I/O-method value to the process chain value raises them to a level which can certainly be considered as an upper boundary. With respect to the mass of reactor materials, an increase of 100 % seems inconceivable since the dimensions of the reactor used here (see Table 2) are based on rather moderate requirements for the wall load. The above-named 25 % increase may therefore be seen as an upper limit of uncertainty for the energy input.

With respect to operation, two additional items have to be taken into account: the materials for repairs and for fuel. The mass of materials for repairs will probably depend on the replacement frequency of the first wall and the pertinent support installations. Assuming a "quality" of the first wall material of 9 MWa/m^2 (high-alloyed steel) results in total first wall replacement every 3 years at a wall load of approximately 3 MW/m^2. During the lifetime of the plant (30a) ten first walls are then needed, each at 90 Mg according to the mass determination. With the respective energy intensity (see Table 4) 900 Mg/30a of high-alloyed steel require an energy input of 11.5 $MWh_{th\ equiv}/(MWe \cdot 30a)$. This is lower than 0.3 % of the energy input for plant construction, so that even if it turns out to be a factor of 2 or 3 higher it will remain within the margin of uncertainty.

As to the fuel supply, the lithium required has already been included in the construction materials, so that only the provision of deuterium has to be additionally taken into account. Depending on the kind of processing, the production of deuterium requires 39 to 47 $MWh_{th\ equiv}/kg_{D2}$ (derived from [27]), which yields with the data from Table 2 an energy input of 78 to 94 $MWh_{th\ equiv}/(MWe \cdot 30a)$.

The energy input for operation thus results in a maximum value of

about 106 MWh$_{th\ equiv}$/(MWe·30a). The total energy input for the fusion power plant can now be compared with the other power plant types.

3. COMPARISON OF ENERGY INPUT FOR DIFFERENT PLANT TYPES

Figure 8 is an extended version of Fig. 2, the data for the fusion power plant having been added. As can easily be seen, the total energy input for construction and operation of the fusion plant is much less than that for LWR, HTR, and coal-fired plants and is nearly the same as for FBR plants. However, considering the energy input before commissioning of the plant, 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 differ significantly from the respective values for 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.

4. RELATIVE EVALUATION OF ENERGY INPUT AND OUTPUT

The bars of Fig. 8 are shown on a severely reduced scale at the bottom of Fig. 9, 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, which is only shown in one case (PWR; 0.2% U content; diffusion enrichment) at an availability of f = 0.8. The general impression is that the output far exceeds the input. In the case of the fusion reactor power plant it is shown that the energy input for construction and operation is energetically equivalent to a difference in plant availability of 0.5 % during the lifetime of the plant. This means that increasing the availability by this amount is worthwile even at the expense of a higher energy input if this energy input increase is lower than the original amount for construction and operation. Thus, improving the availability of the plant must have a much higher priority than saving some energy in plant construction. Figure 9 makes it seem reasonable to deduct the input from the output and consider the difference, i.e. the absolute gain from the "enterprise" power plant as a figure of merit.

However, as can be seen from [1], it has generally been attempted to use ratios of energy input and output as figures of merit, e.g. "harvesting factor" or the product of its inverse with the life time of the plant, the "pay-back time". A recent study [28] shows in addition to [1] that the payback time is highly dependent on the different possibilities of the relative

evaluation of electric and thermal energies, on the different treatments of energy input for first core or refuelling, on different ways of energy redelivery, and on the time dependence of the plant availability. It may thus happen that the pay-back times calculated for the same values of energy input and output may differ by a factor of 25. As one instinctively compares the pay-back time with the life time of the plant, the pay-back time is not useful as a figure of merit.

5. COMPARISON WITH THE RESULTS OF OTHER AUTHORS

As a general result it is stated in [4] that with respect to the net energy balance the fusion power plant is superior to the PWR plant using diffusion-enriched uranium from conventional ($\cong$ 0.2 % U) ore. The fusion plant is inferior in the case of centrifuge enrichment of the PWR fuel from the same kind of ore. This is in accordance with Fig. 8 of this paper. The reason is that with a PWR power plant most of the energy input is needed for fuel provision, whereas in the fusion case the construction of the plant requires by far the largest share of the energy input. This agreement in assessing the general situation exists in spite of considerable disagreement on absolute data: for instance, the construction energy for a fusion plant is calculated in [4] to be 6 times that of the equivalent PWR plant, whereas in this paper the factor calculated is slightly lower than 2. This discrepancy is probably due to the fact that the result of [4] is based entirely on a fusion plant cost calculation. As was pointed out earlier (see Sec. 2.1), especially for new products costs are not at all representative of the energy input. This paper has tried to avoid this by using the energetically weighted masses of materials for scaling purposes. In addition, [4] uses the UWMAK-III cost calculation, which gives extremely high costs because of some extremly costly design features which are by no means mandatory e.g. the extensive use of the material TZM. Furthermore, it is incomprehensible why, for instance, the turbine plant equipment of the UWMAK-III plant should have 5-fold PWR turbine plant costs. Nevertheless it is reassuring to see that even with these discrepancies the general result is the same.

