Parametric Analyses of Fusion-Fission Systems

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Abstract

After a short review of the nuclear reactions relevant to fusion-fission systems the various types of blankets and characteristic model cases are presented.

The fusion-fission system is modelled by its energy flow diagram. The system components and the system as a whole are characterized by "component parameters" and "system parameters" all of which are energy ratios. A cost estimate is given for the net energy delivered by the system, and a collection of formulas for the various energies flowing in the system in terms of the thermal energy delivered by the fusion part is presented.

For sensitivity analysis four reference cases are defined which combine two plasma confinement schemes (mirror and tokamak) with two fissile fuel cycles (thorium-uranium and uranium-plutonium). The sensitivity of the critical plasma energy multiplication, of the circulating energy fraction, and of the energy cost with respect to changes of the component parameters is analysed. For the mirror case only superconducting magnets are considered, whereas the tokamak cases take into account both superconducting and normal-conducting coils. A section presenting relations between the plasma energy multiplication and the confinement parameter $n\tau_E$ of driven tokamak plasmas is added for reference.

The conclusions summarize the results which could be obtained within the framework of energy balances, cost estimates and their parametric sensitivities. This is supplemented by listing those issues which lie beyond this scope but have to be taken into account when assessments of fusion-fission systems are made.

Contents

1. Introduction

The aim here is to investigate the energy balances of power systems composed of fusion devices and fission reactors.

1.1 Nuclear blanket reactions

The fusion devices deliver energy carried by neutrons and charged particles. The neutrons enter a blanket the ingredients of which include a fertile material such as thorium-232 (^{232}Th) or uranium-238 (^{238}U), which may be converted to uranium-233 (^{233}U) or plutonium-239 (^{239}Pu) by neutron capture and subsequent ß-decay. The processes are described by the following equations, which neglect side reactions of minor importance as far as "breeding" of ^{233}U or ^{239}Pu is concerned:

$$^{233}Th + n \longrightarrow {}^{233}Th \longrightarrow {}^{233}Pa + e^- \longrightarrow {}^{233}U + e^- \;, \tag{1}$$

$$^{238}U + n \longrightarrow {}^{239}U \longrightarrow {}^{239}Np + e^- \longrightarrow {}^{239}Pu + e^- \;. \tag{2}$$

The products ^{233}U and ^{239}Pu can be burnt in thermal fission reactors because they undergo fission by slow neutrons.

More complete diagrams of the reactions involved are shown in Figs. 1 and 2, which are based on /1/ and /2/.

The basis of hybrid concepts is the high kinetic energy (14,06 MeV) of the neutrons from DT fusion. They cause neutron multiplication and fission reactions when impinging on a blanket containing ^{232}Th or ^{238}U. In a neutron multiplication reaction one energetic neutron is captured and subsequently 2 or 3 neutrons are released. The threshold energies for these (n,2n) and (n,3n) processes are rather high: 6.37 MeV (^{232}Th) and 6.07 MeV (^{238}U) for the (n,2n) reaction; 11.42 MeV (^{232}Th) and 11.51 MeV (^{238}U) for the (n,3n) reaction. The cross-sections for these reactions may be found in /2, p.9/.

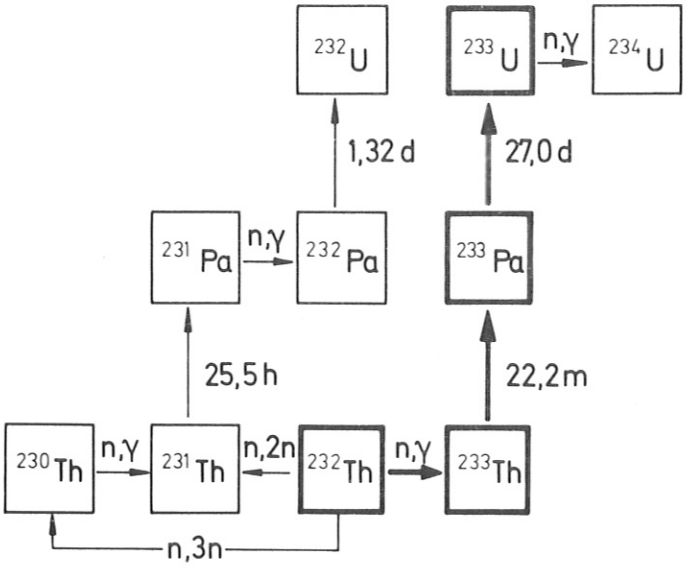


Fig. 1
Schematic representation of ^{233}U-breeding from ^{232}Th including the half-lives of the most important intermediate products and by-products

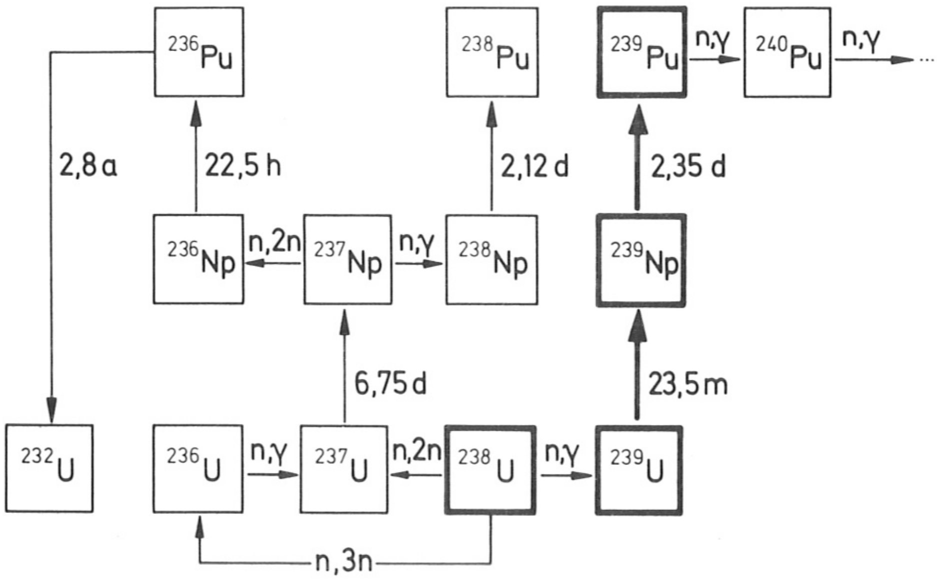


Fig. 2
Schematic representation of ^{239}Pu-breeding from ^{238}U including the half-lives of the most important intermediate products and by-products

In a fission reaction the nucleus is split into at least two fragments which take over the major part of the binding energy as kinetic energy. Furthermore, an average of n neutrons are set free. This number n is approximately a linear function of the neutron energy (see Fig. 3). Fission by 14 MeV neutrons produces on the average 3.87 neutrons from

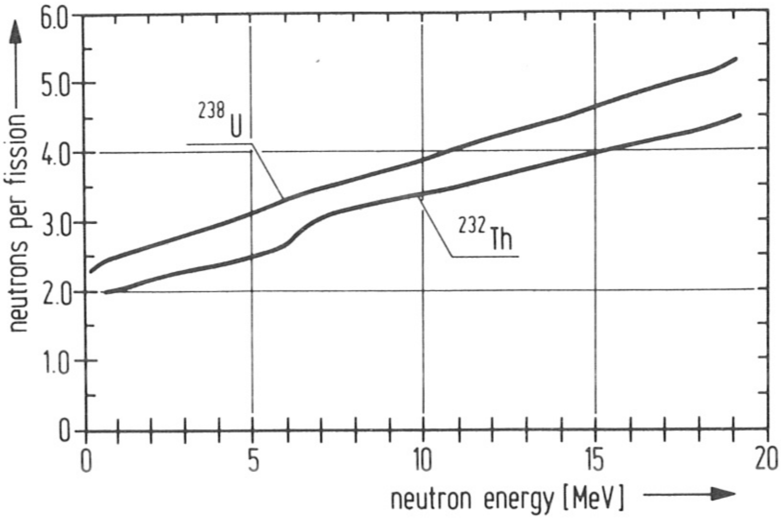


Fig. 3
Number of neutrons per fission as a function of neutron energy

^{232}Th and 4.5 neutrons from ^{238}U. An appreciable amount of fission is only produced by neutrons with an energy above 1.2 MeV, as can be seen from the fission cross-sections shown in Fig. 4. Above 1.2 MeV the fission

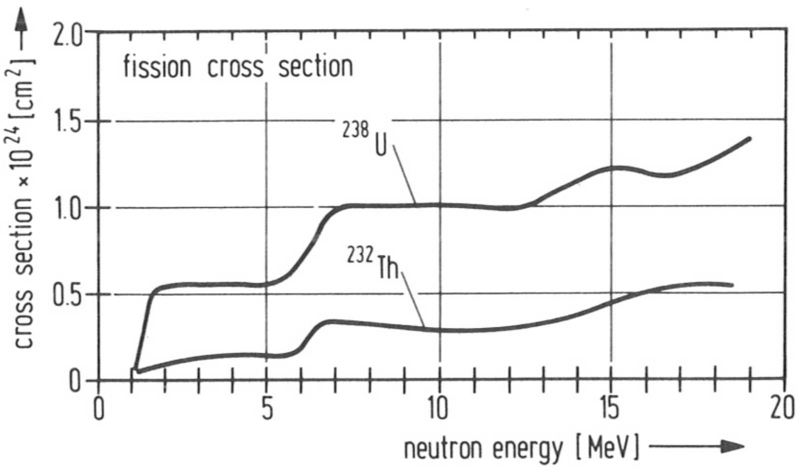


Fig. 4
Cross-sections for fission by neutrons as a function of neutron energy

cross-section of ^{232}Th is always about one-third of the value for ^{238}U. More details of these fission cross-sections may be found in /2, p. 4/.

On the whole the use of fissile material in a blanket leads to neutron and energy multiplication.

Neutron multiplication can also be achieved by using materials such as ^{9}Be, Pb, Mo, and Nb in the front zone of a blanket where the spectrum of the neutrons is still so hard that they initiate (n,2n) reactions. Also ^{7}Li may be counted in this category since the reaction

$$^{7}Li + n \longrightarrow {}^{4}He + T + n' - 2{,}47\ MeV \qquad (3)$$

has the same overall effect as an (n,2n) reaction: the bred tritium saves one neutron which would otherwise be consumed at some point in the fusion-fission system to provide the tritium needed as fuel for fusion reactions.

1.2 Blanket types

Fusion-fission systems may be roughly classified according to their purpose: If emphasis is put on breeding of fissile fuel so that energy multiplication in the blanket is only a by-product to be kept on a low level, one speaks of a "fuel factory" or of a "symbiosis" of fusion and fission. If both breeding and heat production in the blanket are desired features, the fusion-fission system is called a "hybrid" system.

In the first case fission is suppressed as far as compatible with the desired fuel breeding. This is achieved by placing non-fissioning neutron multipliers in the front zone of the blanket and by moderating the outcoming neutrons before they impinge on the breeding material ^{232}Th. ^{238}U is not used because its high fission cross-section (see Fig. 4) counteracts the suppression of fission due to the fast tail of the neutron spectrum. This still exists behind the multiplier and moderator zones and initiates fission of the ^{238}U. To avoid thermal fission of the bred fuel ^{233}U, this must not be enriched to more than about one percent of the total amount of heavy metal (^{232}Th + ^{233}U), which necessitates frequent extraction of ^{233}U from the blanket. For breeding of tritium one may include ^{6}Li in the thorium containing zone. The left column of Fig. 5 shows schematically the geometrical arrangement and the processes characteristic of a fission suppressed blanket together with the zones where the "fuels" (T and ^{233}U) are produced.

