Equations for Conceptual Tokamak Fusion Reactor Design

Albert F. Knobloch

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A.F. Knobloch

Abstract
Simplified tokamak reactor design equations are collected and commented. They allow a fast approximation (and optimization) of consistent tokamak reactor parameter sets that comply with the most important design rules and constraints known. Different operating points in a given reactor configuration can also be studied. Unshielded reactor experiments are covered as well. Examples based on short Mathematica® programs are included and discussed.

Introduction

Tokamak fusion reactor studies have already been conducted since about the 1970s. A wealth of information has been gathered and elaborate software has been written for this purpose. On the other hand, the plasma physics basis and the engineering experience, of course, do not yet fully extend into the parameter domain of a commercial fusion reactor. Hence a number of important physics design relations are not available in exact form and some careful guesswork is still necessary. In the last two decades international negotiations and activities have been devoted to the Next Step Tokamak definition and design. Over the years it has been observed that a large range of input parameter combinations have been considered for that purpose without greatly modifying the design goals, but with important changes in the input assumptions and hence the resulting parameter sets. Thus it appears helpful to have a set of (not too much) simplified equations that may allow - in contrast to computer programs starting from differential equations - an immediate insight into the basic impact of, for instance, different combinations of input parameters or of the specific composition of exponents in a specific energy confinement scaling. This does not exclude further specific refinement of the simplified relations. It has become possible to compile a collection of such equations since many sources have provided basic equations, approximations, and fitting formulae that allow one to take the particularly important dependences into account in a simplified manner. Examples can be found in [1,2,3,4]. Not all design rules required, however, are available yet. A prominent example is the lack of simplified design guidelines for the divertor. There are also interrelations between certain parameters that have to be taken into account here by avoiding particular value domains.

The simplified tokamak fusion reactor design equations are meant to provide fast access to relevant reactor parameter sets, including their parametric variation. The approach started from the problem of determining and justifying a certain tokamak reactor configuration. It is obvious that at the present time such a set of equations will yield approximate results and awaits further improvement and completion.

In section 1 the approach for arriving at the equations listed is described, section 2 gives a commented listing of the equations themselves, section 3 gives simple Mathematica® programs for evaluation of the equations, and in section 4 a number of evaluation results are given with additional remarks. The conclusions are presented in Section 5.

1. Approach towards the tokamak reactor design equations

One starts with the geometric facts in a tokamak configuration. First there is the radial build along the minor plasma radius, which consists of the OH coil outer radius (including the OH coil thickness and the inner bore radius), the toroidal field coil thickness, the blanket/shield and first wall thickness, the distance between the first wall surface and the plasma surface, and finally the plasma minor radius, all taken at the plasma horizontal midplane. The sum of these distances makes up the plasma major radius. For the engineering design the maximum toroidal field occurring roughly at the innermost surface of the toroidal magnet system is of great importance; in the plasma physical calculations the central toroidal field value is used (averaging over the plasma torus cross-section). The two are related according to the geometry described.
A second consideration also referring to the ratio of the two field values searches for an optimum configuration or at least for one that could be used as a reference in the infinite domain of possible configurations. It turns out, for instance, that there is - with all input assumptions kept constant - a maximum average neutron wall load for any fixed fusion power or a minimum fusion power for any fixed average neutron wall load. The extrema occur for a certain ratio of the two toroidal field values, and together with the first condition the optimum situation is represented by a certain aspect ratio essentially depending on a certain ratio of the major radius and the blanket/shield thickness [5].
One can, of course, deviate arbitrarily from that optimum, which by itself is rather flat vs. the rate of deviation, but a remarkable impact is seen in individual reactor parameters that vary monotonically. It is also interesting to observe that quite a number of elaborate reactor design studies have arrived at or close to that optimum (e.g. SSTR[6]).
A consistent aspect ratio in the above optimum condition and the other equations requires the plasma current from the current-q equation to be the same as that deriving from the plasma power balance (for a certain energy confinement scaling in the usual power product form). In other words, the aspect ratio follows from equal energy confinement times as required for the plasma power balance and as possible according to the respective scaling. The evaluation takes into account by what factor the above field ratio should deviate from the optimum and hence allows the parameter space to be screened in a well defined manner.

Iteration has to be used for solving since the aspect ratio equation is in implicit form.

From here on the aspect ratio is fixed and all subsequent equations have to use that value. The implicit equation for the aspect ratio - which can take different forms according to the set of input parameters - is important for understanding the impact of modifications in the input assumptions. An increase of the maximum toroidal field, of the blanket/shield thickness, of the confinement enhancement factor, and of the elongation will generally lead to an increase in the aspect ratio, while an increase in current-q will lead to a lower aspect ratio. (Note, however, that q itself may be a function of the aspect ratio with fixed q_ψ at the plasma boundary.) The plasma pressure includes an enhancement factor due to the fast alpha particles represented by a simple fitting formula.

Each of the geometry and power related quantities can be described in more than one form. The form to be preferred, however, is the version composed of the basic input data. As far as possible the equations have been written in a form that separates the input data dependent part from the aspect ratio dependent part. Nevertheless they cannot be used right away for investigating the impact of changes in the input data since the aspect ratio and hence its functions are input data dependent.

For the bootstrap fraction a simple approximation is used. The aspect ratio dependent Q relation has to be included in the iterative evaluation of the aspect ratio.

The radial build mentioned above plays a particular role in the evaluation of the inductive burn time . Apart from the central solenoid field level the conductor current and the average tensile stress level in the coil reinforcement cross-section are given. For the toroidal field coils the same applies in principle, the vertical tensile and the circumferential compressive stress in the inner coil legs being taken into account. The toroidal coil thickness has to be evaluated by iteration.

The volume and stored energy related equations are rather crude approximations and are intended more for the purpose of comparison between different parameter sets.

Note that the aspect ratio iteration equation may be rewritten for different sets of given input parameters, but rewriting any of the consecutive equations for separate parametric evaluation leading to a deviating parameter set obviously does not work.

In a first version the reactor configuration includes a blanket/shield thickness. In the second version the relations derived for the first one are transformed to the situation of unshielded experiments using two transformation equations. The geometric considerations in this case lead to a direct simple relation for the aspect ratio which becomes independent of all input data except the ratio of the plasma to vessel radius and the factor describing the intended deviation from the optimum. It is

easily seen that the optimum unshielded configuration has a lower aspect ratio than the shielded one. Formally, in the equations the role of the non-existing blanket/shield thickness is taken over by a characteristic length which is very small, but variable with the input data and the aspect ratio. The subsequent equations for other reactor parameters have a similar appearance to those for a finite blanket/shield thickness, but the aspect ratio dependent part is implicit.
With unshielded configurations it is also necessary to iterate in order to obtain consistent parameter sets. The iteration here is in the evaluation of Q, which yields a consistent value of C_{si}^*. In general, the ease of understanding the impact of input data changes on the results is reduced for unshielded configurations. Because of the iterative solution involved, parametric equation evaluation involves Q iteration in this case.

2. Design equations with comments (tokamak reactor formulary)

The following equations are useful for a quick evaluation of consistent accessible tokamak reactor parameter sets based on existing knowledge. They were derived in an attempt at a more general description of the accessible configurations and parameter sets for both pulsed and steady-state next-step and prototype reactors. While for the plasma and nuclear physics input the state-of-the art relations and data are applied, the configuration aspect is taken care of by considering the fact that for a tokamak reactor configuration there is an "optimum" aspect ratio for which, with the input data kept constant, the neutron wall load has a maximum for a given fusion power. Such an optimum is rather flat in the parameter domain of interest. Its position can therefore easily be shifted, depending on the confinement scaling selected. In that situation a purely geometric definition of the optimum is retained, which yields a reasonable practical approximation. That case is characterised by $f_A = 1$. It does not necessarily constitute an economic optimum, although quite a number of economically optimized reactor design studies are at or close to $f_A = 1$. Other ("off-optimum") cases may be defined by $f_A \neq 1$, which enables a structured evaluation of the infinite space of possible configurations. The fundamental differences in accessible parameters and geometries between unshielded tokamak experiments (in which also fusion reactions are produced) and reactor devices including a blanket/shield zone t_{BS} can already be seen in the formal appearance of the respective equations when modifying the general equations (as derived for $t_{BS} > 0$) for the case of $t_{BS} = 0$.
For $t_{BS} > 0$ the aspect ratio has to be iterated from all essential specific input data. The reactor geometry and operating parameters then mainly derive from g and B_{max}. For $t_{BS} = 0$ the aspect ratio follows from a few input data only, then the value of Q has to be iterated from all essential

specific input data. Subsequently the reactor geometry and operating parameters follow. Only the static operating parameters are covered.

2.1 Tokamak reactor formulary for $t_{BS} > 0$ (shielded configurations, reactors):

The general geometry relation and optimum conditions (see 2.6.4) read

$$\frac{B}{B_{max}} = 1 - \frac{1}{A\, f_{pw}} - \frac{t_{BS}}{R} \; ; \qquad \frac{B}{B_{max}} = \frac{4}{9\, f_A}\left(1 + \frac{1}{A\, f_{pw}}\right)$$

In order to satisfy both equations the aspect ratio has to be

$$A = \frac{1}{f_{pw}} \frac{\left(9\, f_A + 4\right)}{\left(9\, f_A - 4\right) - 9\, f_A \dfrac{t_{BS}}{R}} = \frac{\left(9\, f_A + 4\right)}{\left[f_{pw}\left(9\, f_A - 4\right)\right] - f_3 \dfrac{t_{BS}}{R}}$$

from which $R(A, t_{BS})$ is later derived. The abbreviations below are used:

$$f_1 = 4\left(A\, f_{pw} + 1\right)$$

$$f_2 = A\, f_{pw}\left(9\, f_A - 4\right) - \left(9\, f_A + 4\right) = f_3\left(A - \frac{1}{f_{pw}}\right) - f_1$$

$$f_3 = 9\, f_A\, f_{pw}$$

A leading condition is that the possible energy confinement time for a given scaling is equal to the confinement time as called for by the plasma power balance (see 2.4). Including the q-equation (Kruskal condition) and the Troyon coefficient g, one obtains the following iteration equation for the consistent aspect ratio based on specific input data.

$$A = \left\{ \frac{\left(5\, B_{max}\, f_1\right)^{\left[2\left(1+\alpha_n-2\alpha_P\right)+\alpha_I+\alpha_B\right]} \left(\dfrac{t_{BS}}{f_2}\right)^{\left[\alpha_a+\alpha_R+\alpha_I-3\alpha_P\right]}}{\dfrac{\left[\dfrac{C^*_{sI}}{f_H}\, k^{\left(\alpha_P-\alpha_k\right)}\right] f_3{}^{\left[3\alpha_P+2\left(1+\alpha_n-2\alpha_P\right)+\alpha_B-\alpha_R-\alpha_a\right]}}{\left[\dfrac{f(k)}{q}\right]^{\left[\left(1+\alpha_n-2\alpha_P\right)+\alpha_I\right]}}} \right\}^{\dfrac{1}{\left[3\left(1+\alpha_n-2\alpha_P\right)+2\alpha_I-\alpha_R+\alpha_P+\alpha_B\right]}}$$

with

$$C_{sI}^{*} = \frac{\left[\frac{4.80}{\left(1 - \frac{5}{F_{Br}} + \frac{5}{Q}\right)}\right]^{(1-\alpha_p)} \frac{\left(1+\frac{n_i}{n_e}\right)^{(2+\alpha_n-2\alpha_p)}}{\left(\frac{n_{DT}}{n_e}\right)^{2(1-\alpha_p)} C_{\sigma Ef}^{(1-\alpha_p)}} \frac{T_{10}^{\alpha_n}}{\left(\frac{g}{2\,C_{fa}}\right)^{(1+\alpha_n-2\alpha_p)}}}{C_{\tau E}^{(1-\alpha_p)}}$$

$$C_{\tau E}^{(1-\alpha_p)} = \frac{C_\tau}{5^{\alpha_B}\left(0.48\pi^2\right)^{\alpha_p}}$$

Since C_{si}^{*} depends on Q, for moderate to low Q the aspect ratio has to be calculated including the Q(A) formula (see below). For $C_{\sigma Ef}$ (reactivity), $5/F_{Br}$ (bulk radiation losses), and n_{DT}/n_e, n_i/n_e see 2.4, 2.6.1, 2.6.3. C_{fa} denotes the plasma pressure increase from fast alpha particles. One has as an approximation

$$C_{fa} = 1 + 0.2\left[T_{10} - 0.37\right]$$

The exponents in the iteration formula for A derive from the particular energy confinement scaling adopted:

$$\tau_E = C_\tau\, f_H \frac{I^{\alpha_I} R^{\alpha_R} a^{\alpha_a}\, n_e^{\alpha_n}\, B^{\alpha_B}\, k^{\alpha_k}}{P^{\alpha_P}} = \left[\frac{C_\tau\, f_H\, I^{\alpha_I}\, R^{(\alpha_R-\alpha_P)}\, n_e^{(\alpha_n-\alpha_P)}\, B^{\alpha_B}}{\left(0.48\pi^2\right)^{\alpha_P} a^{(2\alpha_P-\alpha_a)}\, k^{(\alpha_P-\alpha_k)}\, T_{10}^{\alpha_P}}\left(1+\frac{n_i}{n_e}\right)^{-\alpha_P}\right]^{\frac{1}{1-\alpha_P}}$$

q may be inserted as a function of A, which generally implies that f_A is also A-dependent. For $q \neq f(A)$ $f_A = 1$ describes the "optimum" situation in which for a given fusion power the neutron wall load is a maximum. $f_A > 1$ means that the configuration has a lower aspect ratio than the optimum one and vice versa. For q(A) a factor C_{fA} may be imposed on $f_A(A)$ again with $C_{fA} > 1$ for lower than optimum aspect ratio and vice versa. Since the inclusion of typical energy confinement scalings in the optimization process produces extremely flat A dependences and hence misleading results, the geometric optimization is kept independent of any confinement scaling (see 2.6.4).
An example for q(A) is the relation used for the ITER studies[7]:

$$q = q_\psi \frac{\left(1 - \frac{1}{A^2}\right)^2}{\left(1.17 - \frac{0.65}{A}\right)}$$

which implies the following definition of f_A for $q = f_q(A)$ (see 2.6.4)

$$f_A = C_{fA}\left\{1 + \frac{4}{9}\left[\frac{4}{\left(A^2 - 1\right)} - \frac{0.65}{\left(1.17\,A - 0.65\right)}\right]\right\}$$

In order to show one example of how the aspect ratio iteration equation may be modified for another set of given input parameters, an expression listed and explained below is used for substituting a given q value in the A iteration for a given value of the fusion power. With

$$\frac{f(k)}{q} = \left(\frac{P_f}{C_{Pf}}\right)^{0.5} \frac{f_2^{1.5}\, f_3^{0.5}\, A^{2.5}}{f_1^2\, t_{BS}^{1.5}} \quad \text{with} \quad C_{Pf} = C_{PfB}^{*}\, B_{max}^{4}$$

and after insertion into the above A iteration relation, one gets

$$A = \left\{ \frac{\left(f_1\, B_{max}\right)^{(\alpha_I-\alpha_B)} \left[\frac{t_{BS}}{f_2}\right]^{\left[1.5(1+\alpha_n-2\alpha_p)+3\alpha_p+0.5\alpha_I-\alpha_a-\alpha_R\right]}}{\dfrac{\dfrac{5^{\left[2(1+\alpha_n-2\alpha_p)+\alpha_I+\alpha_B\right]}}{\left[C_{sI}^{*}\, k^{(\alpha_p-\alpha_k)}\right]}\, f_H \left(\dfrac{P_f}{C_{PfB}^{*}}\right)^{0.5\left[(1+\alpha_n-2\alpha_p)+\alpha_I\right]}}{f_3^{\left[3\alpha_p+1.5(1+\alpha_n-2\alpha_p)+\alpha_B-0.5\alpha_I-\alpha_R-\alpha_a\right]}}} \right\}^{\frac{1}{\left[0.5\alpha_I+\alpha_R-\alpha_p-\alpha_B-0.5(1+\alpha_n-2\alpha_p)\right]}}$$

All further equations hold for the above iterated aspect ratio only.
The ratio of the plasma current divided by B_{max} deriving from the q-equation and consistent with the above iterated aspect ratio is

$$\frac{I}{B_{max}} = \left[\frac{5\, f(k)}{q}\right] \frac{f_1}{f_2\ A^2}\, t_{BS}$$

or

$$\frac{I}{B_{max}} = \frac{\dfrac{\left[\dfrac{C_{sI}^{*}}{f_H}\, k^{(\alpha_p-\alpha_k)}\right]^{\frac{2}{\left[3(1+\alpha_n-2\alpha_p)+2\alpha_I-\alpha_R+\alpha_p+\alpha_B\right]}}}{5^{\frac{\left[\alpha_R-\alpha_p+(1+\alpha_n-2\alpha_p)+\alpha_B\right]}{\left[3(1+\alpha_n-2\alpha_p)+2\alpha_I-\alpha_R+\alpha_p+\alpha_B\right]}} \left[\dfrac{f(k)}{q}\right]^{\frac{\left[\alpha_R-\alpha_p-(1+\alpha_n-2\alpha_p)-\alpha_B\right]}{\left[3(1+\alpha_n-2\alpha_p)+2\alpha_I-\alpha_R+\alpha_p+\alpha_B\right]}}}}{B_{max}^{\frac{2\left[2(1+\alpha_n-2\alpha_p)+\alpha_I+\alpha_B\right]}{\left[3(1+\alpha_n-2\alpha_p)+2\alpha_I-\alpha_R+\alpha_p+\alpha_B\right]}}\ t_{BS}^{\frac{\left[2\alpha_a+3\alpha_R-7\alpha_p-3(1+\alpha_n-2\alpha_p)-\alpha_B\right]}{\left[3(1+\alpha_n-2\alpha_p)+2\alpha_I-\alpha_R+\alpha_p+\alpha_B\right]}}} \text{ x}$$

$$\frac{f_2^{\frac{\left[2\alpha_a+3\alpha_R-7\alpha_p-3(1+\alpha_n-2\alpha_p)-\alpha_B\right]}{\left[3(1+\alpha_n-2\alpha_p)+2\alpha_I-\alpha_R+\alpha_p+\alpha_B\right]}}\ f_3^{\frac{2\left[3\alpha_p+2(1+\alpha_n-2\alpha_p)+\alpha_B-\alpha_R-\alpha_a\right]}{\left[3(1+\alpha_n-2\alpha_p)+2\alpha_I-\alpha_R+\alpha_p+\alpha_B\right]}}}{f_1^{\frac{\left[\alpha_R-\alpha_p+(1+\alpha_n-2\alpha_p)+\alpha_B\right]}{\left[3(1+\alpha_n-2\alpha_p)+2\alpha_I-\alpha_R+\alpha_p+\alpha_B\right]}}}$$

The blanket/shield thickness is about 1 m and varies rather weakly with the neutron wall load, and hence it may be adjusted in a final step.
The relative toroidal field is

$$\frac{B}{B_{max}} = \frac{f_1}{f_3\,A}$$

The major plasma radius becomes

$$R = \frac{f_3\,A}{f_2}\,t_{BS} = \left[\frac{q}{5\,f(k)}\right]\frac{I}{B_{max}}\,\frac{f_3\,A^3}{f_1}$$

The fusion power is

$$P_f = \frac{C^*_{PfB}\,B^4_{max}}{5^2}\,\frac{I^2}{B^2_{max}}\,\frac{f_1^2}{f_2\,f_3\,A}\,t_{BS} = \frac{C^*_{PfB}\,B^4_{max}}{5^2}\left[\frac{q}{5\,f(k)}\right]\frac{I^3}{B^3_{max}}\,\frac{f_1\,A}{f_3}$$

$$= \frac{C^*_{PfB}\,B^4_{max}}{5^2}\left[\frac{5\,f(k)}{q}\right]^2\frac{f_1^4\,t_{BS}^3}{f_2^3\,f_3\,A^5}$$

The average neutron wall load follows from

$$p_w = \frac{C^*_{PfB}\,B^4_{max}}{5^2\,C_{Pfw}}\,\frac{I^2}{B^2_{max}}\,\frac{f_1^2\,f_2}{f_3^3\,A^2}\,\frac{1}{t_{BS}} = \frac{C^*_{PfB}\,B^4_{max}}{5^2\,C_{Pfw}}\left[\frac{5\,f(k)}{q}\right]\frac{I}{B_{max}}\,\frac{f_1^3}{f_3^3\,A^4}$$

$$= \frac{C^*_{PfB}\,B^4_{max}}{5^2\,C^*_{Pfw}}\left[\frac{5\,f(k)}{q}\right]^2\frac{f_{pw}\,f_1^4\,t_{BS}}{f_2\,f_3^3\,A^6}$$

and the average fusion power density from

$$p_f = \frac{C^*_{PfB}}{5^2}\,\frac{B^4_{max}}{2\,\pi^2\,k}\,\frac{I^2}{B^2_{max}}\,\frac{f_1^2\,f_2^2}{f_3^4\,A^2}\,\frac{1}{t_{BS}^2} = \frac{C^*_{PfB}}{5^2}\,\frac{B^4_{max}}{2\,\pi^2\,k}\left[\frac{5\,f(k)}{q}\right]^2\frac{f_1^4}{f_3^4\,A^6}$$

The definitions of $C^*_{PfB} = C_{PfB}\,[q/f(k)]^2$, C^*_{Pfw}, and $f(k)$ are

$$C^*_{PfB} = C_{PfB}\left[\frac{q}{f(k)}\right]^2 = \frac{5^4\,\pi^2}{2^3}\,\frac{\left(\frac{n_{DT}}{n_e}\right)^2}{\left(1+\frac{n_i}{n_e}\right)^2}\,C_{\sigma Ef}\left[\frac{g}{C_{fa}}\right]^2 k$$

$$C^*_{Pfw} = C_{Pfw}\,f_{pw} = 5\,\pi^2\sqrt{\frac{1+k^2}{2}} \qquad f(k) = \frac{1 + k^2\left(1 + 2\,\Delta^2 - 1.2\,\Delta^3\right)}{2}$$

For the average electron density one has

$$n_e = \frac{2.5\,g}{C_{fa}\,T_{10}}\,\frac{B^2_{max}}{\left(1+\frac{n_i}{n_e}\right)}\,\frac{I}{B_{max}}\,\frac{f_1\,f_2}{f_3^2\,A}\,\frac{1}{t_{BS}} = \frac{2.5\,g}{C_{fa}\,T_{10}}\,\frac{B^2_{max}}{\left(1+\frac{n_i}{n_e}\right)}\left[\frac{5\,f(k)}{q}\right]\frac{f_1^2}{f_3^2\,A^3}$$

These equations are written in terms of t_{BS} or of $f(k)/q$, where obviously the second form is more suitable for exploring the appropriate range of the safety factor. Consistent inclusion of t_{BS} is taken care of by the A-iteration already.

For Q one has (with $C_B = 0.675$, e.g.)

$$Q = \frac{5\,\pi^2}{4}\,\frac{\gamma_o\,k\,g}{F_B}\,\frac{\left(\dfrac{n_{DT}}{n_e}\right)^2}{\left(1+\dfrac{n_i}{n_e}\right)}\,\frac{C_{\sigma Ef}T_{10}}{C_{fa}}\,B_{max}\,t_{BS}\,\frac{f_1}{A\,f_2}$$

$$F_B = 1 - \frac{I_B}{I} = 1 - C_B\,\frac{\beta_p}{\sqrt{A}} = 1 - 5\,C_B\,\frac{g\,k\,q\,\sqrt{A}}{f(k)}$$

Since C_{si}^* is a function of Q, for lower finite Q the aspect ratio has to be calculated including the A-dependence of Q (see above).

Sometimes it may be attractive to prescribe the value of β_{pol}. This leads to an additional condition on, for instance, the Troyon coefficient g

$$g = \frac{f(k)}{q}\,\frac{\beta_p}{5\,k\,A}$$

which must be used in the iteration of A and in C_{PfB}, Q, n_e, and F_B.

The inductive burn pulse length for pulsed operation decisively determines the necessary configuration. For steady-state operation it has to be sufficiently above zero to ensure the implied inductive start-up condition. It can be approximately calculated from

$$t_B = \frac{0.4\,\pi\,f_3^2\,t_{BS}^2}{f_2^2}\,\frac{\left[C_\Phi\left(\dfrac{f_1}{A\,f_3} - \dfrac{t_{TF}}{R}\right)^2 A^3\,\dfrac{f_3}{f_1}\,\dfrac{q}{f(k)}\,\dfrac{B_{OH}}{B_{max}} - C_I\,f_L(A)\right]}{F_B\,F_{OH}\,f(\alpha,A)}$$

For explanation of various functions contained in this equation see 2.4. C_I is a correction factor that can be set to 1.0. For large t_B: $B_{OH} = B_{max}$.

Geometry and energy related quantities can be calculated as follows.

For the plasma volume one has

$$V = 2\,\pi^2\,k\,t_{BS}^3\,\frac{f_3^3}{f_2^3}\,A$$

In order to evaluate the toroidal magnet energy roughly, one can use the ratio of the toroidal magnet volume to the plasma volume. One gets

$$\frac{V_{TM}}{V} = \left(\frac{1}{f_{pw}} + \frac{t_{BS}}{a}\right)^2 = \left(\frac{1}{f_{pw}} + \frac{f_2}{f_3}\right)^2 = \left(\frac{1}{f_{pw}} + A - \frac{1}{f_{pw}} - \frac{f_1}{f_3}\right)^2$$

which gives an approximation for the toroidal coil bore volume

$$V_{TM} = 2\,\pi^2\,k\,t_{BS}^3\,\frac{f_3^3}{f_2^3}\,A\left(A - \frac{f_1}{f_3}\right)^2$$

The toroidal magnetic energy is then (approximation)

$$W_{TM} = \left(2 - f_{TM}\right) \frac{5\,\pi}{2}\, B_{max}^2\, k\, t_{BS}^3 \left(A - \frac{f_1}{f_3}\right)^2 \frac{f_1^2\, f_3}{f_2^3\, A}$$

Similarly, the approximate evaluation of the poloidal field energy yields

$$W_{PM} = \frac{1}{2}\, 0.4\, \pi\, R \left(\ln \frac{8\, A}{\sqrt{k}} - 1.75\right) I^2$$

which translates into

$$W_{PM} = \frac{\pi}{5} \left(\ln \frac{8\, A}{\sqrt{k}} - 1.75\right) \left[\frac{5\, f(k)}{q}\right]^2 B_{max}^2\, t_{BS}^3\, \frac{f_1^2\, f_3}{f_2^3\, A^3}$$

2.2 Tokamak reactor formulary for $t_{BS} = 0$ (unshielded configurations, DT experiments):

For this case all equations as shown for $t_{BS} > 0$ can be converted into their form for $t_{BS} = 0$ using the following transformation equations. Starting from the general geometry relations modified for $t_{BS} = 0$

$$\frac{B}{B_{max}} = 1 - \frac{1}{A\, f_{pw}}\ ; \quad \frac{B}{B_{max}} = \frac{4}{9\, f_A} \left(1 + \frac{1}{A\, f_{pw}}\right)$$

one finds A to be fixed already by f_{pw} and f_A:

$$A = \frac{\left(9\, f_A + 4\right)}{f_{pw} \left(9\, f_A - 4\right)}$$

For q(A) an iterative solution is required with $f_A(A)$ (see 2.1).
For f_1 one gets after insertion of A

$$f_1 = 8\, \frac{9\, f_A}{9\, f_A - 4} = \frac{8\, f_3}{f_{pw} \left(9\, f_A - 4\right)}$$

The new definition equation for A leads to $f_2 = 0$ for $t_{BS} = 0$.
From the general expression for $t_{BS} > 0$

$$\frac{t_{BS}}{f_2} = \frac{A^6\, f_3^3}{f_1^4}\, L_A$$

deriving from abbreviating the above neutron wall load equation

$$p_w = \frac{C_{PfB}\, B_{max}^4}{C_{Pfw}}\, \frac{t_{BS}}{A^6}\, \frac{f_1^4}{f_2\, f_3^3} \qquad \text{using a length} \qquad L_A = \frac{C_{Pfw}\, p_w}{C_{PfB}\, B_{max}^4}$$

one finds for $t_{BS} = 0$ by insertion of the above relations for A, f_1, and f_2

$$\lim \left(\frac{t_{BS}}{f_2}\right)_{t_{BS} = 0} = \frac{\left(9\, f_A + 4\right)^6}{f_3\, 8^4 \left[f_{pw} \left(9\, f_A - 4\right)\right]^2}\, L_A = \frac{\left(9\, f_A + 4\right)^4 A^2}{f_3\, 8^4}\, L_A$$

By inserting the above equations for f_1, $\lim(t_{BS}/f_2)$, and A into the respective parameter equations for $t_{BS} > 0$ the corresponding equations for $t_{BS} = 0$ can be obtained (t_{BS} and f_2 occur only in the form t_{BS}/f_2).
For L_A, which takes the position that t_{BS} has for $t_{BS} > 0$, but at the same time is a rather involved function of the input assumptions, one gets

$$L_A = \left[\frac{q}{f(k)}\right]^{\frac{(1+\alpha_n-2\alpha_P)+\alpha_I}{\alpha_I+\alpha_a+\alpha_R-3\alpha_P}} \frac{\left[\frac{C_{sI}^{*}}{f_H}\, k^{(\alpha_P-\alpha_k)}\right]^{\frac{1}{\alpha_I+\alpha_a+\alpha_R-3\alpha_P}}}{5^{\frac{2(1+\alpha_n-2\alpha_P)+\alpha_I+\alpha_B}{\alpha_I+\alpha_a+\alpha_R-3\alpha_P}}\; B_{max}^{\frac{2(1+\alpha_n-2\alpha_P)+\alpha_I+\alpha_B}{\alpha_I+\alpha_a+\alpha_R-3\alpha_P}}} \text{ x}$$

$$\frac{8^{\frac{4(\alpha_a+\alpha_R)+3\alpha_I-8\alpha_P-\alpha_B-2(1+\alpha_n)}{\alpha_I+\alpha_a+\alpha_R-3\alpha_P}} \left[f_{pw}\,(9\,f_A-4)\right]^{\frac{\alpha_I+2\alpha_a+3\alpha_R-5\alpha_P-(1+\alpha_n)}{\alpha_I+\alpha_a+\alpha_R-3\alpha_P}}}{(9\,f_A+4)^{\frac{6\alpha_a+7\alpha_R+4\alpha_I-13\alpha_P-\alpha_B-3(1+\alpha_n)}{\alpha_I+\alpha_a+\alpha_R-3\alpha_P}}}$$

The plasma current divided by B_{max} becomes

$$\frac{I}{B_{max}} = \left[\frac{5\,f(k)}{q}\right] \frac{(9\,f_A+4)^4}{8^3\,f_{pw}\,(9\,f_A-4)}\, L_A$$

or

$$\frac{I}{B_{max}} = \frac{\left[\frac{C_{sI}^{*}}{f_H}\, k^{(\alpha_P-\alpha_k)}\right]^{\frac{1}{\alpha_I+\alpha_a+\alpha_R-3\alpha_P}}}{5^{\frac{2(1+\alpha_n-2\alpha_P)+\alpha_B-\alpha_a-\alpha_R+3\alpha_P}{\alpha_I+\alpha_a+\alpha_R-3\alpha_P}}\; B_{max}^{\frac{2(1+\alpha_n-2\alpha_P)+\alpha_I+\alpha_B}{\alpha_I+\alpha_a+\alpha_R-3\alpha_P}} \left[\frac{f(k)}{q}\right]^{\frac{3\alpha_P+(1+\alpha_n-2\alpha_P)-\alpha_a-\alpha_R}{\alpha_I+\alpha_a+\alpha_R-3\alpha_P}}} \text{ x}$$

$$\frac{\left[f_{pw}\,(9\,f_A-4)\right]^{\frac{\alpha_a+2\alpha_R-2\alpha_P-(1+\alpha_n)}{\alpha_I+\alpha_a+\alpha_R-3\alpha_P}}}{(9\,f_A+4)^{\frac{2\alpha_a+3\alpha_R-\alpha_P-\alpha_B-3(1+\alpha_n)}{\alpha_I+\alpha_a+\alpha_R-3\alpha_P}}\; 8^{\frac{\alpha_B-\alpha_a-\alpha_R-\alpha_P+2(1+\alpha_n)}{\alpha_I+\alpha_a+\alpha_R-3\alpha_P}}}$$

For relatively low finite values Q has to be calculated iteratively (see formula below) - for the above aspect ratio - for getting the consistent value of C_{sI}^* to be used in I/B_{max}. The relative toroidal field becomes

$$\frac{B}{B_{max}} = \frac{8}{(9\,f_A+4)}$$

The plasma major radius is

$$R = \left[\frac{q}{5f(k)}\right] \frac{I}{B_{max}} \frac{(9\,f_A+4)^3}{8\,[f_{pw}(9f_A-4)]^2} = \left[\frac{q}{5f(k)}\right] \frac{I}{B_{max}} \frac{[f_{pw}(9f_A-4)]A^3}{8} = \frac{(9f_A+4)^4 A^3}{8^4}\, L_A$$

For the fusion power one obtains

$$P_f = \frac{C^*_{PfB}\, B^4_{max}}{5^2}\left[\frac{q}{5\, f(k)}\right]\frac{I^3}{B^3_{max}}\frac{8\,(9\, f_A + 4)}{[f_{pw}(9f_A - 4)]^2} = \frac{C^*_{PfB}\, B^4_{max}}{5^2}\left[\frac{q}{5\, f(k)}\right]\frac{I^3}{B^3_{max}}\frac{8\, A}{[f_{pw}(9f_A - 4)]}$$

$$= \frac{C^*_{PfB}\, B^4_{max}}{5^2}\left[\frac{5\, f(k)}{q}\right]^2 \frac{(9\, f_A + 4)^8\, A^5}{8^8}\, L_A^3$$

and for the average neutron wall load

$$p_w = \frac{C^*_{PfB} B^4_{max}}{C^*_{Pfw}\, 5^2}\left[\frac{5f(k)}{q}\right]\frac{I}{B_{max}}\frac{f_{pw} 8^3 [f_{pw}(9f_A - 4)]}{(9\, f_A + 4)^4} = \frac{C^*_{PfB} B^4_{max}}{C^*_{Pfw}\, 5^2}\left[\frac{5f(k)}{q}\right]\frac{I}{B_{max}}\frac{f_{pw}\, 8^3}{[f_{pw}(9f_A - 4)]^3 A^4}$$

$$= \frac{C^*_{PfB}\, B^4_{max}}{C^*_{Pfw}\, 5^2}\left[\frac{5\, f(k)}{q}\right]^2 f_{pw}\, L_A$$

For the average fusion power density one has

$$p_f = \frac{C^*_{PfB}}{5^2}\, \frac{B^4_{max}}{2\, \pi^2\, k}\left[\frac{5\, f(k)}{q}\right]^2 \frac{8^4}{(9\, f_A + 4)^4\, A^2}$$

$$= \frac{C^*_{PfB}}{5^2}\, \frac{B^4_{max}}{2\, \pi^2\, k}\left[\frac{5\, f(k)}{q}\right]^2 \frac{8^4}{[f_{pw}\,(9\, f_A - 4)]^4\, A^6}$$

Also the plasma electron density has no L_A dependent form:

$$n_e = \frac{2.5\, g}{C_{fa}\, T_{10}}\, \frac{B^2_{max}}{\left(1 + \dfrac{n_i}{n_e}\right)}\left[\frac{5\, f(k)}{q}\right]\frac{8^2}{(9\, f_A + 4)^2\, A}$$

$$= \frac{2.5\, g}{C_{fa}\, T_{10}}\, \frac{B^2_{max}}{\left(1 + \dfrac{n_i}{n_e}\right)}\left[\frac{5\, f(k)}{q}\right]\frac{8^2}{[f_{pw}\,(9\, f_A - 4)]^2\, A^3}$$

For Q one has

$$Q = \frac{\pi^2}{4}\, \frac{\gamma_o\, k\, g}{F_B}\, \frac{\left(\dfrac{n_{DT}}{n_e}\right)^2}{\left(1 + \dfrac{n_i}{n_e}\right)}\, \frac{C_{\sigma Ef} T_{10}}{C_{fa}}\, \frac{\left[\dfrac{C^*_{sI}}{f_H}\, k^{(\alpha_p - \alpha_k)}\right]^{\frac{1}{\alpha_I + \alpha_a + \alpha_R - 3\alpha_p}} \left[\dfrac{q}{f(k)}\right]^{\frac{(1 + \alpha_n - 2\alpha_p) + \alpha_I}{\alpha_I + \alpha_a + \alpha_R - 3\alpha_p}}}{(5\, B_{max})^{\frac{2(1 + \alpha_n - 2\alpha_p) + \alpha_B - \alpha_a - \alpha_R + 3\alpha_p}{\alpha_I + \alpha_a + \alpha_R - 3\alpha_p}}}\, x$$

$$\frac{(9\, f_A + 4)^{\frac{\alpha_I + 4\alpha_p + \alpha_B + 3(1 + \alpha_n - 2\alpha_p) - \alpha_a - 2\alpha_R}{\alpha_I + \alpha_a + \alpha_R - 3\alpha_p}}}{8^{\frac{3\alpha_p + \alpha_B + 2(1 + \alpha_n - 2\alpha_p) - \alpha_a - \alpha_R}{\alpha_I + \alpha_a + \alpha_R - 3\alpha_p}}\, [f_{pw}\,(9\, f_A - 4)]^{\frac{\alpha_I + \alpha_p + (1 + \alpha_n - 2\alpha_p) - \alpha_R}{\alpha_I + \alpha_a + \alpha_R - 3\alpha_p}}}$$

or
$$Q = \frac{5\,\pi^2}{4}\,\frac{\gamma_o\,k\,g}{F_B}\,\frac{\left(\frac{n_{DT}}{n_e}\right)^2}{\left(1+\frac{n_i}{n_e}\right)}\,\frac{C_{\sigma Ef}T_{10}}{C_{fa}}\,B_{max}\,L_A\,\frac{\left(9\,f_A+4\right)^3 A^2}{8^3}$$

with
$$F_B = 1 - \frac{I_B}{I} = 1 - 5\,C_B\,\frac{g\,k\,q\,\sqrt{A}}{f(k)} = 1 - 5\,C_B\,\frac{g\,k\,q}{f(k)}\sqrt{\frac{\left(9\,f_A+4\right)}{f_{pw}\left(9\,f_A-4\right)}}$$

Since C_{si}^* is a function of Q, lower finite Q values have to be determined iteratively for $t_{BS} = 0$, also in order to calculate C_{si}^* (see above).
Sometimes it may be attractive to prescribe the value of β_{pol}. This leads to an addditional condition on, for instance, the Troyon coefficient g
$$g = \frac{f(k)}{q}\,\frac{\beta_p}{5\,k}\,\frac{f_{pw}\left(9\,f_A-4\right)}{\left(9\,f_A+4\right)}$$

which must be included in the evaluation of C_{PfB}, Q, n_e, and F_B.
The inductive burn pulse length can be approximately calculated from
$$t_B = 0.4\,\pi\,\frac{\left(9\,f_A+4\right)^8 A^4\,L_A^2}{8^8}\,\frac{\left\{C_\Phi\,\frac{\left(\frac{8}{9\,f_A+4}-\frac{t_{TF}}{R}\right)^2 A^3}{\frac{8}{\left[f_{pw}\left(9\,f_A-4\right)\right]}}\,\frac{q}{f(k)}\,\frac{B_{OH}}{B_{max}} - C_I\,f_L(A)\right\}}{F_B\,F_{OH}\,f(\alpha,A)}$$

For explanation of various functions contained in this equation see 2.5. C_I is a correction factor that can be set to 1.0. Usually $B_{OH} = B_{max}$.
Geometry and energy related quantities can be calculated as follows.
For the plasma volume one has
$$V = 2\,\pi^2\,k\,\frac{\left(9\,f_A+4\right)^{12} A^7}{8^{12}}\,L_A^3$$

In order to evaluate the toroidal magnet energy roughly, one can use the ratio of the toroidal magnet volume to the plasma volume. One gets
$$\frac{V_{TM}}{V} = \frac{1}{f_{pw}^2}$$

The toroidal field energy is then (approximation)
$$W_{TM} = \left(2 - f_{TM}\right)\frac{B_{max}^2}{0.8\,\pi}\,V\,\frac{V_{TM}}{V} = \left(2 - f_{TM}\right)\frac{B_{max}^2}{0.8\,\pi}\,V\,\frac{1}{f_{pw}^2}$$

One obtains

$$W_{TM} = \left(2 - f_{TM}\right) \frac{B_{max}^{2}}{0.8\ \pi} V \frac{V_{TM}}{V} = \left(2 - f_{TM}\right) \frac{5\ \pi}{2} \frac{B_{max}^{2}}{f_{pw}^{2}} k\ L_A^3 \frac{\left(9\ f_A + 4\right)^{12} A^7}{8^{12}}$$

The poloidal field energy becomes

$$W_{PM} = \frac{\pi}{5} \left(\ln \frac{8\ A}{\sqrt{k}} - 1.75\right) \left[\frac{5\ f(k)}{q}\right]^2 B_{max}^2\, L_A^3 \frac{\left(9\ f_A + 4\right)^{10} A^5}{8^{10}}$$

2.3 A formal check of exponents

The fact that for $t_{BS} > 0$ R, a, and B each depend on f_3/f_2, and f_1/f_3 respectively leads to the consequence that the sums of the exponents of f_1, f_2, f_3 in the numerator and denominator of any expression must be equal. For $t_{BS} = 0$ this holds for 8, $(9\ f_A + 4)$, and f_{pw} $(9\ f_A - 4)$ correspondingly.