The rather disastrous implications of [5] for the fusion plant (see Sec. 1) is simply due to the fact that the upscaling from the mass of the PWR pressure vessel to that of the fusion reactor within the outer boundary of the toroidal magnets is based on a wrong assumption. This assumption con-

cerns the percentage of the pressure vessel mass in relation to the total
mass of energy-relevant material in the PWR plant. For this a value of 37 %
was used in [5]. However, a value of 1.3 % to 1.4 % would have been ad-
equate. With this correction the method applied in [5] gives results that
are in agreement with those of this study.

6. CONCLUSIONS

The result of this work is summarized in Fig. 9. As with PWR, HTR, FBR,
and coal-fired boiler power plants, a fusion reactor power plant will yield
an energy output which considerably exceeds the energy input.

A principal difference between the fusion plant and the other plant
types except the FBR is that with fusion most of the energy input is re-
quired for construction of the plant, while the others consume most of the
energy input for fuel supply. This is true even in the case of centrifuge
enrichment of U for PWR and HTR plants since the U content in ores to be
processes will decrease in parallel to the market penetration of the centri-
fuge system.

Even with allowance for uncertainties in the layout of the fusion plant
and methodological uncertainties, a fusion plant remains a system which
converts fuel energy into a usable form of energy without consuming more
energy for plant construction and operation that it provides.

ACKNOWLEDGEMENT

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Table 1 Mass of Materials for Fission Power Plant

Materials / Account Items	Earth Work [m³]	Gravel + Sand [Mg]	Cement [Mg]	Unalloyed Steels [Mg]	High-Alloyed Steels [Mg]	B$_4$C [Mg]	Pb [Mg]	Cu [Mg]	CuZn28Sn [Mg]	Various Non-Fe Metals [Mg]	Insulation Materials [Mg]	Sum of Masses (Excl. Gravel + Sand + Cement)
21 Structures and Site Fac. A	600000	390000	60450	24100	2500	-	-	-	-	-	-	
21 Structures and Site Fac. B		594000	92070	39100	6000							
22 Reactor Plant Equ	-	-	-	1102	10298	0	0	-	-	-	-	
23 Turbine Plant Equ	-	-	-	3739	10341	-	-	100	660	-	-	
24 Electr. Plant Equ	-	-	-	-	1018	-	-	1550	-	654	2876	
Sum of Masses A	600000	390000	60450	28941	24157	0	0	1650	660	654	2876	58938
Sum of Masses B		594000	92070	43941	27657							77438

Table 2 Characteristic Data for the Tokamak Fusion Power Plant

Net electric power output	1230 MW_{net}	$\bar{\beta}_{toroidal}$	6 %
Gross electric power output	1378 MW_{gr}	Magnetic field on axis	5.2 T
Reactor thermal power output	4009 MW_{th}	Major radius	9.24 m
Plasma power output [+]	3550 MW_{th}	Minor radius	2.31 m
Plasma power density [+]	2.12 MW_{th}/m^3	Elongation	1.6
Wall load (fictitous) [+]	3.1 MW_{th}/m^2	Outer reactor radius (toroidal coils)	16.4 m
Burn time	300 s	Height of toroidal coils	8.6 m
Dwell time	30 s	Deuterium consumption	0.07 $g_D/(MW_{th}\,d)$
		Plant availability (actual energy output/nominal output)	0.8