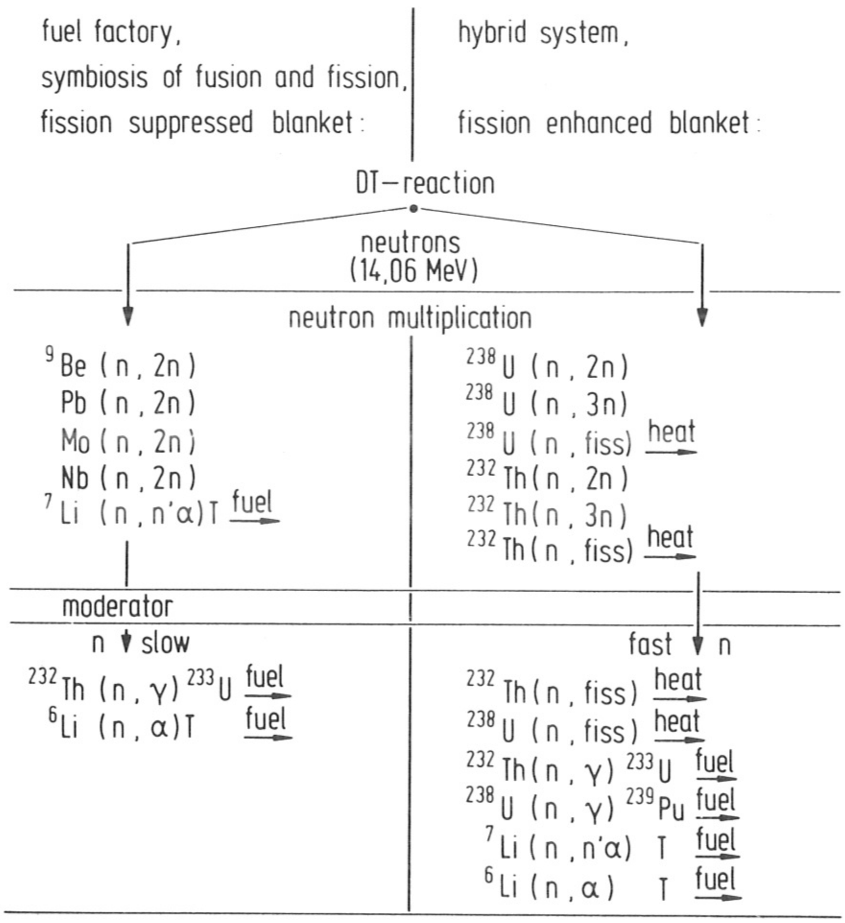


Fig. 5
Schematic representation of the processes in fission-suppressed and fission-enhanced blankets

A fission-enhanced blanket can be realized by placing ^{232}Th or ^{238}U in the front zone of the blanket, where they are hit by the fast fusion neutrons (see Fig. 5). The neutron multiplication is achieved by (n,2n), (n,3n), and fission reactions. The energy multiplication is due to the fission reactions. The neutrons leaving this zone and entering the following one are not moderated and therefore initiate fast fission of ^{232}Th or ^{238}U. The fuels ^{233}U or ^{239}Pu are produced by neutron capture in ^{232}Th or ^{238}U. Both ^{7}Li and ^{6}Li may be added for breeding tritium from fast and slow neutrons respectively. If the fuels ^{233}U or ^{239}Pu are allowed to enrich to high concentrations, they are fissioned themselves and deliver additional energy. In the latter case this blanket zone can come close to a critical fission assembly which is similar to the fuel elements of a fission reactor.

Blankets containing fertile and fissile elements as well as lithium can be characterized by the breeding ratio b_f for fissile fuel, the tritium breeding ratio b_T, and the multiplication factor M_t for thermal energy:

$$b_f = \frac{\text{number of fissile atoms produced in the blanket}}{\text{number of fusion neutrons entering the blanket}}\,, \tag{4}$$

$$b_T = \frac{\text{number of tritium atoms produced in the blanket}}{\text{number of fusion neutrons entering the blanket}}\,, \tag{5}$$

$$M_t = \frac{\text{energy released in the blanket}}{\text{energy entering the blanket via fusion neutrons}}\,. \tag{6}$$

The amount of fissile fuel produced (expressed by b_f) can be converted to an energy ratio M_{fu} which is given by

$$M_{fu} = \frac{\text{energy released by fission of the bred fuel}}{\text{energy entering the blanket via fusion neutrons}}\,. \tag{7}$$

Because the usable energy delivered by the fission of one heavy nucleus is about 190 MeV /3, p.10/, the ratios b_f and M_{fu} are related by

$$M_{fu} \approx 190/14 \cdot b_f \approx 13.5 \cdot b_f\,. \tag{8}$$

Typical ranges for the parameters b_f, $(b_f + b_T)$, and M_t are shown in Table 1.

type of blanket	b_f	$b_f + b_T$	M_t
fission-suppressed	0.1 - 0.8	1.1 - 1.8	1.0 - 1.6
fission-enhanced	0.5 - 3.5	1.5 - 4.5	2 - 80

Table 1

Typical parameter ranges for blankets containing fertile and fissile elements as well as lithium

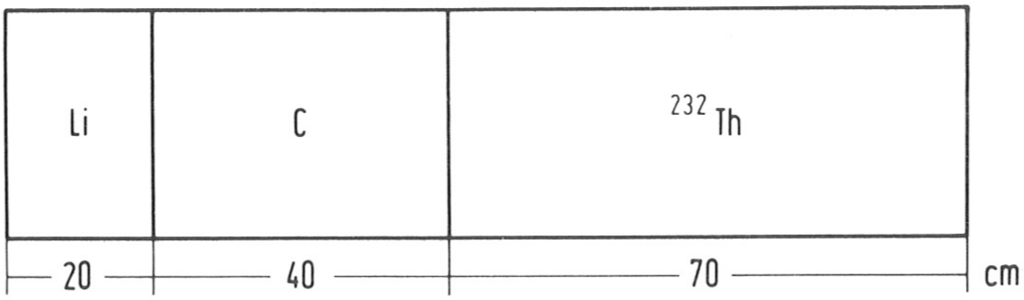
The lower numbers in the line "fission-enhanced" pertain to blankets containing ^{232}Th (which undergoes fast fission) but no ^{238}U or ^{239}Pu, the higher numbers to blankets containing ^{238}U and ^{239}Pu.

A survey of the various blanket designs published up to now is given in /4/.

1.3 Model blankets

Figures 6 to 8 show schematically the materials and their arrangement for various blankets. The data are taken from /5/, where spherical blankets were analyzed by using the Monte Carlo Code TART for neutronics together with the cross-section library ENDL. The materials are assumed to be homogeneously distributed over the blanket regions they occupy. The stainless-steel front wall is 0.5 cm thick and is at a distance of 3 m from the fusion neutron source. In the figures only the portion behind the first wall is shown.

Figure 6 shows a case with extreme suppression of fission: a 20 cm thick layer of (presumably natural) lithium for tritium breeding is followed by 40 cm of a graphite moderator to avoid too much fast fission in the 70 cm of thorium. The number of fissions per fusion neutron is thus kept very low: 0.004. The thermal energy multiplication M_t essentially produced by



$b_f = 0.139$ $b_T = 1.12$ $M_t = 1.1$

Fig. 6
Model blanket with extreme suppression of fission

tritium breeding, fuel breeding, and fission reactions is indeed very low for this blanket. Unfortunately, this is coupled with the low fuel breeding ratio $b_f = 0.139$. The tritium breeding ratio b_T appears somewhat high compared with the results of Daenner /6, p.196/ for cylindrical lithium blankets. Perhaps the difference is due to the reflector action of the 40 cm graphite and to the spherical arrangement assumed in /5/.

Fig. 7 shows a blanket in which the suppression of fission is relaxed by removing the graphite moderator. To get enough tritium breeding, the thickness of the lithium zone was enhanced to 40 cm. The number of

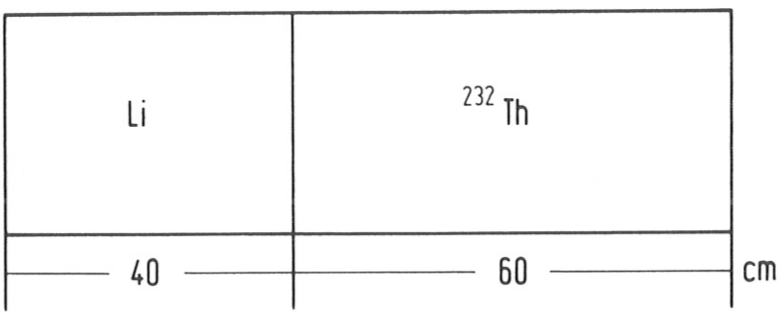


Fig. 7
Model blanket with a moderate suppression of fission

$b_f = 0.55$ $b_T = 1.07$ $M_t = 1.6$

fissions per fusion neutron has increased to 0.029. In keeping with this number and the higher fuel breeding ratio $b_f = 0.55$ the thermal energy multiplication now amounts to $M_t = 1.6$.

Figure 8 shows a blanket in which fission is enhanced by placing a fuel layer in the front part. This layer contains 63 % fuel, 24 % coolant (lithium), and 13 % structure (stainless steel) by volume. The fuel is depleted uranium metal (^{238}U with 0.25 wt % of ^{235}U). The number of fissions per fusion neutron amounts to 0.64, essentially fast ones. This high value leads to the high values b_f = 1.95 and M_t = 10.

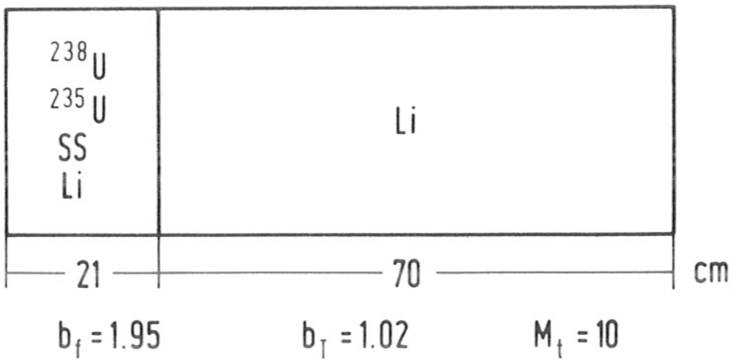


Fig. 8
Model blanket with enhancement of fast fission

2. Fusion-fission system model

2.1 Structure of the model

The fusion-fission system is represented by its energy flow diagram, which is made up of the most important components and the energies flowing between them. These energies are the time integrals of the corresponding powers over a certain time period characteristic of the case treated. Such a period may be, for example, one year if one is interested in the overall energy balance of the whole system. The average powers flowing between the system components are the energies defined above divided by the integration time interval.

Figure 9 shows the energy flow diagram of a fusion-fission system which delivers electric energy. The fusion device F in the centre delivers the thermal energy E_{ft}, for some concepts the energy E_{fd} being directly convertible to electric energy, and the energy E_{fu} stored in bred fuel. The thermal energy primarily consists of the energy E_{bt} released in the blanket. Its amount is equal to the kinetic energy E_{fu} of the fusion neutrons multiplied by the factor M_t, which describes the reactions in the blanket. A second contribution to E_{ft} is the energy (E_{fct} + E_{pat}) of plasma ions (α-particles and fuel ions) transferred to the chamber walls by convection, heat conduction, and electromagnetic radiation. The energy E_{fct} is part of or the total α-particle energy E_{fc} from fusion; E_{pat} is part of or the total energy E_{pa} deposited in the plasma by external heating. The heating energy not absorbed by the plasma $(1-\eta_a)E_{hf}$ and the pulsed magnetic energy $(1-\varepsilon_m)E_{pf}$ not transferred back to the pulsed field power supply P are assumed to be absorbed by the structure and thus contribute to the total energy E_{ft}. The directly convertible energies E_{fcd} and E_{pad} stem from fusion reactions and plasma heating. Their sum is E_{fd}.