2.4 Definitions for $t_{BS} > 0$

The following approximate approach is used for the evaluation of the central solenoid and toroidal field coil radial build. Besides the iterated reactor configuration, it includes the condition of stabilized superconductors and the magnet safety discharge condition in the sense that with a given magnet stored energy both the temperature rise and the safety discharge time constant will not exceed certain given limits[5]. In this work $k_h >> 2$, $w_h = 0.3 \times 10^{-2}$ MW/m^2, $f(T_{TM}) = f(T_{OH}) = 5 \times 10^4$ MA^2 s/m^4 ($T_{TF} = T_{OH} = 50 - 150$ K), $\rho = 3 \times 10^{-4}$ V m/MA are assumed.
The values of j_{cTF}, j_{cOH}, σ_{sTF}, σ_{sTFc}, σ_{sOH} are imposed. This means setting the levels of the average current density in the stabilizer and superconductor cross-section of the magnets and the average tensile and compressive (suffix $_c$) stress levels in the mechanical reinforcement cross-section without taking into account the conductor part for carrying the mechanical load. In this work $\sigma_{cTF} + \sigma_{sTFc} = 800$ MPa (the individual stress levels being determined consistently) , $\sigma_{cOH} = 400$ MPa, $j_{cTF} = j_{cOH} = 35 - 90$ MA/m^2 are assumed (for rapid safety discharge). The lower values are taken for the OH magnet in order to account for pulsed vs. steady-state operation and reduced stability with enhanced transient losses. The filling factors giving the stabilized conductor magnet cross-section fraction f_{TM} and f_{OH} can be evaluated from the input parameters. The parameters C_{VMTF} and C_{VMOH} are fixed by j_{cTF}, and j_{cOH} respectively and by the values of k_h, w_h, ρ, and $f(T_{TM})$, $f(T_{OH})$. The values of the winding currents are set by the the average current density in the stabilizer and superconductor cross-section of the magnets and the values of w_h, k_h, ρ, and $f(T_{TM})$, $f(T_{OH})$. The values of $\Sigma V_{max\ TM}$ and

ΣV_{maxOH} are determined by the toroidal and OH field energy. Generally, the resulting rather large voltages for all windings connected in series can be accommodated by appropriate circuitry. In order to take into account appproximately the impact of discrete toroidal field coils (compared with a closed torus magnet), adjustment factors f_{TF} and f_{TFc} are applied. In the case of the toroidal field energy a factor of $(2\text{-}f_{TF})$ is applied in order to take into account the energy increase in a discrete coil set vs. a closed toroidal magnet. The basic (approximate) equations are

$$\frac{t_{TF}}{R} = f_{TF} \frac{\dfrac{B_{max}^2}{0.8\,\pi\,\sigma_{TF}}}{\dfrac{f_1}{A\,f_3} - \dfrac{t_{TF}}{2\,R}} \left[\frac{2 - \dfrac{f_1}{A\,f_3} + \dfrac{t_{BS}}{R} + \dfrac{t_{TF}}{2\,R}}{2 - 2\dfrac{f_1}{A\,f_3} + \dfrac{t_{BS}}{R} + \dfrac{t_{TF}}{R}} \ln\left(\frac{2 + \dfrac{t_{BS}}{R}}{\dfrac{f_1}{A\,f_3}} - 1 \right) - \frac{2 - 2\dfrac{f_1}{A\,f_3} + \dfrac{t_{BS}}{R}}{2 - 2\dfrac{f_1}{A\,f_3} + \dfrac{t_{BS}}{R} + \dfrac{t_{TF}}{R}} \right]$$

$$R_{OH} = \left(\frac{0.8\pi\sigma_{OH}}{B_{OH}^2} + \frac{2}{3} \right) \frac{B_{OH}}{0.4\pi j_{OH}} = \left(\frac{0.8\pi\sigma_{OH}}{B_{OH}^2} + \frac{2}{3} \right) d_{OH} = \left(\frac{f_1}{A\,f_3} - \frac{t_{TF}}{R} \right) R$$

$$\frac{d_{OH}}{R} = \frac{\left(\dfrac{f_1}{A\,f_3} - \dfrac{t_{TF}}{R} \right)}{\left(\dfrac{0.8\pi\sigma_{OH}}{B_{OH}^2} + \dfrac{2}{3} \right)} \qquad H_{OH} = 4 \left(\frac{R}{A} k + \frac{t_{TF}}{2\,k} \right)$$

$$C_\phi = \left(1 - \frac{d_{OH}}{R_{OH}} + \frac{1}{3} \frac{d_{OH}^2}{R_{OH}^2} \right)$$

$$C_\phi = 1 - \frac{1}{\left(\dfrac{0.8\pi\sigma_{OH}}{B_{OH}^2} + \dfrac{2}{3} \right)} + \frac{1}{3} \frac{1}{\left(\dfrac{0.8\pi\sigma_{OH}}{B_{OH}^2} + \dfrac{2}{3} \right)^2}$$

with the specific relations for the safety discharge conditions

$$I_{TM} = \left(\frac{k_h\,w_h}{\rho} \right)^2 \frac{1}{j_{cTM}^3} \qquad \Sigma V_{max\,TM} = j_{cTM}^2 \frac{W_{TM}}{I_{TM}\, f(T_{TM})}$$

$$j_{TF} = f_{TM}\, j_{cTM} = f_{TM} \sqrt[5]{\frac{\Sigma V_{max\,TM}}{W_{TM}} \left(\frac{k_h\,w_h}{\rho} \right)^2 f(T_{TM})} = \frac{B_{max}}{0.4\,\pi\,t_{TF}}$$

$$I_{OH} = \left(\frac{k_h\,w_h}{\rho} \right)^2 \frac{1}{j_{cOH}^3} \qquad \Sigma V_{max\,OH} = j_{cOH}^2 \frac{W_{OH}}{I_{OH}\, f(T_{OH})}$$

$$j_{OH} = f_{OH}\, j_{cOH} = f_{OH} \sqrt[5]{\frac{\Sigma V_{max\,OH}}{W_{OH}} \left(\frac{k_h\,w_h}{\rho} \right)^2 f(T_{OH})} = \frac{B_{OH}}{0.4\,\pi\,d_{OH}}$$

One has

$$j_{cTM} = \sqrt[5]{\frac{\sum V_{max\,TM}}{W_{TM}} \left(\frac{k_h\, w_h}{\rho}\right)^2 f(T_{TM})} = \frac{B_{max}}{0.4\,\pi\, f_{TM}\, t_{TF}}$$

$$j_{cOH} = \sqrt[5]{\frac{\sum V_{max\,OH}}{W_{OH}} \left(\frac{k_h\, w_h}{\rho}\right)^2 f(T_{OH})} = \frac{B_{max}}{0.4\,\pi\, f_{OH}\, d_{OH}}$$

and

$$C_{VMTF} = \frac{\sum V_{max\,TM}}{W_{TM}} = \frac{j_{cTM}^5}{\left(\frac{k_h\, w_h}{\rho}\right)^2 f(T_{TM})}$$

$$C_{VMOH} = \frac{\sum V_{max\,OH}}{W_{OH}} = \frac{j_{cOH}^5}{\left(\frac{k_h\, w_h}{\rho}\right)^2 f(T_{OH})}$$

Introducing the tensile stress in the coil support structure incl. casing

$$\sigma_{sTF} = \frac{\sigma_{TF}}{(1 - f_{TM})} \qquad \sigma_{sOH} = \frac{\sigma_{OH}}{(1 - f_{OH})}$$

one has the following iteration equation for t_{TF}/R:

$$\frac{t_{TF}}{R} = f_{TF} \frac{\frac{B_{max}^2}{0.8\,\pi\,\sigma_{sTF}}}{\frac{f_1}{A\, f_3} - \frac{t_{TF}}{2\,R}} \frac{\left[\frac{2 - \frac{f_1}{A\, f_3} + \frac{t_{BS}}{R} + \frac{t_{TF}}{2\,R}}{2 - 2\frac{f_1}{A\, f_3} + \frac{t_{BS}}{R} + \frac{t_{TF}}{R}} \ln\left(\frac{2 + \frac{t_{BS}}{R}}{\frac{f_1}{A\, f_3}} - 1\right) - \frac{2 - 2\,\frac{f_1}{A\, f_3} + \frac{t_{BS}}{R}}{2 - 2\frac{f_1}{A\, f_3} + \frac{t_{BS}}{R} + \frac{t_{TF}}{R}}\right]}{\left(1 - \frac{B_{max}}{0.4\,\pi\,\frac{t_{TF}}{R}\,\frac{A\, f_3}{f_2}\, t_{BS}\, j_{cTF}}\right)}$$

which leads to the toroidal magnet filling factor

$$f_{TM} = \frac{B_{max}}{0.4\,\pi\, j_{cTF}\,\frac{t_{TF}}{R}\,\frac{A\, f_3}{f_2}\, t_{BS}}$$

The compressive stress from the toroidal magnet centering force is

$$\sigma_{sTFc} = \frac{\sigma_{TFc}}{(1 - f_{TM})} = \frac{\frac{B_{max}^2}{0.8\,\pi}}{(1 - f_{TM})} \frac{\frac{f_1}{A\, f_3}}{\frac{t_{TF}}{R}} \left[1 - f_{TFc}\,\frac{\frac{f_1}{A\, f_3}}{2 - \frac{f_1}{A\, f_3} + \frac{t_{BS}}{R}}\right]$$

assuming the same filling factor.
The relation beween σ_{sTFc} and σ_{sTF} is given by

$$\frac{\sigma_{sTFc}}{\sigma_{sTF}} = \frac{\dfrac{\left(\dfrac{f_1}{A\,f_3} - \dfrac{t_{TF}}{2\,R}\right)\dfrac{f_1}{A\,f_3}}{f_{TF}}\left[1 - f_{TFc}\dfrac{\dfrac{f_1}{A\,f_3}}{2 - \dfrac{f_1}{A\,f_3} + \dfrac{t_{BS}}{R}}\right]}{\left[\dfrac{2 - \dfrac{f_1}{A\,f_3} + \dfrac{t_{BS}}{R} + \dfrac{t_{TF}}{2\,R}}{2 - 2\dfrac{f_1}{A\,f_3} + \dfrac{t_{BS}}{R} + \dfrac{t_{TF}}{R}} \ln\left(\dfrac{2 + \dfrac{t_{BS}}{R}}{\dfrac{f_1}{A\,f_3}} - 1\right) - \dfrac{2 - 2\dfrac{f_1}{A\,f_3} + \dfrac{t_{BS}}{R}}{2 - 2\dfrac{f_1}{A\,f_3} + \dfrac{t_{BS}}{R} + \dfrac{t_{TF}}{R}}\right]}$$

If the sum $\sigma_{sTFg} = \sigma_{sTFc} + \sigma_{sTF}$ is taken as a relevant measure of the mechanical stress in the TF coils, one has the following iteration equation

$$\frac{t_{TF}}{R} = \frac{\dfrac{\dfrac{2 - \dfrac{f_1}{A\,f_3} + \dfrac{t_{BS}}{R} + \dfrac{t_{TF}}{2R}}{2 - 2\dfrac{f_1}{A\,f_3} + \dfrac{t_{BS}}{R} + \dfrac{t_{TF}}{R}} \ln\left[\dfrac{2 + \dfrac{t_{BS}}{R}}{\dfrac{f_1}{A\,f_3}} - 1\right] - \dfrac{2 - 2\dfrac{f_1}{A\,f_3} + \dfrac{t_{BS}}{R}}{2 - 2\dfrac{f_1}{A\,f_3} + \dfrac{t_{BS}}{R} + \dfrac{t_{TF}}{R}}}{\dfrac{\left(\dfrac{f_1}{A\,f_3} - \dfrac{t_{TF}}{2\,R}\right)}{f_{TF}}} + \dfrac{1 - f_{TFc}\dfrac{\dfrac{f_1}{A\,f_3}}{2 - \dfrac{f_1}{A\,f_3} + \dfrac{t_{BS}}{R}}}{\dfrac{1}{\left(\dfrac{f_1}{A\,f_3}\right)}}}{\dfrac{\left(1 - \dfrac{B_{max}}{0.4\,\pi\,\dfrac{t_{TF}}{R}\,\dfrac{A\,f_3}{f_2}\,t_{BS}\,j_{cTF}}\right)}{\dfrac{B_{max}^2}{0.8\,\pi\,\sigma_{sTFg}}}}$$

For the relative OH coil thickness one gets

$$\frac{d_{OH}}{R} = \frac{\left(\dfrac{f_1}{A\,f_3} - \dfrac{t_{TF}}{R}\right)\dfrac{B_{OH}^2}{0.8\,\pi\,\sigma_{sOH}} + \dfrac{B_{OH}}{0.4\,\pi\,\dfrac{A\,f_3}{f_2}\,t_{BS}\,j_{cOH}}}{\left(1 + \dfrac{2}{3}\,\dfrac{B_{OH}^2}{0.8\,\pi\,\sigma_{sOH}}\right)}$$

and for the OH coil filling factor

$$f_{OH} = \frac{B_{OH}}{0.4\,\pi\, j_{cOH} \frac{d_{OH}}{R} \frac{A\,f_3}{f_2}\, t_{BS}} = \frac{\left(1 + \frac{2}{3} \frac{B_{OH}^2}{0.8\,\pi\,\sigma_{sOH}}\right)}{\left[\left(\frac{f_1}{A\,f_3} - \frac{t_{TF}}{R}\right) \frac{A\,f_3}{f_2}\, t_{BS} \frac{B_{OH}\, j_{cOH}}{2\,\sigma_{sOH}} + 1\right]}$$

Now the OH magnet energy can be determined:

$$W_{OH} = \frac{B_{OH}^2}{0.8} R_{OH}^2 \left\{ 1 - \frac{1}{\left[\frac{0.8\pi\sigma_{sOH}\left(1-f_{OH}\right)}{B_{OH}^2} + \frac{2}{3}\right]} + \frac{1}{3} \frac{1}{\left[\frac{0.8\pi\sigma_{sOH}\left(1-f_{OH}\right)}{B_{OH}^2} + \frac{2}{3}\right]^2} \right\} H_{OH}$$

From

$$\sum V_{maxTM} = C_{VMTF}\, W_{TM} \qquad \sum V_{maxOH} = C_{VMOH}\, W_{OH}$$

the safety discharge voltages follow.
The safety discharge time constants can be evaluated from

$$\tau_{TM} = \frac{2\,W_{TM}}{I_{TM} \sum V_{max\,TM}} = \frac{2\,f(T_{TM})}{j_{cTM}} \qquad \tau_{OH} = \frac{2\,W_{OH}}{I_{OH} \sum V_{max\,OH}} = \frac{2\,f(T_{OH})}{j_{cOH}}$$

The method adopted yields a uniform and consistent picture of the parameter variation in the f_A range considered, particularly for the attainable inductive burn pulse length.
For evaluation of the inductive burn time one has the following additional definitions:

$$F_{OH} = 7x10^{-3} \left(\frac{\pi}{5}\right)^2 \frac{Z_{eff}}{1.5} \frac{\left(1 + \alpha_j\right)^2}{k} T_{10}^{-3/2}$$

$$f(\alpha,A) = \frac{4.3 - 0.6\,A}{2\alpha_j - 1.5\,\alpha_T + 1} \left(\frac{1 + \alpha_N}{1 + \alpha_N + \alpha_T}\right)^{3/2}$$

$$F_B = 1 - \frac{I_B}{I} = 1 - C_B \frac{\beta_p}{\sqrt{A}} = 1 - 5\,C_B \frac{g\,k\,q\,\sqrt{A}}{f(k)}$$

$$f_L(A) = \left(\ln \frac{8\,A}{\sqrt{k}} - 1.75\right)$$

One can put $B_{OH} = B_{max}$ for maximum inductive burn pulse length.

For the average radiation loss density one has from bremsstrahlung and impurity radiation[8]

$$p_{rad} \approx n_e^2 \left[0.01695\, T_{10}^{0.5}\left(\frac{n_{DT}}{n_e}+4\frac{n_{He}}{n_e}\right)+10^{-3}\left(1+3T_{10}\right)\sum_{Z=6}^{Z_{max}}\frac{n_Z}{n_e}Z^{\left(3.7-0.33\ln 10\, T_{10}\right)}\right]$$

and from synchrotron radiation (total reflection coefficient R_w)[9]

$$p_{sy} = n_e^2\, 0.000002731\left[\frac{(1-R_w)}{B_{max}\, t_{BS}}\right]^{0.5}\left[\frac{C_{fa}\, q}{g\, f(k)}\left(1+\frac{n_i}{n_e}\right)\right]^{1.5} T_{10}^{4}\, \frac{f_2^{0.5}\, A^2}{f_1^{0.5}}$$

It has to be noted that the radiation loss density for synchrotron radiation is a fictitious quantity which just relates the radiation escaping from the plasma to the plasma volume. Also the form depending on n_e^2 is given for practical reasons. The total reflection coefficient R_w in fact would have to be calculated for any combination of plasma parameters and first wall material and properties. For metallic surfaces without holes $R_w = 0.85$ seems to be a good estimate.

This yields with the definition

$$\frac{5}{F_{Br}} = \frac{5\left(p_{rad}+p_{sy}\right)}{p_f}$$

the following equation for the relative radiation losses:

$$\frac{5}{F_{Br}} = \frac{0.3390}{\left(\frac{n_{DT}}{n_e}\right)^2 C_{\sigma Ef}\, T_{10}^{1.5}}\left(\frac{n_{DT}}{n_e}+4\frac{n_{He}}{n_e}\right)+$$

$$0.020\,\frac{\left(1+3T_{10}\right)}{\left(\frac{n_{DT}}{n_e}\right)^2 C_{\sigma Ef}\, T_{10}^{2}}\sum_{Z=6}^{Z}\frac{n_Z}{n_e}Z^{\left(3.7-0.33\ln 10\, T_{10}\right)}+$$

$$\frac{0.00005462}{\left(\frac{n_{DT}}{n_e}\right)^2 C_{\sigma Ef}}\left[\frac{(1-R_w)}{B_{max}\, t_{BS}}\right]^{0.5}\left[\frac{C_{fa}\, q}{g\, f(k)}\left(1+\frac{n_i}{n_e}\right)\right]^{1.5} T_{10}^{2}\, \frac{f_2^{0.5}\, A^2}{f_1^{0.5}}$$

which has to be included in the aspect ratio iteration equation.

The following β-values can be derived:

$$\beta = \frac{5\, g\, f(k)}{q\, A} \qquad \beta_p = \frac{25\, k\, g^2}{\beta} = \frac{5\, k\, g\, q\, A}{f(k)}$$

For the purpose of understanding the relations essentially determining an accessible aspect ratio one can derive the following equations for the energy confinement time, namely one for the confinement requirement:

$$\tau_E^{(1-\alpha_P)} = \frac{\dfrac{4.80^{(1-\alpha_P)}}{\left[\dfrac{5\,f(k)}{q}\right]^{(1-\alpha_P)}}\left(1+\dfrac{n_i}{n_e}\right)^{2(1-\alpha_P)}\left(\dfrac{f_3}{f_1}\right)^{2(1-\alpha_P)} A^{3(1-\alpha_P)}}{\left(\dfrac{2.5\,g}{C_{fa}}\right)^{(1-\alpha_P)}\left(\dfrac{n_{DT}}{n_e}\right)^{2(1-\alpha_P)} B_{max}^{2(1-\alpha_P)}\, C_{\sigma Ef}^{(1-\alpha_P)}\left(1-\dfrac{5}{F_{Br}}+\dfrac{5}{Q}\right)^{(1-\alpha_P)}}$$

and one for the confinement capability offered by the respective scaling:

$$\tau_E^{(1-\alpha_P)} = \frac{\dfrac{C_{\tau E}^{(1-\alpha_P)}\, 5^{\alpha_B} f_H}{\left(\dfrac{2.5\,g}{C_{fa}}\right)^{(\alpha_P-\alpha_n)}}\left[\dfrac{5\,f(k)}{q}\right]^{[(\alpha_n-\alpha_P)+\alpha_I]} B_{max}^{[2(\alpha_n-\alpha_P)+\alpha_I+\alpha_B]}\left(\dfrac{f_3\, t_{BS}}{f_2}\right)^{[\alpha_a+\alpha_R+\alpha_I-3\alpha_P]}}{\left(1+\dfrac{n_i}{n_e}\right)^{\alpha_n} T_{10}{}^{\alpha_n}\, k^{(\alpha_P-\alpha_k)}\left(\dfrac{f_3}{f_1}\right)^{[2(\alpha_n-\alpha_P)+\alpha_I+\alpha_B]} A^{[3(\alpha_n-\alpha_P)+2\alpha_I-\alpha_R+\alpha_P+\alpha_B]}}$$

It can be shown that equality of the two expressions (quoted in a form that lends itself to an easy transformation for $t_{BS} = 0$) leads to the iteration equation for the aspect ratio. It is seen that there is no reactor geometry or operation parameter involved rather than the specific input data. The required confinement time increases with increasing aspect ratio, while the confinement capability decreases as the configuration gets more slender. It can be seen from the above equations in what sense the intersection point for the confinement time determining the configuration and the reactor power will shift if any input data are changed. Note, however, that A itself is fixed by the input data.

So far one selected confinement scaling has been assumed. It is, however, straightforward to evaluate the necessary enhancement factor required for any confinement power scaling on the basis of a given consistent reactor parameter set using a certain confinement power law. Below as an example the evaluation equation for f_{H93HP} based on the parameters resulting from a given value of f_{H89P} is shown:

$f_{H93HP} =$

$$\frac{\left\{ \frac{ \frac{ \left(5\ B_{max}\ f_1\right)^{\left[2\left(1+\alpha_n-2\alpha_P\right)+\alpha_I+\alpha_B\right]_{89P}} \left(\frac{t_{BS}}{f_2}\right)^{\left[\alpha_a+\alpha_R+\alpha_I-3\alpha_P\right]_{89P}} }{ \left[\frac{\left(C^*_{sI}\right)_{89P}}{f_{H89P}}\ k^{\left(\alpha_P-\alpha_k\right)_{89P}}\right] f_3^{\left[3\alpha_P+2\left(1+\alpha_n-2\alpha_P\right)+\alpha_B-\alpha_R-\alpha_a\right]_{89P}} } }{ \left[\frac{f(k)}{q}\right]^{\left[\left(1+\alpha_n-2\alpha_P\right)+\alpha_I\right]_{89P}} } \right\}^{\frac{\left[3\left(1+\alpha_n-2\alpha_P\right)+2\alpha_I-\alpha_R+\alpha_P+\alpha_B\right]_{93HP}}{\left[3\left(1+\alpha_n-2\alpha_P\right)+2\alpha_I-\alpha_R+\alpha_P+\alpha_B\right]_{89P}}}}{\left\{ \frac{ \frac{ \left(5\ B_{max}\ f_1\right)^{\left[2\left(1+\alpha_n-2\alpha_P\right)+\alpha_I+\alpha_B\right]_{93HP}} \left(\frac{t_{BS}}{f_2}\right)^{\left[\alpha_a+\alpha_R+\alpha_I-3\alpha_P\right]_{93HP}} }{ \left[\left(C^*_{sI}\right)_{93HP}\ k^{\left(\alpha_P-\alpha_k\right)_{93HP}}\right] f_3^{\left[3\alpha_P+2\left(1+\alpha_n-2\alpha_P\right)+\alpha_B-\alpha_R-\alpha_a\right]_{93HP}} } }{ \left[\frac{f(k)}{q}\right]^{\left[\left(1+\alpha_n-2\alpha_P\right)+\alpha_I\right]_{93HP}} } \right\}}$$

A density limit definition according to Petrie[10] reads

$$\frac{n_e\ R\ q_\psi}{B} \leq C_n$$

with $C_n = 5$.
After insertion of the respective relations this yields

$$\frac{2.5\ g}{C_{fa}\ T_{10}}\ \frac{B_{max}}{\left(1+\frac{n_i}{n_e}\right)}\ 5\ f(k)\ \frac{1.17-\frac{0.65}{A}}{\left(1-\frac{1}{A^2}\right)^2}\ \frac{f_1}{f_2\ A}\ t_{BS} \leq C_n$$

This relation can be used for determining g (during the A iteration) in such a way as to comply with the density limit corresponding to a given value of C_n. The ratio $C_{\tau p}$ of the particle confinement time to the energy confinement time can be evaluated from

$$C_{\tau p} = \frac{n_{He}}{n_e}\ \frac{n_e\ E_f}{\tau_E\ p_f}$$

which after insertion of the respective equations becomes

$$C_{\tau p} = \frac{n_{He}}{n_e} \frac{\left(1 - \frac{5}{F_{Br}} + \frac{5}{Q}\right) E_f}{1.20 \left(1 + \frac{n_i}{n_e}\right) T_{10}}$$

From the equation for the inductive burn time one can derive a minimum aspect ratio that would be required for inductive start-up of the plasma current without any subsequent inductive burn time. If attainable at all by the main iteration, the aspect ratio has to be

$$A > A_{min}.$$

The condition is defined by the following iteration equation:

$$A_{min} = \frac{\left[C_I \, f_L(A_{min})\right]^{\frac{1}{3}}}{\left[C_\Phi \left(\frac{f_1}{A_{min} \, f_3} - \frac{t_{TF}}{R}\right)^2 \frac{f_3}{f_1} \frac{q(A_{min})}{f(k)} \frac{B_{OH}}{B_{max}}\right]^{\frac{1}{3}}}$$

for each specific set of input parameters.

The operating point of a certain reactor parameter set can be checked for thermal stability by satisfying the condition that the temperature derivative of any additional heating power is negative. The pertinent equations are written in terms of the volume average power:

$$\left(\frac{\partial p_h}{\partial T_{10}}\right)_{n_e = const.} < 0$$

with the definition below

$$\left(\frac{\partial p_h}{\partial T_{10}}\right)_{n_e = const.} = - \frac{n_e^2}{20} \left(\frac{n_{DT}}{n_e}\right)^2 \frac{\partial\left(C_{\sigma Ef} \, T_{10}^2\right)}{\partial T_{10}} + 0.24 \, n_e \left(1 + \frac{n_i}{n_e}\right) \frac{2}{\tau_E \left(1 - \alpha_p\right)}$$

$$+ n_e^2 \left\{ \frac{0.008475}{T_{10}^{0.5}} \left(\frac{n_{DT}}{n_e} + 4 \frac{n_{He}}{n_e}\right) + 10^{-3} \frac{\partial\left[\left(1 + 3T_{10}\right) \sum_{Z=6}^{Z_{max}} \frac{n_Z}{n_e} Z^{(3.7 - 0.33 \ln 10 \, T_{10})}\right]}{\partial T_{10}} \right\}$$

$$+ n_e^{0.5} \, 0.000002731 \, [12.5]^{1.5} \left[\frac{B_{max}^5 (1 - R_w)}{t_{BS}}\right]^{0.5} 2.5 \, T_{10}^{1.5} \frac{f_1^{2.5} \, f_2^{0.5}}{f_3^3 \, A^{2.5}}$$

The consistent reactor parameter values for the operating point have to be inserted.

2.5 Definitions for $t_{BS} = 0$

For the evaluation of the central solenoid and toroidal field coil radial build only those equations are listed that differ from the case $t_{BS} > 0$:

$$\frac{t_{TF}}{R} = \frac{f_{TF} \dfrac{B_{max}^2}{0.8\,\pi\,\sigma_{TF}}}{\dfrac{8}{(9\,f_A + 4)} - \dfrac{t_{TF}}{2\,R}} \left[\frac{2 - \dfrac{8}{(9\,f_A + 4)} + \dfrac{t_{TF}}{2\,R}}{2 - \dfrac{16}{(9\,f_A + 4)} + \dfrac{t_{TF}}{R}} \ln\left(\frac{9\,f_A}{4}\right) - \frac{2 - \dfrac{16}{(9\,f_A + 4)}}{2 - \dfrac{16}{(9\,f_A + 4)} + \dfrac{t_{TF}}{R}} \right]$$

$$R_{OH} = \left(\frac{0.8\pi\sigma_{OH}}{B_{OH}^2} + \frac{2}{3}\right) \frac{B_{OH}}{0.4\pi j_{OH}} = \left(\frac{0.8\pi\sigma_{OH}}{B_{OH}^2} + \frac{2}{3}\right) d_{OH} = \left(\frac{8}{9\,f_A + 4} - \frac{t_{TF}}{R}\right) R$$

$$\frac{d_{OH}}{R} = \frac{\left(\dfrac{8}{9\,f_A + 4} - \dfrac{t_{TF}}{R}\right)}{\left(\dfrac{0.8\pi\sigma_{OH}}{B_{OH}^2} + \dfrac{2}{3}\right)}$$

The following iteration yields t_{TF}/R

$$\frac{t_{TF}}{R} = f_{TF} \frac{\dfrac{B_{max}^2}{0.8\,\pi\,\sigma_{sTF}}}{\dfrac{8}{(9\,f_A + 4)} - \dfrac{t_{TF}}{2\,R}} \frac{\left[\dfrac{2 - \dfrac{8}{(9\,f_A + 4)} + \dfrac{t_{TF}}{2\,R}}{2 - \dfrac{16}{(9\,f_A + 4)} + \dfrac{t_{TF}}{R}} \ln\left(\dfrac{9\,f_A}{4}\right) - \dfrac{2 - \dfrac{16}{(9\,f_A + 4)}}{2 - \dfrac{16}{(9\,f_A + 4)} + \dfrac{t_{TF}}{R}} \right]}{\left[1 - \dfrac{B_{max}}{0.4\,\pi \dfrac{t_{TF}}{R} R\, j_{cTF}} \right]}$$

which leads to the toroidal magnet filling factor

$$f_{TM} = \frac{B_{max}}{0.4\,\pi\, j_{cTF} \dfrac{t_{TF}}{R} R}$$

Considering the the compressive stress deriving from the centering force in the toroidal magnet system, one has

$$\sigma_{sTFc} = \frac{\sigma_{TFc}}{(1 - f_{TM})} = \frac{\dfrac{B_{max}^2}{0.8\,\pi}}{(1 - f_{TM})} \frac{\dfrac{8}{(9\,f_A + 4)}}{\dfrac{t_{TF}}{R}} \left[1 - f_{TFc} \frac{4}{9\,f_A} \right]$$

assuming the same filling factor.

The relation beween σ_{sTFc} and σ_{sTF} is given by

$$\frac{\sigma_{sTFc}}{\sigma_{sTF}} = \frac{\dfrac{\left(\dfrac{8}{(9\ f_A + 4)} - \dfrac{t_{TF}}{2\ R}\right)\dfrac{8}{(9\ f_A + 4)}}{f_{TF}}\left[1 - f_{TFc}\dfrac{\dfrac{8}{(9\ f_A + 4)}}{2\ - \dfrac{8}{(9\ f_A + 4)}}\right]}{\left[\dfrac{2 - \dfrac{8}{(9\ f_A + 4)} + \dfrac{t_{TF}}{2\ R}}{2 - \dfrac{16}{(9\ f_A + 4)} + \dfrac{t_{TF}}{R}}\ln\left(\dfrac{9\ f_A}{4}\right) - \dfrac{2 - \dfrac{16}{(9\ f_A + 4)}}{2 - \dfrac{16}{(9\ f_A + 4)} + \dfrac{t_{TF}}{R}}\right]}$$

If the sum $\sigma_{sTFg} = \sigma_{sTFc} + \sigma_{sTF}$ is taken as a relevant measure of the mechanical stress in the TF coils, one has the following iteration equation:

$$\frac{t_{TF}}{R} = \frac{f_{TF}\dfrac{\left(2 - \dfrac{8}{9\ f_A + 4} + \dfrac{t_{TF}}{2\ R}\right)\ln\left(\dfrac{9\ f_A}{4}\right) - \left(2 - \dfrac{16}{9\ f_A + 4}\right)}{\left(\dfrac{8}{9\ f_A + 4} - \dfrac{t_{TF}}{2\ R}\right)\left(2 - \dfrac{16}{9\ f_A + 4} + \dfrac{t_{TF}}{R}\right)} + \dfrac{1 - f_{TFc}\dfrac{4}{9\ f_A}}{\dfrac{(9\ f_A + 4)}{8}}}{\dfrac{0.8\ \pi\ \sigma_{cTFg}}{B_{max}^2}\left(1 - \dfrac{B_{max}}{0.4\ \pi\ \dfrac{t_{TF}}{R}\ R\ j_{cTF}}\right)}$$

For the relative OH coil thickness one gets

$$\frac{d_{OH}}{R} = \frac{\left(\dfrac{8}{9\ f_A + 4} - \dfrac{t_{TF}}{R}\right)\dfrac{B_{OH}^2}{0.8\ \pi\ \sigma_{sOH}} + \dfrac{B_{OH}}{0.4\ \pi\ R\ j_{cOH}}}{\left(1 + \dfrac{2}{3}\ \dfrac{B_{OH}^2}{0.8\ \pi\ \sigma_{sOH}}\right)}$$

and for the OH coil filling factor

$$f_{OH} = \frac{B_{OH}}{0.4\ \pi\ j_{cOH}\ \dfrac{d_{OH}}{R}\ R} = \frac{\left(1 + \dfrac{2}{3}\ \dfrac{B_{OH}^2}{0.8\ \pi\ \sigma_{sOH}}\right)}{\left[\left(\dfrac{8}{9\ f_A + 4} - \dfrac{t_{TF}}{R}\right)R\ \dfrac{B_{OH}\ j_{cOH}}{2\ \sigma_{sOH}} + 1\right]}$$

For the (fictitious) synchrotron radiation density one has the relation

$$p_{sy} = n_e^2\ 0.000002731\left[\frac{(1 - R_w)}{B_{max}}\right]^{0.5}\left[\frac{C_{fa}\ q}{g\ f(k)}\left(1 + \frac{n_i}{n_e}\right)\right]^{1.5} T_{10}^4\ \frac{\left[f_{pw}\left(9 f_A - 4\right)\right]^{0.5}\ 8^{1.5}\ A}{\left(9\ f_A + 4\right)^2\ L_A^{0.5}}$$

(The form of the L_A equation would suggest subdividing it into an A-dependent part and the rest for insertion in p_{sy}.)