[+] averaged over cycle time

Table 3 Mass of Materials for Fusion Power Plant

	Earth Work [m³]	Gravel + Sand [Mg]	Cement [Mg]	Unalloyed Steels [Mg]	High-Alloyed Steels [Mg]	B_4C [Mg]	Pb [Mg]	NbTi [Mg]	Cu [Mg]	CuZn28Sn [Mg]	Non-Fe Metals [Mg]	Insulation Material [Mg]	Li [Mg]	He Liquid [m³]	Sum of Masses (excl. Gravel + Sand + Cement)
21 Struct. + Site F.	604000	411218	63740	23850	4722	-	-	-	-	-	-	-	-	-	
22 Reactor Plant E.	-	-	-	2086	19498	583	3855	62	4134	-	-	-	-	-	
23 Turbine Plant E.	-	-	-	3865	10685	-	-	-	103	682	-	-	-	-	
24 Electr. Plant E.	-	-	-	-	1073	•	-	-	1635	-	689	3032	-	-	
25 Misc. Plant E	-	-	-	-	534	•	-	-	-	-	-	-	-	-	
25 Special Mater.	-	-	-	-	-	-	-	-	-	-	-	-	1480	500	
Sum of Masses	604000	411218	63740	29801	36512	583	3855	62	5872	682	689	3032	1480	500	83086
Sum of Masses (incl. 5% Contingency for Production)	604000	411218	63740	31291	38338	612	4048	65	6166	716	723	3184	1480	500	87123

Table 4 Energy Intensities of Materials as Determined by Process Chain Analysis

|	Earth Work	Gravel and Sand	Cement	Unalloyed Steels	High-Alloyed Steels	B_4C	Pb	NbTi	Cu	CuZn28Sn	Non-Fe Metals ≡ Al	Insulation Materials	Li	He, liquid
Main source of Information;	[18]	[10]	[10]	[10][20]	[20]	[22]	[20]	[22]	[24]	[24]	[10]	[20]	[22]	[26]
Basis for Further Assessment			[19]	[21]			[21]	[23]			[20]		[25]	
Specific Energy Demand of Semi-products (Indir. Input) — $\frac{MWh_{el}}{Mg\ or\ m^3}$	0	0.0010	0.0889	0.5778	2.967	17.286	0	17.286	2.65	2.65	17.719	0.925	60.0	0.925
$\frac{MWh_{th}}{Mg\ or\ m^3}$	0.0157	0.017	1.197	6.889	4.692	2.864	15.0	2.864	9.361	9.361	19.289	20.833	40.0	0
Specific Energy Input of Assembled Products (Total Input) — $\frac{MWh_{el}}{Mg\ or\ m^3}$	0	0.0011	0.1049	0.6818	3.501	20.398	0	20.398	3.127	3.127	20.909	1.092	70.8	1.091
$\frac{MWh_{th}}{Mg\ or\ m^3}$	0.0176	0.0018	1.341	7.716	5.255	3.208	16.8	3.208	10.484	10.484	21.60	23.333	44.8	0
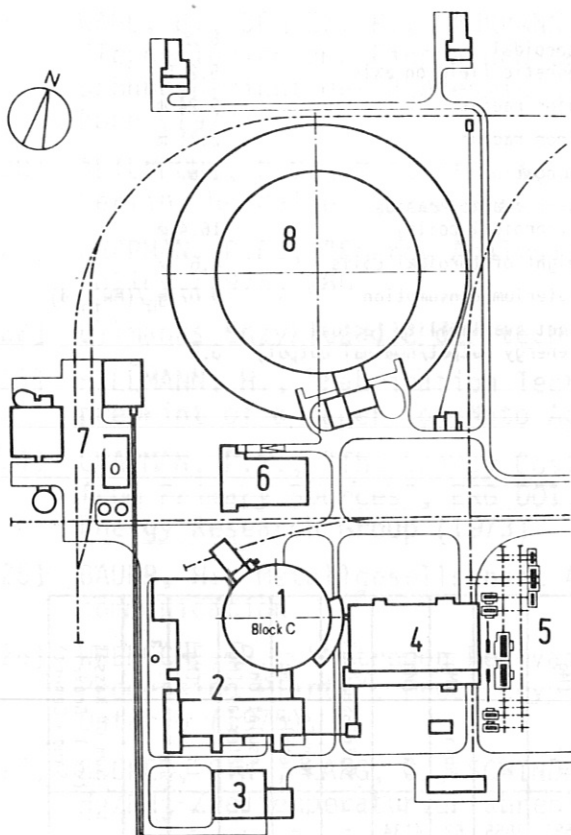
Fig.1 Plant arrangement of BIBLIS-C
1 Reactor, 2 Reactor aux. systems,
3 Emergency power supply, 4 Turbine
hall, 5 Transformers, 6 Emergency
coolg s., 7 Water treatment s.,
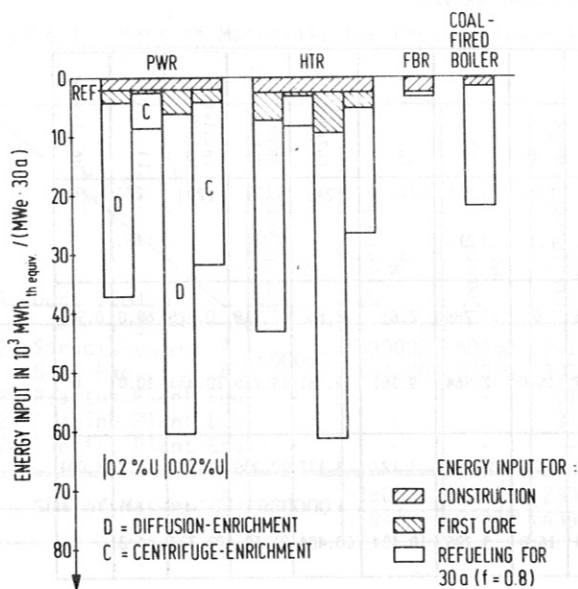8 Cooling tower (d_{max} = 180 m)