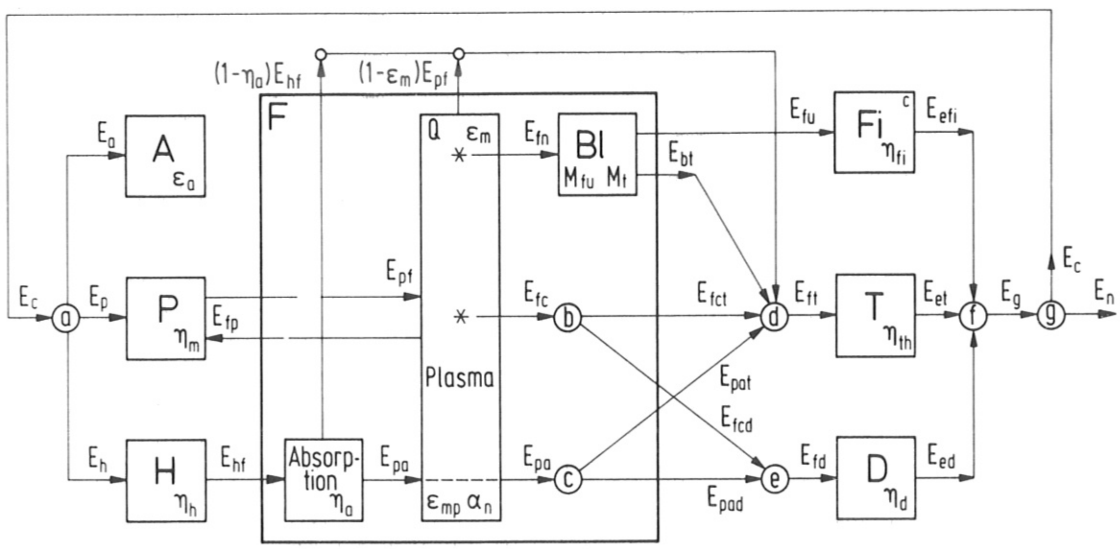


Fig. 9

Energy flow diagram of a fusion-fission system delivering electric energy

The energies E_{ft} and E_{fd} are converted to the electric energies E_{et} and E_{ed} by the thermal energy conversion T and the direct energy conversion D respectively. The fissile fuel energy E_{fu} is converted to the electric energy E_{efi} by fission reactors Fi, which have the conversion ratio c. The sum (E_{efi} + E_{et} + E_{ed}) is the gross electric energy delivered by the complete fusion-fission system.From E_g the "circulating energy" E_c is subtracted and fed back to the entrance of the system. The remaining net energy E_n is delivered to the grid.

The portion E_a of the circulating energy is used for driving auxiliary installations (e.g. pumps, control), for covering the losses of superconducting or resistive coils, and for providing the energy stored in steady-state magnetic fields.

The energy E_p is used to cover the energy stored by pulsed magnetic field coils. E_p is fed into the power supply P, which feeds the energy E_{pf} into the coils and gets back the energy E_{fp} at the end of operating cycle.

The energy E_{hf} is fed into the plasma, which absorbs the portion E_{pa}, whereas the rest $E_{hf}-E_{pa}$ becomes part of the thermal energy E_{ft} delivered by the fusion device. The energy E_{pa} absorbed by the plasma contributes to the output energy of the fusion device as thermal and/or directly convertible energy, as already mentioned.

As a whole the fusion device acts as an energy amplifier which, when supplied with a certain amount of energy, adds fusion and bred fuel energy and delivers the total as its output.

It is important to note that the system considered may be interpreted as one fusion device F coupled with a number of fission reactors Fi, which are not necessarily located at the same site as F. The coupling between F and Fi may be loose so that the influence of cyclic fusion operation and outages is damped by the inventory of the transport system for E_{fu}. On the other hand, the direct feedback of an energy E_c may only be formal to close the model, whereas in practice it has to be taken from a grid not necessarily fed by Fi. So the magnitude of the power P_c corresponding to E_c may be subject to constraints imposed by the electric power system.

2.2 Characterization of the system components by "component parameters"

The components of the fusion-fission system are characterized by the following dimensionless parameters:

$Q = E_f/E_{pa}$	energy multiplication by the fusion plasma	(9)
with		
$E_f = E_{fn} + E_{fc}$,		(10)
$\alpha_n = E_{fn}/E_f$	neutron energy fraction,	(11)
$\eta_a = E_{pa}/E_{hf}$	absorption efficiency,	(12)
$M_t = E_{bt}/E_{fn}$	thermal energy multiplication by the blanket,	(13)
$M_{fu} = E_{fu}/E_{fn}$	fuel energy multiplication by the blanket,	(14)
$\varepsilon_{fct} = E_{fct}/E_{fc}$	fraction of charged particle fusion energy used thermally,	(15)
$\varepsilon_{pat} = E_{pat}/E_{pa}$	fraction of absorbed heating energy used thermally,	(16)
$\eta_{th} = E_{et}/E_{ft}$	efficiency of thermal energy conversion,	(17)
$\eta_d = E_{ed}/E_{fd}$	efficiency of direct energy conversion,	(18)
$\eta_{fi} = (1-c)E_{efi}/E_{fu}$	net efficiency of fission reactor with conversion ratio c ,	(19)
$\varepsilon_a = E_a/(E_{ft}+E_{fd})$	auxiliary energy fraction,	(20)
$\eta_m = E_{pf}/(E_p+E_{fp})$	efficiency of providing pulsed magnetic energy ,	(21)
$\varepsilon_m = E_{fp}/E_{pf}$	fraction of pulsed magnetic energy that can be recovered,	(22)
$\varepsilon_{mp} = E_{pf}/E_{pa}$	ratio of pulsed magnetic energy and absorbed heating energy,	(23)
$\eta_h = E_{hf}/E_h$	efficiency of heating device.	(24)

2.3 Characterization of the system by "system parameters"

The system contains the following 24 energies:

E_c, E_a, E_p, E_h, E_{pf}, E_{fp}, E_{hf}, E_{fn}, E_{fc}, E_f, E_{pa}, E_{fu}, E_{bt}, E_{fct}, E_{pat}, E_{fcd}, E_{pad}, E_{ft}, E_{fd}, E_{efi}, E_{et}, E_{ed}, E_g, E_n

all of which except E_f are displayed by the energy flow diagram (Fig. 9).

These energies are related to each other by the sixteen eqs. (19) to (34) and by the following seven equations describing the energy balances in the nodes a, b, c, d, e, f, and g:

$$E_c = E_a + E_p + E_h, \tag{25}$$

$$E_{fc} = E_{fct} + E_{fcd}, \tag{26}$$

$$E_{pa} = E_{pat} + E_{pad}, \tag{27}$$

$$E_{ft} = E_{bt} + E_{fct} + E_{pat} + (1-\eta_a)E_{hf} + (1-\varepsilon_m)E_{pf}, \tag{28}$$

$$E_{fd} = E_{fcd} + E_{pad}, \tag{29}$$

$$E_g = E_{efi} + E_{et} + E_{ed}, \tag{30}$$

$$E_g = E_n + E_c. \tag{31}$$

With the total of 16 + 7 = 23 equations for 24 energies one can determine energy ratios which are characteristic of the system as a whole. Such ratios, which shall be named "system parameters", are the "critical energy multiplication" Q_c, the "thermal support ratio" ε_{th}, the "fusion support ratio" ε_f, the "electric to fusion energy ratio" ε_{nf}, and the "relative circulating energy fraction" C:

Q_c	=	$(E_f/E_{pa})_c$	critical energy multiplication,	(32)
ε_{th}	=	$E_{fu}/(1-c)E_{ft}$	thermal support ratio,	(33)
ε_f	=	$E_{fu}/(1-c)E_f$	fusion support ratio	(34)
ε_{nf}	=	E_n/E_f	electric to fusion energy ratio,	(35)
C	=	E_c/E_n	circulating energy fraction.	(36)

The critical energy multiplication Q_c is that value of Q which leads to the system output energy $E_n = 0$. The system is thus just self-sustaining energetically for $Q = Q_c$.

The thermal support ratio ε_{th} is the energy stored in the bred fuel divided by the thermal energy of the fusion device times the factor $1/(1-c)$. This factor describes the assumption that the additional fuel produced by the fission reactor with the conversion ratio c when burning the bred fuel is used by recycling.

The fusion support ratio ε_f is the ratio of the energy stored in the bred fuel divided by the fusion energy times 1/(1-c).

The electric to fusion energy ratio ε_{nf} is the net electric energy delivered to the grid in units of the fusion energy.

The circulating energy fraction C is the circulating electric energy divided by the net electric energy delivered to the grid by the fusion-fission system.

The formulas for Q_c, ε_{th}, ε_f, ε_{nf} and C derived from the 23 equations mentioned above are as follows:

$$Q_c = 1/\eta_a(\eta^*_{fi}\alpha_n M_{fu}+\eta^f_{eff})\cdot(1/\varepsilon-\eta_{th}[\eta_a\varepsilon_{pat}+\eta_a\varepsilon_{mp}(1-\varepsilon_m)+(1-\eta_a)]-\eta_d\eta_a(1-\varepsilon_{pat})+\varepsilon_a[1+\eta_a\varepsilon_{mp}(1-\varepsilon_m)]), \quad (37)$$

$$\varepsilon_{th} = (\alpha_n M_t+\varepsilon_{fct}(1-\alpha_n)+[\varepsilon_{pat}-\varepsilon_{mp}(1-\varepsilon_m)+(1/\eta_a-1)]/Q)\cdot \alpha_n M_{fu}/(1-c), \quad (38)$$

$$\varepsilon_f = \alpha_n M_{fu}/(1-c), \quad (39)$$

$$\varepsilon_{nf} = (1-Q_c/Q)(\eta^*_{fi}\alpha_n M_{fu}+\eta^f_{eff}), \quad (40)$$

$$C = (1/\varepsilon\eta_a+\varepsilon_a[M_t\alpha_n Q-\alpha_n Q+Q+1/\eta_a+\varepsilon_{mp}(1-\varepsilon_m)])/(Q-Q_c)(\eta^*_{fi}\alpha_n M_{fu}+\eta^f_{eff}), \quad (41)$$

with

$$\varepsilon = E_{hf}/(E_h+E_p) = \eta_h\eta_m/[\eta_m+\eta_h\eta_a\varepsilon_{mp}(1-\varepsilon_m\eta_m)], \quad (42)$$

$$\eta^*_{fi} = \eta_{fi}/(1-c), \quad (43)$$

$$\eta^f_{eff} = (E_n/E_f)_{M_{fu}=0} = \eta_{th}[\alpha_n M_t+\varepsilon_{fct}(1-\alpha_n)]+\eta_d(1-\varepsilon_{fct})(1-\alpha_n)-\varepsilon_a(\alpha_n M_t-\alpha_n+1). \quad (44)$$

The critical energy multiplication Q_c is a measure of the imperfection of the system components surrounding the fusion plasma with respect to converting and transferring energies. If these components were neither to lose nor to consume energy (i.e.for $\eta_h=\eta_m=\eta_a=\eta_{th}=\eta_d=\varepsilon_m=1$ and $\varepsilon_a=0$), one would get $Q_c=0$. This means that the fusion plasma would not need to deliver energy because no internal consumption would be present.

Obviously, the fission reactors would not run in this case since no fuel would be bred. The parameter Q_c is a natural unit to measure the quality Q of a fusion plasma under the conditions imposed by the system it drives. Hence the energy multiplication Q of a fusion plasma is qualified as "large" if Q/Q_c is large compared with unity.

2.4 Cost estimate for the net energy delivered by the system

It is reasonable to assume that the cost K of the net energy E_n delivered by the fusion-fission system is dominated by the cost of installation. For an estimate of this cost we use the following breakdown:

$$K = K_f + K_e + K_{fi} + K_c, \qquad (45)$$

K_f = cost of installation for delivering the fusion power P_f,

K_e = cost of installation for handling the power $(P_{ft} + P_{fd})$ inside the fusion part of the system,

K_{fi} = cost of all fission reactors delivering the thermal energy $E_{fu}/(1-c)$,

K_c = cost of installation for handling the circulating power P_c.