In order to understand the relations between the energy confinement time and the aspect ratio (when obviously the aspect ratio is determined independently of almost all of the input data), one can derive the following equations for the energy confinement time, namely one for the confinement requirement:

$$\tau_E^{(1-\alpha_p)} = \frac{\dfrac{4.80^{(1-\alpha_p)}}{\left[\dfrac{5\,f(k)}{q}\right]^{(1-\alpha_p)}} \left(1+\dfrac{n_i}{n_e}\right)^{2(1-\alpha_p)} \left[\dfrac{f_{pw}(9f_A-4)}{8}\right]^{2(1-\alpha_p)} A^{3(1-\alpha_p)}}{\left(\dfrac{2.5\,g}{C_{fa}}\right)^{(1-\alpha_p)} \left(\dfrac{n_{DT}}{n_e}\right)^{2(1-\alpha_p)} B_{max}^{2(1-\alpha_p)}\, C_{\sigma Ef}^{(1-\alpha_p)} \left(1-\dfrac{5}{F_{Br}}+\dfrac{5}{Q}\right)^{(1-\alpha_p)}}$$

and one for the confinement capability offered by the respective scaling:

$$\tau_E^{(1-\alpha_p)} = \frac{\dfrac{C_{\tau E}^{(1-\alpha_p)}\, C_{sI}^{*}}{\left(\dfrac{2.5\,g}{C_{fa}}\right)^{(\alpha_p-\alpha_n)} \left[\dfrac{5\,f(k)}{q}\right]^{(1-\alpha_p)}} \left[\dfrac{f_{pw}\,(9f_A-4)}{8}\right]^{2(1-\alpha_p)} A^{3(1-\alpha_p)}}{\left(1+\dfrac{n_i}{n_e}\right)^{\alpha_n} T_{10}{}^{\alpha_n}\, 5^{(1+\alpha_n-2\alpha_p)}\, B_{max}^{2(1-\alpha_p)}}$$

It is seen that both equations exhibit the same aspect ratio dependence (which is an increase of the energy confinement time with increasing aspect ratio), and also the dependence on $f(k)/q$ and B_{max} is the same. It can be shown that equality of the two expressions leads to the definition equation for $C_{si}{}^{*}$.

The equation for calculating, for example, f_{H93HP} from f_{H89P} for a consistent reactor parameter set in this case reads

$$f_{H93HP} = \frac{\left\{ \frac{\frac{(5\ B_{max})^{[2(1+\alpha_n-2\alpha_P)+\alpha_I+\alpha_B]_{89P}}}{\left[\frac{(C^*_{sI})_{89P}}{f_{H89P}}\ k^{(\alpha_P-\alpha_k)_{89P}}\right]}\left(A^6\ L_A\right)^{[\alpha_a+\alpha_R+\alpha_I-3\alpha_P]_{89P}}}{\frac{\left[\frac{8}{f_{pw}(9f_A-4)}\right]^{[4\alpha_a+4\alpha_R+3\alpha_I-\alpha_B-2(1+\alpha_n-2\alpha_P)-12\alpha_P]_{89P}}}{\left[\frac{f(k)}{q}\right]^{[(1+\alpha_n-2\alpha_P)+\alpha_I]_{89P}}}} \right\}^{\frac{[3(1+\alpha_n-2\alpha_P)+2\alpha_I-\alpha_R+\alpha_P+\alpha_B]_{93HP}}{[3(1+\alpha_n-2\alpha_P)+2\alpha_I-\alpha_R+\alpha_P+\alpha_B]_{89P}}}}{\left\{ \frac{\frac{(5\ B_{max})^{[2(1+\alpha_n-2\alpha_P)+\alpha_I+\alpha_B]_{93HP}}}{\left[(C^*_{sI})_{93HP}\ k^{(\alpha_P-\alpha_k)_{93HP}}\right]}\left(A^6\ L_A\right)^{[\alpha_a+\alpha_R+\alpha_I-3\alpha_P]_{93HP}}}{\frac{\left[\frac{8}{f_{pw}(9f_A-4)}\right]^{[4\alpha_a+4\alpha_R+3\alpha_I-\alpha_B-2(1+\alpha_n-2\alpha_P)-12\alpha_P]_{93HP}}}{\left[\frac{f(k)}{q}\right]^{[(1+\alpha_n-2\alpha_P)+\alpha_I]_{93HP}}}} \right\}}$$

For the density limit the equation given in 2.4 translates into

$$\frac{2.5\ g}{C_{fa}\ T_{10}}\ \frac{B_{max}}{\left(1+\frac{n_i}{n_e}\right)}\ 5\ f(k)\ \frac{1.17-\frac{0.65}{A}}{\left(1-\frac{1}{A^2}\right)^2}\ \frac{(9\ f_A+4)^3\ A^2}{8^3}\ L_A \le C_n$$

This relation may be used for adjusting g in the Q iteration in such a way as to comply with the density limit corresponding to a given value of C_n.

The ratio of the particle to the energy confinement time remains

$$C_{\tau p} = \frac{n_{He}}{n_e}\ \frac{\left(1-\frac{5}{F_{Br}}+\frac{5}{Q}\right)E_f}{1.20\left(1+\frac{n_i}{n_e}\right)T_{10}}$$

From the equation for the inductive burn time one can derive a minimum aspect ratio that would be required for inductive start-up of the plasma current without any subsequent inductive burn time. If attainable at all by the main iteration, the aspect ratio has to be

$$A > A_{min}.$$

The condition is defined by the following iteration equation:

$$A_{min} = \frac{\left[C_I\, f_L(A_{min})\right]^{\frac{1}{3}}}{\left[C_\Phi \left(\frac{A_{min} f_{pw} - 1}{A\, f_{pw}} - \frac{t_{TF}}{R}\right)^2 \frac{f_{pw}}{\left(A_{min} f_{pw} - 1\right)} \frac{q(A_{min})}{f(k)} \frac{B_{OH}}{B_{max}}\right]^{\frac{1}{3}}} \; ; \; f_A = \frac{4\left(A_{min} f_{pw} + 1\right)}{9\left(A_{min} f_{pw} - 1\right)}$$

for each specific set of input parameters. f_A is variable during iteration. In this case the temperature derivative of any additional heating power is given by

$$\left(\frac{\partial p_h}{\partial T_{10}}\right)_{n_e = const.} = -\frac{n_e^2}{20}\left(\frac{n_{DT}}{n_e}\right)^2 \frac{\partial\left(C_{\sigma Ef}\, T_{10}^2\right)}{\partial T_{10}} + 0.24\, n_e \left(1 + \frac{n_i}{n_e}\right) \frac{2}{\tau_E\left(1 - \alpha_p\right)}$$

$$+ n_e^2 \left\{ \frac{0.008475}{T_{10}^{0.5}} \left(\frac{n_{DT}}{n_e} + 4\frac{n_{He}}{n_e}\right) + 10^{-3} \frac{\partial\left[\left(1 + 3T_{10}\right) \sum_{Z=6}^{Z_{max}} \frac{n_Z}{n_e} Z^{(3.7 - 0.33 \ln 10\, T_{10})}\right]}{\partial T_{10}} \right\}$$

$$+ n_e^{0.5}\, 0.000002731 [12.5]^{1.5} \left[B_{max}^5 (1 - R_w)\right]^{0.5} 2.5\, T_{10}^{1.5} \left[\frac{8}{f_{pw}\left(9 f_A - 4\right)}\right]^{4.5} \frac{1}{A^{5.5}\, L_A^{0.5}}$$

Other definitions are identical to or correspond to those in 2.4.

2.6 Generally applicable relations and remarks

The above equations show a fundamental difference between unshielded and shielded configurations. While for $t_{BS} = 0$ the confinement capability formally increases with increasing aspect ratio, it decreases for shielded configurations for more slender geometries. In both cases, naturally, the confinement requirement provides the configuration limit. Note, however, that A is in fact fixed by the input data.
The equations are written in the following units: m, MPa, s, T, MA, MW, 10 keV (for plasma temperature), 10^{20} m^{-3} (for plasma density).
The plasma density, temperature, and current density are assumed to have parabolic profiles (without pedestals) with given exponents. The volume-averaged density and density-weighted volume-averaged temperature values are used.

2.6.1 Fusion power density

The fusion power density is given by

$$p_f = \frac{n_e^2}{4}\left(\frac{n_{DT}}{n_e}\right)^2 \langle\sigma\, v\rangle\, E_f = \frac{n_e^2}{4}\left(\frac{n_{DT}}{n_e}\right)^2 \frac{\langle\sigma\, v\rangle\, E_f}{T_{10}^2}\, T_{10}^2 = \frac{n_e^2}{4}\left(\frac{n_{DT}}{n_e}\right)^2 C_{\sigma Ef}\, T_{10}^2$$

$\langle\sigma\, v\rangle$ is calculated according to the approach of Johner and Fidone[9], who use the Peres fit for calculating the average reaction cross-section for given parabolic density and temperature profiles for a 50 : 50 DT mix:

$$\langle\sigma v\rangle = \left(1+\alpha_N\right)^2 \int_0^1 u^{2\alpha_N}\, \overline{\sigma v}\left(T\right) du$$

with

$$T = 10\, T_{10}\, \frac{1+\alpha_N+\alpha_T}{1+\alpha_N}\, u^{\alpha_T}$$

and the Peres fit

$$\overline{\sigma v} = \frac{a_e}{T^{ex1}}\, \frac{e^{ex4}}{U^{ex2}}$$

with $$ex1 = \frac{2}{3}\ ;\ ex2 = \frac{5}{6};\ ex3 = \frac{1}{3};\ ex4 = -\, b_e\left(\frac{U}{T}\right)^{ex3}$$

and $a_e = 2.310700\mathrm{x}\ 10^{-18}$; $b_e = 19.98303$

U(T) is given as a Padé expansion:

$$U\left(T\right) = 1 - T\, \frac{P_2 + \left(P_4 + P_6 T\right)T}{1 + \left(P_3 + P_5 T\right)T}$$

$P_2 = 2.818412\mathrm{x}10^{-2}$; $P_3 = 6.116184\mathrm{x}10^{-2}$; $P_4 = 2.834474\mathrm{x}10^{-3}$

$P_5 = 8.955113\mathrm{x}10^{-3}$; $P_6 = -5.734052\mathrm{x}10^{-5}$

For the reaction rate as used in this work one has

$$C_{\sigma Ef} = \frac{\langle\sigma v\rangle\, E_f}{T_{10}^2} = \frac{\langle\sigma v\rangle\, 2.81952\mathrm{x}10^{22}}{T_{10}^2}$$

2.6.2 Required confinement time

The confinement requirement deriving from the plasma power balance is expressed in the form

$$n_{DT}\, \tau_E\, T_{10} = \frac{4.80\left(1 + \frac{n_i}{n_e}\right)}{\left(1 - \frac{5}{F_{Br}} + \frac{5}{Q}\right)\left(\frac{n_{DT}}{n_e}\right) C_{\sigma Ef}}$$

which leads to a relation between the required energy confinement time and plasma fusion power density

$$\tau_E = \frac{2.40\left(1 + \frac{n_i}{n_e}\right)}{\left(1 - \frac{5}{F_{Br}} + \frac{5}{Q}\right)\left(\frac{n_{DT}}{n_e}\right) C_{\sigma Ef}^{0.5}} \frac{1}{p_f^{0.5}}$$

For the available energy confinement time deriving from the confinement capability there is no general relation (see under 2.4, 2.5).

2.6.3 Impurities

While n_{He}/n_e has to be estimated n_{DT}/n_e, n_i/n_e, and Z_{eff} are determined by means of the following relations:

$$\frac{n_{DT}}{n_e} = 1 - 2\frac{n_{He}}{n_e} - \sum_{Z=6}^{Z_{max}} Z \frac{n_Z}{n_e}$$

$$1 + \frac{n_i}{n_e} = 2 - \frac{n_{He}}{n_e} - \sum_{Z=6}^{Z_{max}} (Z-1) \frac{n_Z}{n_e}$$

$$Z_{eff} = 1 + 2\frac{n_{He}}{n_e} + \sum_{Z=6}^{Z_{max}} Z(Z-1) \frac{n_Z}{n_e}$$

$$\frac{n_{He}}{n_e} = 0.1 \qquad \text{(estimate: helium content)}$$

$$\frac{n_C}{n_e} = 0.009 + 0.006\left(\frac{0.7}{n_e}\right)^{2.6} \; ; \; Z = 6 \qquad \text{(carbon imp.)}$$

$$\frac{n_O}{n_e} = 0.001 \; ; \; Z = 8 \qquad \text{(oxygen impurity)}$$

$$\frac{n_{Fe}}{n_e} = 0.0005\left(\frac{0.7}{n_e}\right)^{2.3} \; ; \; Z = 26 \qquad \text{(iron impurity)}$$

The above assumptions about the impurity content correspond to these assumed in the ITER studies (derived from JET results).

2.6.4 Optimum reactor geometry

The "optimum" reactor geometry can be determined in the following way by using just the fusion power equation and the radial build .
Before introducing the abbreviations f_1, f_2, and f_3 (see 2.1), one generally has the following equations. The fusion power is given by

$$P_f = C_{PfB}\, B_{max}^4 \left(\frac{B}{B_{max}}\right)^4 \frac{a^3}{A}$$

with the geometry condition on the minor radius

$$a = \frac{t_{BS}}{A\left(1 - \frac{B}{B_{max}}\right) - \frac{1}{f_{pw}}}$$

In addition one has

$$P_f = C_{Pfw}\, p_w\, A\, a^2$$

and hence

$$p_w = \frac{C_{PfB}}{C_{Pfw}} B_{max}^4 \left(\frac{B}{B_{max}}\right)^4 \frac{a}{A^2}$$

A further expression for P_f is obtained from this equation

$$P_f = \frac{p_w^3}{B_{max}^8} \frac{C_{Pfw}^3}{C_{PfB}^2} \frac{A^5}{\left(\frac{B}{B_{max}}\right)^8}$$

which is equivalent to

$$p_w^3 = P_f\; B_{max}^8 \frac{C_{PfB}^2}{C_{Pfw}^3} \frac{\left(\frac{B}{B_{max}}\right)^8}{A^5}$$

This provides two equations for P_f and p_w that can be used to determine the specific configuration in which p_w is a maximum for fixed P_f or P_f is a minimum for fixed p_w. The extrema are determined by differentiation with respect to B/B_{max}, it being taken into account that A is a function of B/B_{max} and that q (contained in C_{PfB}) can be a function of A. Since two equations are always available, and the remaining differentials of A with respect to B/B_{max} have to be equal, one obtains an expression for the optimum B/B_{max} as a function of the aspect ratio. It turns out that for both optimization goals the result is the same, namely

$$\frac{B}{B_{max}} = \frac{4\left(A\, f_{pw} + 1\right)}{9\, f_A\, f_{pw}\, A} = \frac{f_1}{f_3\, A}$$

For q = const. $f_A = 1$ denotes the optimum situation, whereas $f_A > 1$ means configurations with a lower than optimum aspect ratio and vice versa. For $q = f_q(A)$ one has $f_A = f_A(A)$ and a factor C_{fA} may be imposed on $f_A(A)$ again with $C_{fA} = 1$ for the optimum situation, $C_{fA} > 1$ for lower than optimum aspect ratio and vice versa. Hence generally one has

$$f_A\left(A\right) = C_{fA}\left[1 + \frac{4}{9}\frac{\frac{\partial f_q\left(A\right)}{\partial A}}{\frac{f_q\left(A\right)}{A}}\right]$$

This optimization definition is used here throughout. An attempt to include the energy confinement scaling has unsatisfactory results in that, depending on the scaling, the optimum may differ for the two optimization goals and the optimum itself may get extremely flat with the reference value outside the A-range of interest.
Thus the pure geometric approach is retained, leading to reasonable reference configurations.

2.6.5 Three specific confinement scalings, their exponents, coefficients

It has been stated that particularly for $t_{BS} > 0$ the aspect ratio iteration equation allows one to identify differences in impact from certain input parameters according to the respective assumed energy confinement scal-ing. The values of individual and composite exponents as occurring in the above equations for $t_{BS} > 0$ and $t_{BS} = 0$ are compared below for three consecutive scalings introduced in 1983, 1989, and 1993.

Scaling Exponent	Goldston[13]	ITER89P[14]	ITER93HP[16]	referring to
α_I	1.0	0.85	1.06	I
α_R	1.75	1.2	1.9	R
α_a	-0.37	0.3	-0.11	a
α_B	0	0.2	0.3	B
α_n	0	0.1	0.17	n_e
α_p	0.5	0.5	0.67	P
α_k	0.5	0.5	0.66	k
$t_{BS} > 0$:				
$(I)=(1+\alpha_n-2\alpha_p)$	0	0.1	-0.17	g/C_{fa}
$(II)=(\alpha_R+\alpha_a)$	1.38	1.5	1.79	
$2(I)+\alpha_I+\alpha_B$	1.0	1.25	1.04	$B_{max}\ f_1$
$(II)+\alpha_I-3\alpha_p$	0.88	0.85	0.84	t_{BS}/f_2
$3\alpha_p+2(I)-(II)+\alpha_B$	0.12	0.4	0.2	f_3
$\alpha_p-\alpha_k$	0	0	0.01	k
$3(I)+2\alpha_I+\alpha_B+\alpha_p-\alpha_R$	0.75	1.5	0.7	A incl. C_{sI}^*/f_H
$(I)+\alpha_I$	1.0	0.95	0.89	$f(k)/q$
$1-\alpha_p$	0.5	0.5	0.33	$1/[(1-5/F_{Br}+5/Q)(n_{DT}/n_e)^2C_{\sigma Ef}]$
$1+(I)$	1.0	1.1	0.83	$1+n_i/n_e$
$t_{BS} = 0$:				
$4(II)-2(I)+3\alpha_I-12\alpha_p-\alpha_B$	2.52	2.15	2.32	8
$2\alpha_a+3\alpha_R+\alpha_I-(I)-7\alpha_p$	2.01	1.45	2.02	$f_{pw}(9f_A-4)$
$6\alpha_a+7\alpha_R+4\alpha_I-3(I)-19\alpha_p-\alpha_B$	4.53	3.6	4.34	$(9f_A+4)$

The pertinent coefficients transformed for the average density in 10^{20} m^{-3} and for the fuel ion mass of 2.5 with the respective exponents are

$C_{\tau E}$	0.0004816	0.0006600	0.000004249

Comparing the exponents, one notes a certain similarity between the Goldston and ITER 93HP scalings except for α_a, α_n, α_B, with some of the differences cancelling at least partially in the composite exponents. ITER 89P scaling deviates notably from the other two in α_a and α_R. When commenting on the rather different coefficients one has to take into account that Goldston and ITER 89P are L-mode scalings with enhancement factors of about 1.7 and 1.9 respectively for the desired ELMy H-mode, whereas ITER 93HP is an H-mode scaling implying a reduction factor of 0.85 for the ELMy H-mode in JET. Generally at the reactor level ITER 93HP scaling with $f_{H93HP} = 0.85$ leads to more optimistic values for the confinement time than ITER 89P scaling with $f_{H89P} = 1.9$ (see 2.6.6).

2.6.6 Figure of merit f_H/q_ψ

In the course of the ITER studies[7] it has been claimed that there is a figure of merit f_H/q_ψ which for ITER 89P confinement scaling should be typically about 0.6. It can be seen that this expression in fact occurs in a somewhat modified form in the A iteration equation for $t_{BS} > 0$ and in the L_A equation for $t_{BS} = 0$. After inserting $q(q_\psi)$ it appears as

$$\frac{f_H}{{q_\psi}^{[(1+\alpha_n-2\alpha_p)+\alpha_I]}}$$

which clearly indicates the dependence of the resulting figure of merit on the selected confinement scaling. If f_H is meant to describe a certain operating mode like the ELMy H-mode it may have a certain fixed value, but it appears more likely that, depending on the selected confinement rule, it may by itself imply a scaling dependence of the type as for τ_E itself. Indications for this with f_{H93HP} can be seen from JET results[11].

The exponent of q_ψ ranges from about 0.9 to 1 for Goldston, ITER 89P, and ITER 93HP scalings.

Thus that figure of merit appears - assuming fixed f_H-values in the respective case - more as an indicator for the relation between a consistent configuration and the combination of the main input assumptions.

2.6.7 Basic equations for evaluation of given reactor parameter sets

The reactor design equations were derived from a number of basic relations consisting of reactor parameters. These can be useful to check given tokamak reactor parameter sets for consistency or for any inclusion of specific assumptions not mentioned explicitly.

One has the following expressions (with alternative forms) consistent with the design equations in this report:

$$P_f = \frac{5^2\,\pi^2}{2^3}\frac{\left(\frac{n_{DT}}{n_e}\right)^2}{\left(1+\frac{n_i}{n_e}\right)^2} C_{\sigma Ef}\left(\frac{g}{C_{fa}}\right)^2 I^2\,B^2\,R\,k = \frac{\pi^2}{2^3}\frac{\left(\frac{n_{DT}}{n_e}\right)^2}{\left(1+\frac{n_i}{n_e}\right)^2} C_{\sigma Ef}\left[\frac{g\,q}{f(k)\,C_{fa}}\right]^2 \frac{k}{R}\,I^4\,A^4$$

$$= \frac{5^4\,\pi^2}{2^3}\frac{\left(\frac{n_{DT}}{n_e}\right)^2}{\left(1+\frac{n_i}{n_e}\right)^2} C_{\sigma Ef}\left[\frac{g\,f(k)}{q\,C_{fa}}\right]^2 \frac{k}{R}\,B^4\,a^4 = \frac{5^2\,\pi^2}{2^3}\frac{\left(\frac{n_{DT}}{n_e}\right)^2}{\left(1+\frac{n_i}{n_e}\right)^2}\,C_{\sigma Ef}\,\frac{k}{A}\,\beta^2\,B^4\,a^3$$

$$p_f = \frac{5^2}{2^4} \frac{\left(\frac{n_{DT}}{n_e}\right)^2}{\left(1+\frac{n_i}{n_e}\right)^2} C_{\sigma Ef} \left(\frac{g}{C_{fa}}\right)^2 \frac{I^2\,B^2}{a^2} = \frac{1}{2^4} \frac{\left(\frac{n_{DT}}{n_e}\right)^2}{\left(1+\frac{n_i}{n_e}\right)^2} C_{\sigma Ef} \left[\frac{g\,q}{f(k)\,C_{fa}}\right]^2 \frac{I^4\,A^2}{a^4}$$

$$= \frac{5^4}{2^4} \frac{\left(\frac{n_{DT}}{n_e}\right)^2}{\left(1+\frac{n_i}{n_e}\right)^2} C_{\sigma Ef} \left[\frac{g\,f(k)}{q\,C_{fa}}\right]^2 \frac{B^4}{A^2} = \frac{5^2}{2^4} \frac{\left(\frac{n_{DT}}{n_e}\right)^2}{\left(1+\frac{n_i}{n_e}\right)^2} C_{\sigma Ef}\,\beta^2\,B^4$$

$$p_w = p_f \,\frac{2}{5}\, f_{pw}\, a \sqrt{\frac{2\,k^2}{1+k^2}}$$

$$p_w = \frac{5}{2^3} f_{pw} \frac{\left(\frac{n_{DT}}{n_e}\right)^2}{\left(1+\frac{n_i}{n_e}\right)^2} C_{\sigma Ef} \left(\frac{g}{C_{fa}}\right)^2 \frac{I^2\,B^2}{a} \sqrt{\frac{2\,k^2}{1+k^2}}$$

$$= \frac{1}{2^3\,5} f_{pw} \frac{\left(\frac{n_{DT}}{n_e}\right)^2}{\left(1+\frac{n_i}{n_e}\right)^2} C_{\sigma Ef} \left[\frac{g\,q}{f(k)\,C_{fa}}\right]^2 \frac{I^4\,A^2}{a^3} \sqrt{\frac{2\,k^2}{1+k^2}}$$

$$p_w = \frac{5^3}{2^3} f_{pw} \frac{\left(\frac{n_{DT}}{n_e}\right)^2}{\left(1+\frac{n_i}{n_e}\right)^2} C_{\sigma Ef} \left[\frac{g\,f(k)}{q\,C_{fa}}\right]^2 \frac{B^4}{A^2}\, a \sqrt{\frac{2\,k^2}{1+k^2}}$$

$$= \frac{5}{2^3} f_{pw} \frac{\left(\frac{n_{DT}}{n_e}\right)^2}{\left(1+\frac{n_i}{n_e}\right)^2} C_{\sigma Ef}\,\beta^2\,B^4\,a \sqrt{\frac{2\,k^2}{1+k^2}}$$

For the toroidal beta value one has

$$\beta = 0.4\,\frac{n_e\,T_{10}}{B^2}\left(1+\frac{n_i}{n_e}\right) C_{fa}$$

while for the poloidal beta the following relations hold:

$$\beta_p = \frac{4}{0.4\,\pi\,I^2\,R}\int_V p\,dV \approx 10\left(1+\frac{n_i}{n_e}\right) C_{fa}\frac{n_e T_{10}}{I^2} k\,a^2 = 0.4\left(1+\frac{n_i}{n_e}\right) C_{fa}\frac{n_e T_{10}}{B^2} k \left[\frac{q\,A}{f(k)}\right]^2$$

which means

$$\beta\,\beta_p = \beta^2\,k\left[\frac{q\,A}{f(k)}\right]^2 = 25\,k\,g^2$$

For the density one has

$$n_e = \frac{5\,g}{2\,C_{fa}\,T_{10}}\frac{I\,B}{a\left(1+\frac{n_i}{n_e}\right)} = \frac{g\,q}{2\,f(k)\,C_{fa}\,T_{10}}\frac{I^2\,A}{a^2\left(1+\frac{n_i}{n_e}\right)} = \frac{5^2\,g\,f(k)}{2\,q\,C_{fa}\,T_{10}}\frac{B^2}{A\left(1+\frac{n_i}{n_e}\right)}$$

g/C_{fa} is the so-called thermal Troyon coefficient.
The plasma current has to agree with the Kruskal relation and with the confinement scaling

$$I = \frac{5\,B\,a\,f(k)}{q\,A} = \left(\frac{\tau_E\,P^{\alpha_P}}{C_\tau\,f_H\,R^{\alpha_R}\,a^{\alpha_a}\,n_e^{\alpha_n}\,B^{\alpha_B}\,k^{\alpha_k}}\right)^{\frac{1}{\alpha_I}}$$

This condition leads to the aspect ratio iteration equation.
The total loss power is given by the plasma energy and its confinement and by the plasma power balance.

$$P = \frac{W_{th}}{\tau_E} = \frac{0.24\,n_e\,T_{10}}{\tau_E}\left(1+\frac{n_i}{n_e}\right)V = P_\alpha + P_h - P_{rad} - P_{sy}$$

The external heating power (for heating and/or non-inductive current drive) can be written (second form: non-inductive current drive only)

$$P_h = \frac{P_f}{Q}$$

$$P_h = \frac{I\,n_e\,R}{\gamma_o}\left(1-\frac{I_B}{I}\right)$$

Since for DT fuel $P_f \approx 5\,P_\alpha$, one gets

$$\frac{W_{th}}{\tau_E} = \frac{P_f}{5}\left[1+\frac{5}{Q} - 5\frac{(P_{rad}+P_{sy})}{P_f}\right] = \frac{P_f}{5}\left[1-\frac{5}{F_{Br}}+\frac{5}{Q}\right]$$

For non-inductive current drive Q can be expressed as

$$Q = \frac{\pi^2}{4}\frac{\gamma_o\,g\,q\,k}{\left(1-\frac{I_B}{I}\right)f(k)}\frac{\left(\frac{n_{DT}}{n_e}\right)^2}{\left(1+\frac{n_i}{n_e}\right)}\frac{C_{\sigma Ef}T_{10}}{C_{fa}}\,I\,A = \frac{5\,\pi^2}{4}\frac{\gamma_o\,g\,k}{\left(1-\frac{I_B}{I}\right)}\frac{\left(\frac{n_{DT}}{n_e}\right)^2}{\left(1+\frac{n_i}{n_e}\right)}\frac{C_{\sigma Ef}T_{10}}{C_{fa}}\,B\,a$$

The inductive burn time can be derived from (for input parameters not explained here see 2.4)

$$t_B = \frac{2\,\pi\,a^2}{5\,F_B\,F_{OH}\,f(\alpha,A)}\left[C_\Phi\left(\frac{B}{B_{max}} - \frac{t_{TF}}{R}\right)^2 A^2\,\frac{q}{f(k)}\,\frac{B_{OH}}{B} - C_I\,f_L(A)\right]$$

$$\frac{R_{OH}}{R} = \frac{B}{B_{max}} - \frac{t_{TF}}{R}$$

3. Mathematica®[12] programs for tokamak reactor parameter evaluation

The files below show two simple Mathematica® programs for evaluation of tokamak reactor parameter sets with and without a blanket/shield. It is seen that certain values (zeff, fbr, ndte, nie) are initially given and finally recalculated (zeffz, fbrz, ndtez, niez). This indicates that a number of overall iterations (not contained in the programs shown) are necessary in order to adjust the impurity levels to be consistent with their definition equations. One example each is shown.

3.1 Program determining a shielded reactor configuration ($t_{BS} > 0.2$ m)

The input data and hence the results (both indicated by oblique letters) given in the first program refer to a reactor based on ITER 89P scaling with an enhancement factor of 1.8, a blanket/shield/cryostat thickness of 1.25 m, a maximum toroidal and poloidal field level of 16.5 T, a plasma temperature of 17 keV, parabolic profiles with $\alpha_n = 0.5$, $\alpha_T = 1.0$, a Troyon coefficient of 0.03, a boundary q_ψ of 4.5, a plasma to vessel radius ratio of 0.85, an elongation of 1.85. The design point is selected for $C_{fA}\,f_A \approx 1$.

The result is a 3268 MW reactor with an average neutron wall load of 2.27 MW/m^2 , a plasma current of 14.5 MA, a major radius of 8.34 m.

