INTOR

Cost Approximation

A.F. Knobloch

IPP 4/185 January 1980

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

8046 GARCHING BEI MÜNCHEN

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

GARCHING BEI MÜNCHEN

INTOR

Cost Approximation

A.F. Knobloch

IPP 4/185 January 1980

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

IPP 4/185

INTOR Cost Approximation

A.F. Knobloch

January 1980

Abstract:

A simplified cost approximation for INTOR parameter sets in a narrow parameter range is shown. Plausible constraints permit the evaluation of the consequences of parameter variations on overall cost.

INTOR cost approximation

The international negotiations on INTOR have brought forward a number of suggested parameter sets of which set "B" is being preferred at present.
Using some rough cost scaling relationships already used for the INTOR cost estimate (European contribution to the 3rd session of the INTOR workshop) one can form a couple of equations to show the cost dependence from parameter variations in the vicinity of set "B". (Parameter sets see enclosure 1).

Constraints

It corresponds to the existing results of the INTOR workshop to assume

$$\bar{\beta} = \text{const.}$$

$$kT = \text{const.}$$

$$\Delta = \text{const. (distance plasma surface to toroidal field winding surface)}$$

$$a'/a = \text{const. (elongation)}$$

$$\beta_{pol} = c_\beta \cdot A \quad \text{with } c_\beta = \text{const.}$$

$$\tau_E \text{ - scaling like Alcator}$$

$$(n.\tau_E)_{ign} = \text{const.}$$

Also the density and temperature profiles shall be the same for all cases. From these assumptions the following equations derive (subscript n: case considered ; subscript 1: reference case):

$$\text{thermal power} \qquad \frac{P_{thn}}{P_{th1}} = \frac{A_n}{A_1} \cdot \frac{a_n}{a_1} \qquad (1)$$

$$\text{wall load} \qquad \frac{p_{wn}}{p_{w1}} = \frac{a_1}{a_n} \qquad (2)$$

$$\text{tor. field} \qquad \frac{B_{ton}}{B_{to1}} = \sqrt{\frac{a_1}{a_n}} \qquad (3)$$

$$\text{safety factor} \qquad \frac{q_n}{q_1} = \sqrt{\frac{A_1}{A_n}} \qquad (4)$$

$$\text{max.tor.field} \qquad \frac{B_{tmn}}{B_{tm1}} = \frac{A_n}{A_1} \cdot \sqrt{\frac{a_n}{a_1}} \cdot \frac{\frac{a_1}{a_n}(A_1-1) - \frac{\Delta}{a_n}}{A_n - 1 - \frac{\Delta}{a_n}} \qquad (5)$$

Cost items

Following a preliminary cost breakdown as used for the INTOR workshop (see enclosure 2)one can introduce the above equations in order to see the parameter dependence of the INTOR cost. When first introducing equations 1 and 2 , the result is Table 1 with parameter set "A" as the reference case.

Table 1: Approximate INTOR cost (percent of total incl. overheads)