We set the various K's proportional to the associated energies E_f, $(E_{ft}+E_{fd})$, E_{fu}, and E_c, which in turn are proportional to the corresponding power for given values of operating time and availability. We thus get

$$K = c_f \cdot E_f + c_e \cdot (E_{ft}+E_{fd}) + c_{fi} \cdot E_{fu}/(1-c) + c_c E_c. \qquad (46)$$

Finally, we define parameters ß which express the various c's in units c_{fi}:

$$\beta_f = c_f/c_{fi}, \qquad (47)$$

$$\beta_e = c_e/c_{fi}, \qquad (48)$$

$$\beta_c = c_c/c_{fi}. \qquad (49)$$

By using eq. (46) for K, the definitions for the ß's, and the relations between the relevant energies we get

$$K/E_n = c_{fi}/\varepsilon_{nf} \cdot [\beta_f + \varepsilon_f + \beta_c C \varepsilon_{nf} + \beta_e (M_t \alpha_n - \alpha_n + 1 + 1/Q \cdot [\varepsilon_{mp}(1-\varepsilon_m) + 1/\eta_a])]. \qquad (50)$$

To normalize K/E_n, we use the value $(K/E_n)_o$ which results from eq. (50) for $Q \to \infty$. The result is $(K/E_n)_n$.

2.5 Formulas for the energies flowing in the system

We assume that the thermal power delivered at the site of the fusion device is subject to a constraint, presumably imposed by waste heat rejection. The most important energies flowing in the system will therefore be expressed as products of the thermal energy E_{ft} with functions of component and systems parameters as follows:

$$E_f = \varepsilon_{th}(1-c)/\alpha_n M_{fu} \cdot E_{ft}, \quad (51)$$

$$E_{fu} = \varepsilon_{th}(1-c)/M_{fu} \cdot E_{ft}, \quad (52)$$

$$E_{fc} = \varepsilon_{th}(1-c)(1-\alpha_n)/\alpha_n M_{fu} \cdot E_{ft}, \quad (53)$$

$$E_{fu} = \varepsilon_{th}(1-c) \cdot E_{ft}, \quad (54)$$

$$E_{bt} = \varepsilon_{th}(1-c)M_t/M_{fu} \cdot E_{ft}, \quad (55)$$

$$E_{efi} = \eta_{fi}\varepsilon_{th} \cdot E_{ft}, \quad (56)$$

$$E_{et} = \eta_{th} \cdot E_{ft}, \quad (57)$$

$$E_{et}+E_{ed} = \varepsilon_{th}[\varepsilon_{nf}(1-c)(1+C)/\alpha_n M_{fu}-\eta_{fi}] \cdot E_{ft}, \quad (58)$$

$$E_g = \varepsilon_{th}\varepsilon_{nf}(1-c)(1+C)/\alpha_n M_{fu} \cdot E_{ft}, \quad (59)$$

$$E_n = \varepsilon_{th}\varepsilon_{nf}(1-c)/\alpha_n M_{fu} \cdot E_{ft}, \quad (60)$$

$$E_c = C\varepsilon_{th}\varepsilon_{nf}(1-c)/\alpha_n M_{fu} \cdot E_{ft}, \quad (61)$$

$$E_a = \varepsilon_a\varepsilon_{th}(1-c)/\alpha_n M_{fu} \cdot (M_t\alpha_n+1-\alpha_n+ 1/Q \cdot [1/\eta_a+\varepsilon_{mp}(1-\varepsilon_m)]) \cdot E_{ft}, \quad (62)$$

$$E_{pa} = \varepsilon_{th}(1-c)/\alpha_n M_{fu} Q \cdot E_{ft}, \quad (63)$$

$$E_h = \varepsilon_{th}(1-c)/\alpha_n M_{fu}\eta_h\eta_a Q \cdot E_{ft}. \quad (64)$$

3. Parametric analyses

3.1 Reference Cases

As starting points for analyzing the sensitivity of system parameters with respect to changes of the component parameters we define two reference cases for the plasma confinement and two reference cases for the blankets and the associated fission reactors:

mirror machine (case M)
tokamak (case T)

and

fission-suppressed thorium blanket (case Th)
fission-enhanced uranium blanket (case U).

For characterizing the confinement systems the following component parameters are chosen:

Component parameter	case M	case T
Q	20	50
η_h	0.5	0.5
η_a	0.5	0.5
η_m	1.0	0.8
ε_m	1.0	0.5
ε_a	0.1	0.1
ε_{mp}	0	5.0
α_n	0.8	0.8
ε_{fct}	0	1.0
ε_{pat}	0.5	1.0
η_{th}	0.36	0.36
η_d	0.5	0

Table 2

Component parameters chosen for the reference cases "mirror machine" (M) and "tokamak" (T)

Obviously, the Q values chosen are speculative. The speculation mainly concerns the prospects of the tandem mirror concept with thermal barrier and of controlling disruptions, impurities and α-particles in the tokamak.

Case M: The product $\eta_h \eta_a = 0.25$ is at present a realistic assumption for plasma heating by neutral injection using positive ion technology. The actual breakdown seems to be about $\eta_h = 0.3$, $\eta_a = 0.8$. For RF heating by ion cyclotron waves $\eta_h = 0.5$, $\eta_a = 0.5$ is at present a reasonable assumption. The values $\varepsilon_{mp} = 0$, $\eta_m = 1$, $\varepsilon_m = 1$ describe the intention of not using pulsed magnetic fields in mirror machines. The auxiliary energy fraction $\varepsilon_a = 0.1$ is much larger than the corresponding value for light-water reactor (LWR) plants (typically $\varepsilon_a = 0.02$) and thus accounts for the higher complexity of fusion-based systems. The magnets are assumed to be superconducting; their cooling contributes to ε_a. The assumption of DT fusion yields $\alpha_n = 0.8$. The value $\varepsilon_{fct} = 0$ means that the α-particle energy is used direct and not via thermal energy. Half of the absorbed heating energy is assumed to be recovered as thermal energy which leads to $\varepsilon_{pat} = 0.5$. Thermal energy conversion by steam turbines at moderate live steam conditions is described by $\eta_{th} = 0.36$. The direct conversion efficiency $\eta_d = 0.5$ is a reasonable number in the light of present-day small-scale conversion experiments.

Case T: For η_h and η_a the same values as in case M were chosen.
The values $\eta_m = 0.8$ and $\varepsilon_m = 0.5$ mean that the pulsed magnetic energy is supplied with 80 % efficiency and that half of it is recovered after a pulse. The assumption $\varepsilon_{mp} = 5.0$ describes a large volume filled by pulsed magnetic energy with respect to the plasma volume. This is characteristic of, for example, divertor coils located outside the blanket. The values $\varepsilon_{fct} = 1.0$ and $\varepsilon_{pat} = 1.0$ mean that α-particle and absorbed heating energy are delivered by the plasma in thermal form. The value $\eta_d = 0$ describes the fact that no direct conversion is assumed (consistent with $\varepsilon_{fct} = \varepsilon_{pat} = 1$); $\varepsilon_a = 0.1$, $\alpha_n = 0.8$ and $\eta_{th} = 0.36$ are chosen for the same reasons as in case M.

To describe the fission systems assumed the following parameters are chosen:

component parameter	case Th	case U
M_t	1.6	10
M_{fu}	7.5	25
c	0.8	0.5
η_{fi}	0.3	0.3

Table 3
Component parameters chosen for the reference case "fission-suppressed thorium blanket" (Th) and "fission-enhanced uranium blanket" (U)

Case Th: The values $M_t = 1.6$, $M_{fu} = 7.5$ are realized by the blanket configurations shown in Fig. 7 ($M_{fu} \approx 190/14 \cdot b_f = 190/14 \cdot 0.55 = 7.46$). For similar blankets and for the relation between b_f and M_t in fission-suppressed blankets not burning the bred ^{233}U by thermal fission see the lower left corner in the graph on page 19 in /4/. The conversion factor c = 0.8 is an optimistic value for a high-temperature gas-cooled reactor (HTGR) used in an electric power plant and designed for converting a ^{232}Th seed into ^{233}U to be used by recycling /7, p. 276/. The net efficiency $\eta_{fi} = 0.3$ is a somewhat pessimistic value for present-day nuclear power plants (LWR plants), which are quoted with $\eta_{fi} \approx 0.325$. For HTGR's higher values ($\eta_{fi} = 0.37 - 0.38$) are envisaged but not yet proved in practice.

Case U: The values $M_t = 10$, $M_{fu} = 25$ are realized by the blanket configuration shown in Fig. 8 ($M_{fu} \approx 190/14 \cdot b_f = 190/14 \cdot 1.95 = 26.5$). For similar blankets and for the relation between b_f and M_t in fast fission blankets not burning the bred ^{239}Pu by thermal fission see the lower right-hand corner in the graph on page 21 in /4/. The value c = 0.5 is characteristic of an LWR with recycling of ^{239}Pu. Concerning $\eta_{fi} = 0.3$ the same comments are valid as in case Th.

In all cases the fuel energy multiplication M_{fu} of the blanket as a whole strongly depends on the fraction of the total solid angle covered by a realistic blanket. Coverage is reduced by, for example, penetrations for plasma heating and pumping. The reduction of M_{fu} increases very strongly with decreasing coverage if the overall breeding ratio b_T of tritium has to be kept above unity /14, p. 22/. The sensitivity of the whole fusion-fission system to variations of M_{fu} can be assessed by using the results presented in Secs. 3.2 and 3.3.

3.2 Sensitivity analyses of mirror and tokamak systems with superconducting coils

From the reference component parameters listed in Tables 2 and 3 one gets the reference system parameters shown in Table 4.

system parameter	case M-Th	case M-U	case T-Th	case T-U
Q_c	0.362	0.241	0.701	0.466
ε_{nf}	9.242	13.900	9.253	14.000
C	0.0387	0.0736	0.0337	0.0703
ε_{th}	22.140	4.954	19.108	4.825
ε_f	30.000	40.000	30.000	40.000

Table 4
Reference system parameters following from the reference component parameters

Because of the high fusion support ratios ε_f for all the four reference cases (30 or 40) the energy cost (K/E_n) according to eq. (50) is dominated by the factor $1/\varepsilon_{nf}$. This means that the normalized energy cost $(K/E_n)_n$ is approximately given by

$$(K/E_n)_n \approx 1/\varepsilon_{nf} = 1/(1-Q_c/Q), \qquad (65)$$

which follows from eq. (50).

To approach minimal costs, it is necessary that Q be much larger - say by a factor of 10 to 20 - than Q_c. The sensitivity of the necessary $Q \approx (10 \text{ to } 20) \cdot Q_c$ with respect to variations of the component parameters can be assessed from Figs. 10 to 13, which show Q_c vs. normalized component parameters.