(program Test mod. 2.1)

```
alphi=0.85;alphr=1.2;alpha=0.3;alphn=0.1;
alphb=0.2;alphk=0.5;alphp=0.5;
bralp=1.0+alphn-2.0 alphp;
al1=2.0 bralp+alphi+alphb;
al2=alpha+alphr+alphi-3.0 alphp;
al3=3.0 alphp+2 bralp+alphb-alphr-alpha;
al4=bralp+alphi;al5=alphp-alphk;
ala=1.0/(3.0 bralp+2.0 alphi-alphr+alphp+alphb);
al6=al2/al4;al7=(bralp+alphb)/al4;
al8=(al2-bralp-alphb)/al4;
al9=(alphi+alphr-alphp-alphb)/al4;
al10=1.0/al4;al11=al1/al4;
ci=1;zeff=1.64297;an=0.5;at=1.0;ai=1.5;
fbr=24.992;ctaue=0.00066;cb=0.6746;
tbs=1.25;del=0.35;kk=1.85;ndte=0.727413;nie=0.838767;
bm=16.5;boh=16.5;
```

```
pi=3.141592654;gamo=0.5;
qpsi=4.5;fpw=0.85;gtr=0.03;
t10=1.7;fh89p=1.8;faaa=0.96506227;
NIntegrate[ex1=2/3;ex2=5/6;ex3=1/3;
be=19.98303;ae=2.3107 10^-18;
p2=2.818421 10^-2;p3=6.116184 10^-2;
p4=2.834474 10^-3;p5=8.955113 10^-3;
p6=-5.734052 10^-5;
tu=10 t10 u^at (1+an+at)/(1+an);
ut=1-tu (p2+tu (p4+tu p6))/(1+tu (p3+tu p5));
ex4=-be (ut/tu)^ex3;
sval=(ae E^ex4)/(tu^ex1 ut^ex2);
y=(u^(2 an)) sval,{u,0,1}];
% ((1+an)^2)/t10^2 2.81952 10^22;
csef=%;
ao=3.8/faaa^1.3;
cfa=1.0+0.2 (t10-0.37);
fk=0.5 (1+(kk^2) (1.0+2.0 del^2-1.2 del^3));
cpfbx=5^2 (5 pi)^2/8 (ndte/(1+nie))^2 csef (gtr/cfa)^2 kk;
cpfw=5/fpw pi^2 Sqrt[(1+kk^2)/2];
FindRoot[f1=4 (a fpw+1.0);f2=a fpw (9 (faaa (1.0+4/9 (
4/(a^2-1)-0.65/(1.17 a-0.65))))-4.0)
-9.0 (faaa (1.0+4/9 (4/(a^2-1)-0.65/(1.17 a-0.65))))
-4.0;
f3=9.0 fpw (faaa (1.0+4/9 (4/(a^2-1)-0.65/(1.17 a-0.65)
)));
a-(((5.0 bm f1)^al1)
 ((tbs/f2)^al2)
 ((fk/(qpsi ((1-1/a^2)^2/(1.17-0.65/a))))^al4)/
(((((4.8/(1-5.0/fbr+5.0/((5/4) pi^2 gamo (kk/
(1-(5.0 cb gtr (kk/
fk) Sqrt[a] (qpsi ((1-1/a^2)^2/(1.17-0.65/a)))))) (
(gtr ndte^2)/
(1.0+nie)) csef (t10/cfa) bm tbs f1/(a f2))
))^(1.0-alphp)) (((1+nie)^(2.0+alphn-2.0 alphp))/
ndte^(2.0 (1.0-alphp))) ((t10^(alphn))/csef^
(1.0-alphp))/(((gtr/(2.0 cfa))^bralp) ctaue^
(1.0-alphp)))/
fh89p) (kk^al5) f3^al3))^ala
==0,{a,ao}];
a/.%;
a=N[%];
a=%;
faab=faaa (1.0+4/9 (4/(a^2-1)-0.65/(1.17 a-0.65)));
```

```
f1=4 (a fpw+1.0);
f2=a fpw (9 faab-4.0)-9.0 faab-4.0;
f3=9.0 fpw faab;
rr=f3 a tbs/f2;
ak=rr/a;bk=ak kk;bb=bm f1/(f3 a);
qq=(qpsi ((1-1/a^2)^2/(1.17-0.65/a)));
ibm=(5 fk/qq) f1 tbs/(f2 a^2);
ii=ibm bm;
pfu=cpfbx/5^2 bm^4 qq/(5 fk) ibm^3 f1 a/f3;
pw=cpfbx/cpfw bm^4 1/5 fk/qq ibm/a^4 (f1/f3)^3;
pf=cpfbx/5^2 (bm^4)/(2.0 pi^2 kk) (5.0 fk/qq)^2.0 (f1/f3)^4 1/a^6;
ibi=5.0 cb gtr (kk/fk) Sqrt[a] qq;
qgr=1.25 pi^2 gamo (kk/(1-ibi)) ((gtr ndte^2)/
(1.0+nie)) csef (t10/cfa) bm tbs f1/(a f2);
csix=((4.8/(1.0-5.0/fbr+5.0/qgr))^(1.0-alphp)) (((1.0+nie)
^(2.0+alphn-2.0 alphp))/ndte^(2.0 (1.0-alphp))) ((t10^alphn)/
csef^(1.0-alphp))/(((gtr/(2.0 cfa))^bralp) ctaue^
(1.0-alphp));ftf=0.5;
vau=2 pi^2 kk a (tbs f3/f2)^3;vautm=vau (a-f1/f3)^2;
wtm=(2-ftf) 2.5 pi kk (bm^2) (tbs^3) ((a-f1/f3)^2) (f1^2/
f2^3) f3/a;
wpm=0.2 pi rr bm^2 (Log[8 (a/Sqrt[kk])]-1.75) ibm^2;
fla=Log[8 (a/Sqrt[kk])]-1.75;
foh=0.007 (pi/5)^2 zeff/1.5 (1+ai)^2/kk 1/t10^1.5;
fala=((4.3-0.6 a)/(2 ai-1.5 at+1)) ((1+an)/
(1+an+at))^1.5;
ne=2.5 (gtr/(cfa t10)) (bm^2/(1+nie)) 5 fk/qq (f1/f3)^2 1/a^3;
zz3=6.0;zz4=8.0;zz5=26.0;nalp=0.1;
nz3=0.009+0.006 (0.7/ne)^2.6;
nz4=0.001;nz5=0.0005 (0.7/ne)^2.3;
ndtez=1-2 nalp-zz3 nz3-zz4 nz4-zz5 nz5;
niez=1-nalp-(zz3-1) nz3-(zz4-1) nz4-(zz5-1) nz5;
zeffz=1+2 nalp+zz3 (zz3-1) nz3+zz4 (zz4-1) nz4+
zz5 (zz5-1) nz5;
nez=2.5 (gtr/(cfa t10)) (bm^2/(1+niez)) 5 fk/qq (f1/f3)^2 1/a^3;
rw=0.85;alz=3.7-0.33 Log[10 t10];
fbrz=5.0 (ndtez^2 csef t10^1.5)/(0.339 (ndtez+4 nalp)+
0.02 (1+3 t10)/t10^0.5 (nz3 zz3^alz+nz4 zz4^alz+
nz5 zz5^alz)+0.00005462 ((1-rw)/(bm tbs))^0.5/
((gtr/(cfa qq) fk/(1+niez))^1.5) (t10^3.5) (
f2^0.5 a^2)/f1^0.5);
prad=nez^2 (0.01695 t10^0.5 (ndtez+4 nalp)+0.001 (1+3 t10) (
nz3 zz3^alz+nz4 zz4^alz+nz5 zz5^alz));
psy=nez^2 0.000002731 ((1-rw)/(bm tbs))^0.5/
```

```
((gtr/(cfa qq) fk/(1+niez))^1.5) (t10^4) (
f2^0.5 a^2)/f1^0.5;fbrzc=pf/(prad+psy);
taue=(ctaue^(1-alphp) 5^alphb fh89p ii^alphi rr^(
alphr-alphp) ne^(alphn-alphp) bb^alphb/(ak^(2 alphp-
alpha) kk^(alphp-alphk) t10^alphp (1+nie)^alphp))^
(1/(1-alphp));
beta=gtr ii/(ak bb);betap=25/beta kk gtr^2;
cnx=ne rr qpsi/bb;ctpe=2.81952 100 ne nalp/(taue pf);
khtm=25.0;khoh=8.48528;wh=0.003;rho=0.0003;sigstg=800.0;
ftt=50000;fto=50000;jctm=90.0;jcoh=55.1743;sigsp=400;
ftfc=0.5;
FindRoot[ftm=(bm/(0.4 pi))/(ttfr rr) 1/jctm;
tfr1=2-f1/(f3 a)+tbs/rr+ttfr/2;
tfr2=2-2 f1/(f3 a)+tbs/rr;
ttfr-(bm^2/(0.8 pi sigstg (1-ftm)) ((ftf/(f1/(f3 a)-ttfr/2) (tfr1/
(tfr2+ttfr) Log[(2+tbs/rr)/(f1/(f3 a))-1]-tfr2/(tfr2+ttfr))+
(f1/(f3 a)) (1-ftfc f1/(f3 a)/(tfr1-ttfr/2)))))==0,
{ttfr,0.1}, MaxIterations ->30];
ttfr/.%;
ttfr=N[%];
ttfr=%;
ttf=ttfr rr;roh=(f1/(f3 a)-ttfr) rr;
ftm=(bm/(0.4 pi))/(ttfr rr) 1/jctm;
sigstc=bm^2/(0.8 pi)/(1-ftm) f1/(f3 a)/ttfr (1-ftfc f1/(f3 a)/
(tfr1-ttfr/2));
sigst=sigstg-sigstc;
sigt=sigst (1-ftm);
sigtc=sigstc (1-ftm);
fohm=(1+2/3 boh^2/(0.8 pi sigsp))/(1+roh boh jcoh/
(2 sigsp));
dohr=boh/(0.4 pi rr fohm jcoh);
hoh=4 (ak kk+ttf/(2 kk));
woh=boh^2/0.8 (1-1/((0.8 pi sigsp (1-fohm)/
boh^2)+2/3)+1/3 1/((0.8 pi sigsp (1-fohm)/boh^2)+2/3)^2
) roh^2 hoh;doh=dohr rr;
cphi=1-1/((0.8 pi sigsp (1-fohm)/
boh^2)+2/3)+1/3 1/((0.8 pi sigsp (1-fohm)/boh^2)+2/3)^2;
jtf=bm/(0.4 pi ttf);joh=boh/(0.4 pi doh);
iitm=10^3 ((khtm wh/rho)^2)/jctm^3;tautm=2 10^3/(cvmtf iitm);
iioh=10^3 ((khoh wh/rho)^2)/jcoh^3;tauoh=2 10^3 woh/(vmoh iioh);
tb=0.4 pi (f3 tbs/f2)^2 (cphi (f1/(f3 a)-ttfr)^2 a^3 f3
/f1 qq/fk boh/bm-ci fla)/
((1-ibi) foh fala);
sigp=sigsp (1-fohm);
```

```
cvmtf=jctm^5/((khtm wh/rho)^2 ftt);
cvmoh=jcoh^5/((khoh wh/rho)^2 fto);
vmtf=cvmtf wtm;vmoh=cvmoh woh;
tautm=2 1000/(iitm cvmtf);tauoh=2 1000/(iioh cvmoh);
roh+ttf+tbs+ak/fpw
StringForm["g = ``, qy = ``, D = ``, k = ``",gtr,qpsi,del,kk]
StringForm["fpw = ``, go = ``, T10 = ``, Bmax = ``",fpw,gamo,t10,bm]
StringForm["CsEf = ``, Cfa = ``, fH89P = ``",csef,cfa,fh89p]
StringForm["CfA = ``, CfA x fA = ``, tBS = ``",faaa,faab,tbs]
StringForm["nDT/ne = ``, ni/ne = ``, Fbr = ``",ndte,nie,fbr]
StringForm["Csi* = ``, CPfB* = ``, CPfw = ``",csix,cpfbx,cpfw]
StringForm["CtE = ``,CB = ``",ctaue,cb]
StringForm["a1 = ``, a2 = ``, a3 = ``, a4 = ``",al1,al2,al3,al4]
StringForm["a5 = ``, aN = ``, aT = ``, aI = ``",al5,an,at,ai]
StringForm["a6 = ``, a7 = ``, a8 = ``, a9 = ``",al6,al7,al8,al9]
StringForm["a10 = ``, a11 = ``, Ci = ``, BOH = ``",al10,al11,ci,boh]
StringForm["A = ``, R = ``, a = ``, b = ``",a,rr,ak,bk]
StringForm["Pf = ``, pw = ``, pf = ``, IB/I = ``",pfu,pw,pf,ibi]
StringForm["I = ``, q = ``, B = ``, f(k) = ``",ii,qq,bb,fk]
StringForm["Q= ``, I/Bmax = ``, ne = ``",qgr,ibm,ne]
StringForm["V = ``, VTM = ``, Wt = ``, Wp = ``",vau,vautm,wtm,wpm]
StringForm["ndtez = ``, niez = ``, zeffz = ``",ndtez,niez,zeffz]
StringForm["nez = ``, nz2 = ``, Zeff = ``",nez,nalp,zeff]
StringForm["nz3 = ``, nz4 = ``, nz5 = ``",nz3,nz4,nz5]
StringForm["fbrz = ``, cnx = ``, ctpe = ``",fbrz,cnx,ctpe]
StringForm["prad = ``, psy = ``, fbrzc = ``",prad,psy,fbrzc]
StringForm["tauE = ``, ß = ``, ßp = ``",taue,beta,betap]
StringForm["khtm = ``, khoh = ``, ftt = ``, fto = ``",khtm,khoh,ftt,fto]
StringForm["wh = ``, rho = ``, ftm = ``",wh,rho,ftm]
StringForm["fohm = ``, Cvmtf = ``, Cvmoh = ``, Vmoh = ``
",fohm,cvmtf,cvmoh,vmoh]
StringForm["Vmtf = ``, ITM = ``, IOH = ``, WOH = ``",vmtf,iitm,iioh,woh]
StringForm["tTF = ``, dOH = ``, ROH = ``, HOH = ``",ttf,doh,roh,hoh]
StringForm["st = ``, sp = ``, jTF = ``, jOH = ``",sigt,sigp,jtf,joh]
StringForm["sst = ``, ssp = ``, jcTM = ``, jcOH = ``",sigst,sigsp,jctm,jcoh]
StringForm["ssg = ``, sstc  = ``, ftf = ``, ftfc = ``",sigstg,sigstc,ftf,ftfc]
StringForm["tb = ``,tautm = ``,tauoh = ``",tb,tautm,tauoh]
sigst=sigstc (ftf/(f1/(f3 a)-ttfr/2) (tfr1/
(tfr2+ttfr) Log[(2+tbs/rr)/(f1/(f3 a))-1]-tfr2/(tfr2+ttfr)))/
((f1/(f3 a)) (1-ftfc f1/(f3 a)/(tfr1-ttfr/2)))
```

```
8.3378
g = 0.03, qy = 4.5, D = 0.35, k = 1.85
fpw = 0.85, go = 0.5, T10 = 1.7, Bmax = 16.5
CsEf = 4.23043, Cfa = 1.266, fH89P = 1.8
```

```
CfA = 0.96506227, CfA x fA = 1.00395, tBS = 1.25
nDT/ne = 0.727413, ni/ne = 0.838767, Fbr = 24.992
Csi* = 183.565, CPfB* = 0.53031, CPfw = 86.3316
CtE = 0.00066,CB = 0.6746
a1 = 1.25, a2 = 0.85, a3 = 0.4, a4 = 0.95
a5 = 0., aN = 0.5, aT = 1., aI = 1.5
a6 = 0.894737, a7 = 0.315789, a8 = 0.578947, a9 = 1.42105
a10 = 1.05263, a11 = 1.31579, Ci = 1, BOH = 16.5
A = 4.16631, R = 8.3378, a = 2.00124, b = 3.7023
Pf = 3268.33, pw = 2.26884, pf = 2.68023, IB/I = 0.592341
I = 14.5123, q = 3.94132, B = 9.3671, f(k) = 2.54246
Q = 25.7346, I/Bmax = 0.879535, ne = 1.28734
V = 1219.42, VTM = 3955.67, Wt = 207148., Wp = 1598.59
ndtez = 0.727413, niez = 0.838767, zeffz = 1.64297
nez = 1.28734, nz2 = 0.1, Zeff = 1.64297
nz3 = 0.0102308, nz4 = 0.001, nz5 = 0.00012314
fbrz = 24.9919, cnx = 5.15647, ctpe = 7.47315
prad = 0.069307, psy = 0.0379371, fbrzc = 24.9919
tauE = 1.81214, ß = 0.0232248, ßp = 1.79226
khtm = 25., khoh = 8.48528, ftt = 50000, fto = 50000
wh = 0.003, rho = 0.0003, ftm = 0.107873
fohm = 0.24354, Cvmtf = 1.88957, Cvmoh = 1.42031, Vmoh = 66420.5
Vmtf = 391421., ITM = 85.7339, IOH = 42.8669, WOH = 46764.9
tTF = 1.35244, dOH = 0.977163, ROH = 3.38096, HOH = 16.2713
st = 402.591, sp = 302.584, jTF = 9.70861, jOH = 13.4371
sst = 451.271, ssp = 400, jcTM = 90., jcOH = 55.1743
ssg = 800., sstc  = 348.729, ftf = 0.5, ftfc = 0.5
tb = 34457.1,tautm = 12.3457,tauoh = 32.8493
451.271
```

3.2 Program for determining an unshielded reactor configuration

The input data and hence the results in the second program given refer to an unshielded reactor configuration based on ITER 89P scaling with an enhancement factor of 1.8, a maximum toroidal and poloidal field level of 16.5 T, a plasma temperature of 17 keV, parabolic profiles with α_n = 0.5, α_T = 1.0, a Troyon coefficient of 0.03, a boundary q_ψ of 4.5, a plasma to vessel radius ratio of 0.85, and an elongation of 1.85. The design point is selected to have the same C_{fA} f_A close to1 and the other input data as in the previous case.

The result is a 2290 MW reactor configuration with a neutron wall load of 4.52 MW/m^2, a current of 15.7 MA, and a major radius of 4.21 m.

(program Test mod. 2 0.1)

```
alphi=0.85;alphr=1.2;alpha=0.3;alphn=0.1;
```

```
alphb=0.2;alphk=0.5;alphp=0.5;
bralp=1.0+alphn-2.0 alphp;
al1=2.0 bralp+alphi+alphb;
al2=alpha+alphr+alphi-3.0 alphp;
al3=3.0 alphp+2 bralp+alphb-alphr-alpha;
al4=bralp+alphi;al5=alphp-alphk;
ala=1.0/(3.0 bralp+2.0 alphi-alphr+alphp+alphb);
al6=al2/al4;al7=(bralp+alphb)/al4;
al8=(al2-bralp-alphb)/al4;
al9=(alphi+alphr-alphp-alphb)/al4;
al10=1.0/al4;al11=al1/al4;al12=1.0/al2;
al13=al4/al2;al14=al3/al2;al15=al5/al2;
al16=al1/al2;al17=(6 alpha+7 alphr+4 alphi
-19 alphp-alphb-3 bralp)/al2;al18=(alphi
+2 alpha+3 alphr-7 alphp-bralp)/al2;
al19=(4 alpha+4 alphr+3 alphi-12 alphp
-alphb-2 bralp)/al2;
ci=1;zeff=1.56002;
fbr=31.6508;ctaue=0.00066;cb=0.6746;
pi=3.141592654;gamo=0.5;
an=0.5;at=1.0;ai=1.5;
qpsi=4.5;fpw=0.85;gtr=0.03;
t10=1.7;fh89p=1.8;faaa=0.902622;
del=0.35;kk=1.85;ndte=0.735097;nie=0.845456;
bm=16.5;boh=16.5;
NIntegrate[ex1=2/3;ex2=5/6;ex3=1/3;
be=19.98303;ae=2.3107 10^-18;
p2=2.818421 10^-2;p3=6.116184 10^-2;
p4=2.834474 10^-3;p5=8.955113 10^-3;
p6=-5.734052 10^-5;
tu=10 t10 u^at (1+an+at)/(1+an);
ut=1-tu (p2+tu (p4+tu p6))/(1+tu (p3+tu p5));
ex4=-be (ut/tu)^ex3;
sval=(ae E^ex4)/(tu^ex1 ut^ex2);
y=(u^(2 an)) sval,{u,0,1}];
% ((1+an)^2)/t10^2 2.81952 10^22;
csef=%;
ao=3.1/faaa^0.85;qgro=30 gamo;
cfa=1.0+0.2 (t10-0.37);
fk=0.5 (1+(kk^2) (1.0+2.0 del^2-1.2 del^3));
cpfbx=5^2 (5 pi)^2/8 (ndte/(1+nie))^2 csef (gtr/cfa)^2 kk;
cpfw=5/fpw pi^2 Sqrt[(1+kk^2)/2];
FindRoot[a-(9 (faaa (1.0+4/9 (4/(a^2-1)-0.65/
(1.17 a-0.65))))+4)/(fpw(9 (faaa (1.0+4/9 (4/
```

```
(a^2-1)-0.65/(1.17 a-0.65)))))-4))==0,{a,ao}];
a/.%;
a=N[%];
a=%;
qq=(qpsi ((1-1/a^2)^2/(1.17-0.65/a)));
faab=faaa (1.0+4/9 (4/(a^2-1)-0.65/(1.17 a-0.65)));
f11=9 faab+4;f22=fpw (9 faab-4);
FindRoot[ibi=5.0 cb gtr (kk/fk) Sqrt[a] qq;
qgr-1.25 pi^2 gamo (kk/(1-ibi)) ((gtr ndte^2)/
(1.0+nie)) csef (t10/cfa) bm ((qq/fk)^al13 ((((4.8/
(1.0-5.0/fbr+5.0/qgr))^(1.0-alphp)) (((1.0+nie)
^(2.0+alphn-2.0 alphp))/ndte^(2.0 (1.0-alphp))) (
(t10^alphn)/csef^(1.0-alphp))/(((gtr/(2.0 cfa))^
bralp) ctaue^(1.0-alphp)))/fh89p)^al12 (kk^al15)/
(5 bm)^al16 8^al19 (f22^al18)/f11^al17) (f11/8)^
3 a^2==0,{qgr,qgro}];
qgr/.%;
qgr=N[%];
qgr=%;
csix=((4.8/(1.0-5.0/fbr+5.0/qgr))^(1.0-alphp)) (((1.0+nie)
^(2.0+alphn-2.0 alphp))/ndte^(2.0 (1.0-alphp))) ((t10^alphn)/
csef^(1.0-alphp))/(((gtr/(2.0 cfa))^bralp) ctaue^
(1.0-alphp));
lagr=(qq/fk)^al13 (csix/fh89p)^al12 (kk^al15)/(5 bm)^
al16 8^al19 (f22^al18)/f11^al17;
rr=(f11/8)^4 a^3 lagr;
ak=rr/a;
bk=ak kk;bb=bm 8/f11;
ibm=(5 fk/qq) (f11^4 lagr)/(8^3 f22);
ii=ibm bm;
pfu=cpfbx/5^2 bm^4 qq/(5 fk) ibm^3 8 a/f22;
pw=cpfbx/cpfw bm^4 1/5 fk/qq ibm/a^4 (8/f22)^3;
pf=cpfbx/5^2 (bm^4)/(2.0 pi^2 kk) (5.0 fk/qq)^2.0 (8/f22)^4 1/a^6;
ibi=5.0 cb gtr (kk/fk) Sqrt[a] qq;
qgr=1.25 pi^2 gamo (kk/(1-ibi)) ((gtr ndte^2)/
(1.0+nie)) csef (t10/cfa) bm lagr (f11/8)^3 a^2;
vau=2 pi^2 kk (f11/8)^12 a^7 lagr^3;
vautm=vau/fpw^2;ftf=0.5;
wtm=(2-ftf) 2.5 pi kk ((bm/fpw)^2) lagr^3 (f11/8)^12 a^7;
wpm=0.2 pi (Log[8 (a/Sqrt[kk])]-1.75) bm^2 (5 fk/
qq)^2 lagr^3 (f11/8)^10 a^5;
fla=Log[8 (a/Sqrt[kk])]-1.75;
foh=0.007 (pi/5)^2 zeff/1.5 (1+ai)^2/kk 1/t10^1.5;
fala=((4.3-0.6 a)/(2 ai-1.5 at+1)) ((1+an)/
```

```
(1+an+at))^1.5;
ne=2.5 (gtr/(cfa t10)) (bm^2/(1+nie)) 5 fk/qq (8/f22)^2 1/a^3;
zz3=6.0;zz4=8.0;zz5=26.0;nalp=0.1;
nz3=0.009+0.006 (0.7/ne)^2.6;
nz4=0.001;nz5=0.0005 (0.7/ne)^2.3;
ndtez=1-2 nalp-zz3 nz3-zz4 nz4-zz5 nz5;
niez=1-nalp-(zz3-1) nz3-(zz4-1) nz4-(zz5-1) nz5;
zeffz=1+2 nalp+zz3 (zz3-1) nz3+zz4 (zz4-1) nz4+
zz5 (zz5-1) nz5;
nez=2.5 (gtr/(cfa t10)) (bm^2/(1+niez)) 5 fk/qq (8/f22)^2 1/a^3;
rw=0.85;alz=3.7-0.33 Log[10 t10];
fbrz=5.0 (ndtez^2 csef t10^1.5)/(0.339 (ndtez+4 nalp)+
0.02 (1+3 t10)/t10^0.5 (nz3 zz3^alz+nz4 zz4^alz+
nz5 zz5^alz)+0.00005462 ((1-rw)/bm)^0.5/
((gtr/(cfa qq) fk/(1+niez))^1.5) (t10^3.5) ((8^1.5 f22^0.5)/
f11^2) (a^2/lagr)^0.5);
prad=nez^2 (0.01695 t10^0.5 (ndtez+4 nalp)+0.001 (1+3 t10) (
nz3 zz3^alz+nz4 zz4^alz+nz5 zz5^alz));
psy=nez^2 0.000002731 ((1-rw)/(bm))^0.5/
((gtr/(cfa qq) fk/(1+niez))^1.5) (t10^4) ((8^1.5 f22^0.5)/
f11^2) (a^2/lagr)^0.5;
fbrzc=pf/(prad+psy);
taue=(ctaue^(1-alphp) 5^alphb fh89p ii^alphi rr^(
alphr-alphp) ne^(alphn-alphp) bb^alphb/(ak^(2 alphp-
alpha) kk^(alphp-alphk) t10^alphp (1+nie)^alphp))^
(1/(1-alphp));
beta=gtr ii/(ak bb);betap=25/beta kk gtr^2;
cnx=ne rr qpsi/bb;ctpe=2.81952 100 ne nalp/(taue pf);
khtm=25.0;khoh=8.48528;wh=0.003;rho=0.0003;sigstg=800.0;
ftt=50000;fto=50000;jctm=90.0;jcoh=55.1743;sigsp=400;
ftfc=0.5;
csbt=(bm^2)/(0.8 pi sigstg);
FindRoot[tfr1=8/f11-ttfr/2;tfr2=2+ttfr-16/f11;
ttfr-((ftf/tfr1 ((2-tfr1) Log[9 faab/4]-(tfr2-ttfr))/
tfr2+(1-ftfc/faab 4/9)/(f11/8)) csbt/(1-bm/(0.4 pi ttfr rr jctm
)))==0,{ttfr,0.1},MaxIterations ->30];
ttfr/.%;
ttfr=N[%];
ttfr=%;
ftm=bm/(0.4 pi ttfr rr jctm);
sigstc=bm^2/(0.8 pi)/(1-ftm) 8/f11/ttfr (1-ftfc 4/9/faab);
sigst=sigstg-sigstc;
sigt=sigst (1-ftm);
sigtc=sigstc (1-ftm);
```

```
roh=(8/f11-ttfr) rr;
fr=roh/rr;
csbo=(boh^2)/(0.8 pi sigsp);
dohr=((8/f11-ttfr) csbo+boh/(0.4 pi rr jcoh))/(1+2/
3 csbo);
fohm=boh/(0.4 pi jcoh dohr rr);
sigp=sigsp (1-fohm);
doh=dohr rr;ttf=ttfr rr;
hoh=4 (ak kk+ttf/(2 kk));
woh=boh^2/0.8 (1-1/((0.8 pi sigsp (1-fohm)/
boh^2)+2/3)+1/3 1/((0.8 pi sigsp (1-fohm)/boh^2)+2/3)^2
) roh^2 hoh;doh=dohr rr;
cphi=1-1/((0.8 pi sigsp (1-fohm)/
boh^2)+2/3)+1/3 1/((0.8 pi sigsp (1-fohm)/boh^2)+2/3)^2;
jtf=bm/(0.4 pi ttf);joh=boh/(0.4 pi doh);
iitm=10^3 ((khtm wh/rho)^2)/jctm^3;tautm=2 10^3/(cvmtf iitm);
iioh=10^3 ((khoh wh/rho)^2)/jcoh^3;tauoh=2 10^3 woh/(vmoh iioh);
tb=(f11/8)^8 a^4 0.4 pi lagr^2 ((cphi qq/fk boh/
bm (8/f11-ttf/rr)^2 (f11^3)/(8 f22^2))-(ci fla))/
((1-ibi) foh fala);
joh=boh/(0.4 pi doh);jtf=bm/(0.4 pi ttf);
cvmtf=jctm^5/((khtm wh/rho)^2 ftt);
cvmoh=jcoh^5/((khoh wh/rho)^2 fto);
vmtf=cvmtf wtm;vmoh=cvmoh woh;
tautm=2 1000/(iitm cvmtf);tauoh=2 1000/(iioh cvmoh);
roh+ttf+ak/fpw
StringForm["g = ``, qy = ``, D = ``, k = ``",gtr,qpsi,del,kk]
StringForm["fpw = ``, go = ``, T10 = ``, Bmax = ``",fpw,gamo,t10,bm]
StringForm["CsEf = ``, Cfa = ``, fH89P = ``",csef,cfa,fh89p]
StringForm["CfA = ``, CfA x fA = ``, LA = ``",faaa,faab,lagr]
StringForm["nDT/ne = ``, ni/ne = ``, Fbr = ``, ",ndte,nie,fbr,lagr]
StringForm["Csi* = ``, CPfB* = ``, CPfw = ``",csix,cpfbx,cpfw]
StringForm["CtE = ``,CB = ``",ctaue,cb]
StringForm["a1 = ``, a2 = ``, a3 = ``, a4 = ``",al1,al2,al3,al4]
StringForm["a5 = ``, aN = ``, aT = ``, aI = ``",al5,an,at,ai]
StringForm["a6 = ``, a7 = ``, a8 = ``, a9 = ``",al6,al7,al8,al9]
StringForm["a10 = ``, a11 = ``, Ci = ``, BOH = ``",al10,al11,ci,boh]
StringForm["A = ``, R = ``, a = ``, b = ``",a,rr,ak,bk]
StringForm["Pf = ``, pw = ``, pf = ``, IB/I = ``",pfu,pw,pf,ibi]
StringForm["I = ``, q = ``, B = ``, f(k) = ``",ii,qq,bb,fk]
StringForm["Q = ``, I/Bmax = ``, ne = ``",qgr,ibm,ne]
StringForm["V = ``, VTM = ``, Wt = ``, Wp = ``",vau,vautm,wtm,wpm]
StringForm["jTF = ``, jOH = ``, st = ``, sp = ``",jtf,joh,sigt,sigp]
StringForm["ndtez = ``, niez = ``, zeffz = ``",ndtez,niez,zeffz]
```

```
StringForm["nez = ``, nz2 = ``,Zeff = ``",nez,nalp,zeff]
StringForm["nz3 = ``, nz4 = ``, nz5 = ``",nz3,nz4,nz5]
StringForm["fbrz = ``, cnx = ``, ctpe = ``",fbrz,cnx,ctpe]
StringForm["prad = ``, psy = ``, fbrzc = ``",prad,psy,fbrzc]
StringForm["tauE = ``, ß = ``, ßp = ``",taue,beta,betap]
StringForm["khtm = ``, khoh = ``, ftt = ``, fto = ``",khtm,khoh,ftt,fto]
StringForm["wh = ``, rho = ``, ftm = ``",wh,rho,ftm]
StringForm["fohm = ``, Cvmtf = ``, Cvmoh = ``, Vmoh = ``
",fohm,cvmtf,cvmoh,vmoh]
StringForm["Vmtf = ``, ITM = ``, IOH = ``, WOH = ``",vmtf,iitm,iioh,woh]
StringForm["tTF = ``, dOH = ``, ROH = ``, HOH = ``",ttf,doh,roh,hoh]
StringForm["st = ``, sp = ``, jTF = ``, jOH = ``",sigt,sigp,jtf,joh]
StringForm["sst = ``, ssp = ``, jcTM = ``, jcOH = ``",sigst,sigsp,jctm,jcoh]
StringForm["ssg = ``, sstc  = ``, ftf = ``, ftfc = ``",sigstg,sigstc,ftf,ftfc]
StringForm["tb = ``,tautm = ``,tauoh = ``",tb,tautm,tauoh]
sigst=sigstc ftf ((2-tfr1) Log[9 faab/4]-(tfr2-ttfr))/tfr2/
(tfr1 8/f11 (1-ftfc 8/f11 1/(2-8/f11)))
```

```
4.2107
g = 0.03, qy = 4.5, D = 0.35, k = 1.85
fpw = 0.85, go = 0.5, T10 = 1.7, Bmax = 16.5
CsEf = 4.23043, Cfa = 1.266, fH89P = 1.8
CfA = 0.902622, CfA x fA = 1.00873, LA = 0.021197
nDT/ne = 0.735097, ni/ne = 0.845456, Fbr = 31.6508,
Csi* = 168.262, CPfB* = 0.537654, CPfw = 86.3316
CtE = 0.00066,CB = 0.6746
a1 = 1.25, a2 = 0.85, a3 = 0.4, a4 = 0.95
a5 = 0., aN = 0.5, aT = 1., aI = 1.5
a6 = 0.894737, a7 = 0.315789, a8 = 0.578947, a9 = 1.42105
a10 = 1.05263, a11 = 1.31579, Ci = 1, BOH = 16.5
A = 3.02969, R = 4.2107, a = 1.38981, b = 2.57116
Pf = 2285.13, pw = 4.52304, pf = 7.69382, IB/I = 0.479253
I = 15.7393, q = 3.73948, B = 10.0928, f(k) = 2.54246
Q = 15.3391, I/Bmax = 0.953896, ne = 2.15832
V = 297.009, VTM = 411.085, Wt = 66796.1, Wp = 740.799
jTF = 19.8469, jOH = 20.495, st = 294.764, sp = 251.417
ndtez = 0.735098, niez = 0.845456, zeffz = 1.56002
nez = 2.15832, nz2 = 0.1,Zeff = 1.56002
nz3 = 0.00932115, nz4 = 0.001, nz5 = 0.0000375172
fbrz = 31.6508, cnx = 4.052, ctpe = 8.74743
prad = 0.172051, psy = 0.0710336, fbrzc = 31.6507
tauE = 0.904207, ß = 0.0336618, ßp = 1.23657
khtm = 25., khoh = 8.48528, ftt = 50000, fto = 50000
wh = 0.003, rho = 0.0003, ftm = 0.220521
fohm = 0.371458, Cvmtf = 1.88957, Cvmoh = 1.42031, Vmoh = 13686.
```

```
Vmtf = 126216., ITM = 85.7339, IOH = 42.8669, WOH = 9635.98
tTF = 0.66158, dOH = 0.640659, ROH = 1.91405, HOH = 10.9998
st = 294.764, sp = 251.417, jTF = 19.8469, jOH = 20.495
sst = 378.155, ssp = 400, jcTM = 90., jcOH = 55.1743
ssg = 800., sstc  = 421.845, ftf = 0.5, ftfc = 0.5
tb = 4782.67,tautm = 12.3457,tauoh = 32.8493
378.155
```

A comparison of the two cases as principal alternatives (the second extreme alternative being of some interest for assessing the possibility of reducing the outlay of intermediate steps on the way towards a tokamak power reactor) shows that omitting the blanket/shield zone shifts the optimum configuration from an aspect ratio of about 4 to a lower value of about 3. At the same time, keeping the input data, the plasma current increases somewhat, while the fusion power is only about 70% as compared with the first case. Since the major radius is reduced to about 53%, the volumes are much smaller and the magnetic energies are less than half of those in the first case. The capability for inductively driven burn is strongly reduced. The average winding current densities are larger and the average winding tensile stress values are lower than in the first case. The plasma fusion power density, the neutron wall loading, and the plasma density are much larger than in the first case. Q is about 15 as compared with 25, and the power for noninductive current drive is 149 MW as compared with 129 MW for the first case with the larger fusion power. While the first case is close to the density limit, the second case attains only about 80% of that limit. The bootstrap fraction is about 10% lower in the second case. Since both cases are very close to the respective optimum configuration, the results indicate the problem encountered when trying to establish low aspect ratio reactor configurations with a blanket/shield zone. It is only a deviation from the optimum configuration that renders it possible, but with the implication of much lower inductive burn time.
The following units are used throughout:
10^{20} m^{-3}, 10 keV, T, m, s, MW, MW/m^3, MW/m^2, MJ, MA, MA/m^2, MPa.
The parameters are denoted similarly or directly according to the formulary.

4. Evaluation and discussion

Using the above relations and programs large series of conceptual design points can be readily determined in order to obtain a rough overview of the accessible design space and the impact of the essential input assumptions. The composition of the given specific input parameters is of particular importance both from the point of view of their permitted combinations and from the point of view of the resulting reactor parameter sets.

It turns out that the consideration of certain levels of fusion power is particularly helpful for efficient orientation within the infinite number of possible conceptual design points. With all other input parameters fixed (see Input Parameter List) the definition of a certain band-width for the density limit C_n and the boundary q_ψ value leads to an insight into accessible fusion power levels with certain combinations of the remaining input assumptions. A bandwidth of $4 < C_n < 6$ and $3 < q_\psi < 5$ was chosen. The type of configuration (for example $f_A = 0.77$ for "slender", $f_A = 1.0$ for "optimum", $f_A = 1.3$ for "fat") can have a strong impact on the accessible fusion power, depending on the energy confinement scaling.

Assuming ITER 89P scaling, and for a given set of specific input parameters, one obtains band-like structures in the C_n, q_ψ-diagram, within which accessible reactor configurations are found. Generally these band-like domains are bounded by lines for fixed minimum and maximum f_A, which are of type C_n = const. q_ψ where the boundaries may be cut away in certain regions according to the conditions imposed on the series calculations ($A < 6$, $t_B > 500s$). Within the bands the parametric curves for P_f indicate the location in C_n, q_ψ-space. For individual input modifications the input variable with the largest impact is the plasma operating temperature, which tends to strongly reduce the accessible fusion power level within the C_n, q_ψ-bandwidth, or to shift a certain fusion power level towards large C_n. Next in importance of impact are the non-inductive current-drive efficiency γ_o and the elongation/triangularity combination which shift the fusion power level into the opposite direction. All other essential single input parameter modifications have by comparison a minor impact, as far as the attainable fusion power level is concerned (Figs. 1 through 4).

As soon as different combinations of input assumptions are considered, drastic changes can be generated. One example would be the transition from present "conventional" parameter compositions towards the anticipated future "advanced" ones which can simply be characterized by assuming a larger Troyon coefficient together with an enhanced energy confinement. In this case generally the attainable fusion power level within the C_n, q_ψ bounds decreases notably, as compared to the "conventional" case, and the accessible domain is shifted towards larger q_ψ values (Figs. 6 through 10).

Figures 5 and 10 show each the sensitivity to individual input parameter changes for a fixed fusion power level.

Assuming ITER 93HP scaling, however, changes the picture considerably. The band-like structures in the C_n, q_ψ- diagram become broader, their parametric f_A dependence reverses, and the parametric curves for P_f

are no longer confined in a narrow C_n, q_ψ domain, but rather extend over a considerable C_n, q_ψ range (Fig. 11).

Under all conditions the configuration has strong implications for the resulting individual reactor parameter sets and their selection. Hence it is interesting to show for a fixed fusion power the variation of the pertaining reactor parameter set for $0.77 < f_A < 1.3$ with a given set of input data. This is another way of looking at the results of evaluating the tokamak reactor design equations (Figs. 12 through 22). With ITER 89P scaling ($f_{H89P} = 1.8$ in order to correspond to the ELMy H-mode) and "conventional" input assumptions, a number of parameters of the reference case (input data see Input Parameter List) with a fusion power of 3000 MW is shown vs. f_A in Fig. 12. Figures 13 through 16 show the impact of individual input parameter modifications, namely a change of γ_o from 0.5 to about infinity, of B_{max} from 16.5 T to 13.5 T, of k/Δ = 1.85/0.35 to 1.6/0.30, and of T_{10} from 1.7 to 1.0.

One arrives at the following observations. With constant fusion power the neutron wall load, the fusion power density, and the plasma density have a maximum at about $f_A = 1$, whereas the energy confinement time and the toroidal magnet volume have a minimum. These features indicate the "optimum" configuration. Other parameters vary notably and monotonically. The plasma current and the TF coil average tensile stress component increase with increasing f_A, while the large plasma radius decreases. The inductive burn time decays strongly (by up to several orders of magnitude) as f_A is increased from 0.77 to 1.3. Q , poloidal beta, the toroidal field magnetic energy, the aspect ratio, the bootstrap fraction (not shown), and the field ratio B/B_{max} (not shown) all decrease with increasing f_A. The optimum configuration has typically an aspect ratio of about 4 or larger and a possible inductive burn time of several hours. Fictitious long-pulse reactors would require a burn time of several days and hence would be found at the lower end of the f_A range, where the toroidal field energy rises rapidly. The f_A range in the figures. is limited either by $A < 6$, by $t_B > 500$ s, or by the upper limit taken for f_A (see the dots indicating the active limitations).

Possible short-pulse next step reactor concepts found at the higher end of the f_A range require a large plasma current and plasma volume. They are close to zero burn time (taking into account the steep burn-time dependence on the configuration), the sensitivity of the attainable burn time to modifications in the bootstrap fraction scaling being rather large. In many respects they can neither model a steady-state power reactor with an optimum configuration nor a long-burn pulsed reactor which would have an even larger aspect ratio than the steady-state reactor.

A specific remark on ITER appears appropriate. In order to arrive at the present ITER parameters, the Troyon coefficient has to be reduced notably below the "conventional" assumption of $g = 0.03$, whereas f_{H89P} has

to be increased above 2, and the profile assumptions have to be modified such that the fusion reaction parameter becomes notably lower than for the profiles taken in this work (and previously for ITER).
The corresponding curves for "advanced" input assumptions with about the same q_ψ and C_n values are shown in Figs. 17 through 21. Compared to the "conventional" cases the attainable levels of Q and t_B generally are considerably higher here. The neutron wall load is about the same. With smaller dimensions the fusion power is lower also. The same holds for the plasma current. According to the larger f_{H89P} value the corresponding level of f_{H93HP} is higher as well.
The f_A range in the figures is again limited either by $A < 6$, by $t_B > 500$ s, or by the upper limit taken for f_A (the dots indicate the respective limitations).
With "conventional" input, but ITER 93HP scaling, and for an identical reactor parameter set at $f_A = 1$ as with ITER 89P scaling (keeping constant the corresponding 93HP enhancement factor over the entire f_A range) one observes a notably stronger configuration dependence with this alternative confinement scaling. It generally leads to a clock-wise or counter-clockwise tilt of the curves vs. f_A, thus shifting the above-mentioned maxima and minima towards lower aspect ratio. As an overall result one would, however, still tend retain about $f_A = 1$ since now the deterioration of, for instance, Q and of the non-inductive burn time with increasing f_A is much stronger than for ITER 89P scaling (Fig. 22).
In order to provide a wider overview of the implied parameter variations the attached Reactor Parameter List contains all calculated figures for the respective reference cases, namely for three power levels at three f_A values, each for the "conventional" and the "advanced" input data with ITER 89P scaling, as well as for "conventional" input data with ITER 93HP scaling.
A third element for evaluating and understanding the multidimensional tokamak reactor design relations is a collection of observations on mutual dependences of individual parameters, as given in the following statements.