I	Reactor	
1	TF coils	$11.32 \times \frac{B_{ton}}{B_{to1}} \cdot (\frac{A_n}{A_1})^2 \cdot (\frac{a_n}{a_1})^2$
2	PF coils	$3.60 \times \frac{B_{ton}}{B_{to1}} \cdot (\frac{a_n}{a_1})^2 \cdot \frac{q_1}{q_n}$
3	vacuum system	$3.60 \times \frac{A_n}{A_1} \cdot (\frac{a_n}{a_1})^2$
4	blanket/shield	$2.57 \times \frac{A_n}{A_1} \frac{a_n}{a_1}$
5	divertor	0.51
6	support structure	$0.77 \times \frac{B_{ton}}{B_{to1}} \cdot (\frac{A_n}{A_1})^2 \cdot (\frac{a_n}{a_1})^2$
7	neutral beams	$4.63 \times \frac{A_n}{A_1} \cdot \frac{a_n}{a_1}$
8	Tritium system	$1.29 \times \frac{A_n}{A_1} \cdot \frac{a_n}{a_1}$
9	reactor hall	$2.57 \times \frac{1 + A_n}{1 + A_1} \cdot \frac{a_n}{a_1}$
10	diagnostics	1.03
11	assembly	$k_1 \times \Sigma(I,1 \div I,10)$ with $k_1 = 0.15$
12	design	$k_2 \times \Sigma(I,1 \div I,10)$ with $k_2 = 0.37$
II	Close-support	$4.12 \times \frac{A_n}{A_1} \cdot (\frac{a_n}{a_1})^2$
III	Balance of plant	
1a	electric supplies PF	$7.21 \times (\frac{B_{ton}}{B_{to1}})^2 \cdot \frac{A_n}{A_1} \cdot (\frac{a_n}{a_1})^3 \cdot (\frac{q_1}{q_n})^2$
1b	electric supplies NB	$3.60 \times \frac{A_n}{A_1} \cdot \frac{a_n}{a_1}$
2	electric generation	$1.54 \times \frac{A_n}{A_1} \cdot \frac{a_n}{a_1}$
3	cooling, cryogenics, contr.	$2.06 \times \frac{A_n}{A_1} \cdot \frac{a_n}{a_1}$
4	instrumentation	1.54
5	facilites	$2.06 \times \frac{A_n}{A_1} \cdot \frac{a_n}{a_1}$
6	assembly	$k_1 \times \Sigma(III,1 \div III,5)$
7	design	$k_2 \times \Sigma(III,1 \div III,5)$
IV	Indirects,allowance f.indet.	$k_3 \times \Sigma(I,1 \div I,10;III,1 \div III,5;II)$, $k_3 = 0.37$
	TOTAL COST	$\Sigma(I \div IV)$

The percentage figures given in Table 1, of course, depend on the overhead factors k_1 through k_3 and hold only for the k-values mentioned.

It is seen that several cost items have the same scaling dependence. When combining these and additionally introducing the condition of constant $\bar{\beta}$ for the INTOR versions to be compared (use of equations 3 and 4), the cost breakdown reduces to Table 2.

Table 2: Approximate INTOR cost (percent of total) for $\bar{\beta}$ = const.

	Reactor + Balance of plant	
I, 1+6	TF coils + support structure	$12.10 \times (\frac{A_n}{A_1})^2 \cdot (\frac{a_n}{a_1})^{1.5}$
I, 1	PF coils	$3.60 \times (\frac{A_n}{A_1})^{0.5} \cdot (\frac{a_n}{a_1})^{1.5}$
I,3+III,5	vacuum system + facilities	$5.66 \times (\frac{A_n}{A_1}) \cdot (\frac{a_n}{a_1})^2$
I,4+I,7	blanket/shield + neutr. beams	
I,8+III,1b	Tritium system + NB supplies	$15.70 \times \frac{A_n}{A_1} \cdot \frac{a_n}{a_1}$
III,2+III,3	electr. generation, cooling, cryogenics, control	
I,5+I,10+III,4	divertor, diagn., instrum.	3.09
I,9	reactor hall	$2.57 \times \frac{1 + A_n}{1 + A_1} \cdot \frac{a_n}{a_1}$
III,1a	PF supplies	$7.21 \times (\frac{a_n}{a_1})^2$
	Close support	$4.12 \times \frac{A_n}{A_1} \cdot (\frac{a_n}{a_1})^2$

TOTAL COST $(1+k_1+k_2+k_3)$ (reactor+balance of plant)
$+ \; (1+k_3)$ (close support)

For illustration Figure 1 shows the approximate INTOR total cost according to Table 2 versus a_n/a_1 with A_n as a parameter, the reference case being parameter set "A". The maximum toroidal field of equation 5 is used as a boundary condition which is given by the state of the art in high field superconductors. Also the pertinent thermal power is indicated. Obviously parameter set "B" is slightly more economical than set "A", since the higher field level required seems just to be tolerable at this stage of development. Keeping constant that field level parameter set "B" represents about the optimum to be found for constant $\bar{\beta}$; Lower cost could only be expected when going to larger A, but under the constraints imposed this would mean to achieve a lower safety factor q implying that