Both mirror machine cases (M-Th and M-U) show a strong increase of Q_c if the heating system falls short of its reference assumptions $(\eta_h \cdot \eta_a = 0.25)$. Also very strong are the dependences on the fuel energy multiplication M_{fu} and the conversion ratio c. This is especially pronounced in the thorium case (Fig. 10). This sensitivity is due to

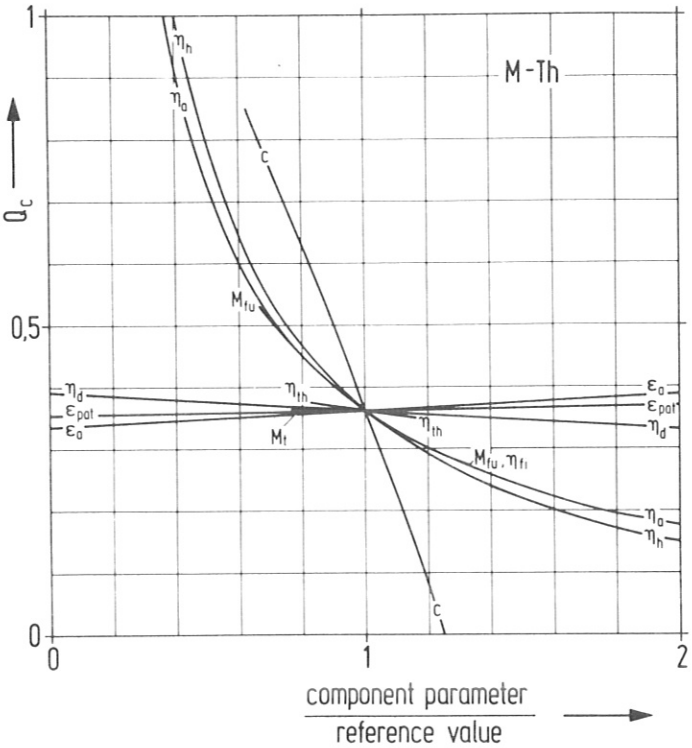


Fig. 10
Variation of Q_c with component parameters normalized to their reference values (case M-Th)

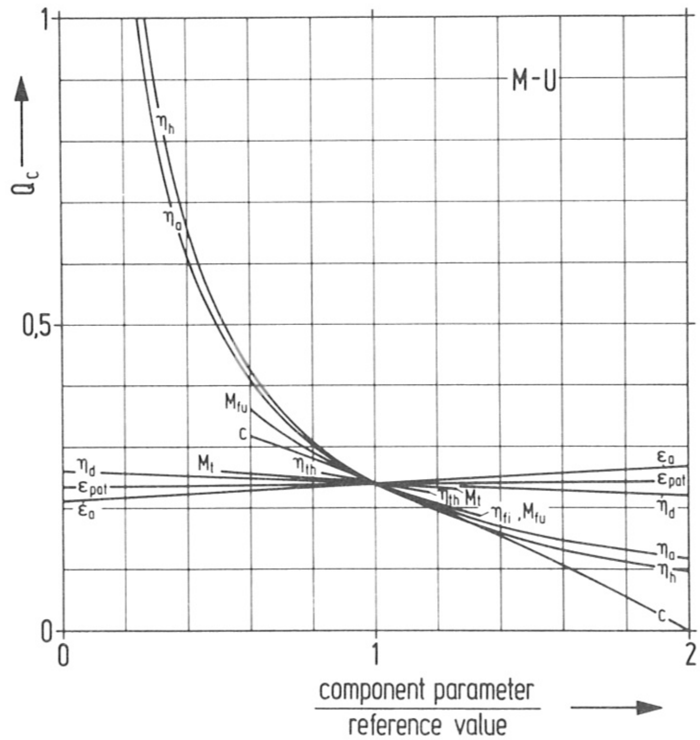


Fig. 11
Variation of Q_c with component parameters normalized to their reference values (case M-U)

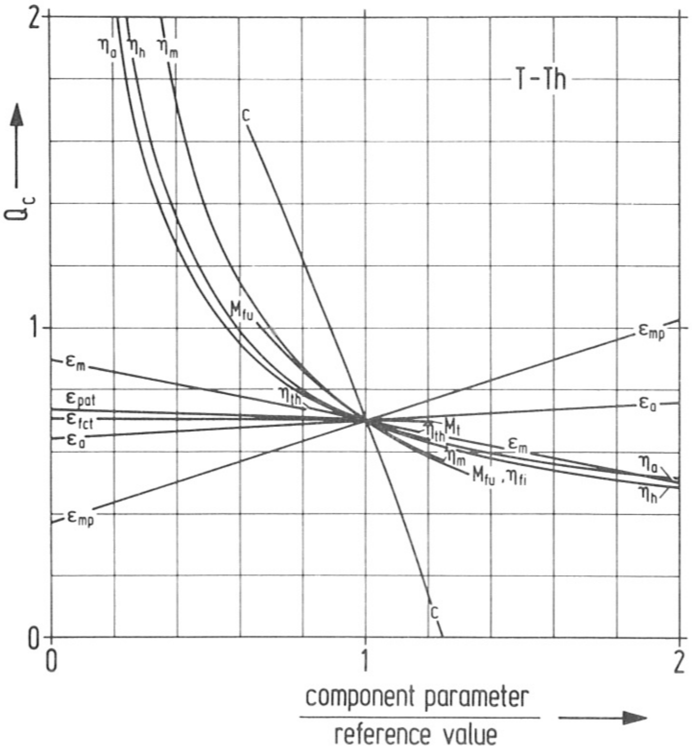


Fig. 12

Variation of Q_c with component parameters normalized to their reference values (case T-Th)

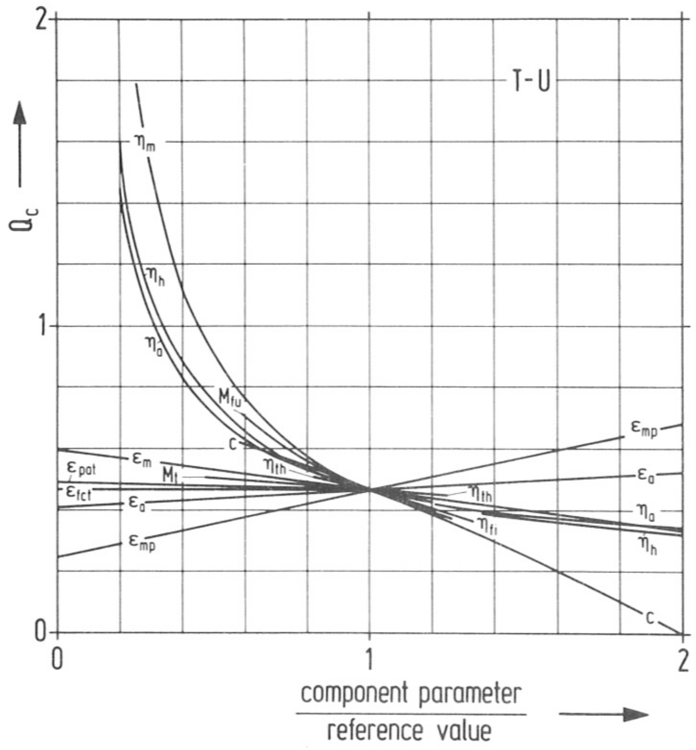


Fig. 13

Variation of Q_c with component parameters normalized to their reference values (case T-U) the high reference value c = 0.8: c enters Q_c as 1/(1-c), which varies strongly if c approaches unity. The influence of the remaining component parameters is only modest.

The reference conditions yield necessary Q-values of 3.5 to 7 for M-Th and 2.5 to 5 for M-U from the energy cost point of view.

Both tokamak cases (T-Th and T-U) show behaviour similar to the mirror cases with respect to η_h, η_a, M_{fu}, and c. Additional strong parameters are the pulsed magnetic field efficiency η_m and - to a certain extent - the ratio ε_{mp} of pulsed magnetic energy to heating energy absorbed. Again the influence of the remaining component parameters is modest.

The reference conditions yield necessary Q-values of 7 to 14 for T-Th and 5 to 10 for M-U.

To complete the assessment of energy cost sensitivity with respect to Q, the variation with Q of the normalized cost according to eq.(50) for the four reference cases has been determined (data taken from Tables 2 and 3).

For the cost parameters β_f, β_e, β_c defined by eqs. (47) to (49) the following values were used:

$$\beta_f = 1 \text{ and } 10,$$
$$\beta_e = 2,$$
$$\beta_c = 0.5.$$

The value $\beta_f = 1$ represents an optimistic view of the cost for delivering fusion power, whereas $\beta_f = 10$ is on the pessimistic side. The cost of handling the power inside the fusion part of the system and the circulating (electric) power are assumed to be rather high in order to avoid an overly optimistic view of fusion-fission systems. This has led to the values $\beta_e = 2$ and $\beta_c = 0.5$.

Figure 14 shows the normalized energy cost $(K/E_n)_n$ as a function of Q.

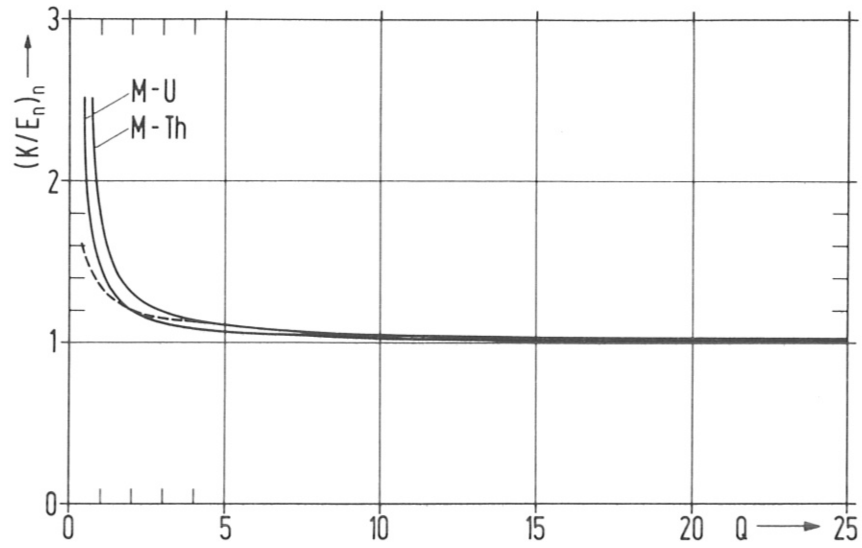


Fig. 14
Relative net energy cost vs. Q for M-Th and M-U. Dashed line: result from a Livermore study normalized to the scale of this figure for M-Th, Q = 4

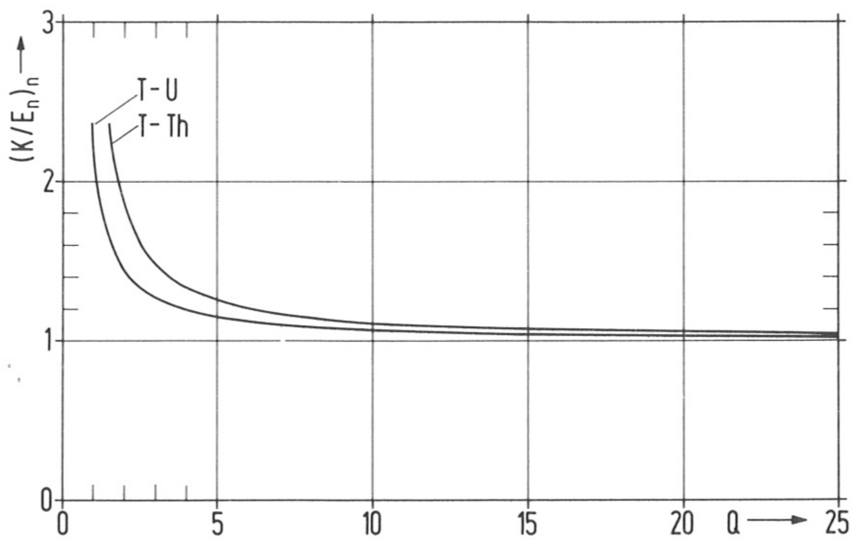


Fig. 15
Relative net energy cost vs. Q for T-Th and T-U

The results for $\beta_f = 1$ and $\beta_f = 10$ cannot be distinguished on the scale of the figure. The absolute cost K depends on β_f to the extent given by the magnitudes of β_f, ε_f, and $\beta_c C \varepsilon_{nf}$ relative to each other and relative to the term in eq. (50) which depends on Q. For comparison a result given in /8, p. 8-12/ for an M-Th case is also shown (dashed line). The absolute numbers given in /8/ are normalized so as to coincide with our M-Th-result for Q = 4. The shapes of the two curves are quite similar. This leads to some confidence in our simple calculation of energy cost vs. Q because the results in /8/ stem from much more involved cost calculations. Most probably the difference between the two curves mainly stems from $\eta_h \cdot \eta_a = 0.25$ in our case, the equivalent $\eta_{inj} = 0.60$ in the Livermore case and the corresponding difference in Q_c (> factor 2).

To supplement our results, which up to now are mostly relative numbers, we have calculated the average powers (in MW) flowing in fusion-fission systems (Fig. 9) by the formulas given in Sec. 2.5 on the basis of a thermal power $P_{ft} = 4000\ MW_{th}$. This is about the thermal power handled in a present-day LWR (Biblis B:$P_{th} = 3733\ MW_{th}$, $P_n = 1240\ MW_e$). All component parameters have the reference values given in Tables 2 and 3. The only exceptions are the Q's, for which we have assumed the values Q = 25 for M and Q = 100 for T.