- C_n tends to rise with q_ψ for increasing fusion power.
- Variation of B_{max} mainly impacts on reactor size for fixed fusion power.
- Non-inductive burn time increases with decreasing B_{max} for $f_A > 1$ for otherwise fixed input assumptions and fixed fusion power.
- With the same input assumptions and within certain C_n, q_ψ bounds lower plasma temperature leads to lower fusion power.
- With the same input assumptions and for the same fusion power the purely ignited reactor with inductive current drive has notably smaller dimensions and consequently larger fusion power density and

neutron wall load than a driven reactor with non-inductive current drive.

- Although a steady-state reactor does not require a long inductive burn time, the imposed condition of a short inductive burn time would unnecessarily lead to a low aspect ratio and hence to a large current-drive power even with a large current-drive efficiency.
- Pulsed reactor concepts operating mainly on the basis of inductive current drive require a large aspect ratio in order to achieve burn times of several days.
- In view of the two preceding points there is no incentive at all to design a next step tokamak facility with low aspect ratio which would be far off any configuration to be considered for a power reactor.
- The existing uncertainties in confinement extrapolation call for a reactor-relevant geometry of future tokamak development steps.
- For finite Q the pertaining non-inductive burn time is valid for a situation in which at this same Q no current drive is present.
- Because of the available very long inductive burn time of steady-state "optimum" reactor configurations these do not require the same high magnetic field level in the central solenoid as in the toroidal field system.
- The introduction of a larger Troyon coefficient and of a larger confinement enhancement factor ("advanced" assumptions) leads to a lower fusion power level for essentially the same C_n and q_ψ values, to a much lower plasma current, smaller plasma dimensions, about the same neutron wall load, a much larger Q value (mainly due to a very large bootstrap fraction) and a very long inductive burn time, as compared to a "conventional" case.
- For "advanced" input assumptions presently envisaged current drive efficiencies may suffice for arriving at very high Q-values in steady-state reactor concepts, provided a thermally stable operating point is possible with the bootstrap current fraction < 1 but close to 1. Note, however, that operating with I_B/I close to 1 renders the operating point very sensitive to minor parameter variations.
- The presently dominating energy confinement scalings differ remarkably. Hence in a series of reactor parameter sets vs. f_A for a constant ITER 89P enhancement factor the corresponding ITER 93HP enhancement factors increase notably with increasing f_A, and vice versa.
- ITER 89P scaling appears almost indifferent against configuration modifications, whereas ITER 93HP scaling introduces a rather strong sensitivity to configuration. The true role of the enhancement factors in both cases is not known. It seems that $f_{H89P} = 1.8$ could characterize ELMy H-mode operation with its value constant for a wide configuration range. The same is not obvious for constant f_{H93HP}.

- A range of $0.77 < f_A < 1.3$ essentially covers the possible relevant variations in torus geometry. Depending on the input assumptions and their composition, the accessible f_A-range may be modified according to imposed limitations in A, t_B, C_n, and q_ψ. The effective limitations are indicated by dots in Figs. 12 through 22.
- In order to be able to really design a fusion power reactor and to safely predict its performance all parametric dependences need to be known very accurately. Hence a development program is needed that aims at a high degree of orientation towards a power reactor.
- Unshielded reactor concepts constitute an extreme case more suited to comparing experimental devices for their reactor capability.
- It is interesting to note that the JET configuration ($t_{BS} = 0$) is close to $f_A = 1$, hence it is at the "optimum" for an unshielded experiment.

5. Conclusions

It has been shown that consistent tokamak reactor parameter sets can be readily evaluated on the basis of the formularies given. Particularly for shielded configurations it is possible to see the essential impact of the input data on the configuration and to understand in some detail the consequences of the energy confinement scaling applied. Previous approaches towards such a tokamak reactor formulary are given in some of the published reactor studies and in, for example, [1,3,4].

The approach described here is particularly well suited for a consistent impact evaluation according to changes made in the input data values and composition. Hence a comparison can readily be made for alternatives that may be under discussion.

The examples given show among others that a low aspect ratio next step tokamak reactor would be relevant neither for a steady-state power reactor nor for a long-pulse reactor. The latter, however, has been shown not to be competitive economically and practically[13].

The above material is restricted to a possible tokamak reactor unit itself, the results still depending on the database being developed as published on, for example, energy confinement scaling[14,15,16,17]. It does not extend to the conceptual power station, which would require consideration of the recycling power and overall efficiency. These matters have been treated elsewhere[2,4].

Finally, it has to be stated that this work and its findings are based primarily on a conventional approach to design tokamak reactors deriving from more or less well-known relations as seen in existing experiments. The ITER 89P energy confinement scaling is assumed as a basis, and the impact of taking ITER 93HP scaling instead is briefly shown. As described recently[18], there is some evidence, however, that a more attractive tokamak regime may become accessible that comprises negative shear, enhanced confinement time, enhanced Troyon coefficient, and a consistent bootstrap current distribution that complies with the pressure and q-profile. The pertinent experiments, however, could establish this regime only in transient operation so far, and it is not clear whether and how it could be attained in steady state at all. Thus, while the present state of the art would lead to the construction of a large and costly tokamak reactor with a relevant aspect ratio of about 4, it may turn out that the outlook to something more attractive may lead to a general decision to include the results of further basic research. While with the anticipated new assumptions the relevant aspect ratio would remain essentally the same, size and cost of a tokamak reactor could be strongly reduced. Further restrictions deriving from expected experimental results such as on divertor layout and confinement prediction remain to be included.

Acknowledgements
The author acknowledges discussions with his colleagues and particularly the help of Mrs. Claudia Alberter who performed numerous series calculations and provided the tables and figures.

References

[1] Uckan, N.A., Relative Merits of Size, Field, and Current on Ignited Tokamak Performance, Fusion Technology 14 (1988), 2, p. 299

[2] Knobloch, A.F., Steady-State Operation Requirements of Tokamak Fusion Reactors, IPP 4/246, June 1991

[3] Knobloch, A.F., Mit welchen Parametern könnte ein stationärer Tokamak-Fusionsreaktor realisiert werden? Vortrag IPP Garching, 21.5.1992

[4] Knobloch, A.F., Reaktoraspekte (Konfiguration, Wirkungsgrad etc.), Beitrag 11.8, Ringberg-Seminar Technologie-Heizung 20.-24.9.1993

[5] Knobloch, A.F., Contribution to an Optimum Tokamak Scaling, Proc. 7th Symposium on Engineering Problems of Fusion Research, Knoxville, October 25 - 28, 1977, 77CH1267-4-NPS, p. 250

Knobloch, A.F., Some Remarks on Technology Constrained Scaling of Conceptual Tokamak Reactors, Proc. IAEA Conference and Workshop on Fusion Reactor Design, Madison, October 10-21, 1977, STI/PUB/478, Vienna, p. 639

[6] Concept Study of the Steady-State Tokamak Reactor (SSTR), JAERI-M 91-08, 1991

[7] Rebut, P.H. et al., ITER Papers and Posters, 15th International Conference on Plasma Physics and Controlled Fusion, Seville, 1994

[8] Behrisch, R., Prozesky, V., Particle and Power Exhaust for a Fusion Plasma, Nuclear Fusion 30 (1990), 10, p.2166

[9] Johner, J., Fidone, I., A Conceptual Steady-State Tokamak Reactor with Passive Current Generation, DRFC-CAD, EUR-CEA-EC-1345, May 1988

Krajcik, R.A., The Effect of a Metallic Reflector upon Cyclotron Radiation, Nuclear Fusion 13 (1973),1 , p.7

Borrass, K., Assessment of the Impact of Cyclotron Emission on the Performance of Next-Genereation Tokamaks in the Presence of an Absorbing Wall, Fusion Technology 16 (1989), 2 , p.172

[10] Petrie, T.W., Plasma Density Limits in DIII-D, Nuclear Fusion 33 (1993), 6, p. 934

[11] Jaquinot, J., JET Relevance to ITER, New Trends and Initial Results, JET-P(94)65, 1994

[12] Mathematica® by Wolfram Research, Inc., Champaign, Illinois

[13] Conn, R.W., et al. Assessment of Fusion Power Plants Based on Pulsed Tokamak Operation: The Pulsar Study, 15th International Conference on Plasma Physics and Controlled Fusion, Seville, 1994

[14] Goldston, R.J., Energy Confinement in Tokamaks: Some Implications of Recent Experiments with Ohmic and Strong Auxiliary Heating, Plasma Physics and Controlled Fusion 26 (1984), 1A, p.87

[15] Yushmanov, P.N. et al., Scalings for Tokamak Energy Confinement, Nuclear Fusion 30 (1990), 10, p.1999

[16] Christiansen, J.P. et al., Global Energy Confinement H-mode Database for ITER, Nuclear Fusion 32 (1992), 2, p.291
[17] Thomsen, K. et al., ITER H mode Confinement Database Update, Nuclear Fusion 34 (1994), 1, p.131
[18] Goldston, R.J., Physics of Steady-State Advanced Tokamaks, Proc. APS Meeting Plasma Physics, Louisville, Kentucky, 6 - 10 November 1995

Input parameter list
for evaluations

Reference case ("conventional input")

$k = 1.85$
$\Delta = 0.35$
$f_{pw} = 0.85$
$t_{BS} = 1.25$ m
$g = 0.03$ T m MA^{-1}
$3 < q_\psi < 5$
$4x10^{20}$ T^{-1} m^{-2} $< C_n <$ $6x10^{20}$ T^{-1} m^{-2}
$\alpha_n = 0.5$
$\alpha_T = 1.0$
$\alpha_j = 1.5$
$T_{10} = 1.7x10$ keV
$\gamma_o = 0.5x10^{20}$ V^{-1} m^{-2}
$B_{max} = 16.5$ T
$B_{OH} = 16.5$ T
$f_{H89P} = 1.8$ (ITER 89P-scaling)
$\sigma_{sTFg} = 800$ MPa
$\sigma_{sOH} = 400$ MPa

Reference case ("advanced input")

see above list for "conventional input", with the following modifications
$g = 0.04$ T m MA^{-1}
$f_{H89P} = 2.6$ (ITER 89P-scaling)

Reference case ("conventional input"), ITER 93HP-scaling

see above list for "conventional input", with the following modifications
$f_{H93HP} = 0.655711$ (equivalent to $f_{H89P} = 1.8$ for $f_A = 1$, $P_f = 3000$ MW)

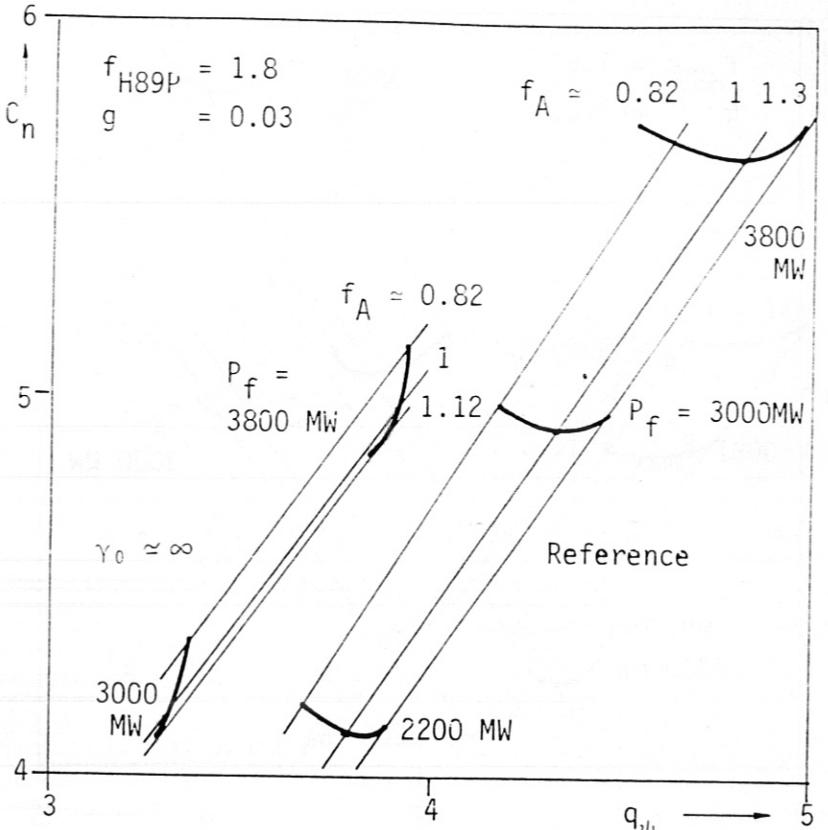

Fig. 1 Accessible parameters - "conventional" input
Reference, impact of a change in γ_0

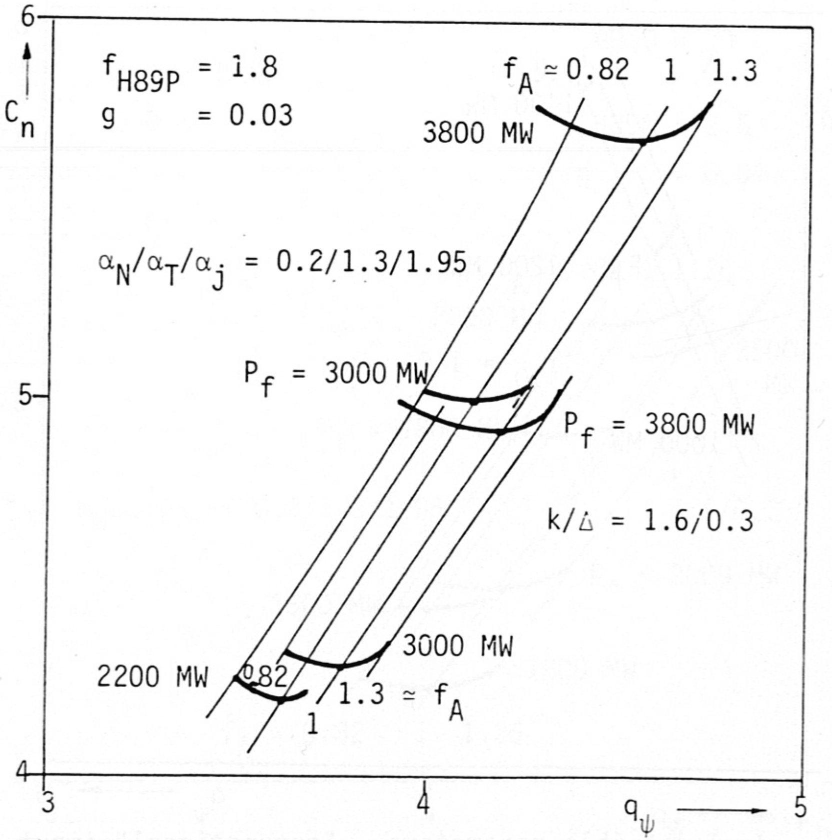

Fig. 2 Accessible parameters - "conventional" input
Impact of changes in k/Δ, $\alpha_N/\alpha_T/\alpha_j$

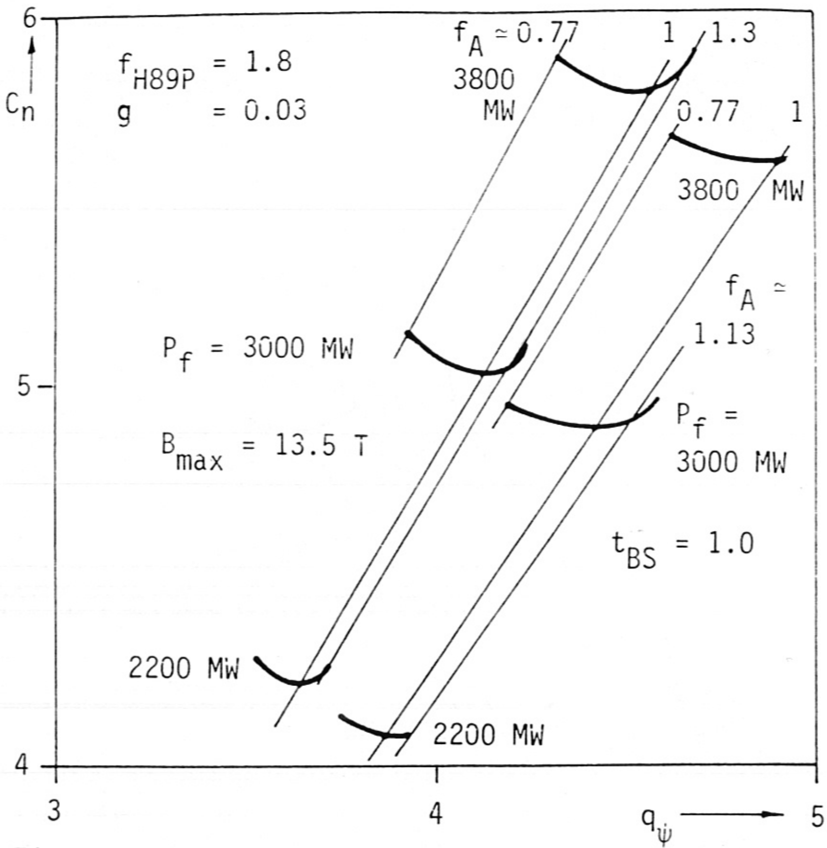

Fig. 3 Accessible parameters - "conventional" input
Impact of changes in B_{max}, t_{BS}

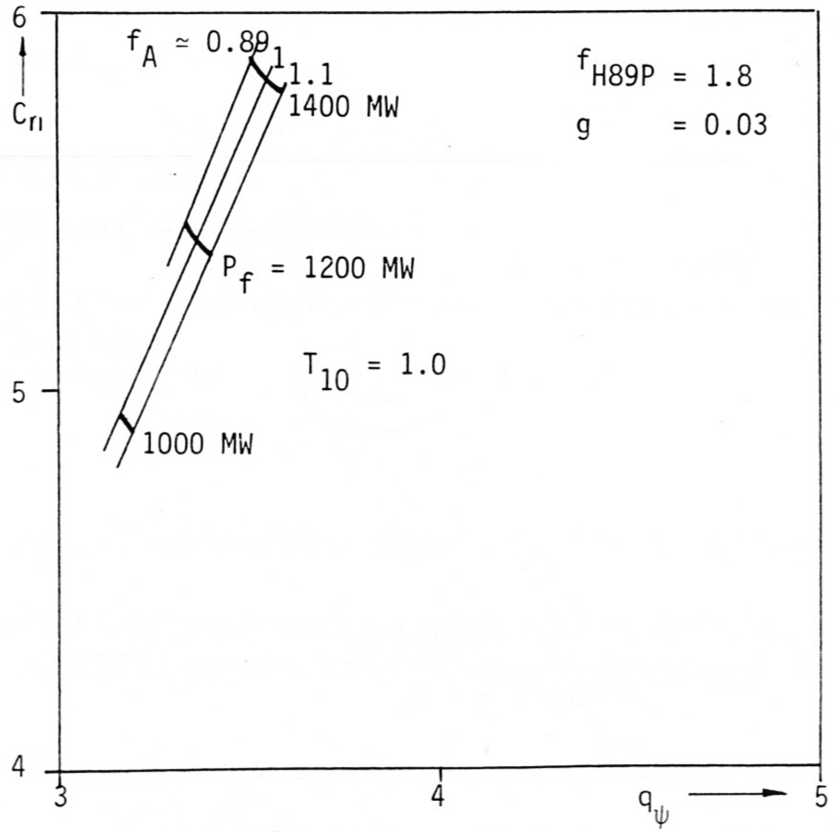

Fig. 4 Accessible parameters - "conventional" input
Impact of a change in T_{10}

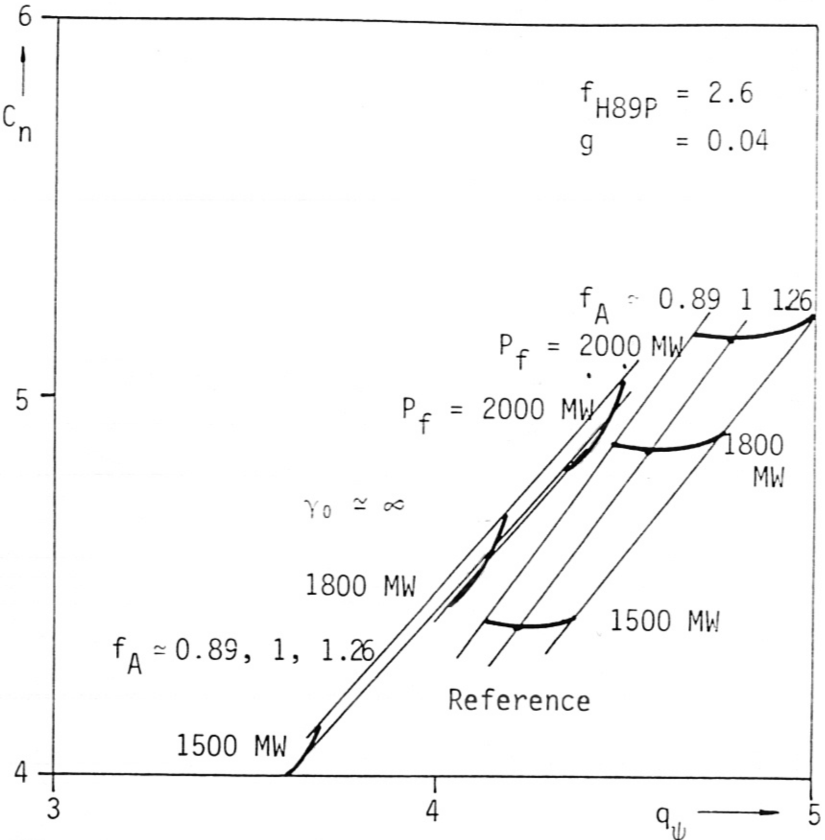

Fig. 6 Accessible parameters - "advanced" input
Reference, impact of a change in γ_0

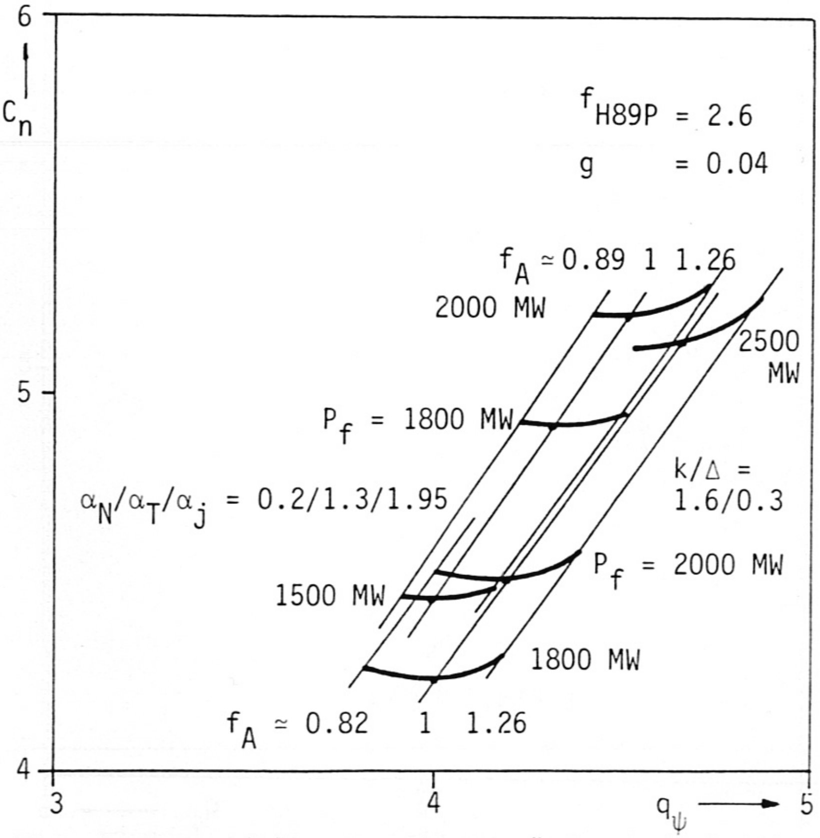

Fig. 7 Accessible parameters - "advanced" input
Impact of changes in k/Δ, $\alpha_N/\alpha_T/\alpha_j$

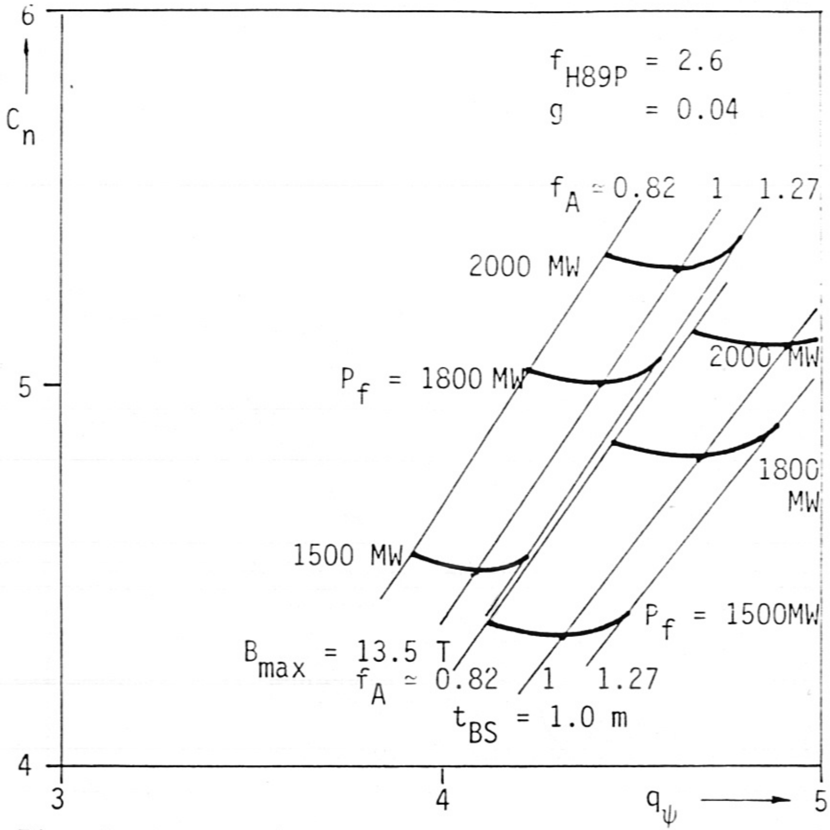

Fig. 8 Accessible parameters - "advanced" input
Impact of changes in B_{max}, t_{BS}

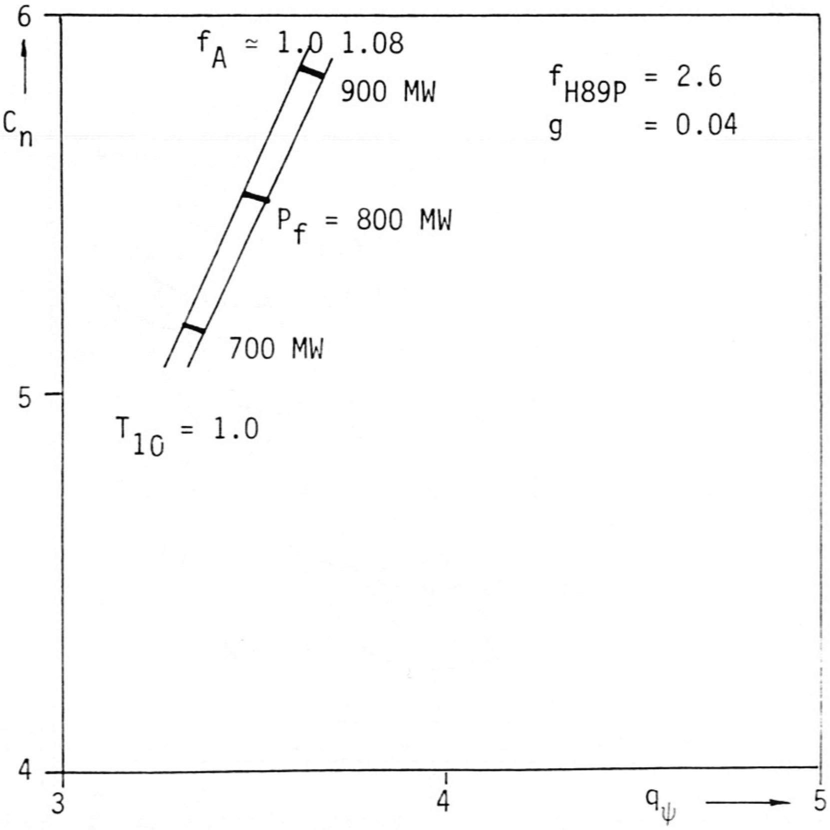

Fig. 9 Accessible parameters - "advanced" input
Impact of a change in T_{10}

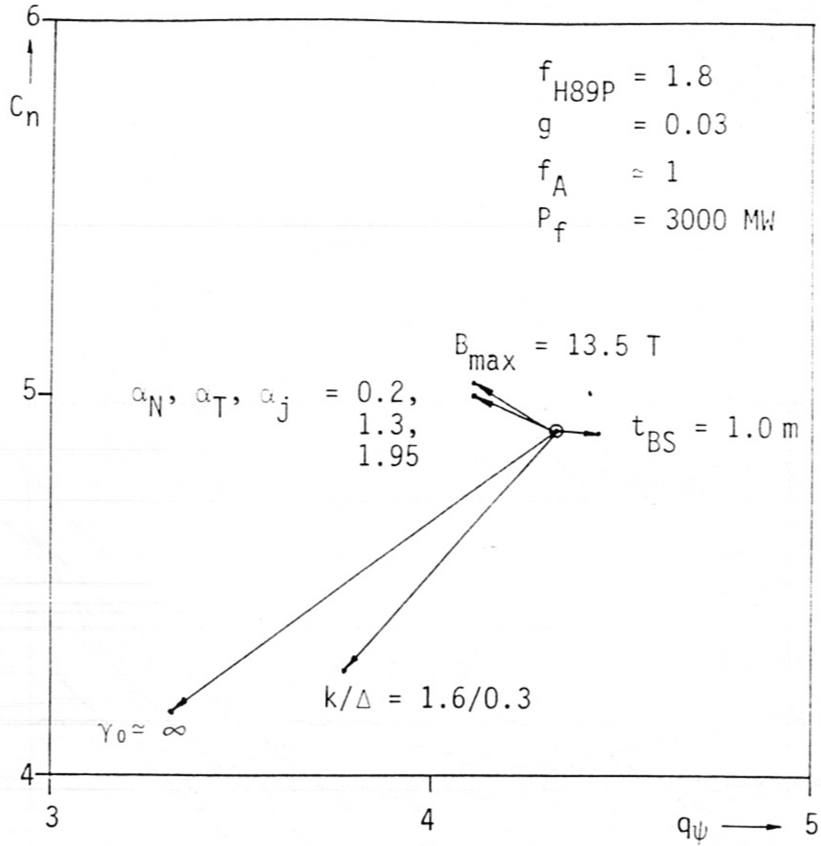

Fig. 5 Sensitivity of 3000 MW case - "conventional" input
Variations of γ_0, $\alpha_{N,T,j}$, k/Δ, B_{max}, t_{BS}

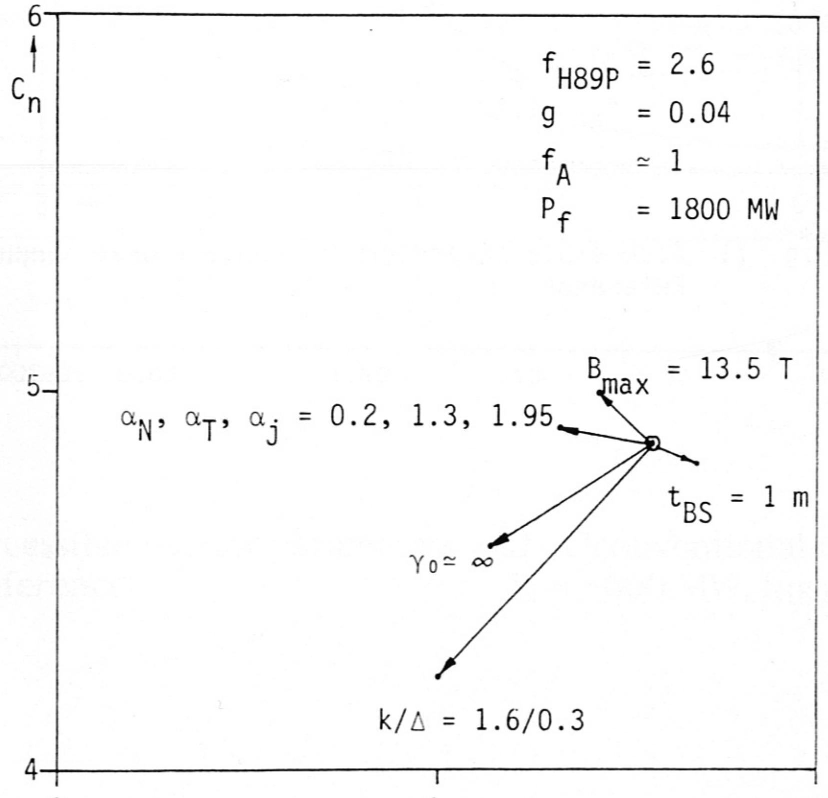

Fig. 10 Sensitivity of 1800 MW case - "advanced" input
Variations of γ_0, $\alpha_{N,T,j}$, k/Δ, B_{max}, t_{BS}

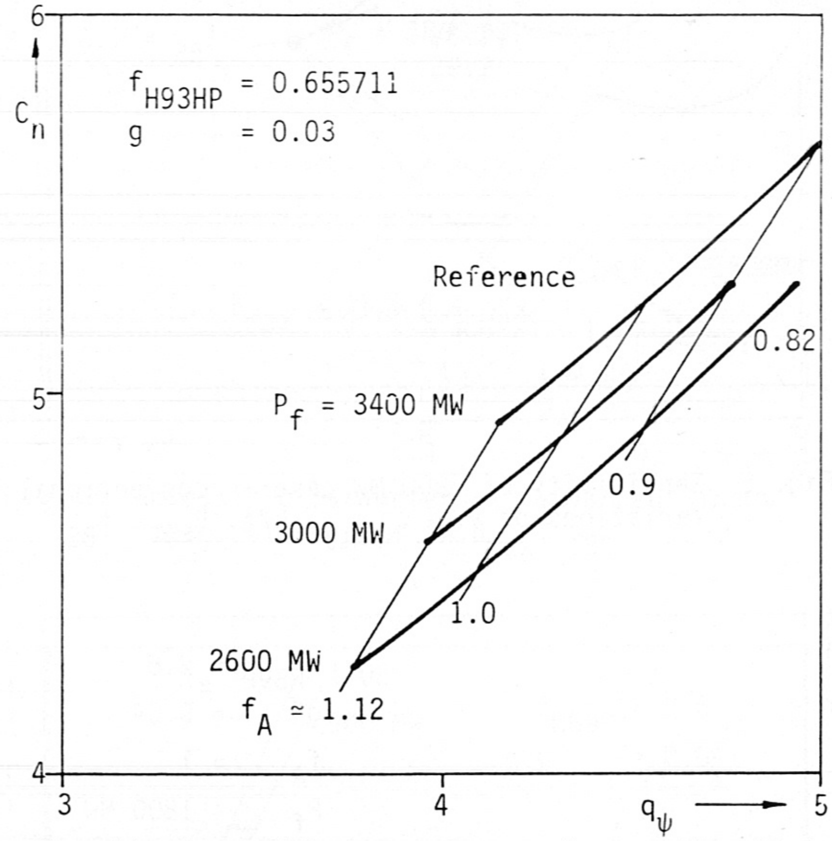

Fig. 11 Accessible parameters - "conventional" input
Reference

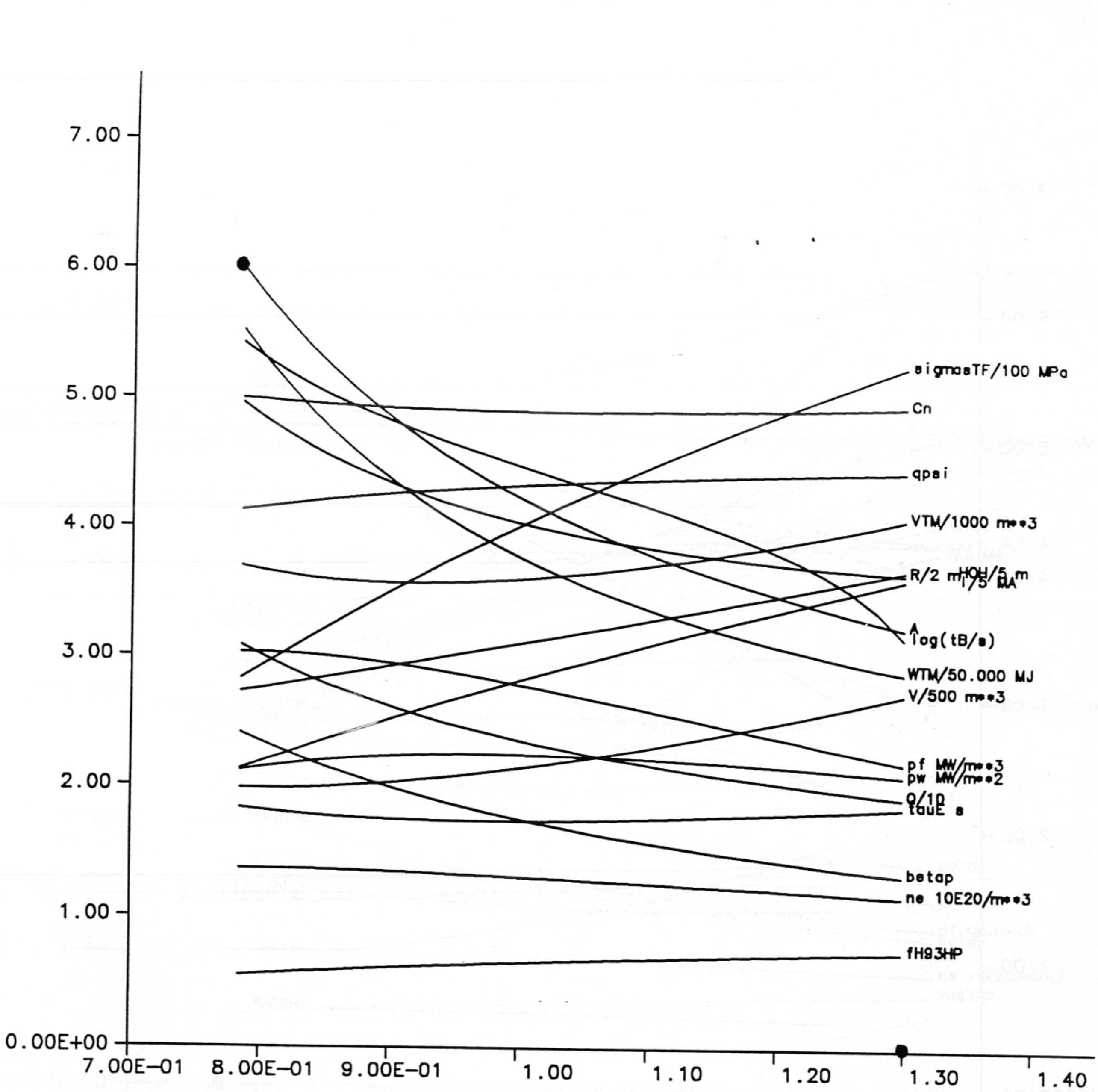

Fig.12 Accessible reactor parameters vs. f_A ("conventional input")
Reference P_f = 3000 MW, f_{H89P} = 1.8