the core constraint would rapidly become much tougher.
The INTOR Guiding parameter set and the suggested parameter set "C" are not consistently to be shown in Figure 1 because they both deviate strongly from sets "A" and "B" assuming a higher safety factor and a larger proportionality factor in $\beta_{pol} = c_{\beta} \cdot A$, resulting in a larger $\bar{\beta}$-value.
Figure 2 gives a cost breakdown following the scheme of Table 2. Every cost item includes its own overheads. The shaded items PF supplies, blanket/shield etc., vacuum system etc. and TF coils etc. show the strongest dependence on plasma size and contribute the essential part of the total cost. (Figure 2 refers to $A_n = 4$ and thus includes case "B" for $a_n/a_1 = 0.93$).
Overall cost percentage figures (including overheads) for the cost items of Table 2 are given for parameter sets "A" and "B" in Table 3.

Table 3: Percentage cost breakdown for parameter sets "A" and "B"

Item	set "A"	set "B"
TF coils + supp.	22.9	23.2
PF coils	6.8	6.7
vacuum system etc.	10.7	10.2
blanket/shield etc.	29.7	30.5
divertor,diagn.,instr.	5.8	6.2
reactor hall	4.9	5.0
PF supplies	13.6	12.7
close support	5.6	5.4
	100.0	100.0

Both cost breakdown columns show rather similar figures implying that the larger absolute cost for parameter set "A" is due to larger size. It should be mentioned, however, that there might be a higher cost for the TF coils in case "B" because of the application of Nb_3Sn-superconductor in that case. This means that in reality the cost of set "B" could be even slightly higher than for "A" as opposed to the cost scaling shown here in which a transition in magnet technology has not been taken into account. Such considerations can play an important role also for other components, and these points have to be identified in due course as costing will be refined.

Modified constraints

The preceeding considerations could be applied only to cases "A" and

"B" because the other two sets assume a higher $\bar{\beta}$-value.
In order to show the influence of varying $\bar{\beta}$ it is assumed now, that

$$\frac{\beta_n}{\beta_1} = X$$

with the other constraints unchanged. Then equations 3 through 5 turn into

toroidal field $$\frac{B_{ton}}{B_{to1}} = \sqrt{\frac{1}{X}\cdot\frac{a_1}{a_n}} \qquad (3a)$$

safety factor $$\frac{q_n}{q_1} = \sqrt{\frac{1}{X}\cdot\frac{A_1}{A_n}} \qquad (4a)$$

max.tor.field $$\frac{B_{tmn}}{B_{tmo}} = \frac{A_n}{A_1}\cdot\sqrt{\frac{1}{X}\cdot\frac{a_n}{a_1}}\cdot\frac{\frac{a_1}{a_n}(A_1-1)-\frac{\Delta}{a_n}}{A_n-1-\frac{\Delta}{a_n}} \qquad (5a)$$

and in Table 2 the component cost I, 1+6 (TF coils and support structure) has to be divided by $\sqrt{X}$.
This means that for $X > 1$ the TF coil cost will be lower and the total cost will consequently be lower as well. This tells that the Guiding parameter set must have lower cost than case "B", and set "C" must be cheaper than "A". (The definitely lower cost estimate for the Guiding parameter set (see enclosure 2) compared to the other sets is also a result of the larger toroidal field ripple assumed in that case, whereas for the others a ripple of ± 0.75% was taken). As can be seen in Figure 1 a modified Guiding parameter set with the same B_{tmn}-restriction as "B" (and with the same $\bar{\beta}$ and q) would cost almost the same as "B" !
Figure 3 illustrates the interesting case of lowering $\bar{\beta}$, because the INTOR negotiations started with $\bar{\beta}$-figures of up to 7%, and they now settle at 5%. For $X = 0.8$ meaning $\bar{\beta} = 4\%$ the total cost at the same plasma size is about 18% larger for constant B_{tmn}, at the same aspect ratio (larger plasma size) it is 21% larger for constant B_{tmn}. The thermal power increases by 17% and 14% respectively.

Summary

A simplified cost approximation for INTOR parameter sets in a narrow parameter range is shown. Plausible constraints also used in the INTOR data base assessment phase permit the evaluation of the consequences of parameter variations on overall cost. Since the influence of the overhead costs on total cost is considerable, further detailed cost studies have to look more closely to the overheads too.