Fig.2 Energy input for different
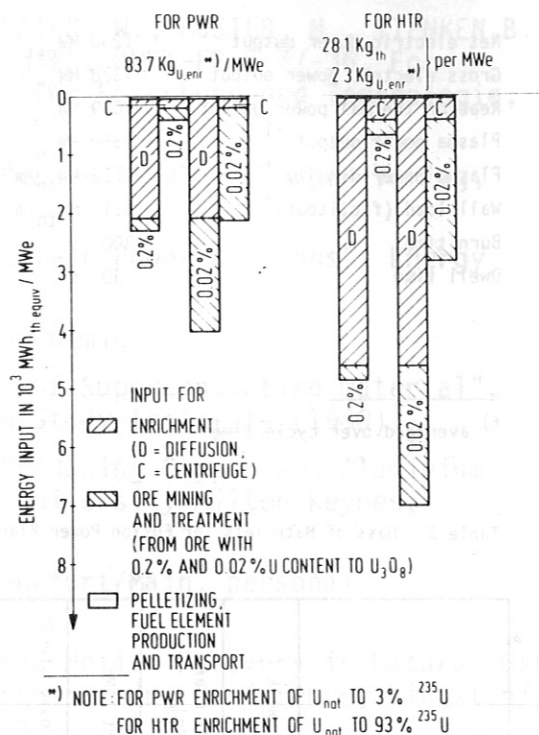types of power plants
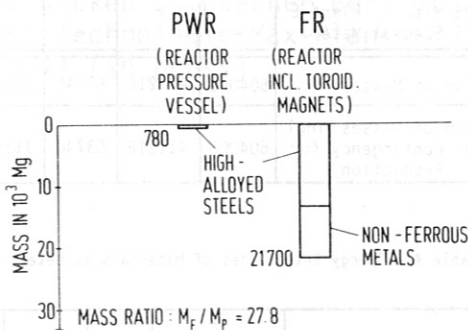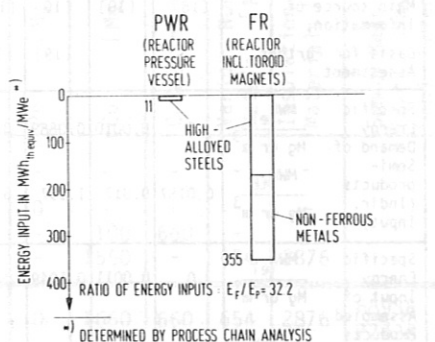