Figures 16 and 17 show the case M-Th and M-U, Figs. 18 and 19 the cases T-Th and T-U. From these figures one reads circulating powers between roughly 450 and 950 MW_e. Probably this means that, in reality, this power is not fed back to the system from anywhere but is supplied by a power plant on the site of the fusion device. This would enhance the thermal power on the site by about $2 \cdot P_c$, which is not at all negligible. To assess the sensitivity of P_c and thus the size of the power plant with respect to Q, one may use Fig. 20, which shows C vs. Q for the four cases considered. Decreasing values for Q lead to strongly increasing C's and, because of eq. (61), to increasing values for the power P_c. This tendency is somewhat damped by the decrease of ε_{th} and ε_{nf} with decreasing Q.

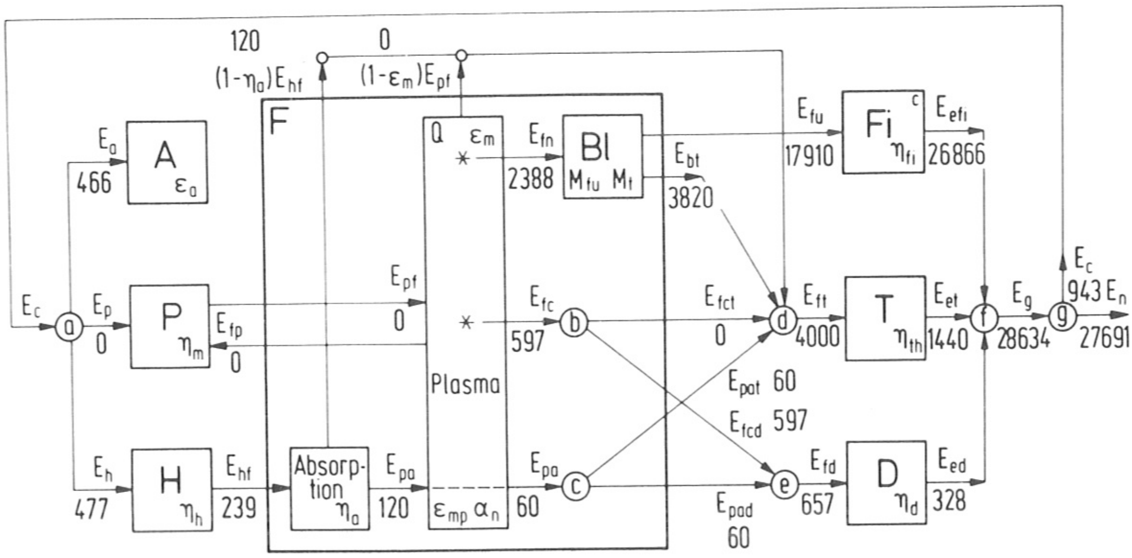


Fig. 16

Case M-Th: average powers (in MW) flowing in the fusion-fission system for P_{ft} = 4000 MW (Q = 25, for remaining component parameters see Tables 2 and 3)

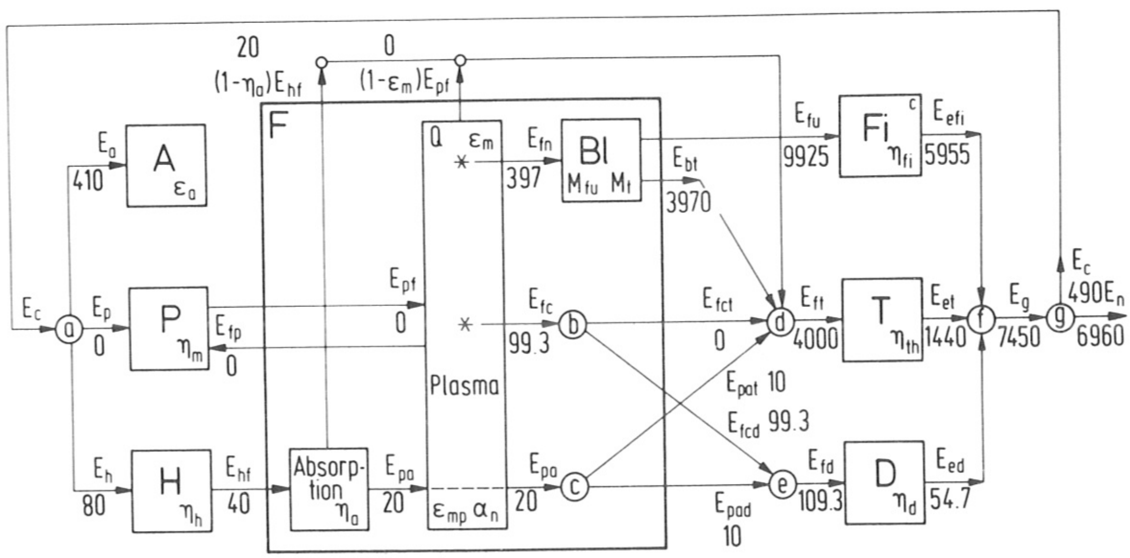


Fig. 17

Case M-U: average powers (in MW) flowing in the fusion-fission system for P_{ft} = 4000 MW (Q = 25, for remaining component parameters see Tables 2 and 3)

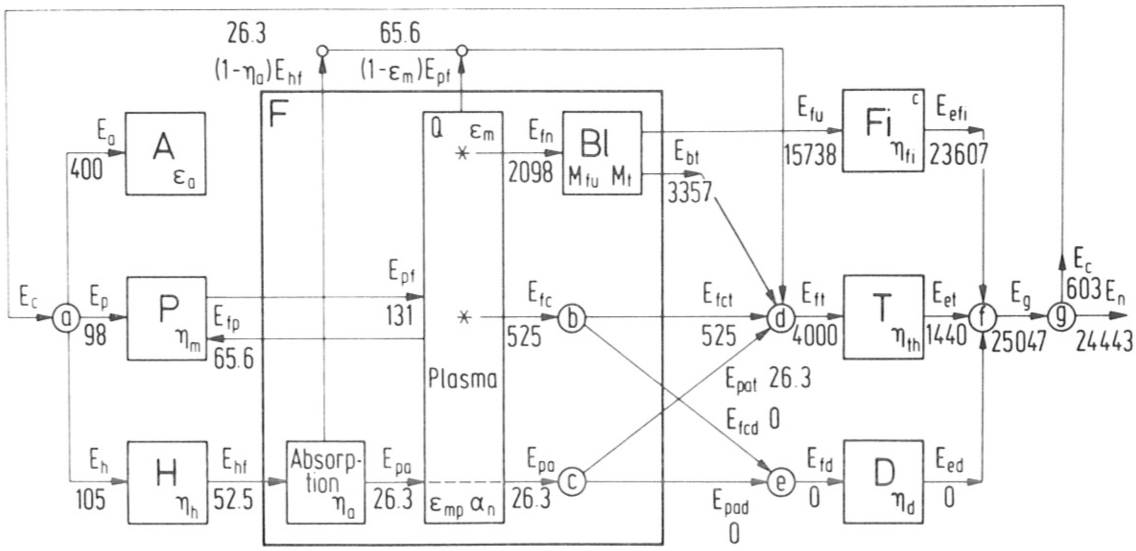


Fig. 18

Case T-Th: average powers (in MW) flowing in the fusion-fission system for P_{ft} = 4000 MW (Q = 100; for remaining component parameters see Tables 2 and 3)

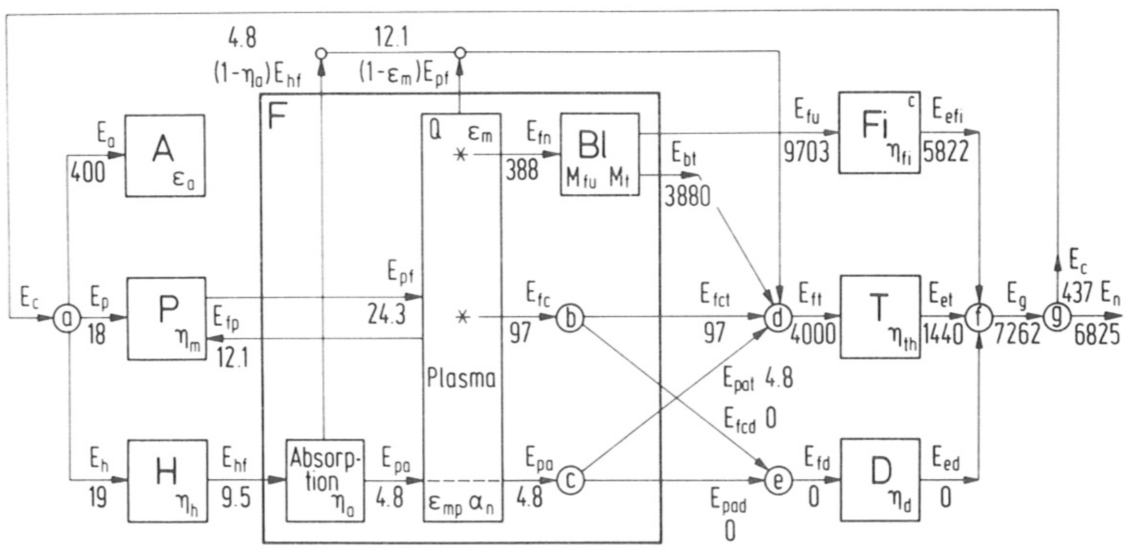


Fig. 19

Case T-U: average powers (in MW) flowing in the fusion-fission system for P_{ft} = 4000 MW (Q = 100; for remaining component parameters see Tables 2 and 3)

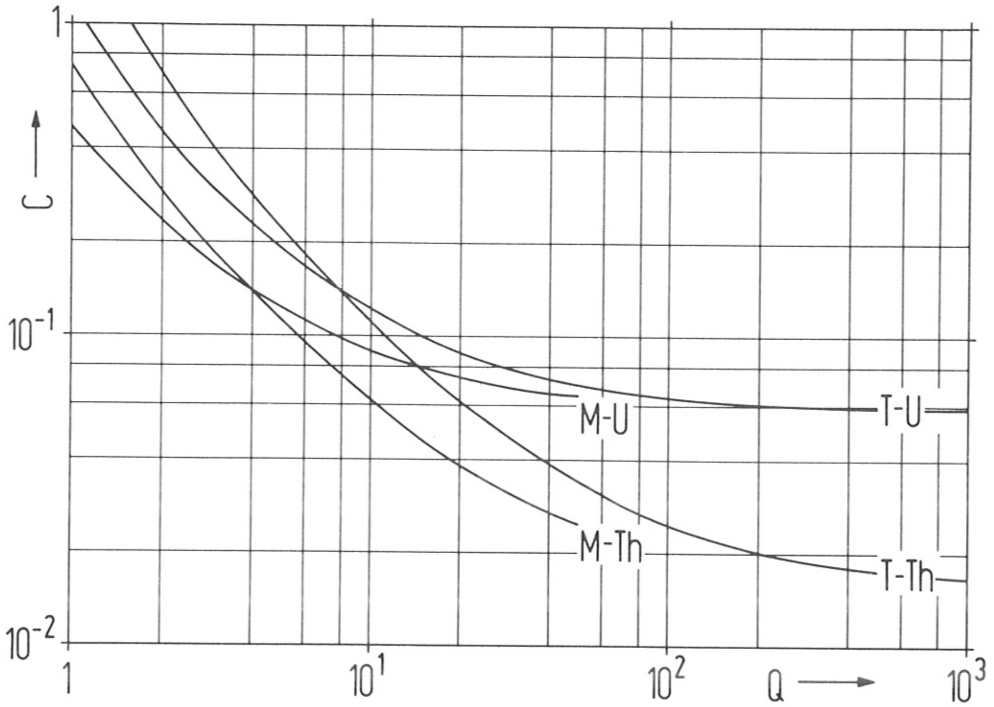


Fig. 20
Variation of the circulating energy fraction C with Q for the reference cases M-Th, M-U, T-Th, and T-U

3.3 Sensitivity analyses of tokamak systems with resistive coils

We shall now restrict ourselves to tokamaks and deviate from the reference parameters used up to now in one major respect: for the auxiliary energy fraction ε_a defined by eq. (20) we assume considerably higher values in order to describe the energy dissipation in resistive coils. The basic data for this stems from a recent study /9/ aimed at clarifying whether tokamaks with steady-state resistive coils might be suitable for the next generation of experiments ("POST JET") or for fusion-fission systems.