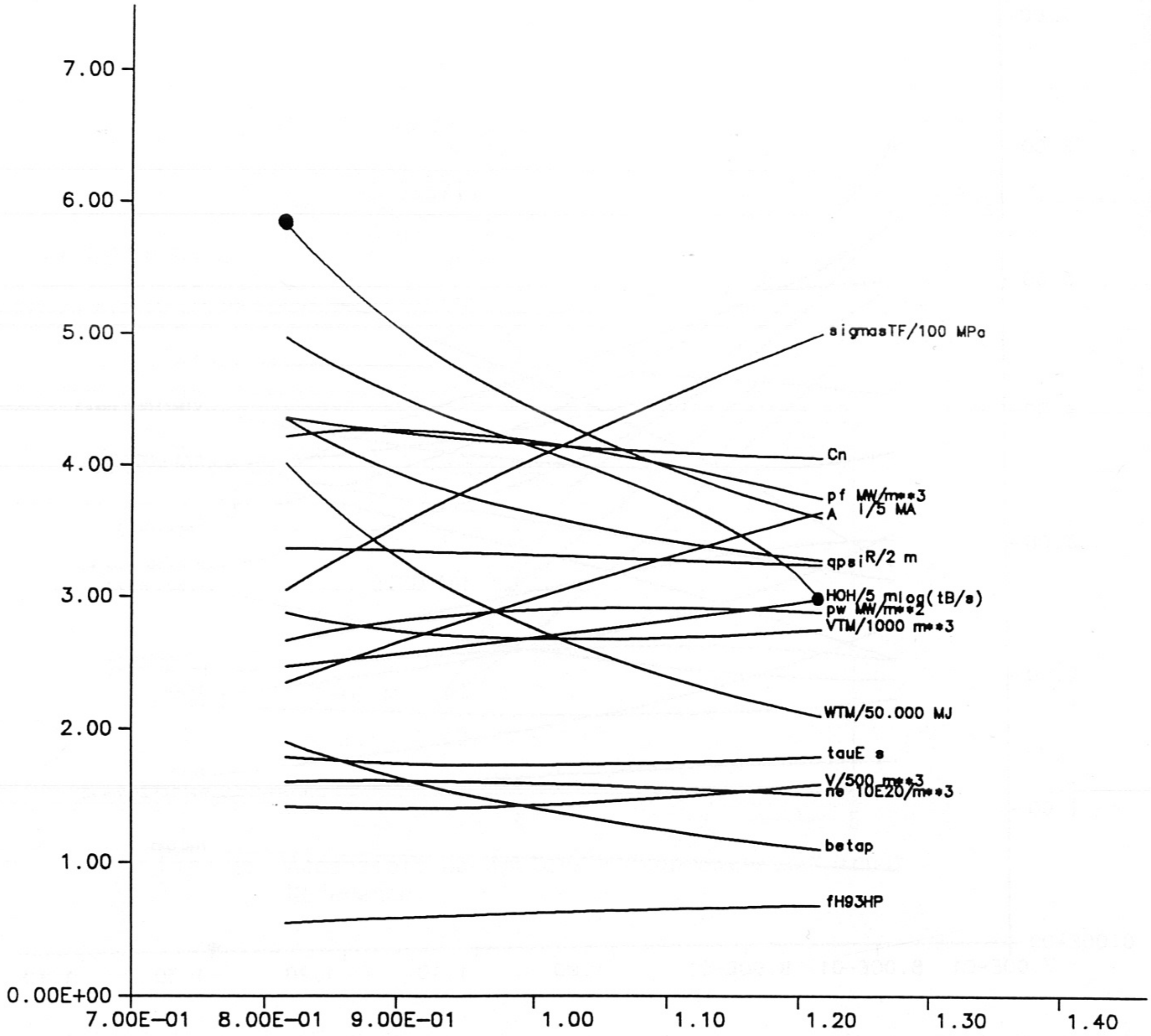

Fig.13 Accessible reactor parameters vs. f_A ("conventional input")
$\gamma_O \sim \infty$ $P_f = 3000$ MW, $f_{H89P} = 1.8$

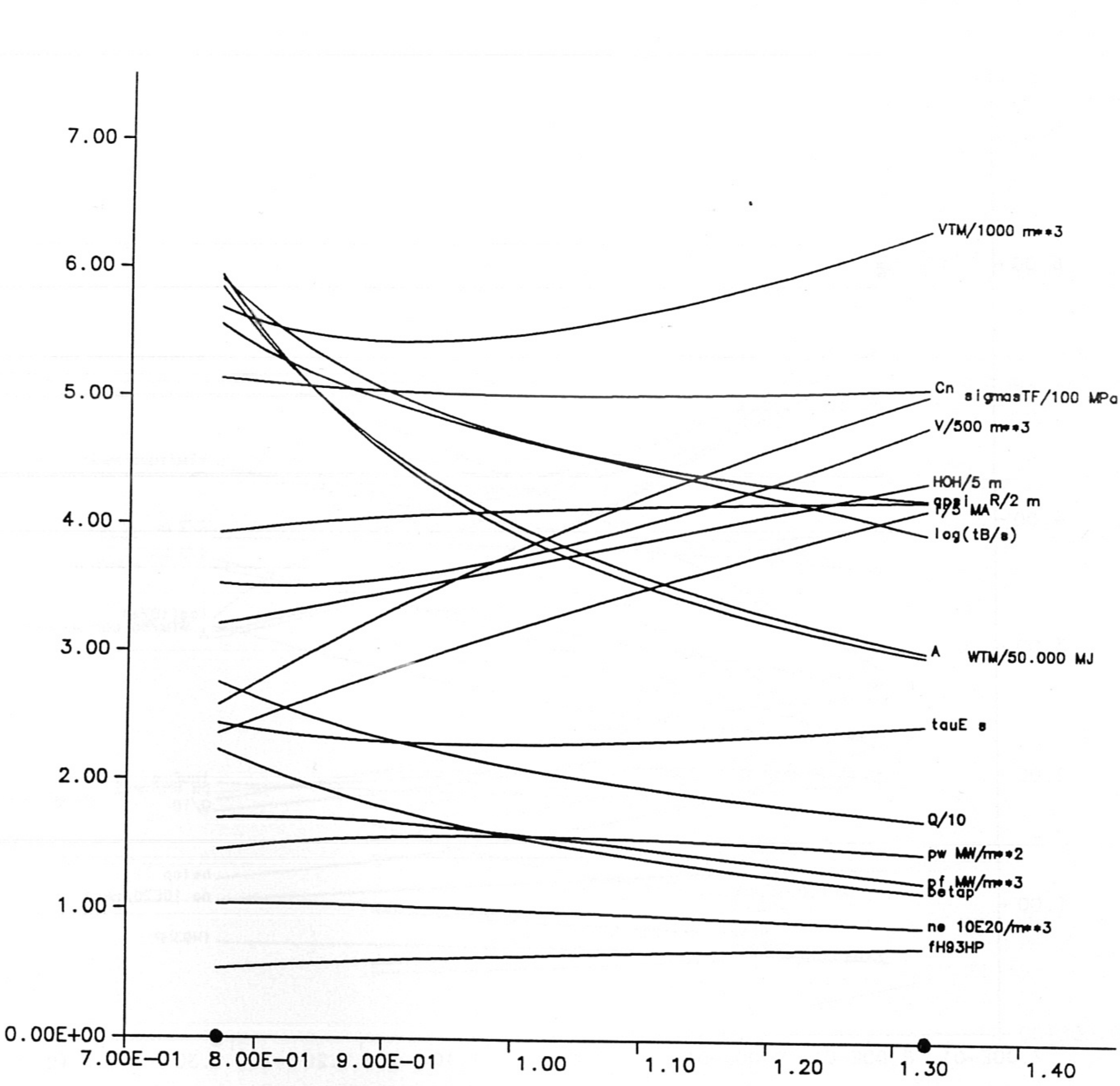

Fig.14 Accessible reactor parameters vs. f_A ("conventional input")
B_{max} = 13.5 T P_f = 3000 MW, f_{H89P} = 1.8

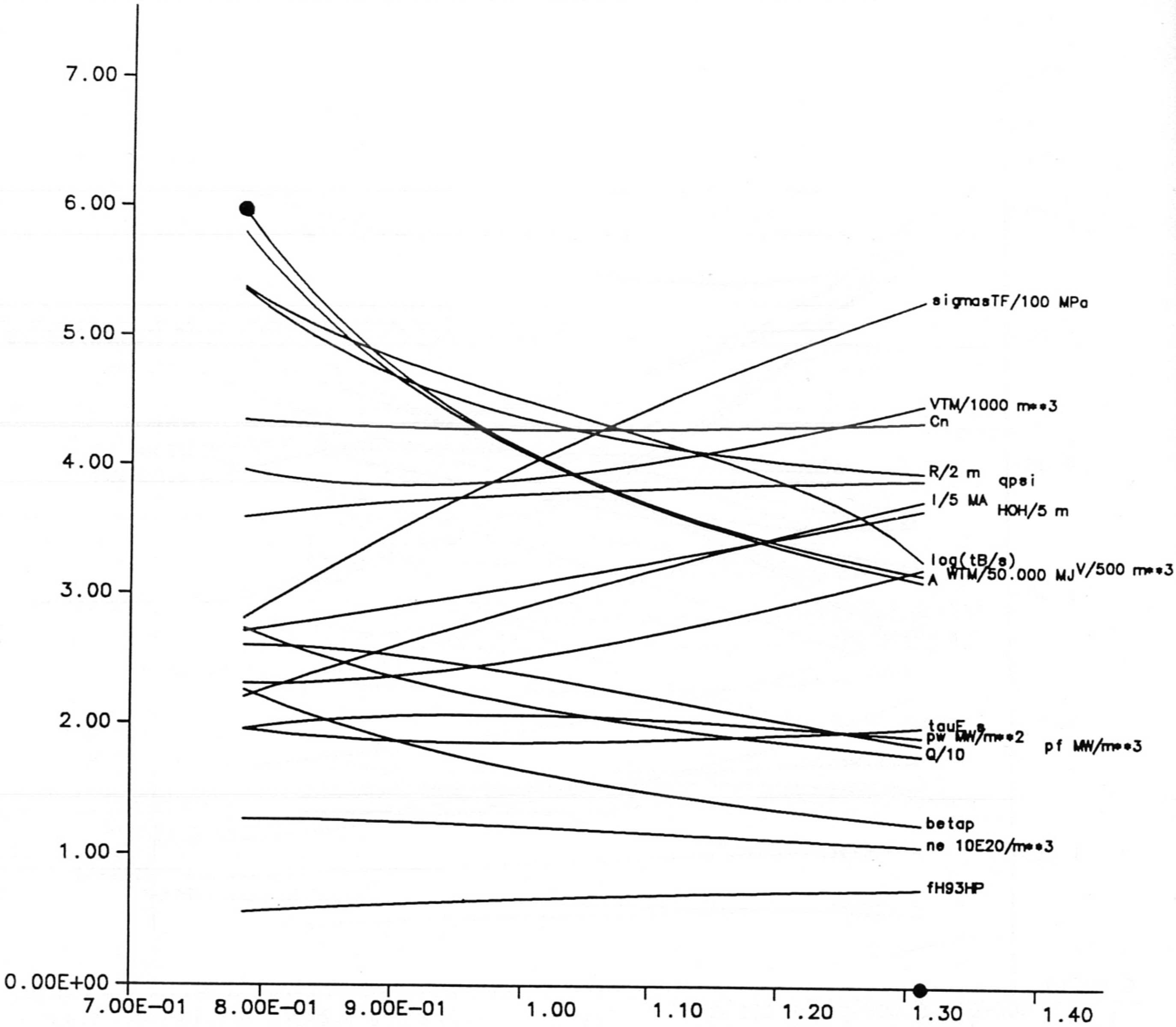

Fig.15 Accessible reactor parameters vs. f_A ("conventional input")
k/Δ = 1.60/0.30 P_f = 3000 MW, f_{H89P} = 1.8

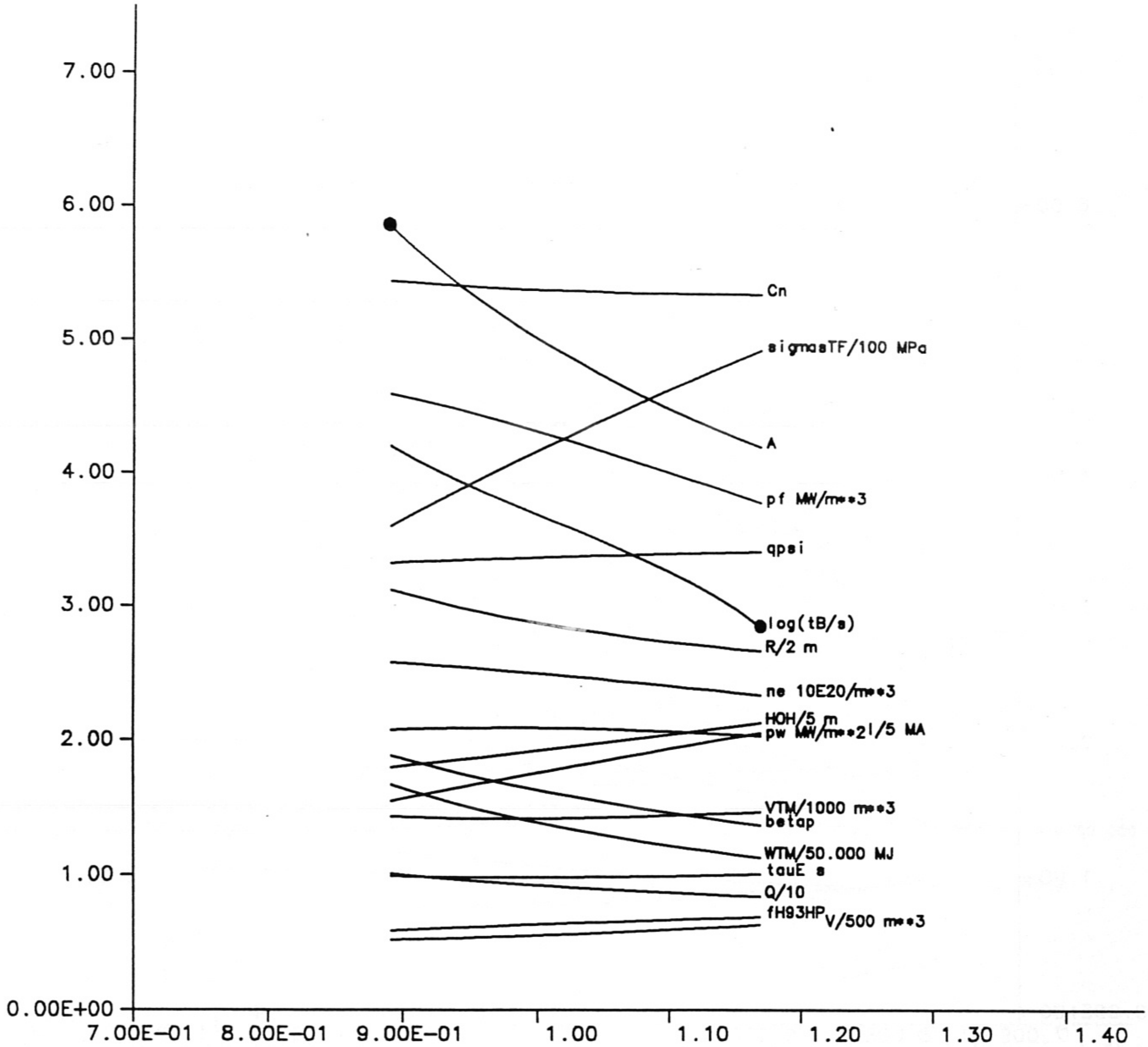

Fig.16 Accessible reactor parameters vs. f_A ("conventional input")
$T_{10} = 1.0$ $P_f = 1200$ MW, $f_{H89P} = 1.8$

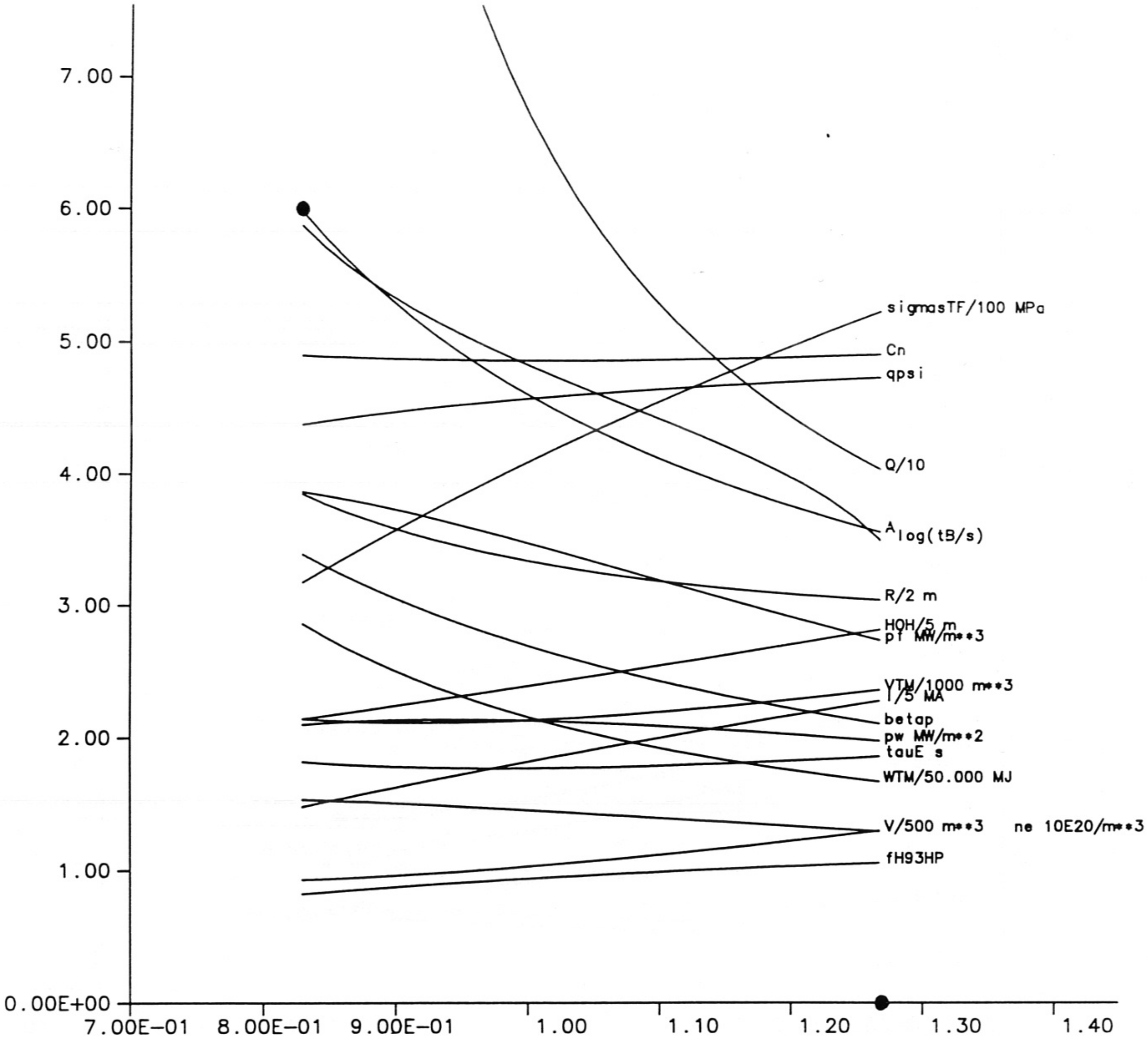

Fig.17 Accessible reactor parameters vs. f_A ("advanced input")
Reference $P_f = 1800$ MW, $f_{H89P} = 2.6$

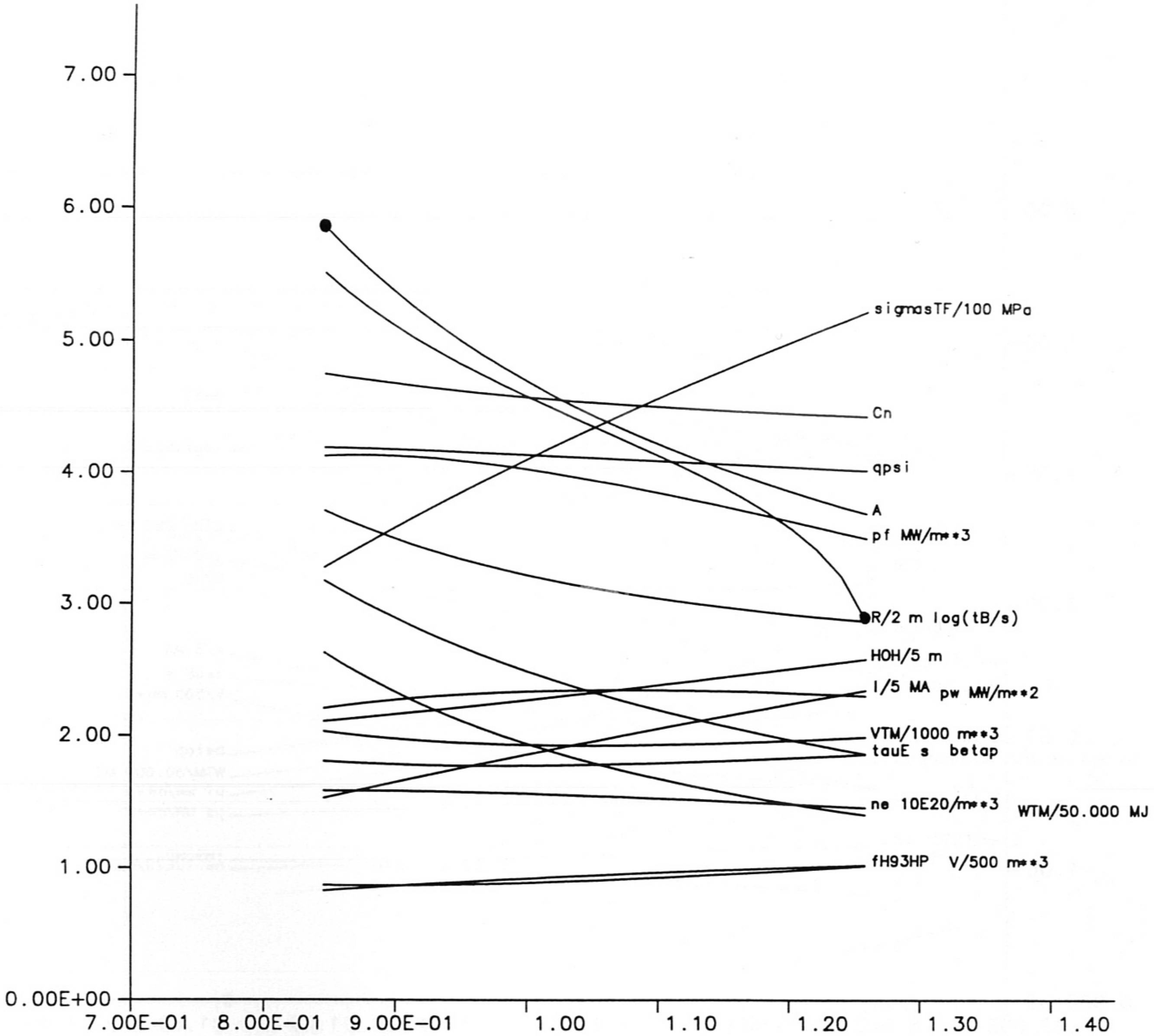

Fig.18 Accessible reactor parameters vs. f_A ("advanced input")
$\gamma_o \sim \infty$ $P_f = 1800$ MW, $f_{H89P} = 2.6$

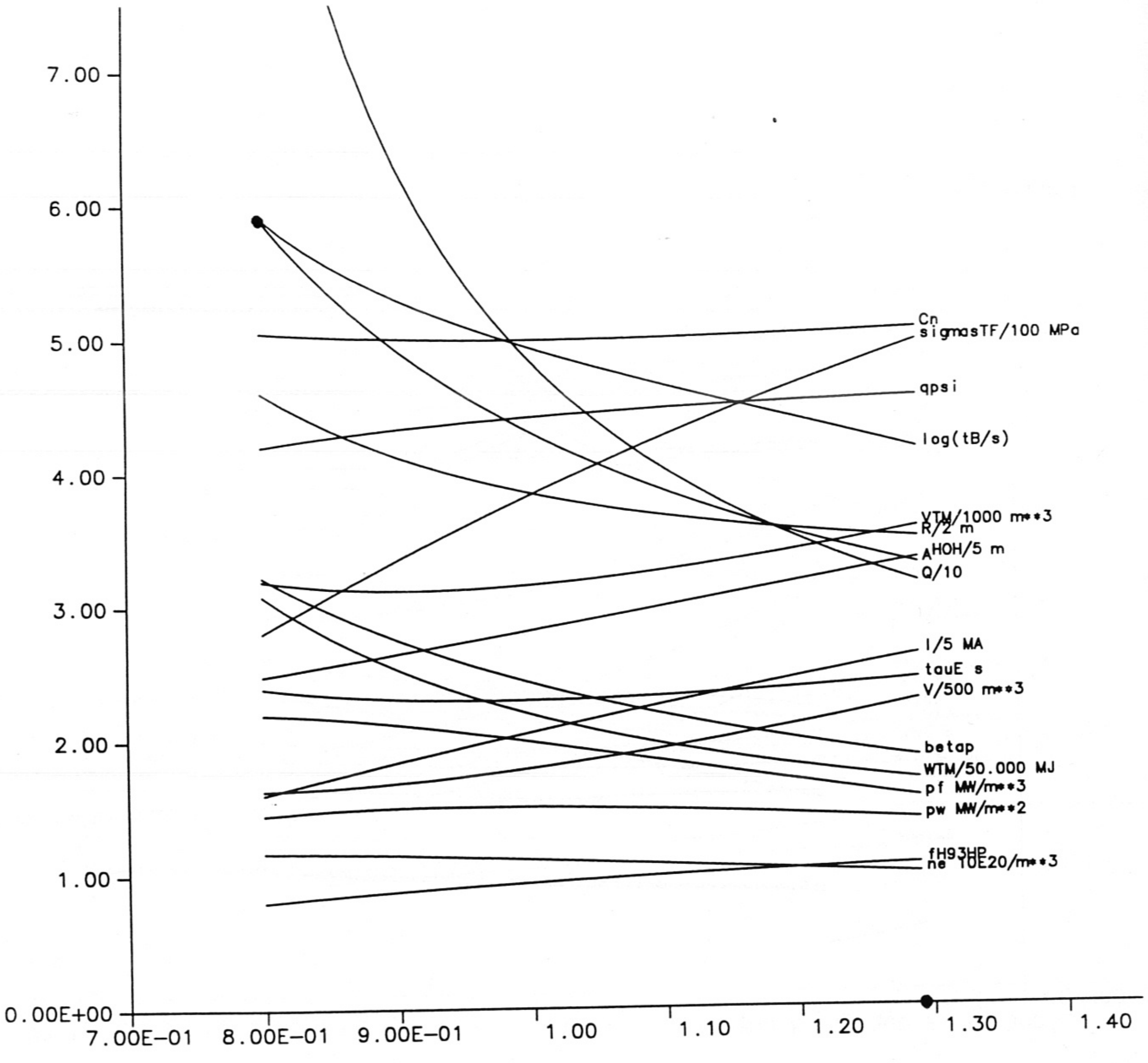

Fig.19 Accessible reactor parameters vs. f_A ("advanced input")
B_{max} = 13.5 T P_f = 1800 MW, f_{H89P} = 2.6

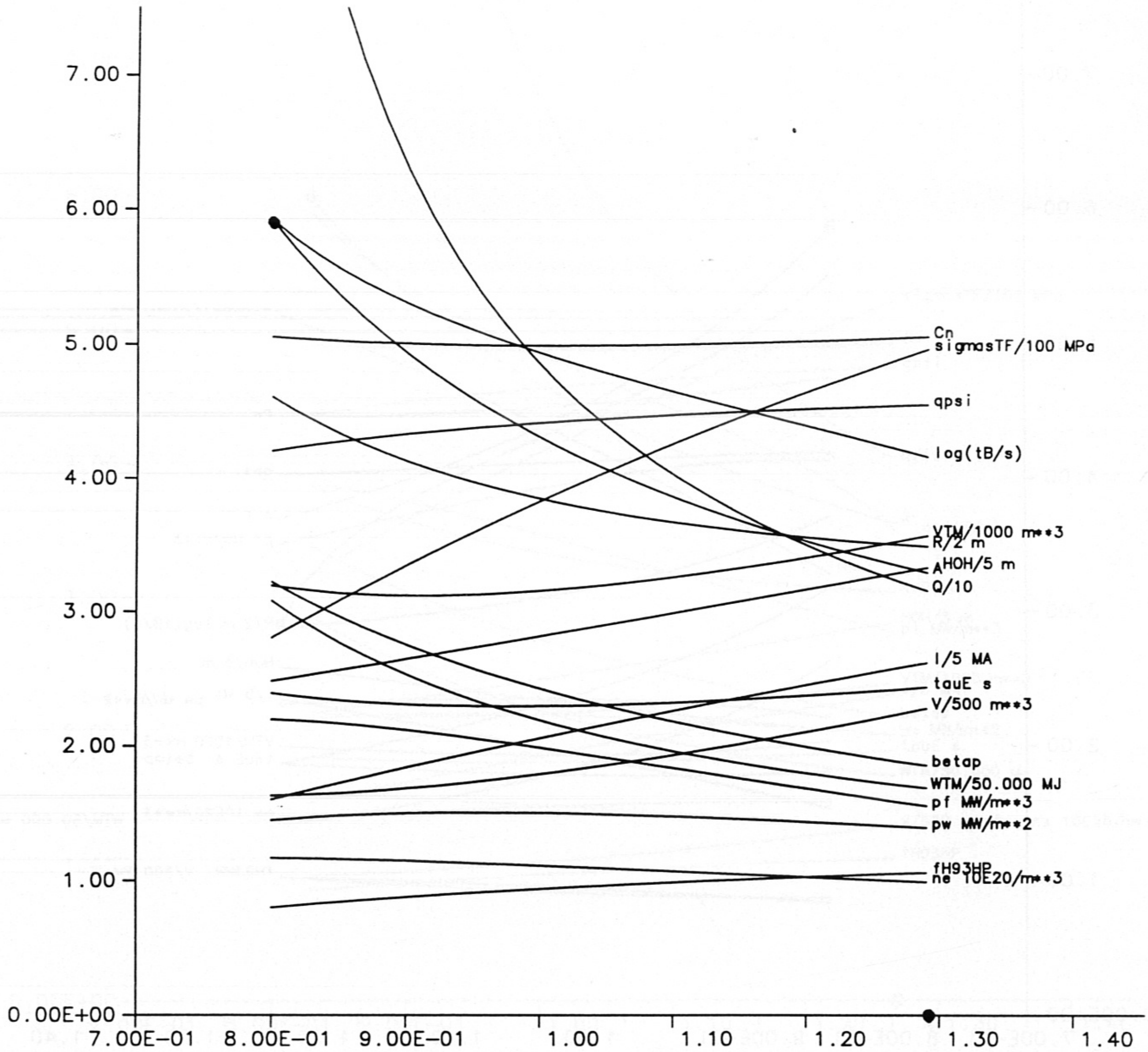

Fig.19 Accessible reactor parameters vs. f_A ("advanced input")
$B_{max} = 13.5$ T $P_f = 1800$ MW, $f_{H89P} = 2.6$

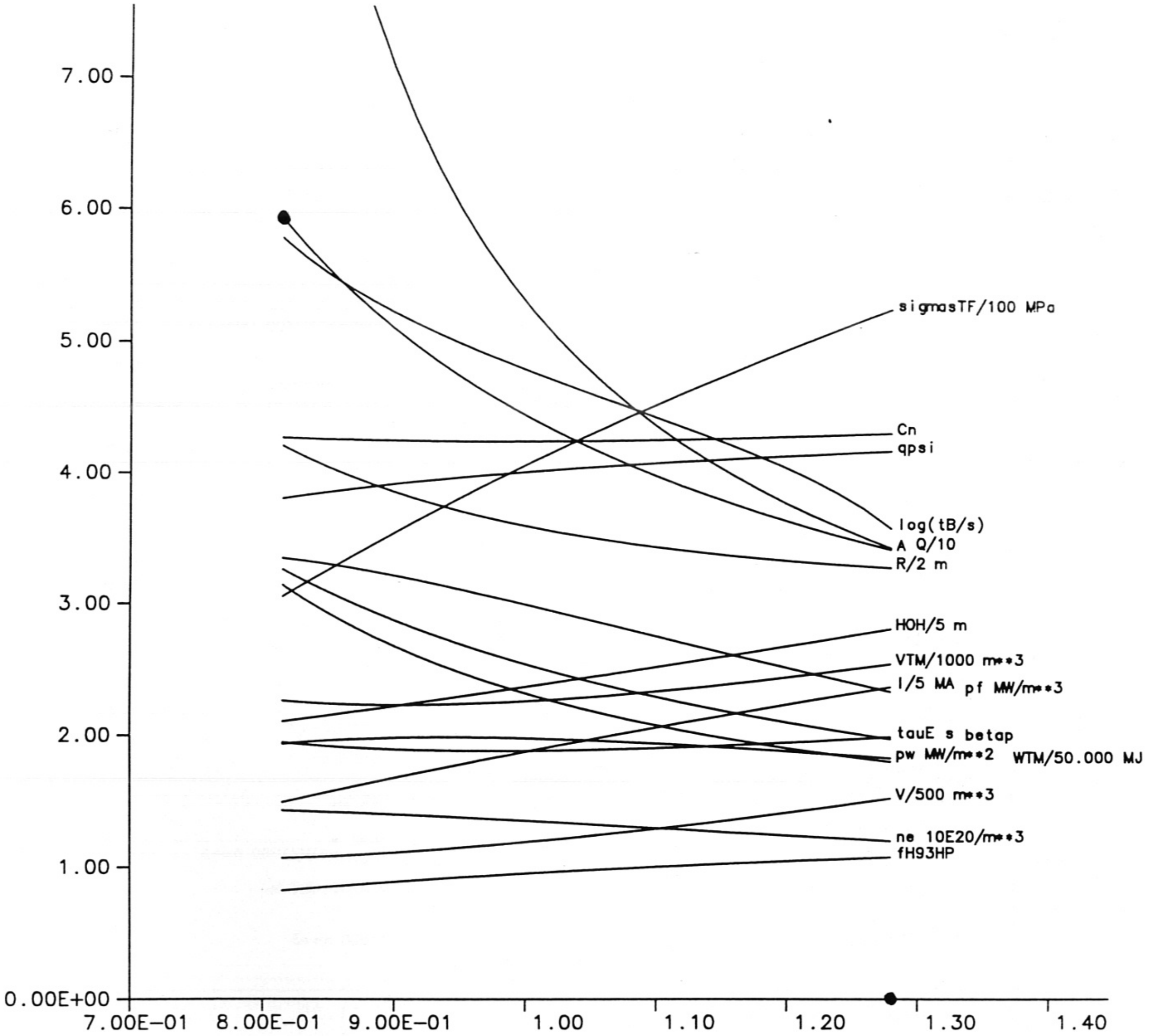

Fig.20 Accessible reactor parameters vs. f_A ("advanced input")
$k/\Delta = 1.60/0.30$ $P_f = 1800$ MW, $f_{H89P} = 2.6$