Fig.3 Energy input for first core

Fig.4 Reactor masses

Fig.5 Reactor energy input
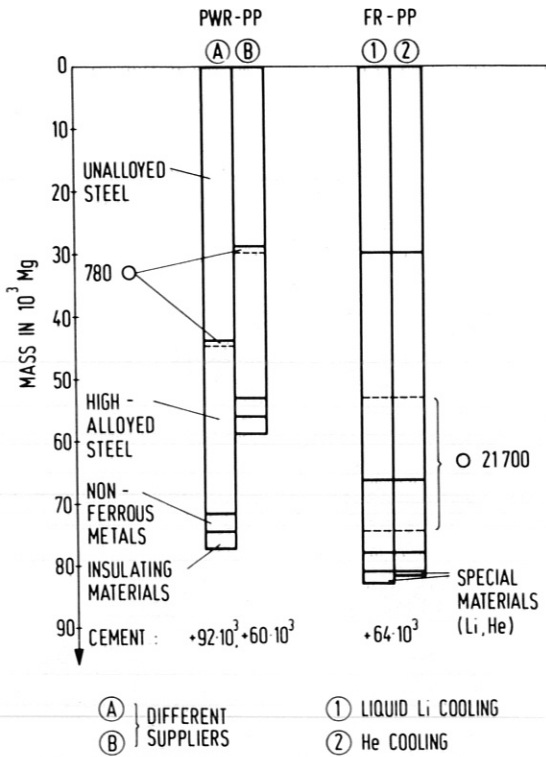
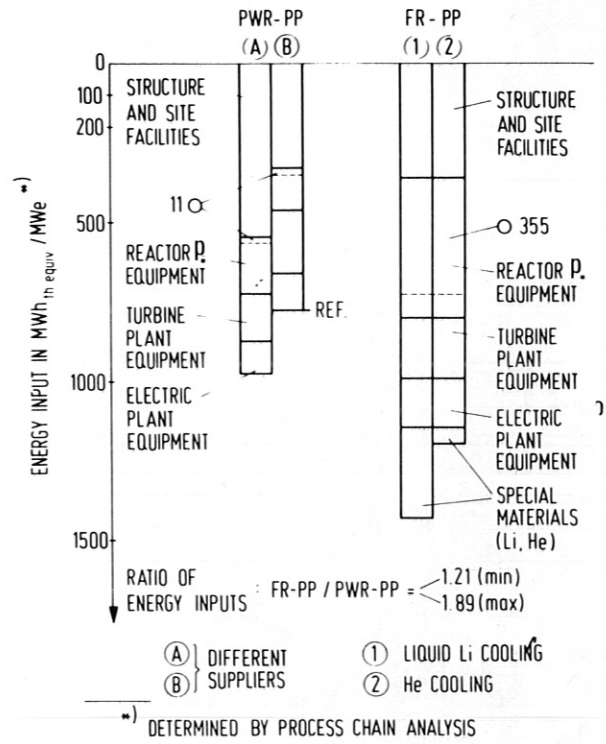Fig.6 Masses of energy relevant materials for PWR and fusion power plant

Fig.7 Energy input for PWR and fusion power plant construction
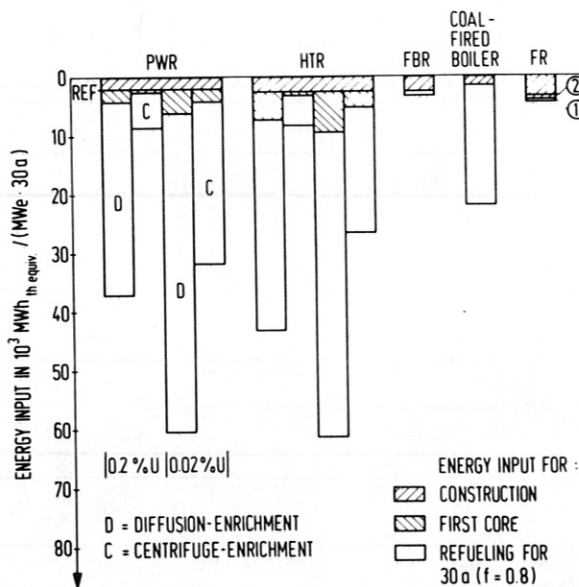

Fig.8 Energy input for construction and operation of different types of power plants
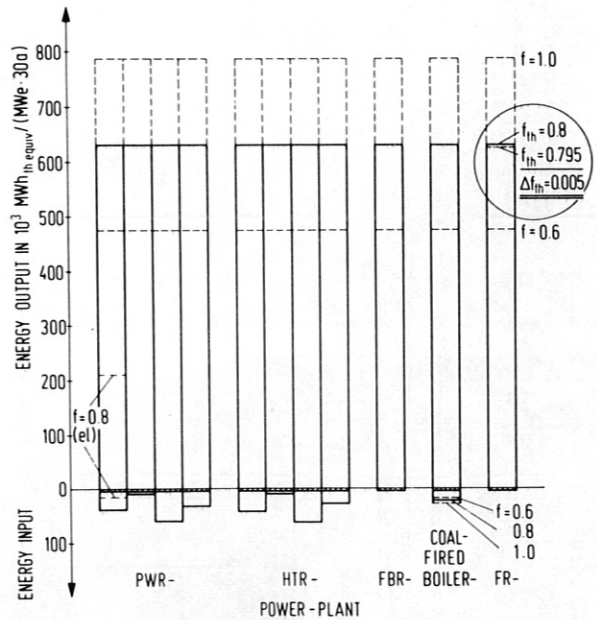

Fig.9 Total energy input and output over the lifetime of different types of power plants