For fusion powers of about 500 MW_{th} as exemplified by the case T-U shown in Fig. 19 the resistive power lost in the main field coils is about 500 MW_e. Assuming this relation, half of that value for resistive poloidal field coils and $0.1 \cdot P_{ft}$ for the remaining auxiliaries (this corresponds to the $\varepsilon_a = 0.1$ used up to now) together with the data in Fig. 19 yields

$$\varepsilon_a = (485 \cdot 1.5 + 0.1 \cdot 4000)/4000 = 0.282 \ .$$

We therefore choose the reference value $\varepsilon_a = 0.3$ for the case T-U-R (R for "resistive").

For a fusion power of about 2500 MW_{th} (case T-Th shown in Fig. 18) the power consumption of the toroidal field coils according to /9/ is about $0.3 \cdot P_f$. With the same assumptions as above this leads to

$$\varepsilon_a = (2623 \cdot 0.45 + 0.1 \cdot 4000)/4000 = 0.395 \ .$$

We therefore choose the reference value $\varepsilon_a = 0.4$ for the case T-Th-R.

With these ε_a's, the value Q = 100 and the remaining data from Tables 2 and 3 the sensitivity of the critical energy multiplication Q_c was investigated for the cases T-Th-R and T-U-R.

parameter	case T-Th-R	case T-U-R
Q	100	100
ε_a	0.4	0.3
Q_c	0.887	0.599
ε_{nf}	8.862	12.417
C	0.0776	0.205
ε_{th}	19.672	4.851
ε_f	30.000	40.000

Table 5
Reference system parameters following from the reference component parameters

Table 5 shows the system parameters resulting for the two reference cases T-Th-R and T-U-R. With respect to the tokamak reference cases shown in Table 4 the Q_c values have increased by 25 to 30 % and the C values by a factor 2.3 to 2.9.

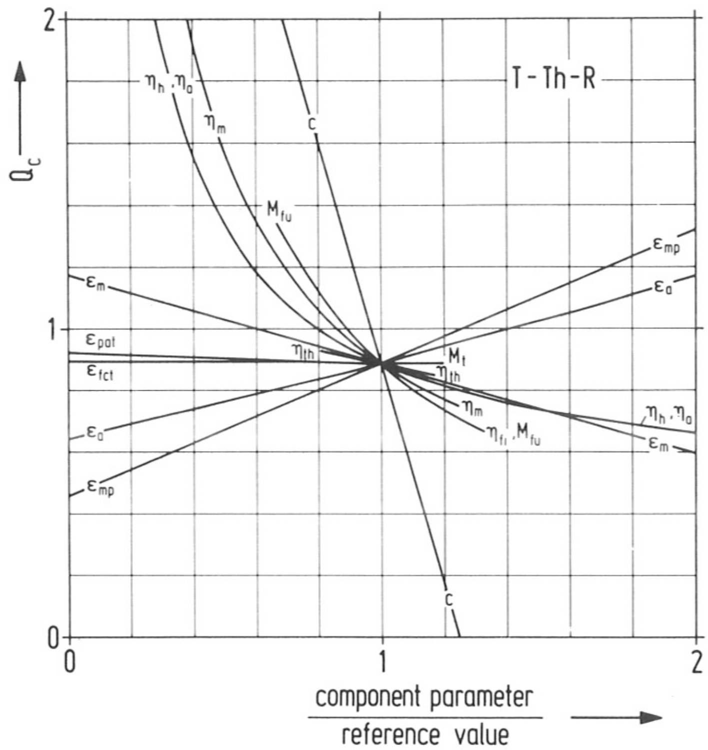


Fig. 21
Variation of Q_c with component parameters normalized to their reference values (case T-Th-R)

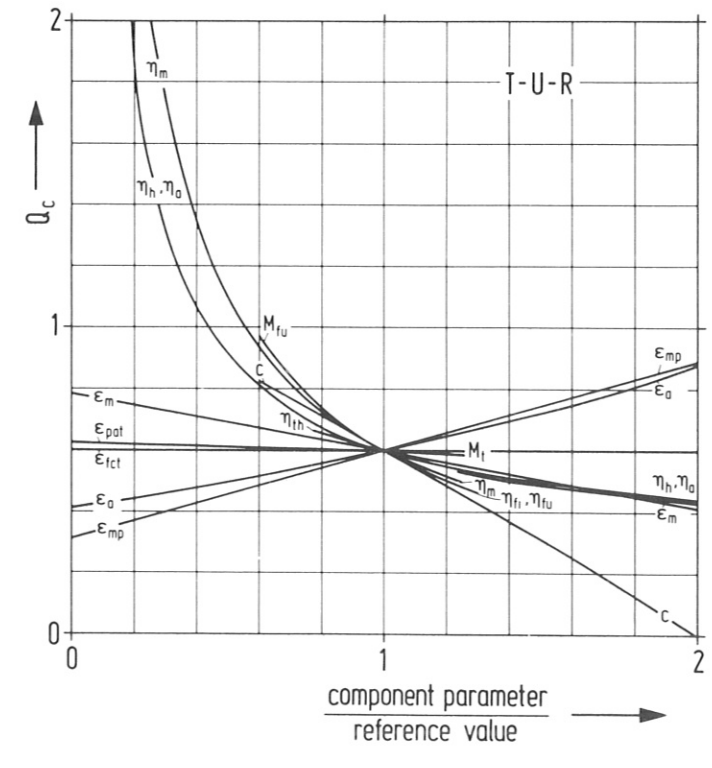


Fig. 22
Variation of Q_c with component parameters normalized to their reference values (case T-U-R)

Figures 21 to 22 show the sensitivity of Q_c with respect to variations of the various component parameters. The tendencies are the same as for the tokamak cases T-Th and T-U shown in Figs. 12 and 13. In both cases, however, the sensitivity with respect to changes of ε_a has markedly increased. The case T-Th-R is generally more sensitive than the case T-U-R.

Figure 23 shows the normalized energy cost based on eq. (50) for T-Th-R and T-U-R. In both cases $\beta_f = 10$, $\beta_e = 2$, and $\beta_c = 0.5$ were used [see eqs. (47) to (49)] as in the cases shown by Figs. 14 and 15. The case T-Th-R falls below 10 % and 5 % deviation from unity for Q = 13 and Q = 25 respectively. The corresponding values for T-U-R are Q = 9 and Q = 17. The sensitivity of this result can be assessed by using Figs. 21 and 22 together with the approximate scaling $(K/E_n)_n \approx 1/(1-Q_c/Q)$.

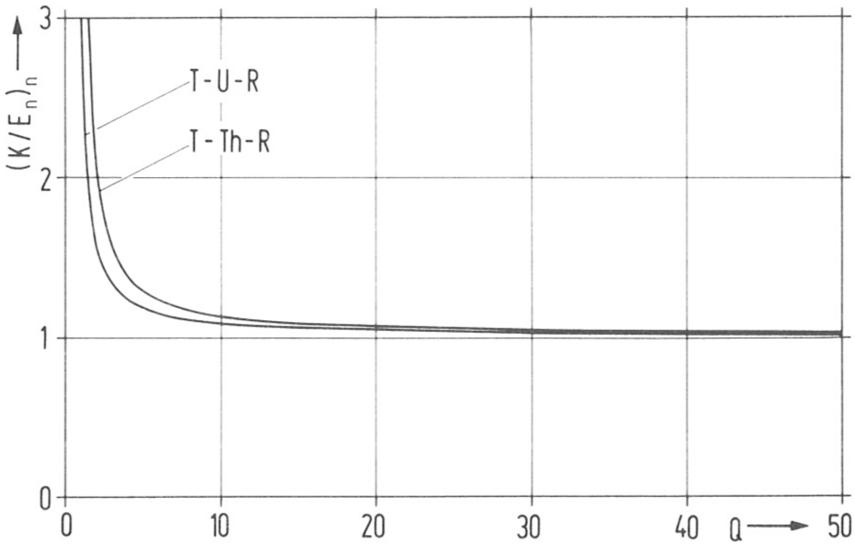


Fig. 23
Relative net energy cost vs. Q for T-Th-R and T-U-R

Figures 24 and 25 show the average powers (in MW) flowing in the systems T-Th-R and T-U-R for $P_{ft} = 4000\ MW_{th}$ as in the previous cases.

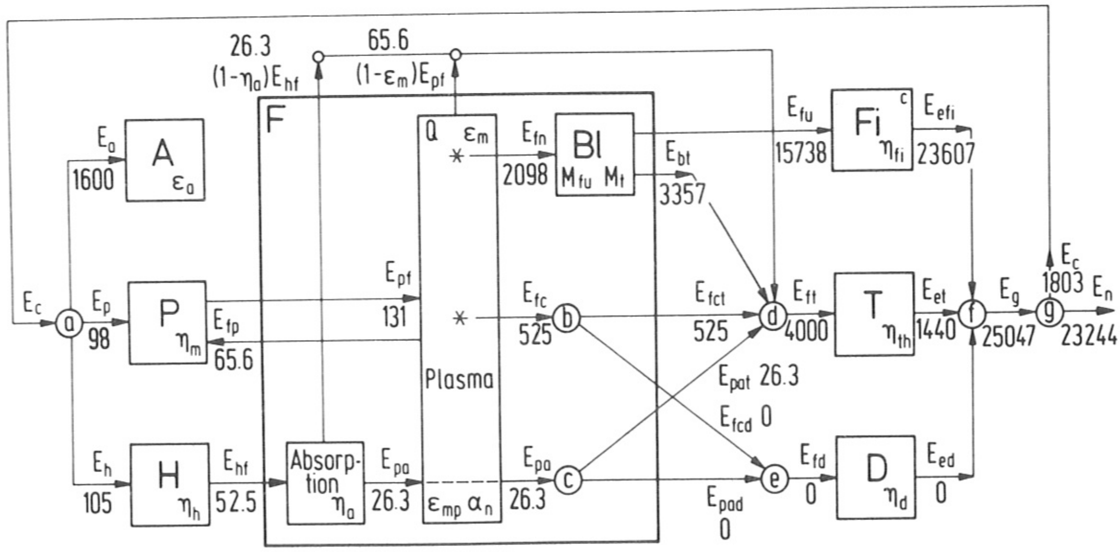


Fig. 24

Case T-Th-R: average powers (in MW) flowing in the fusion-fission system for P_{ft} = 4000 MW (Q = 100, ε_a = 0.4; for remaining parameters see Tables 2 and 3)

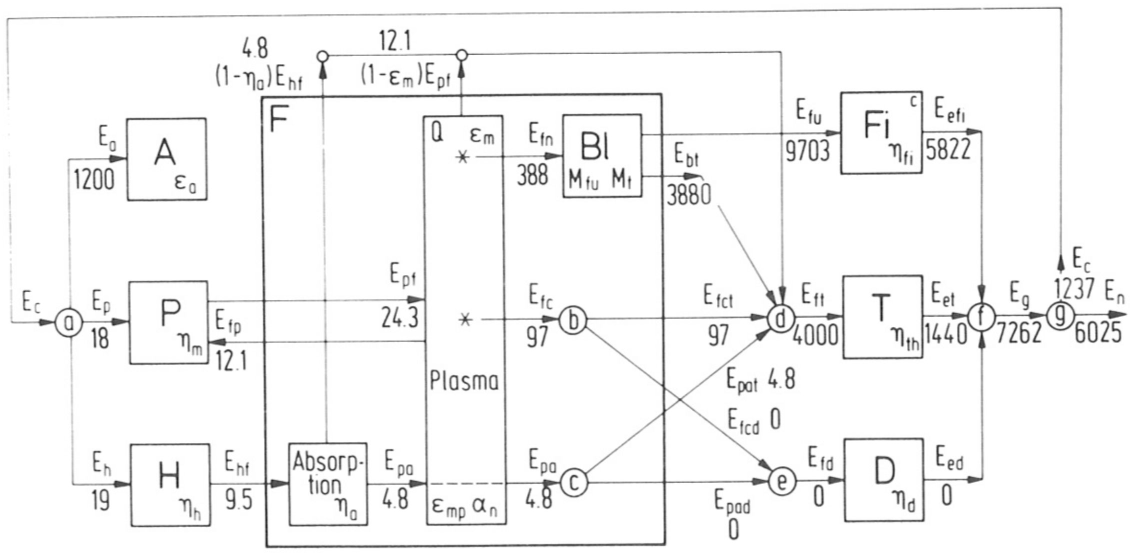


Fig. 25

Case T-U-R: average powers (in MW) flowing in the fusion-fission system for P_{ft} = 4000 MW (Q = 100, ε_a = 0.3; for remaining parameters see Tables 2 and 3)

The figures are the same as in Figs. 16 and 17 respectively except for the net power P_n and the power P_c because of the energy consumed by the resistive coils. The circulating power is rather high. This may call for reducing, at least in case T-Th-R, the thermal power P_{ft} released at the site of the fusion device.