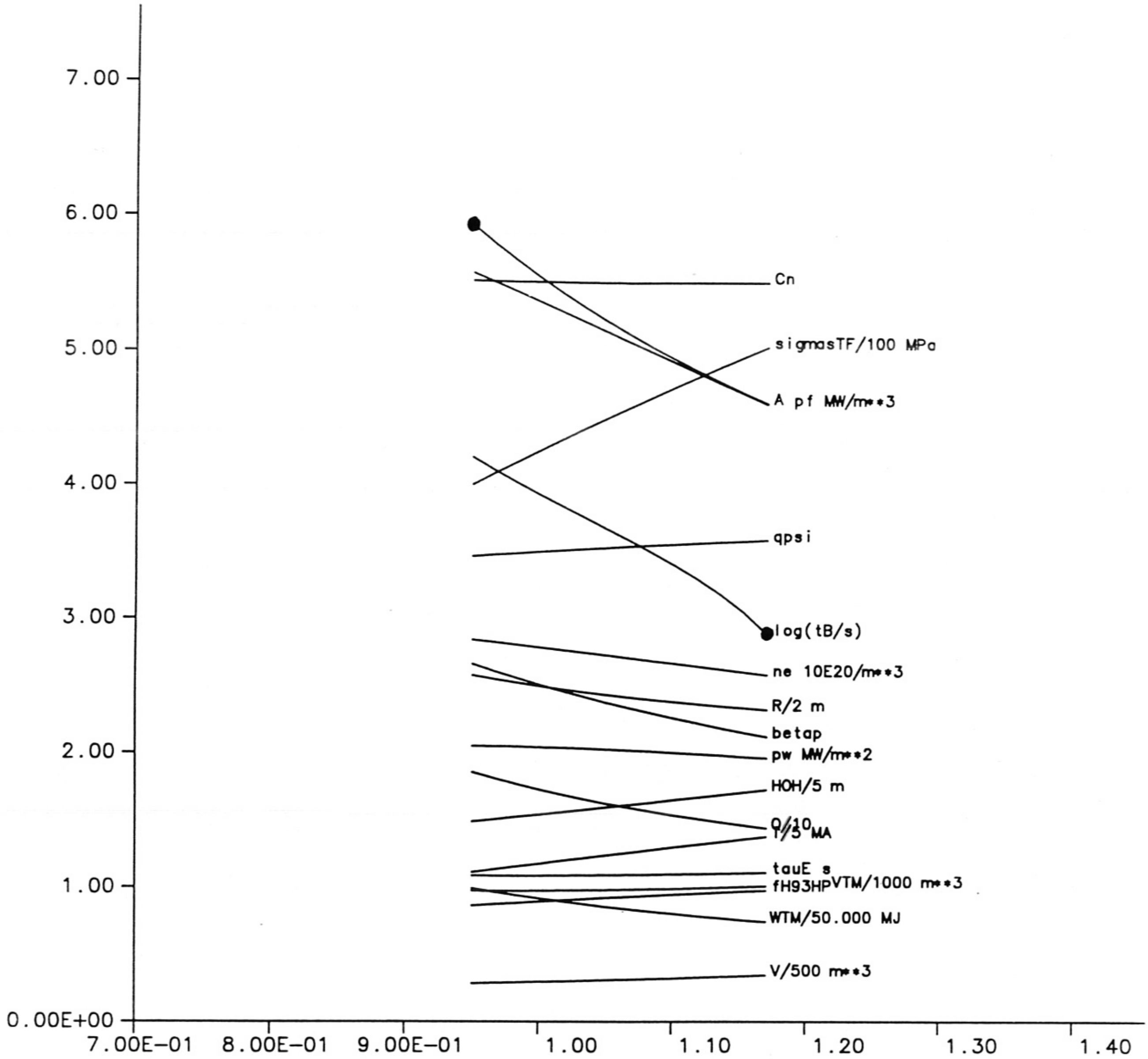

Fig.21 Accessible reactor parameters vs. f_A ("advanced input")
$T_{10} = 1.0$ $P_f = 800$ MW, $f_{H89P} = 2.6$

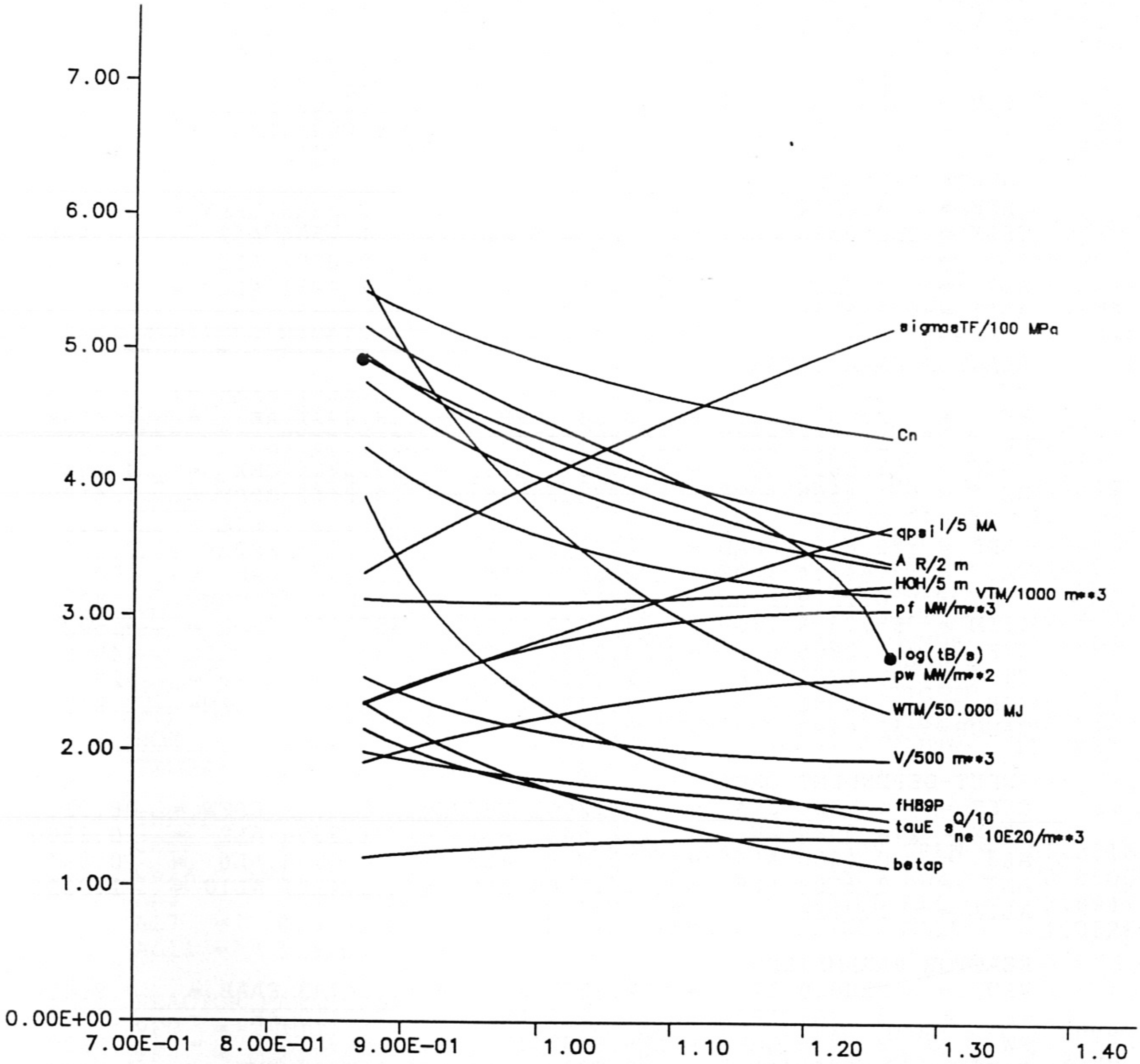

Fig.22 Accessible reactor parameters vs. f_A ("conventional input")
Reference P_f = 3000 MW, f_{H93HP} = 0.655711

Reactor Parameter List

```
"CONVENTIONAL" INPUT DATA
GTR   =    0.0300 T10    =    1.7000 BM     =  16.5000 BOH   =  16.5000
TBS   =    1.2500 FPW    =    0.8500 KK     =   1.8500 DEL   =   0.3500
FAAA = 0.000000 AN     =    0.5000 AT     =   1.0000 AI    =   1.5000
FH89P=    1.8000 CTAUE= 0.000660 CB     =   0.6746 GAMO =.5000E+00
ALPHI=    0.8500 ALPHR=    1.2000 ALPHA=   0.3000 ALPHN=   0.1000
ALPHB=    0.2000 ALPHK=    0.5000 ALPHP=   0.5000 NALP =   0.0000
RHO   =    0.0003 WH     =    0.0030 KHTM =  25.0000 KHOH =  8.48528
FTT   =    50000. FTO    =    50000. FTF    =   0.5000 FTFC =   0.5000
JCTM =   90.0000 JCOH =   55.1743 SIGSTG    800.00 SIGSP=   400.00
CI    =    1.0000 ZZ3    =    6.0000 ZZ4    =   8.0000 ZZ5   =  26.0000

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA    =     1.2660 CPFBX=    0.5329 CPFW =  86.3316
CSIX = 181.0380 FK     =     2.5425 AL1    =    1.2500 AL2   =   0.8500
AL3   =    0.4000 AL4    =     0.9500 AL5    =    0.0000 AL6   =   0.8947
AL7   =    0.3158 AL8    =     0.5789 AL9    =    1.4211 AL10 =   1.0526
AL11 =    1.3158

REACTOR PARAMETERS
PFU   =    2200.0 II     =   10.2512 A      =   5.8841 FAAB =   0.8173
PF    =    3.4302 IBI    =    0.5835 RR     =   8.4721 AK    =   1.4398
PW    =    2.0891 QGR   =.2096E+02 TB     =  112143. BK    =   2.6637
TAUE =    1.5615 QQ     =    3.2670 QPSI =   3.6705 CNX   =   4.1905
NE    =    1.4509 NDTE =    0.7302 NIE    =   0.8412 ZEFF =   1.6139
NZ3   =    0.0099 NZ4    =    0.0010 NZ5   =0.0000935 BETA =   0.0198
FBRZ =   22.6105 PRAD =    0.0845 PSY    =   0.0673 BETAP=   2.0982
VAU   =     641.4 VAUTM=    2681.3 WTM    =  185499. WPM   =   1003.6
FTM   =    0.1229 FOHM =    0.1987 CVMTF=   1.8896 CVMOH=   1.4203
IITM =   85.7339 IIOH =   42.8669 VMTF =  350513. VMOH =   81502.
JTF   =   11.0605 JOH    =   10.9656 SIGST=   350.39 SIGSTC    449.61
TTF   =    1.1871 DOH    =    1.1974 SIGT =   307.33 SIGP =   320.50
HOH   =   11.9381 ROH    =    4.3410 WOH    =  57383.5 TAUTM=  12.3457
TAUOH=   32.8493 FH93HP     0.5616

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA    =     1.2660 CPFBX=    0.5322 CPFW =  86.3316
CSIX = 174.9989 FK     =     2.5425 AL1    =    1.2500 AL2   =   0.8500
AL3   =    0.4000 AL4    =     0.9500 AL5    =    0.0000 AL6   =   0.8947
AL7   =    0.3158 AL8    =     0.5789 AL9    =    1.4211 AL10 =   1.0526
AL11 =    1.3158

REACTOR PARAMETERS
PFU   =    2200.0 II     =   12.8277 A      =   4.4743 FAAB =   0.9945
PF    =    3.1767 IBI    =    0.5199 RR     =   7.2410 AK    =   1.6183
PW    =    2.1746 QGR   =.1765E+02 TB     =   19195. BK    =   2.9939
TAUE =    1.5152 QQ     =    3.3382 QPSI =   3.7900 CNX   =   4.1187
NE    =    1.3977 NDTE =    0.7294 NIE    =   0.8405 ZEFF =   1.6221
NZ3   =    0.0100 NZ4    =    0.0010 NZ5   =0.0001019 BETA =   0.0255
FBRZ =   25.9015 PRAD =    0.0793 PSY    =   0.0433 BETAP=   1.6302
VAU   =     692.5 VAUTM=    2630.3 WTM    =  136160. WPM   =   1138.1
FTM   =    0.1201 FOHM =    0.2766 CVMTF=   1.8896 CVMOH=   1.4203
IITM =   85.7339 IIOH =   42.8669 VMTF =  257283. VMOH =   38692.
JTF   =   10.8054 JOH    =   15.2609 SIGST=   458.61 SIGSTC    341.39
TTF   =    1.2152 DOH    =    0.8604 SIGT =   403.55 SIGP =   289.36
HOH   =   13.2895 ROH    =    2.8719 WOH    =  27242.1 TAUTM=  12.3457
TAUOH=   32.8493 FH93HP     0.6457

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA    =     1.2660 CPFBX=    0.5297 CPFW =  86.3316
CSIX = 170.4104 FK     =     2.5425 AL1    =    1.2500 AL2   =   0.8500
AL3   =    0.4000 AL4    =     0.9500 AL5    =    0.0000 AL6   =   0.8947
AL7   =    0.3158 AL8    =     0.5789 AL9    =    1.4211 AL10 =   1.0526
AL11 =    1.3158
```

```
REACTOR PARAMETERS
PFU  =    2200.0 II   =   16.2451 A    =    3.4605 FAAB =    1.2687
PF   =    2.5578 IBI  =    0.4546 RR   =    6.5581 AK   =    1.8951
PW   =    2.0504 QGR  =.1504E+02  TB   =      616. BK   =    3.5060
TAUE =    1.5979 QQ   =    3.3193 QPSI =    3.8813 CNX  =    4.1363
NE   =    1.2587 NDTE =    0.7268 NIE  =    0.8382 ZEFF =    1.6495
NZ3  =    0.0103 NZ4  =    0.0010 NZ5   =0.0001297 BETA =    0.0332
FBRZ =   28.1642 PRAD =    0.0669 PSY  =    0.0240 BETAP=    1.2537
VAU  =     860.1 VAUTM=    2899.5 WTM  =   103818. WPM  =    1373.7
FTM  =    0.1003 FOHM =    0.4145 CVMTF=    1.8896 CVMOH=    1.4203
IITM =   85.7339 IIOH =   42.8669 VMTF =   196172. VMOH =    13685.
JTF  =    9.0285 JOH  =   22.8684 SIGST=    579.89 SIGSTC    220.11
TTF  =    1.4543 DOH  =    0.5742 SIGT =    521.71 SIGP =    234.21
HOH  =   15.5962 ROH  =    1.6242 WOH  =    9634.9 TAUTM=   12.3457
TAUOH=   32.8493 FH93HP    0.7281

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA  =       1.2660 CPFBX=    0.5317 CPFW =   86.3316
CSIX =  188.0638 FK   =       2.5425 AL1  =    1.2500 AL2  =    0.8500
AL3  =    0.4000 AL4  =       0.9500 AL5  =    0.0000 AL6  =    0.8947
AL7  =    0.3158 AL8  =       0.5789 AL9  =    1.4211 AL10 =    1.0526
AL11 =    1.3158

REACTOR PARAMETERS
PFU  =    3000.0 II   =   11.2833 A    =    5.5694 FAAB =    0.8201
PF   =    3.0243 IBI  =    0.6456 RR   =    9.4450 AK   =    1.6959
PW   =    2.1695 QGR  =.2910E+02  TB   =   154470. BK   =    3.1374
TAUE =    1.7926 QQ   =    3.7157 QPSI =    4.1788 CNX  =    4.9734
NE   =    1.3648 NDTE =    0.7289 NIE  =    0.8400 ZEFF =    1.6277
NZ3  =    0.0101 NZ4  =    0.0010 NZ5   =0.0001077 BETA =    0.0184
FBRZ =   22.0368 PRAD =    0.0762 PSY  =    0.0610 BETAP=    2.2587
VAU  =     992.0 VAUTM=    3632.2 WTM  =   254302. WPM  =    1314.0
FTM  =    0.1131 FOHM =    0.1792 CVMTF=    1.8896 CVMOH=    1.4203
IITM =   85.7339 IIOH =   42.8669 VMTF =   480522. VMOH =   122513.
JTF  =   10.1821 JOH  =    9.8873 SIGST=    343.35 SIGSTC    456.65
TTF  =    1.2896 DOH  =    1.3280 SIGT =    304.51 SIGP =    328.32
HOH  =   13.9436 ROH  =    4.9103 WOH  =   86258.4 TAUTM=   12.3457
TAUOH=   32.8493 FH93HP    0.5699

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA  =       1.2660 CPFBX=    0.5308 CPFW =   86.3316
CSIX =  181.7108 FK   =       2.5425 AL1  =    1.2500 AL2  =    0.8500
AL3  =    0.4000 AL4  =       0.9500 AL5  =    0.0000 AL6  =    0.8947
AL7  =    0.3158 AL8  =       0.5789 AL9  =    1.4211 AL10 =    1.0526
AL11 =    1.3158

REACTOR PARAMETERS
PFU  =    3000.0 II   =   14.1360 A    =    4.2291 FAAB =    1.0018
PF   =    2.7882 IBI  =    0.5754 RR   =    8.0772 AK   =    1.9099
PW   =    2.2525 QGR  =.2358E+02  TB   =    30076. BK   =    3.5334
TAUE =    1.7417 QQ   =    3.7999 QPSI =    4.3329 CNX  =    4.9080
NE   =    1.3121 NDTE =    0.7279 NIE  =    0.8392 ZEFF =    1.6377
NZ3  =    0.0102 NZ4  =    0.0010 NZ5   =0.0001179 BETA =    0.0237
FBRZ =   25.2162 PRAD =    0.0715 PSY  =    0.0391 BETAP=    1.7540
VAU  =    1076.0 VAUTM=    3607.0 WTM  =   188462. WPM  =    1484.5
FTM  =    0.1106 FOHM =    0.2506 CVMTF=    1.8896 CVMOH=    1.4203
IITM =   85.7339 IIOH =   42.8669 VMTF =   356111. VMOH =    58935.
JTF  =    9.9500 JOH  =   13.8277 SIGST=    452.77 SIGSTC    347.23
TTF  =    1.3196 DOH  =    0.9496 SIGT =    402.71 SIGP =    299.75
HOH  =   15.5600 ROH  =    3.2607 WOH  =   41494.8 TAUTM=   12.3457
TAUOH=   32.8493 FH93HP    0.6557

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA  =       1.2660 CPFBX=    0.5277 CPFW =   86.3316
CSIX =  177.0410 FK   =       2.5425 AL1  =    1.2500 AL2  =    0.8500
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AL3   =    0.4000 AL4   =     0.9500 AL5   =    0.0000 AL6   =    0.8947
AL7   =    0.3158 AL8   =     0.5789 AL9   =    1.4211 AL10  =    1.0526
AL11  =    1.3158

REACTOR PARAMETERS
PFU   =    3000.0 II    =   17.9584 A     =    3.2673 FAAB  =    1.2872
PF    =    2.2181 IBI   =    0.5019 RR    =    7.3396 AK    =    2.2464
PW    =    2.1077 QGR   =.1944E+02 TB    =     1899. BK    =    4.1558
TAUE  =    1.8488 QQ    =    3.7712 QPSI  =    4.4581 CNX   =    4.9638
NE    =    1.1755 NDTE  =    0.7247 NIE   =    0.8364 ZEFF  =    1.6714
NZ3   =    0.0106 NZ4   =    0.0010 NZ5   =0.0001518 BETA  =    0.0310
FBRZ  =   27.2613 PRAD  =    0.0601 PSY   =    0.0213 BETAP=    1.3448
VAU   =    1352.5 VAUTM=     4061.5 WTM   =   145545. WPM   =    1793.4
FTM   =    0.0917 FOHM  =    0.3793 CVMTF=     1.8896 CVMOH=    1.4203
IITM  =   85.7339 IIOH  =   42.8669 VMTF  =   275018. VMOH  =    21392.
JTF   =    8.2564 JOH   =   20.9263 SIGST=     577.20 SIGSTC     222.80
TTF   =    1.5903 DOH   =    0.6275 SIGT  =    524.25 SIGP  =    248.29
HOH   =   18.3423 ROH   =    1.8565 WOH   =   15061.5 TAUTM=   12.3457
TAUOH=    32.8493 FH93HP     0.7390

INPUT-DEPENDENT DATA
CSEF  =    4.2304 CFA   =     1.2660 CPFBX=     0.5305 CPFW  =   86.3316
CSIX  =  193.4434 FK    =     2.5425 AL1   =    1.2500 AL2   =    0.8500
AL3   =    0.4000 AL4   =     0.9500 AL5   =    0.0000 AL6   =    0.8947
AL7   =    0.3158 AL8   =     0.5789 AL9   =    1.4211 AL10  =    1.0526
AL11  =    1.3158

REACTOR PARAMETERS
PFU   =    3800.0 II    =   12.1115 A     =    5.3546 FAAB  =    0.8224
PF    =    2.7139 IBI   =    0.7001 RR    =   10.3207 AK    =    1.9275
PW    =    2.2127 QGR   =.3914E+02 TB    =   217005. BK    =    3.5658
TAUE  =    2.0001 QQ    =    4.1093 QPSI  =    4.6261 CNX   =    5.6854
NE    =    1.2951 NDTE  =    0.7276 NIE   =    0.8389 ZEFF  =    1.6413
NZ3   =    0.0102 NZ4   =    0.0010 NZ5   =0.0001214 BETA  =    0.0173
FBRZ  =   21.4860 PRAD  =    0.0700 PSY   =    0.0563 BETAP=    2.4016
VAU   =    1400.2 VAUTM=     4663.4 WTM   =   329245. WPM   =    1616.9
FTM   =    0.1055 FOHM  =    0.1647 CVMTF=     1.8896 CVMOH=    1.4203
IITM  =   85.7339 IIOH  =   42.8669 VMTF  =   622130. VMOH  =   169450.
JTF   =    9.4993 JOH   =    9.0860 SIGST=     338.31 SIGSTC     461.69
TTF   =    1.3822 DOH   =    1.4451 SIGT  =    302.60 SIGP  =    334.13
HOH   =   15.7575 ROH   =    5.4209 WOH   =  119305.4 TAUTM=   12.3457
TAUOH=    32.8493 FH93HP     0.5755

INPUT-DEPENDENT DATA
CSEF  =    4.2304 CFA   =     1.2660 CPFBX=     0.5294 CPFW  =   86.3316
CSIX  =  186.8350 FK    =     2.5425 AL1   =    1.2500 AL2   =    0.8500
AL3   =    0.4000 AL4   =     0.9500 AL5   =    0.0000 AL6   =    0.8947
AL7   =    0.3158 AL8   =     0.5789 AL9   =    1.4211 AL10  =    1.0526
AL11  =    1.3158

REACTOR PARAMETERS
PFU   =    3800.0 II    =   15.1901 A     =    4.0608 FAAB  =    1.0078
PF    =    2.4912 IBI   =    0.6241 RR    =    8.8314 AK    =    2.1748
PW    =    2.2917 QGR   =.3031E+02 TB    =    44395. BK    =    4.0234
TAUE  =    1.9456 QQ    =    4.2060 QPSI  =    4.8140 CNX   =    5.6303
NE    =    1.2428 NDTE  =    0.7264 NIE   =    0.8379 ZEFF  =    1.6533
NZ3   =    0.0103 NZ4   =    0.0010 NZ5   =0.0001335 BETA  =    0.0223
FBRZ  =   24.5588 PRAD  =    0.0655 PSY   =    0.0359 BETAP=    1.8642
VAU   =    1525.4 VAUTM=     4678.0 WTM   =   245877. WPM   =    1822.3
FTM   =    0.1031 FOHM  =    0.2312 CVMTF=     1.8896 CVMOH=    1.4203
IITM  =   85.7339 IIOH  =   42.8669 VMTF  =   464602. VMOH  =    82264.
JTF   =    9.2807 JOH   =   12.7570 SIGST=     448.74 SIGSTC     351.26
TTF   =    1.4148 DOH   =    1.0293 SIGT  =    402.46 SIGP  =    307.51
HOH   =   17.6230 ROH   =    3.6081 WOH   =   57919.7 TAUTM=   12.3457
TAUOH=    32.8493 FH93HP     0.6625
```

```
INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA   =      1.2660 CPFBX=    0.5257 CPFW =   86.3316
CSIX = 182.1412 FK    =      2.5425 AL1   =    1.2500 AL2  =    0.8500
AL3  =    0.4000 AL4   =      0.9500 AL5   =    0.0000 AL6  =    0.8947
AL7  =    0.3158 AL8   =      0.5789 AL9   =    1.4211 AL10 =    1.0526
AL11 =    1.3158

REACTOR PARAMETERS
PFU   =    3800.0 II    =  19.3532 A     =    3.1342 FAAB =    1.3025
PF    =    1.9619 IBI   =   0.5431 RR    =    8.0468 AK   =    2.5674
PW    =    2.1306 QGR   =.2408E+02 TB    =     3631. BK   =    4.7497
TAUE  =    2.0771 QQ    =   4.1664 QPSI  =    4.9713 CNX  =    5.7278
NE    =    1.1087 NDTE  =   0.7226 NIE   =    0.8346 ZEFF =    1.6933
NZ3   =    0.0108 NZ4   =   0.0010 NZ5   =0.0001736 BETA =    0.0292
FBRZ  =   26.4025 PRAD  =   0.0550 PSY   =    0.0193 BETAP=    1.4253
VAU   =    1936.9 VAUTM=    5358.8 WTM   =   191770. WPM  =    2204.7
FTM   =    0.0850 FOHM  =   0.3530 CVMTF=     1.8896 CVMOH=    1.4203
IITM  =   85.7339 IIOH  =  42.8669 VMTF  =   362363. VMOH =    30303.
JTF   =    7.6502 JOH   =  19.4772 SIGST=     575.77 SIGSTC     224.23
TTF   =    1.7163 DOH   =   0.6741 SIGT  =    526.83 SIGP =    258.79
HOH   =   20.8541 ROH   =   2.0600 WOH   =   21335.4 TAUTM=   12.3457
TAUOH=    32.8493 FH93HP     0.7465
```

```
"ADVANCED" INPUT DATA
GTR   =    0.0400 T10   =    1.7000 BM    =   16.5000 BOH   =   16.5000
TBS   =    1.2500 FPW   =    0.8500 KK    =    1.8500 DEL   =    0.3500
FAAA  = 0.000000 AN    =    0.5000 AT    =    1.0000 AI    =    1.5000
FH89P=    2.6000 CTAUE= 0.000660 CB    =    0.6746 GAMO  =.5000E+00
ALPHI=    0.8500 ALPHR=    1.2000 ALPHA=    0.3000 ALPHN=    0.1000
ALPHB=    0.2000 ALPHK=    0.5000 ALPHP=    0.5000 NALP  =    0.0000
RHO   =    0.0003 WH    =    0.0030 KHTM  =   25.0000 KHOH  =   8.48528
FTT   =    50000. FTO   =    50000. FTF   =    0.5000 FTFC  =    0.5000
JCTM  =   90.0000 JCOH  =   55.1743 SIGSTG    800.00 SIGSP=    400.00
CI    =    1.0000 ZZ3   =    6.0000 ZZ4   =    8.0000 ZZ5   =   26.0000

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA   =      1.2660 CPFBX=     0.9498 CPFW =   86.3316
CSIX = 188.5703 FK    =      2.5425 AL1   =     1.2500 AL2   =    0.8500
AL3  =    0.4000 AL4   =      0.9500 AL5   =     0.0000 AL6   =    0.8947
AL7  =    0.3158 AL8   =      0.5789 AL9   =     1.4211 AL10  =    1.0526
AL11 =    1.3158

REACTOR PARAMETERS
PFU   =    1500.0 II    =    7.6125 A     =    5.5725 FAAB  =    0.8887
PF    =    4.0169 IBI   =    0.8497 RR    =    6.8223 AK    =    1.2243
PW    =    2.0802 QGR   =.6131E+02 TB    =   143731. BK    =    2.2649
TAUE  =    1.6601 QQ    =    3.6664 QPSI  =    4.1234 CNX   =    4.4114
NE    =    1.5671 NDTE  =    0.7315 NIE   =    0.8424 ZEFF  =    1.5991
NZ3   =    0.0097 NZ4   =    0.0010 NZ5   =0.0000783 BETA  =    0.0249
FBRZ  =   25.2146 PRAD  =    0.0964 PSY   =    0.0629 BETAP=    2.9733
VAU   =     373.4 VAUTM=    1803.2 WTM   =   107479. WPM   =     432.2
FTM   =    0.1358 FOHM  =    0.2635 CVMTF=    1.8896 CVMOH=    1.4203
IITM  =   85.7339 IIOH  =   42.8669 VMTF  =   203089. VMOH  =    33892.
JTF   =   12.2219 JOH   =   14.5407 SIGST=    410.44 SIGSTC    389.56
TTF   =    1.0743 DOH   =    0.9030 SIGT  =    354.70 SIGP  =    294.58
HOH   =   10.2212 ROH   =    3.0577 WOH   =   23862.2 TAUTM=   12.3457
TAUOH=   32.8493 FH93HP     0.8618

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA   =      1.2660 CPFBX=     0.9489 CPFW =   86.3316
CSIX = 184.8566 FK    =      2.5425 AL1   =     1.2500 AL2   =    0.8500
AL3  =    0.4000 AL4   =      0.9500 AL5   =     0.0000 AL6   =    0.8947
AL7  =    0.3158 AL8   =      0.5789 AL9   =     1.4211 AL10  =    1.0526
AL11 =    1.3158

REACTOR PARAMETERS
PFU   =    1500.0 II    =    8.5326 A     =    4.8439 FAAB  =    0.9859
PF    =    3.7621 IBI   =    0.8056 RR    =    6.3511 AK    =    1.3112
PW    =    2.0865 QGR   =.4690E+02 TB    =    47608. BK    =    2.4256
TAUE  =    1.6477 QQ    =    3.7283 QPSI  =    4.2133 CNX   =    4.3929
NE    =    1.5177 NDTE  =    0.7310 NIE   =    0.8419 ZEFF  =    1.6049
NZ3   =    0.0098 NZ4   =    0.0010 NZ5   =0.0000843 BETA  =    0.0282
FBRZ  =   26.7859 PRAD  =    0.0912 PSY   =    0.0492 BETAP=    2.6282
VAU   =     398.7 VAUTM=    1808.6 WTM   =    92261. WPM   =     464.7
FTM   =    0.1320 FOHM  =    0.3114 CVMTF=    1.8896 CVMOH=    1.4203
IITM  =   85.7339 IIOH  =   42.8669 VMTF  =   174333. VMOH  =    22844.
JTF   =   11.8760 JOH   =   17.1800 SIGST=    467.10 SIGSTC    332.90
TTF   =    1.1056 DOH   =    0.7643 SIGT  =    405.47 SIGP  =    275.45
HOH   =   10.8978 ROH   =    2.4529 WOH   =   16084.0 TAUTM=   12.3457
TAUOH=   32.8493 FH93HP     0.9254

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA   =      1.2660 CPFBX=     0.9450 CPFW =   86.3316
CSIX = 178.8112 FK    =      2.5425 AL1   =     1.2500 AL2   =    0.8500
AL3  =    0.4000 AL4   =      0.9500 AL5   =     0.0000 AL6   =    0.8947
AL7  =    0.3158 AL8   =      0.5789 AL9   =     1.4211 AL10  =    1.0526
AL11 =    1.3158
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REACTOR PARAMETERS
PFU   =    1500.0 II    =  10.7407 A     =    3.7362 FAAB =    1.2481
PF    =    2.9956 IBI   =   0.7164 RR    =    5.7631 AK   =    1.5425
PW    =    1.9545 QGR   =.3144E+02 TB    =     2154. BK   =    2.8536
TAUE  =    1.7247 QQ    =   3.7750 QPSI  =    4.3627 CNX  =    4.4211
NE    =    1.3585 NDTE  =   0.7287 NIE   =    0.8399 ZEFF =    1.6288
NZ3   =    0.0101 NZ4   =   0.0010 NZ5   =0.0001088 BETA =    0.0361
FBRZ  =   29.0611 PRAD  =   0.0757 PSY   =    0.0274 BETAP=    2.0525
VAU   =     500.7 VAUTM=    1976.7 WTM   =    70411. WPM  =     559.7
FTM   =    0.1104 FOHM  =   0.4598 CVMTF=     1.8896 CVMOH=    1.4203
IITM  =   85.7339 IIOH  =  42.8669 VMTF  =   133047. VMOH =     7906.
JTF   =    9.9400 JOH   =  25.3700 SIGST=     584.55 SIGSTC    215.45
TTF   =    1.3210 DOH   =   0.5176 SIGT  =    519.99 SIGP =    216.07
HOH   =   12.8426 ROH   =   1.3774 WOH   =    5566.3 TAUTM=   12.3457
TAUOH=    32.8493 FH93HP    1.0475

INPUT-DEPENDENT DATA
CSEF =     4.2304 CFA   =    1.2660 CPFBX=    0.9488 CPFW =   86.3316
CSIX =   192.5918 FK    =    2.5425 AL1   =   1.2500 AL2  =    0.8500
AL3   =    0.4000 AL4   =    0.9500 AL5   =   0.0000 AL6  =    0.8947
AL7   =    0.3158 AL8   =    0.5789 AL9   =   1.4211 AL10 =    1.0526
AL11 =     1.3158

REACTOR PARAMETERS
PFU   =    1800.0 II    =   8.0707 A     =    5.3689 FAAB =    0.8911
PF    =    3.7544 IBI   =   0.9021 RR    =    7.2333 AK   =    1.3472
PW    =    2.1395 QGR   =.1038E+03 TB    =   244700. BK   =    2.4924
TAUE  =    1.7903 QQ    =   3.9656 QPSI  =    4.4640 CNX  =    4.8795
NE    =    1.5162 NDTE  =   0.7310 NIE   =    0.8419 ZEFF =    1.6051
NZ3   =    0.0098 NZ4   =   0.0010 NZ5   =0.0000845 BETA =    0.0239
FBRZ  =   24.9256 PRAD  =   0.0910 PSY   =    0.0596 BETAP=    3.0984
VAU   =     479.4 VAUTM=    2123.0 WTM   =   127544. WPM  =     504.0
FTM   =    0.1302 FOHM  =   0.2496 CVMTF=     1.8896 CVMOH=    1.4203
IITM  =   85.7339 IIOH  =  42.8669 VMTF  =   241003. VMOH =    42818.
JTF   =   11.7214 JOH   =  13.7696 SIGST=     406.01 SIGSTC    393.99
TTF   =    1.1202 DOH   =   0.9536 SIGT  =    353.13 SIGP =    300.17
HOH   =   11.1807 ROH   =   3.2781 WOH   =   30146.9 TAUTM=   12.3457
TAUOH=    32.8493 FH93HP    0.8721

INPUT-DEPENDENT DATA
CSEF =     4.2304 CFA   =    1.2660 CPFBX=    0.9478 CPFW =   86.3316
CSIX =   188.7843 FK    =    2.5425 AL1   =   1.2500 AL2  =    0.8500
AL3   =    0.4000 AL4   =    0.9500 AL5   =   0.0000 AL6  =    0.8947
AL7   =    0.3158 AL8   =    0.5789 AL9   =   1.4211 AL10 =    1.0526
AL11 =     1.3158
REACTOR PARAMETERS
PFU   =    1800.0 II    =   9.0485 A     =    4.6660 FAAB =    0.9897
PF    =    3.5106 IBI   =   0.8553 RR    =    6.7364 AK   =    1.4437
PW    =    2.1439 QGR   =.6953E+02 TB    =    75334. BK   =    2.6709
TAUE  =    1.7781 QQ    =   4.0331 QPSI  =    4.5668 CNX  =    4.8654
NE    =    1.4673 NDTE  =   0.7304 NIE   =    0.8413 ZEFF =    1.6115
NZ3   =    0.0099 NZ4   =   0.0010 NZ5   =0.0000911 BETA =    0.0270
FBRZ  =   26.4655 PRAD  =   0.0861 PSY   =    0.0466 BETAP=    2.7386
VAU   =     512.7 VAUTM=    2138.6 WTM   =   109872. WPM  =     541.4
FTM   =    0.1266 FOHM  =   0.2952 CVMTF=     1.8896 CVMOH=    1.4203
IITM  =   85.7339 IIOH  =  42.8669 VMTF  =   207611. VMOH =    29039.
JTF   =   11.3895 JOH   =  16.2896 SIGST=     463.09 SIGSTC    336.91
TTF   =    1.1528 DOH   =   0.8061 SIGT  =    404.48 SIGP =    281.90
HOH   =   11.9298 ROH   =   2.6351 WOH   =   20445.8 TAUTM=   12.3457
TAUOH=    32.8493 FH93HP    0.9365

INPUT-DEPENDENT DATA
CSEF =     4.2304 CFA   =    1.2660 CPFBX=    0.9435 CPFW =   86.3316
CSIX =   182.6434 FK    =    2.5425 AL1   =   1.2500 AL2  =    0.8500
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AL3  =    0.4000 AL4   =    0.9500 AL5   =   0.0000 AL6   =    0.8947
AL7  =    0.3158 AL8   =    0.5789 AL9   =   1.4211 AL10  =    1.0526
AL11 =    1.3158

REACTOR PARAMETERS
PFU  =    1800.0 II    =   11.4048 A     =   3.5979 FAAB  =    1.2577
PF   =    2.7770 IBI   =    0.7599 RR    =   6.1249 AK    =    1.7024
PW   =    1.9996 QGR   =.4097E+02 TB    =    4000. BK    =    3.1494
TAUE =    1.8675 QQ    =    4.0806 QPSI  =   4.7414 CNX   =    4.9152
NE   =    1.3096 NDTE  =    0.7279 NIE   =   0.8392 ZEFF  =    1.6383
NZ3  =    0.0102 NZ4   =    0.0010 NZ5   =0.0001184 BETA  =    0.0346
FBRZ =   28.6351 PRAD  =    0.0713 PSY   =   0.0257 BETAP=    2.1366
VAU  =     648.2 VAUTM=     2366.5 WTM   =   84556. WPM   =     651.8
FTM  =    0.1056 FOHM  =    0.4377 CVMTF=    1.8896 CVMOH=    1.4203
IITM =   85.7339 IIOH  =   42.8669 VMTF  =  159774. VMOH  =    10294.
JTF  =    9.5081 JOH   =   24.1516 SIGST=    582.13 SIGSTC     217.87
TTF  =    1.3810 DOH   =    0.5437 SIGT  =   520.63 SIGP  =    224.91
HOH  =   14.0903 ROH   =    1.4912 WOH   =   7247.8 TAUTM=    12.3457
TAUOH=   32.8493 FH93HP     1.0598

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA   =    1.2660 CPFBX=    0.9482 CPFW  =   86.3316
CSIX = 194.9025 FK    =    2.5425 AL1   =   1.2500 AL2   =    0.8500
AL3  =    0.4000 AL4   =    0.9500 AL5   =   0.0000 AL6   =    0.8947
AL7  =    0.3158 AL8   =    0.5789 AL9   =   1.4211 AL10  =    1.0526
AL11 =    1.3158

REACTOR PARAMETERS
PFU  =    2000.0 II    =    8.3433 A     =   5.2576 FAAB  =    0.8925
PF   =    3.5994 IBI   =    0.9348 RR    =   7.4925 AK    =    1.4251
PW   =    2.1697 QGR   =.1651E+03 TB    =  394872. BK    =    2.6364
TAUE =    1.8721 QQ    =    4.1526 QPSI  =   4.6775 CNX   =    5.1769
NE   =    1.4853 NDTE  =    0.7306 NIE   =   0.8415 ZEFF  =    1.6091
NZ3  =    0.0098 NZ4   =    0.0010 NZ5   =0.0000886 BETA  =    0.0233
FBRZ =   24.7307 PRAD  =    0.0879 PSY   =   0.0577 BETAP=    3.1773
VAU  =     555.6 VAUTM=     2343.4 WTM   =  141404. WPM   =     551.0
FTM  =    0.1269 FOHM  =    0.2415 CVMTF=    1.8896 CVMOH=    1.4203
IITM =   85.7339 IIOH  =   42.8669 VMTF  =  267193. VMOH  =    49175.
JTF  =   11.4254 JOH   =   13.3254 SIGST=    403.48 SIGSTC     396.52
TTF  =    1.1492 DOH   =    0.9854 SIGT  =   352.26 SIGP  =    303.39
HOH  =   11.7879 ROH   =    3.4167 WOH   =  34622.8 TAUTM=    12.3457
TAUOH=   32.8493 FH93HP     0.8779

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA   =    1.2660 CPFBX=    0.9471 CPFW  =   86.3316
CSIX = 191.0395 FK    =    2.5425 AL1   =   1.2500 AL2   =    0.8500
AL3  =    0.4000 AL4   =    0.9500 AL5   =   0.0000 AL6   =    0.8947
AL7  =    0.3158 AL8   =    0.5789 AL9   =   1.4211 AL10  =    1.0526
AL11 =    1.3158

REACTOR PARAMETERS
PFU  =    2000.0 II    =    9.3558 A     =   4.5686 FAAB  =    0.9920
PF   =    3.3623 IBI   =    0.8863 RR    =   6.9794 AK    =    1.5277
PW   =    2.1727 QGR   =.9374E+02 TB    =  106117. BK    =    2.8262
TAUE =    1.8600 QQ    =    4.2237 QPSI  =   4.7887 CNX   =    5.1659
NE   =    1.4368 NDTE  =    0.7300 NIE   =   0.8410 ZEFF  =    1.6159
NZ3  =    0.0099 NZ4   =    0.0010 NZ5   =0.0000956 BETA  =    0.0264
FBRZ =   26.2506 PRAD  =    0.0831 PSY   =   0.0450 BETAP=    2.8082
VAU  =     594.8 VAUTM=     2366.7 WTM   =  122065. WPM   =     591.5
FTM  =    0.1233 FOHM  =    0.2859 CVMTF=    1.8896 CVMOH=    1.4203
IITM =   85.7339 IIOH  =   42.8669 VMTF  =  230649. VMOH  =    33463.
JTF  =   11.1012 JOH   =   15.7763 SIGST=    460.82 SIGSTC     339.18
TTF  =    1.1828 DOH   =    0.8323 SIGT  =   403.98 SIGP  =    285.63
HOH  =   12.5837 ROH   =    2.7494 WOH   =  23560.4 TAUTM=    12.3457
TAUOH=   32.8493 FH93HP     0.9427
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INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA   =     1.2660 CPFBX=    0.9425 CPFW =  86.3316
CSIX = 184.8483 FK    =     2.5425 AL1  =    1.2500 AL2  =   0.8500
AL3  =    0.4000 AL4   =     0.9500 AL5  =    0.0000 AL6  =   0.8947
AL7  =    0.3158 AL8   =     0.5789 AL9  =    1.4211 AL10 =   1.0526
AL11 =    1.3158

REACTOR PARAMETERS
PFU  =   2000.0 II   =   11.8021 A    =    3.5221 FAAB =   1.2636
PF   =   2.6489 IBI  =    0.7870 RR   =    6.3536 AK   =   1.8039
PW   =   2.0212 QGR  =.4890E+02 TB   =     5683. BK   =   3.3373
TAUE =   1.9577 QQ   =    4.2713 QPSI =    4.9797 CNX  =   5.2309
NE   =   1.2801 NDTE =    0.7273 NIE  =    0.8386 ZEFF =   1.6446
NZ3  =   0.0102 NZ4  =    0.0010 NZ5  =0.0001248 BETA =   0.0338
FBRZ =  28.3529 PRAD =    0.0687 PSY  =    0.0247 BETAP=   2.1893
VAU  =    755.0 VAUTM=    2638.6 WTM  =    94398. WPM  =    712.2
FTM  =   0.1028 FOHM =    0.4251 CVMTF=    1.8896 CVMOH=   1.4203
IITM =  85.7339 IIOH =   42.8669 VMTF =   178372. VMOH =   12010.
JTF  =   9.2502 JOH  =   23.4525 SIGST=    580.86 SIGSTC   219.14
TTF  =   1.4195 DOH  =    0.5599 SIGT =    521.16 SIGP =   229.98
HOH  =  14.8837 ROH  =    1.5619 WOH  =    8455.9 TAUTM=  12.3457
TAUOH=  32.8493 FH93HP    1.0666
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"CONVENTIONAL" INPUT DATA (FH93HP)
GTR   =    0.0300 T10   =    1.7000 BM    =  16.5000 BOH   =  16.5000
TBS   =    1.2500 FPW   =    0.8500 KK    =   1.8500 DEL   =   0.3500
FAAA = 0.000000 AN    =    0.5000 AT    =   1.0000 AI    =   1.5000
FH93HP 0.655711 CTAUE= 0.000004 CB    =   0.6746 GAMO =.5000E+00
ALPHI=    1.0600 ALPHR=    1.9000 ALPHA=  -0.1100 ALPHN=   0.1700
ALPHB=    0.3000 ALPHK=    0.6600 ALPHP=   0.6700 NALP =   0.0000
RHO   =    0.0003 WH    =    0.0030 KHTM =  25.0000 KHOH =  8.48528
FTT   =    50000. FTO   =    50000. FTF   =   0.5000 FTFC =   0.5000
JCTM =   90.0000 JCOH =   55.1743 SIGSTG   800.00 SIGSP=   400.00
CI    =    1.0000 ZZ3   =    6.0000 ZZ4   =   8.0000 ZZ5   =  26.0000

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA   =     1.2660 CPFBX=    0.5299 CPFW =   86.3316
CSIX =   66.1955 FK    =     2.5425 AL1   =    1.0200 AL2   =    0.8400
AL3   =    0.1800 AL4   =     0.8900 AL5   =    0.0100 AL6   =    0.9438
AL7   =    0.1461 AL8   =     0.7978 AL9   =    2.2360 AL10 =     1.1236
AL11 =    1.1461

REACTOR PARAMETERS
PFU   =    2600.0 II    =   11.7416 A     =   4.8698 FAAB =    0.8985
PF    =    2.5957 IBI   =    0.6513 RR    =   8.6645 AK    =    1.7793
PW    =    1.9535 QGR   =.2891E+02 TB    =   79681. BK    =    3.2916
TAUE =    1.9298 QQ    =    4.0085 QPSI =   4.5288 CNX   =    4.9086
NE    =    1.2676 NDTE =    0.7270 NIE   =   0.8384 ZEFF =    1.6474
NZ3   =    0.0103 NZ4   =    0.0010 NZ5   =0.0001276 BETA =    0.0195
FBRZ =   22.3365 PRAD =    0.0676 PSY   =   0.0486 BETAP=    2.1306
VAU   =    1001.7 VAUTM=    3536.6 WTM   =  216743. WPM   =    1204.6
FTM   =    0.1138 FOHM =    0.2109 CVMTF=   1.8896 CVMOH=    1.4203
IITM =   85.7339 IIOH =   42.8669 VMTF =  409551. VMOH =    85712.
JTF   =   10.2458 JOH   =   11.6373 SIGST=   394.28 SIGSTC   405.72
TTF   =    1.2815 DOH   =    1.1283 SIGT =   349.40 SIGP =    315.63
HOH   =   14.5519 ROH   =    4.0398 WOH   =  60347.6 TAUTM=  12.3457
TAUOH=   32.8493 FH89P=    1.9505

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA   =     1.2660 CPFBX=    0.5313 CPFW =   86.3316
CSIX =   64.1335 FK    =     2.5425 AL1   =    1.0200 AL2   =    0.8400
AL3   =    0.1800 AL4   =     0.8900 AL5   =    0.0100 AL6   =    0.9438
AL7   =    0.1461 AL8   =     0.7978 AL9   =    2.2360 AL10 =     1.1236
AL11 =    1.1461

REACTOR PARAMETERS
PFU   =    2600.0 II    =   13.4927 A     =   4.3291 FAAB =    0.9986
PF    =    2.9172 IBI   =    0.5542 RR    =   7.7049 AK    =    1.7798
PW    =    2.1962 QGR   =.2091E+02 TB    =   25050. BK    =    3.2926
TAUE =    1.6554 QQ    =    3.6174 QPSI =   4.1169 CNX   =    4.5552
NE    =    1.3411 NDTE =    0.7284 NIE   =   0.8397 ZEFF =    1.6320
NZ3   =    0.0101 NZ4   =    0.0010 NZ5   =0.0001121 BETA =    0.0244
FBRZ =   25.4046 PRAD =    0.0741 PSY   =   0.0408 BETAP=    1.7093
VAU   =     891.3 VAUTM=    3146.0 WTM   =  163767. WPM   =    1310.7
FTM   =    0.1146 FOHM =    0.2615 CVMTF=   1.8896 CVMOH=    1.4203
IITM =   85.7339 IIOH =   42.8669 VMTF =  309448. VMOH =    49232.
JTF   =   10.3150 JOH   =   14.4293 SIGST=   455.16 SIGSTC   344.84
TTF   =    1.2729 DOH   =    0.9100 SIGT =   402.99 SIGP =    295.39
HOH   =   14.5465 ROH   =    3.0881 WOH   =  34663.1 TAUTM=  12.3457
TAUOH=   32.8493 FH89P=    1.8128

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA   =     1.2660 CPFBX=    0.5320 CPFW =   86.3316
CSIX =   62.5250 FK    =     2.5425 AL1   =    1.0200 AL2   =    0.8400
AL3   =    0.1800 AL4   =     0.8900 AL5   =    0.0100 AL6   =    0.9438
AL7   =    0.1461 AL8   =     0.7978 AL9   =    2.2360 AL10 =     1.1236
AL11 =    1.1461
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REACTOR PARAMETERS
PFU   =    2600.0 II    =  15.4191 A     =    3.8877 FAAB =    1.1155
PF    =    3.1276 IBI   =   0.4752 RR    =    7.0073 AK   =    1.8024
PW    =    2.3845 QGR   =.1653E+02 TB    =     7328. BK   =    3.3345
TAUE  =    1.4810 QQ    =   3.2733 QPSI  =    3.7641 CNX  =    4.2726
NE    =    1.3872 NDTE  =   0.7292 NIE   =    0.8403 ZEFF =    1.6238
NZ3   =    0.0100 NZ4   =   0.0010 NZ5   =0.0001037 BETA =    0.0300
FBRZ  =   28.0539 PRAD  =   0.0783 PSY   =    0.0332 BETAP=    1.3889
VAU   =     831.3 VAUTM=    2907.0 WTM   =   127230. WPM  =    1444.2
FTM   =    0.1109 FOHM  =   0.3242 CVMTF=     1.8896 CVMOH=    1.4203
IITM  =   85.7339 IIOH  =  42.8669 VMTF  =   240410. VMOH =    27569.
JTF   =    9.9821 JOH   =  17.8863 SIGST=     515.82 SIGSTC    284.18
TTF   =    1.3154 DOH   =   0.7341 SIGT  =    458.61 SIGP =    270.33
HOH   =   14.7600 ROH   =   2.3214 WOH   =   19410.4 TAUTM=   12.3457
TAUOH=    32.8493 FH89P=    1.7025

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA   =    1.2660 CPFBX=    0.5293 CPFW =   86.3316
CSIX =   66.8304 FK    =    2.5425 AL1   =    1.0200 AL2  =    0.8400
AL3  =    0.1800 AL4   =    0.8900 AL5   =    0.0100 AL6  =    0.9438
AL7  =    0.1461 AL8   =    0.7978 AL9   =    2.2360 AL10 =    1.1236
AL11 =    1.1461

REACTOR PARAMETERS
PFU   =    3000.0 II    =  12.2895 A     =    4.7610 FAAB =    0.9005
PF    =    2.4735 IBI   =   0.6773 RR    =    9.0971 AK   =    1.9107
PW    =    1.9992 QGR   =.3357E+02 TB    =    96805. BK   =    3.5349
TAUE  =    2.0339 QQ    =   4.2160 QPSI  =    4.7686 CNX  =    5.2905
NE    =    1.2385 NDTE  =   0.7263 NIE   =    0.8378 ZEFF =    1.6543
NZ3   =    0.0104 NZ4   =   0.0010 NZ5   =0.0001346 BETA =    0.0190
FBRZ  =   22.1299 PRAD  =   0.0652 PSY   =    0.0466 BETAP=    2.1908
VAU   =    1212.9 VAUTM=    4064.7 WTM   =   250200. WPM  =    1366.0
FTM   =    0.1096 FOHM  =   0.2015 CVMTF=     1.8896 CVMOH=    1.4203
IITM  =   85.7339 IIOH  =  42.8669 VMTF  =   472770. VMOH =   102738.
JTF   =    9.8673 JOH   =  11.1202 SIGST=     391.59 SIGSTC    408.41
TTF   =    1.3307 DOH   =   1.1808 SIGT  =    348.66 SIGP =    319.38
HOH   =   15.5781 ROH   =   4.2685 WOH   =   72335.4 TAUTM=   12.3457
TAUOH=    32.8493 FH89P=    1.9378

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA   =    1.2660 CPFBX=    0.5308 CPFW =   86.3316
CSIX =   64.7407 FK    =    2.5425 AL1   =    1.0200 AL2  =    0.8400
AL3  =    0.1800 AL4   =    0.8900 AL5   =    0.0100 AL6  =    0.9438
AL7  =    0.1461 AL8   =    0.7978 AL9   =    2.2360 AL10 =    1.1236
AL11 =    1.1461

REACTOR PARAMETERS
PFU   =    3000.0 II    =  14.1360 A     =    4.2291 FAAB =    1.0018
PF    =    2.7882 IBI   =   0.5754 RR    =    8.0772 AK   =    1.9099
PW    =    2.2525 QGR   =.2358E+02 TB    =    30076. BK   =    3.5334
TAUE  =    1.7417 QQ    =   3.7999 QPSI  =    4.3329 CNX  =    4.9080
NE    =    1.3121 NDTE  =   0.7279 NIE   =    0.8392 ZEFF =    1.6377
NZ3   =    0.0102 NZ4   =   0.0010 NZ5   =0.0001179 BETA =    0.0237
FBRZ  =   25.2162 PRAD  =   0.0715 PSY   =    0.0391 BETAP=    1.7540
VAU   =    1076.0 VAUTM=    3607.0 WTM   =   188462. WPM  =    1484.5
FTM   =    0.1106 FOHM  =   0.2506 CVMTF=     1.8896 CVMOH=    1.4203
IITM  =   85.7339 IIOH  =  42.8669 VMTF  =   356111. VMOH =    58935.
JTF   =    9.9500 JOH   =  13.8277 SIGST=     452.77 SIGSTC    347.23
TTF   =    1.3196 DOH   =   0.9496 SIGT  =    402.71 SIGP =    299.75
HOH   =   15.5600 ROH   =   3.2607 WOH   =   41494.8 TAUTM=   12.3457
TAUOH=    32.8493 FH89P=    1.8000

INPUT-DEPENDENT DATA
CSEF =    4.2304 CFA   =    1.2660 CPFBX=    0.5316 CPFW =   86.3316
CSIX =   63.1201 FK    =    2.5425 AL1   =    1.0200 AL2  =    0.8400
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```
AL3   =    0.1800 AL4   =      0.8900 AL5   =     0.0100 AL6   =     0.9438
AL7   =    0.1461 AL8   =      0.7978 AL9   =     2.2360 AL10  =     1.1236
AL11  =    1.1461

REACTOR PARAMETERS
PFU   =    3000.0 II    =   16.1709 A     =     3.7954 FAAB  =     1.1203
PF    =    2.9950 IBI   =    0.4926 RR    =     7.3380 AK    =     1.9334
PW    =    2.4494 QGR   =.1834E+02 TB    =      8906. BK    =     3.5768
TAUE  =    1.5571 QQ    =    3.4338 QPSI  =     3.9602 CNX   =     4.6035
NE    =    1.3583 NDTE  =    0.7287 NIE   =     0.8399 ZEFF  =     1.6289
NZ3   =    0.0101 NZ4   =    0.0010 NZ5   =0.0001088 BETA  =     0.0293
FBRZ  =   27.8779 PRAD  =    0.0756 PSY   =     0.0318 BETAP=     1.4225
VAU   =    1001.7 VAUTM=    3328.9 WTM   =    146080. WPM   =     1634.4
FTM   =    0.1071 FOHM  =    0.3116 CVMTF=     1.8896 CVMOH=     1.4203
IITM  =   85.7339 IIOH  =   42.8669 VMTF  =    276028. VMOH  =     33025.
JTF   =    9.6376 JOH   =   17.1898 SIGST=     513.88 SIGSTC      286.12
TTF   =    1.3624 DOH   =    0.7638 SIGT  =     458.85 SIGP  =     275.38
HOH   =   15.7800 ROH   =    2.4510 WOH   =    23251.9 TAUTM=    12.3457
TAUOH=    32.8493 FH89P=     1.6899

INPUT-DEPENDENT DATA
CSEF  =    4.2304 CFA   =      1.2660 CPFBX=     0.5286 CPFW  =   86.3316
CSIX  =   67.3884 FK    =      2.5425 AL1   =     1.0200 AL2   =     0.8400
AL3   =    0.1800 AL4   =      0.8900 AL5   =     0.0100 AL6   =     0.9438
AL7   =    0.1461 AL8   =      0.7978 AL9   =     2.2360 AL10  =     1.1236
AL11  =    1.1461

REACTOR PARAMETERS
PFU   =    3400.0 II    =   12.7821 A     =     4.6701 FAAB  =     0.9024
PF    =    2.3628 IBI   =    0.7019 RR    =     9.5075 AK    =     2.0358
PW    =    2.0347 QGR   =.3873E+02 TB    =    116849. BK    =     3.7663
TAUE  =    2.1332 QQ    =    4.4110 QPSI  =     4.9945 CNX   =     5.6548
NE    =    1.2116 NDTE  =    0.7257 NIE   =     0.8373 ZEFF  =     1.6613
NZ3   =    0.0104 NZ4   =    0.0010 NZ5   =0.0001416 BETA  =     0.0185
FBRZ  =   21.9152 PRAD  =    0.0630 PSY   =     0.0449 BETAP=     2.2484
VAU   =    1439.0 VAUTM=    4613.1 WTM   =    284988. WPM   =     1525.5
FTM   =    0.1059 FOHM  =    0.1934 CVMTF=     1.8896 CVMOH=     1.4203
IITM  =   85.7339 IIOH  =   42.8669 VMTF  =    538505. VMOH  =    120834.
JTF   =    9.5327 JOH   =   10.6713 SIGST=     389.28 SIGSTC      410.72
TTF   =    1.3774 DOH   =    1.2304 SIGT  =     348.05 SIGP  =     322.64
HOH   =   16.5543 ROH   =    4.4850 WOH   =    85076.1 TAUTM=    12.3457
TAUOH=    32.8493 FH89P=     1.9274

INPUT-DEPENDENT DATA
CSEF  =    4.2304 CFA   =      1.2660 CPFBX=     0.5303 CPFW  =   86.3316
CSIX  =   65.2716 FK    =      2.5425 AL1   =     1.0200 AL2   =     0.8400
AL3   =    0.1800 AL4   =      0.8900 AL5   =     0.0100 AL6   =     0.9438
AL7   =    0.1461 AL8   =      0.7978 AL9   =     2.2360 AL10  =     1.1236
AL11  =    1.1461

REACTOR PARAMETERS
PFU   =    3400.0 II    =   14.7153 A     =     4.1452 FAAB  =     1.0047
PF    =    2.6701 IBI   =    0.5954 RR    =     8.4305 AK    =     2.0338
PW    =    2.2970 QGR   =.2636E+02 TB    =     35682. BK    =     3.7625
TAUE  =    1.8237 QQ    =    3.9717 QPSI  =     4.5368 CNX   =     5.2448
NE    =    1.2850 NDTE  =    0.7274 NIE   =     0.8387 ZEFF  =     1.6435
NZ3   =    0.0102 NZ4   =    0.0010 NZ5   =0.0001237 BETA  =     0.0232
FBRZ  =   25.0155 PRAD  =    0.0691 PSY   =     0.0376 BETAP=     1.7969
VAU   =    1273.4 VAUTM=    4085.0 WTM   =    214083. WPM   =     1656.1
FTM   =    0.1069 FOHM  =    0.2411 CVMTF=     1.8896 CVMOH=     1.4203
IITM  =   85.7339 IIOH  =   42.8669 VMTF  =    404524. VMOH  =     69226.
JTF   =    9.6254 JOH   =   13.3037 SIGST=     450.76 SIGSTC      349.24
TTF   =    1.3641 DOH   =    0.9870 SIGT  =     402.56 SIGP  =     303.55
HOH   =   16.5247 ROH   =    3.4237 WOH   =    48740.5 TAUTM=    12.3457
TAUOH=    32.8493 FH89P=     1.7894
```

```
INPUT-DEPENDENT DATA
CSEF =   4.2304 CFA   =     1.2660 CPFBX=   0.5311 CPFW =  86.3316
CSIX =  63.6391 FK    =     2.5425 AL1  =   1.0200 AL2  =   0.8400
AL3  =   0.1800 AL4   =     0.8900 AL5  =   0.0100 AL6  =   0.9438
AL7  =   0.1461 AL8   =     0.7978 AL9  =   2.2360 AL10 =   1.1236
AL11 =   1.1461

REACTOR PARAMETERS
PFU  =   3400.0 II    =  16.8492 A     =   3.7179 FAAB =   1.1247
PF   =   2.8727 IBI   =   0.5089 RR    =   7.6517 AK   =   2.0581
PW   =   2.5009 QGR   =.2017E+02 TB    =   10634. BK   =   3.8075
TAUE =   1.6293 QQ    =   3.5849 QPSI  =   4.1457 CNX  =   4.9197
NE   =   1.3312 NDTE  =   0.7283 NIE   =   0.8395 ZEFF =   1.6339
NZ3  =   0.0101 NZ4   =   0.0010 NZ5   =0.0001140 BETA =   0.0286
FBRZ =  27.6874 PRAD  =   0.0732 PSY   =   0.0306 BETAP=   1.4547
VAU  =   1183.5 VAUTM=    3766.1 WTM   =  165597. WPM  =   1822.1
FTM  =   0.1037 FOHM  =   0.3005 CVMTF=    1.8896 CVMOH=   1.4203
IITM =  85.7339 IIOH  =  42.8669 VMTF  =  312906. VMOH =   38800.
JTF  =   9.3296 JOH   =  16.5823 SIGST=    512.30 SIGSTC   287.70
TTF  =   1.4074 DOH   =   0.7918 SIGT  =   459.20 SIGP =   279.78
HOH  =  16.7513 ROH   =   2.5730 WOH   =  27318.0 TAUTM=  12.3457
TAUOH=  32.8493 FH89P=    1.6795
```