Figure 26 shows the circulating energy fraction for the cases T-Th-R and T-U-R as functions of Q. The curves may be used to assess the impact of Q on the circulating power for which Figs. 24 and 25 give absolute values as reference points.

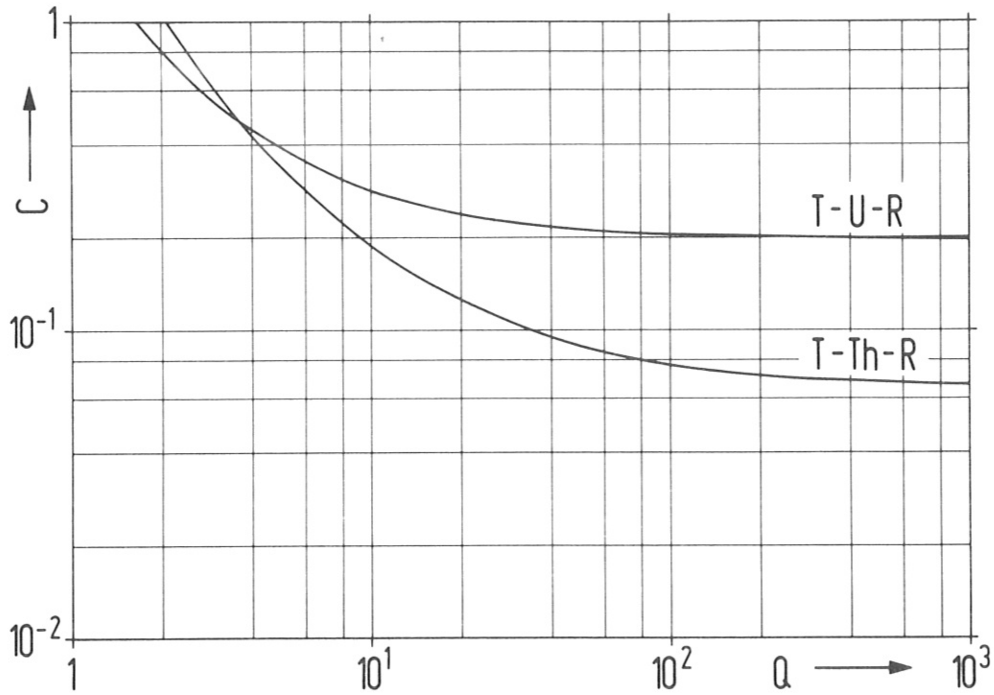


Fig. 26
Variation of the circulating energy fraction C with Q for the reference cases T-Th-R and T-U-R

3.4 Energy multiplication by neutral beam driven tokamak plasmas

The energy multiplication Q of ignited tokamak plasmas is essentially proportional to the plasma burn time /6, p. 268/. This is true as long as the energy dissipated by the axial current is negligible compared with transport and radiation losses. Thus Q can be made rather high

(10^2 to 10^3) if control of burn, impurities, and plasma profiles can be achieved.

The energy (or power) multiplication by a driven tokamak plasma which has to be constantly heated by external power sources is much less than that of an ignited plasma. The Q values which may be achieved by neutral beam driven tokamak plasmas can be assessed on the basis of results published by Jassby. The material to be presented in the following has been worked out and made available by O. Gruber /10/. In all cases heating by neutral beam injection has been assumed.

If a beam of energetic neutral particles (D^0 and/or T^0) is injected into a target plasma (D and/or T) fusion power is delivered by three different processes: thermonuclear reactions between the ions of the target plasma, reactions between the target plasma and the beam particles, and reactions between the beam particles.

By neglecting the beam-target and beam-beam reactions one gets the following simple relation between the plasma ion density n, the global energy confinement time τ_E (describing both transport and radiation losses) and Q:

$$n\tau_E/(n\tau_E)_o = 1/(1+5/Q); \qquad (66)$$

$(n\tau_E)_o$ is the value necessary for the ignited state (losses equal to α-particle heating).

Equation (66) is valid as long as the density and temperature profiles are the same in both cases. In the event of n and T not being constant over the plasma cross-section n in eq. (66) is an average value gained by volume integration. In the case described by eq. (66) the heating by α-particles and beam injection just covers the plasma energy losses. Relation (66) is represented by curve 1 in Fig. 27.

With decreasing ($n\tau$)-values the power multiplication decreases, too,

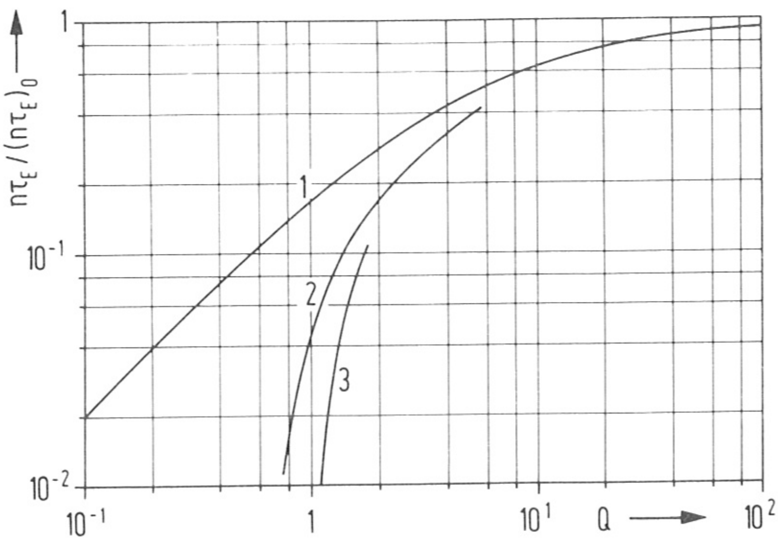


Fig. 27
Relations between the energy confinement parameter $n\tau_E$ and the plasma power amplification Q

because the losses have to be covered more and more by external heating. In such a plasma with poor confinement beam-target and beam-beam reactions must not be neglected with respect to the thermonuclear ones. Curve 2 in Fig. 27 demonstrates their effect for a 50 : 50 DT plasma at $T_i = T_e = 8$ keV (temperatures are assumed constant over the plasma cross-section). The curve is based on results given in /11/ for the injection of a 50 : 50 mixture of D^0 with 200 keV and T^0 with 300 keV. The D^0 and T^0 particles at these energies have equal velocities and hence equal deposition profiles. Furthermore, the fusion energies per particle injected are nearly the same for both species. For Q less than 2 the reactions involving fast injected particles dominate; the plasma approaches a "beam driven" state.

The Q-values can be increased by injecting D^0 into a pure T plasma. This mode has the obvious difficulty of maintaining a T plasma in spite of D^0 injection. Curve 3 in Fig. 27 (based on /12/) demonstrates the effect. By taking into account the beam-target reactions one gets the following relation between $n\tau_E$ and Q:

$$n\tau_E/(n\tau_E)_o = [(2n_f/n_e \cdot \langle\sigma v\rangle_{pb}/\langle\sigma v\rangle_{th} + 1)\cdot(1 + 5/Q)]^{-1} \qquad (67)$$

("f" = fast particle, "pb" = plasma beam, "th" = thermonuclear). The reaction parameter $\langle\sigma v\rangle_{pb}$ varies slowly over a wide range of temperatures at the high injection energies assumed. The reaction parameter $\langle\sigma v\rangle_{th}$ increases with temperature, but so too does the necessary heating power and hence the fast ion population. Hence the curves 2 and 3 in Fig. 27 only weakly depend on the plasma temperature.

For very small values of $n\tau_E$ - typically $n\tau_E/(n\tau_E)_o < 10^{-2}$ - the beam-beam reactions become increasingly important. They compensate for the decreasing beam - target reactions and finally dominate. Therefore Q in this domain remains virtually constant. In the limiting case $n_f/n_e = 1$ the 50 : 50 DT system approaches a plasma dominated by fast ions. If D^o and T^o are injected opposite to each other the multiplication Q can again become larger than unity but remains smaller than 2 /13/.

The necessary Q-values for the cases T-Th, T-Th-R, T-U, and T-U-R range from 7 to 25 (see pages 24 and 32). According to Fig. 27 this span corresponds to $(n\tau_E)$-values of 40 to 80 % of the values necessary for ignition. This means that tokamak plasmas meeting the requirements imposed by fusion-fission systems are close to the ignited state. The remaining step is rather small and should therefore be taken to eliminate the necessity of continous plasma heating and the associated need for extreme reliability.

4. Conclusions

The conclusions refer only to versions of fusion-fission systems but not to the comparison of such systems with pure fusion or fission systems.

The sensitivity of the critical energy multiplication Q_c and hence the sensitivity of necessary Q-values is restricted to factor of 2 changes if the component parameters vary over reasonable ranges. The component parameters with the most pronounced influence for both Th- and U-systems are the efficiencies η_h and η_a ("heating" and "absorption") of the heating system. Of similar importance are the parameters η_m and ε_{mp} of the pulsed magnetic field system in the T-cases ("tokamaks"). Also important are the parameters M_{fu} and c ("fuel energy multiplication" and "conversion") characterizing the fission part. This latter sensitivity is higher for the Th-cases because of the high value c = 0.8 assumed for reference.

Q-values necessary (from the cost point of view) for the M-systems ("mirrors") are in the range 2.5 to 7 with the factor of 2 sensitivity already mentioned. Such values - perhaps with the exception of the upper extreme ones - lie within the projections for tandem mirror devices without thermal barriers.

Necessary Q-values (from the cost point of view) for the T-systems ("tokamaks") lie in the range 5 to 25. They correspond to global $(n\tau_E)$-values which are 40 to 80 % of those necessary for ignition. This is true of systems with both superconducting and resistive coils. Hence the requirements are not relaxed far below those for ignition by the addition of a fission part.

From the cost and energy balance points of view (necessary Q's and circulating energy) resistive coils can be tolerated in T systems with $Q \gtrsim 25$, i.e. with practically ignited plasmas.

The energy cost of fusion-fission systems depends rather weakly on the specific installation cost of the fusion device. This is due to the high values of ε_f (thermal fission energy / thermal fusion energy). In the U cases this is mainly due to a high M_{fu} (fuel energy multiplication by the blanket), in the Th cases the high conversion (c) is the most favourable effect.

To make a decision between Th and U systems at least the following issues have to be considered:

- Th blankets need a higher integrated neutron wall load (MWa/m^2) than similarily structured U blankets to achieve a given degree of fuel enrichment. The reason is the higher fuel breeding ratio b_f

of U-blankets.

- The power density produced by fission in the front zone of U blankets is of the same order as in LWR fuel elements and hence considerably higher than in Th blankets. This difference is very pronounced if fission-suppressed Th blankets are used for comparison. High fission power density necessitates efficient cooling during normal operation and calls for emergency cooling systems. This is still true after shutdown because of the nuclear afterheat.

- The fission reactors and fuel reprocessing devices for ^{239}Pu from U systems already exist on an industrial scale in the form of light-water reactors and the PUREX process. Reactors (for example, high-temperature gas-cooled reactors) and reprocessing of ^{233}U from Th systems still have to be developed to an industrial scale.

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