Abbreviations

in equations	in Mathematica® program files (capital letters in parameter list)	explanation
a	ak	plasma horizontal minor radius
A	a	plasma aspect ratio
α_a	alpha	exponent of a in confinement scaling
α_B	alphb	exponent of B in confinement scaling
α_j	ai	profile exponent: current density
α_I	alphi	exponent of I in confinement scaling
α_k	alphk	exponent of k in confinement scaling
α_n	alphn	exponent of n_e in confinement scaling
α_N	an	profile exponent: plasma density
α_P	alphp	exponent of P in confinement scaling
α_R	alphr	exponent of R in confinement scaling
α_T	at	profile exponent: plasma temperature
b	bk	plasma vertical minor radius
β	beta	plasma press./ toroidal field pressure
β_{pol}	betap	plasma press./ poloidal field pressure
B	bb	toroidal field at horiz. plasma center
B_{max}	bm	max. toroidal field at TF coil midplane
C_B	cb	coefficient in bootstrap current equat.
C_{fa}	cfa	fast alpha pressure β enhancement
C_{fA}	faaa	rel. deviation from q-depend. opt. A
C_Φ	cphi	coefficient for OH flux calculation
C_n	cnx	coefficient in Petrie density limit
C_{PfB}^*	cpfbx	coefficient in fusion power equation
C_{Pfw}^*	cpfw	coefficient in neutron wall load equat.
$C_{\sigma Ef}$	csef	fusion reaction parameter
C_{sI}^*	csix	coefficient in aspect ratio iteration eq.
C_τ		orig. coeff. conf. scalg. (incl. isot. scalg.)
$C_{\tau E}$	ctaue	coeff. of confin. scalg. (incl. isot. scalg.)
$C_{\tau p}$	ctp	ratio: He particle to energy conf. time
C_{VMTF}	cvmtf	TF max. safety disch. voltage/energy
C_{VMOH}	cvmoh	OH max. safety disch. voltage/energy
d_{OH}	doh	OH coil thickness
Δ	del	plasma triangularity
f_A	faab	total rel. deviat. from opt. aspect ratio
f(k)	fk	elongation function in q-equation
f_H	fh89p e.g.	confinement enhancement factor

f_{TM}	ftm	TF coil conductor area/coil cross-sect.
f_{OH}	fohm	OH coil conductor area/coil cross-sect.
F_{OH}	foh	coeff. for plasma ring voltage calc.
f_{pw}	fpw	plasma minor radius/wall min. radius
$f(\alpha; A)$	fala	function for plasma ring voltage calc.
$F_L(A)$	fla	function for plasma ring inductance
F_B	1 - ibi	1 - I_B/I
F_{Br}	fbr, fbrz, fbrzc	fusion power density/rad. power dens.
f_1	f1	geometry factor ($t_{BS} > 0$)
f_2	f2	geometry factor ($t_{BS} > 0$)
f_3	f3	geometry factor ($t_{BS} > 0$)
f_{11}	f11	geometry factor ($t_{BS} = 0$)
f_{22}	f22	geometry factor ($t_{BS} = 0$)
f_{TF}	ftf	reduction factor
f_{Tfc}	ftfc	reduction factor
$f(T_{OH})$	fto	funct. (OH solen. safety disch. warmup)
$f(T_{TM})$	ftt	funct. (TF solen. safety disch. warmup)
g	gtr	total Troyon coefficient (incl. fast α^s)
γ_o	gamo	current drive efficiency w/o bootstr. c.
H_{OH}	hoh	height of central OH solenoid
j_{cOH}	jcoh	OH winding current density
j_{cTM}	jctm	TF winding current density
j_{OH}	joh	average OH coil current density
j_{TF}	jtf	average TF coil current density
I	ii	toroidal plasma current
I_B/I	ibi	relative toroidal bootstrap current
I_{OH}	iioh	OH solenoid conductor current
I_{TM}	iitm	series conn. TF coil conductor current
k	kk	plasma elongation
k_h	kh	geometry coefficient
L_A	lagr	fict. length replacing t_{BS} for $t_{BS} = 0$
n_{DT}		volume average fuel density
n_e	ne	volume average electron density
n_i		volume average ion density
n_C	nz3	average carbon impurity density
n_O	nz4	average oxygen impurity density
n_{Fe}	nz5	average iron impurity density
n_{DT}/n_e	ndte	relative fuel density (dilution factor)
n_i/n_e	nie	relative ion density
n_α/n_e	nalp	relative alpha density
p_f	pf	fusion power density
p_{rad}	prad	line and bremsstr. radiation density
p_{sy}	psy	synchrotron rad. density (fictitious)
p_w	pw	average neutron wall load

P		total loss power from plasma
P_h		external heating power
P_f	pfu	fusion power
P_{rad}		line and bremsstr. radiat. loss power
P_{sy}		synchrotron radiation loss power
q	qq	current-q
q_ψ	qpsi	boundary-q
Q	qgr	fusion power/steady st. heating power
R	rr	major plasma radius
R_{OH}	roh	outer OH coil radius
R_w	rw	eff. wall reflection coeff. (synchr. rad.)
ρ	rho	spec. stabilizer resistance at low temp.
σ_{OH}	sigp	average tensile stress in OH coil
σ_{TF}	sigt	average tens. stress in TF coil inner leg
σ_{sOH}	sigsp	average tensile stress in OH coil casing
σ_{sTFg}	sigstg	given sum of σ_{sTF} and σ_{sTFc}
σ_{sTF}	sigst	av. tens. stress in TF coil inner leg case
σ_{sTFc}	sigstc	av. compr. str. in TF coil inner leg case
t_B	tb	inductive burn time
t_{BS}	tbs	blanket/shield (+TF cyostat) thickness
t_{TF}	ttf	inner leg toroidal field coil thickness
t_{TF}/R	ttfr	ratio TF coil thickness to plasma radius
T_{10}	t10	dens. weight. av. plasma temp. 10 keV
T_{OH}		OH solenoid safety discharge warmup
T_{TM}		TF solenoid safety discharge warmup
τ_E	taue	energy confinement time
τ_{OH}	tauoh	OH solen. safety discharge time const.
τ_{TM}	tautm	TF magnet safety discharge time const.
w_h	wh	heat transfer coefficient
V	vau	plasma volume
V_{TM}	vautm	toroidal magnet volume
$\sum V_{maxOH}$	vmoh	max. OH safety discharge voltage
$\sum V_{max\,TM}$	vmtm	max. TF safety discharge voltage
W_{th}		thermal plasma energy
W_{OH}	woh	OH solenoid energy
W_{PM}	wpm	poloidal field energy
W_{TM}	wtm	toroidal field energy
$Z = 6$	zz3	carbon charge number
$Z = 8$	zz4	oxygen charge number
$Z = 26$	zz5	iron charge number
Z_{eff}	zeff, zeffz	effective charge number

Units applied (see Abbreviations)

in equations	in Mathematica® program files (capital letters in parameter list)	unit
a	ak	m
A	a	1
α_a	alpha	1
α_B	alphb	1
α_j	ai	1
α_I	alphi	1
α_k	alphk	1
α_n	alphn	1
α_N	an	1
α_p	alphp	1
α_R	alphr	1
α_T	at	1
b	bk	m
β	beta	1
β_{pol}	betap	1
B	bb	T
B_{max}	bm	T
C_B	cb	1
C_{fa}	cfa	1
C_{fA}	faaa	1
C_{Φ}	cphi	1
C_n	cnx	10^{20} T^{-1} m^{-2}
C_{PfB}^*	cpfbx	MW m^{-3} T^{-4}
C_{Pfw}^*	cpfw	1
$C_{\sigma Ef}$	csef	see equation p. 28
C_{sI}^*	csix	see equation p. 6
C_{τ}		see equation p.6
$C_{\tau E}$	ctaue	see equation p.6
$C_{\tau p}$	ctp	1
C_{VMTF}	cvmtf	V MJ^{-1}
C_{VMOH}	cvmoh	V MJ^{-1}
d_{OH}	doh	m
Δ	del	1
f_A	faab	1
$f(k)$	fk	1
f_H	fh89p e.g.	1

f_{TM}	ftm	1
f_{OH}	fohm	1
F_{OH}	foh	see equation p. 18
f_{pw}	fpw	1
$f(\alpha; A)$	fala	1
$F_L(A)$	fla	1
F_B	1 - ibi	1
F_{Br}	fbr, fbrz, fbrzc	1
f_1	f1	1
f_2	f2	1
f_3	f3	1
f_{11}	f11	1
f_{22}	f22	1
f_{TF}	ftf	1
f_{TFc}	ftfc	1
$f(T_{OH})$	fto	MA^2 s m^{-4}
$f(T_{TM})$	ftt	MA^2 s m^{-4}
g	gtr	T m MA^{-1}
γ_o	gamo	10^{20} V^{-1} m^{-2}
H_{OH}	hoh	m
j_{cOH}	jcoh	MA m^{-2}
j_{cTM}	jctm	MA m^{-2}
j_{OH}	joh	MA m^{-2}
j_{TF}	jtf	MA m^{-2}
I	ii	MA
I_B/I	ibi	1
I_{OH}	iioh	kA
I_{TM}	iitm	kA
k	kk	1
k_h	kh	1
L_A	lagr	m
n_{DT}		10^{20} m^{-3}
n_e	ne	10^{20} m^{-3}
n_i		10^{20} m^{-3}
n_C	nz3	10^{20} m^{-3}
n_O	nz4	10^{20} m^{-3}
n_{Fe}	nz5	10^{20} m^{-3}
n_{DT}/n_e	ndte	1
n_i/n_e	nie	1
n_α/n_e	nalp	1
p_f	pf	MW m^{-3}
p_{rad}	prad	MW m^{-3}
p_{sy}	psy	MW m^{-3}
p_w	pw	MW m^{-2}

P		MW
P_h		MW
P_f	pfu	MW
P_{rad}		MW
P_{sy}		MW
q	qq	1
q_ψ	qpsi	1
Q	qgr	1
R	rr	m
R_{OH}	roh	m
R_w	rw	1
ρ	rho	V m MA^{-1}
σ_{OH}	sigp	MPa
σ_{TF}	sigt	MPa
σ_{sOH}	sigsp	MPa
σ_{sTFg}	sigstg	MPa
σ_{sTF}	sigst	MPa
σ_{sTFc}	sigstc	MPa
t_B	tb	s
t_{BS}	tbs	m
t_{TF}	ttf	m
t_{TF}/R	ttfr	1
T_{10}	t10	10 keV
T_{OH}		K
T_{TM}		K
τ_E	taue	s
τ_{OH}	tauoh	s
τ_{TM}	tautm	s
w_h	wh	MW m^{-2}
V	vau	m^3
V_{TM}	vautm	m^3
$\sum V_{maxOH}$	vmoh	V
$\sum V_{max\,TM}$	vmtm	V
W_{th}		MJ
W_{OH}	woh	MJ
W_{PM}	wpm	MJ
W_{TM}	wtm	MJ
$Z = 6$	zz3	1
$Z = 8$	zz4	1
$Z = 26$	zz5	1
Z_{eff}	zeff, zeffz	1