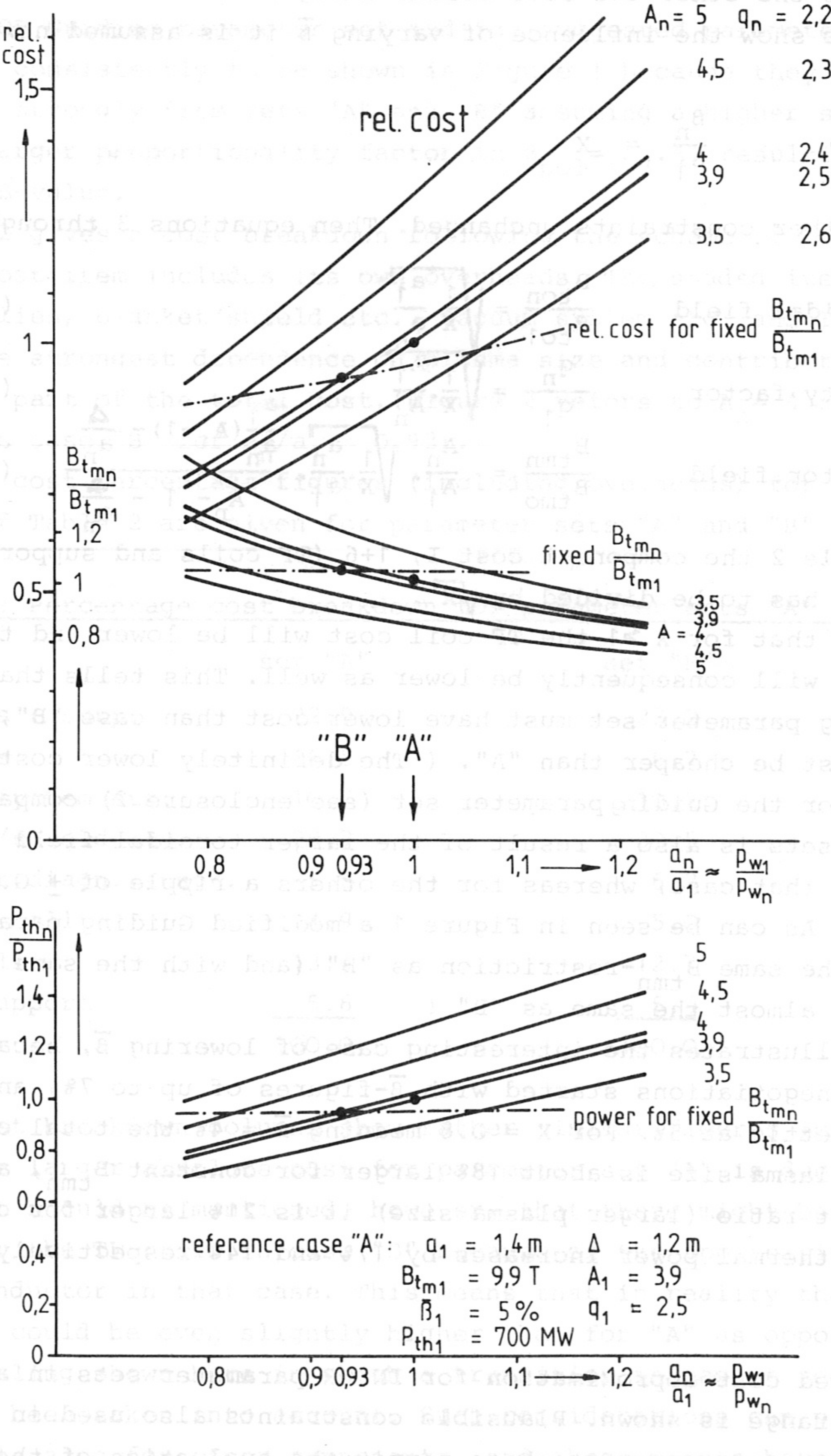

Fig. 1 INTOR cost and power scaling

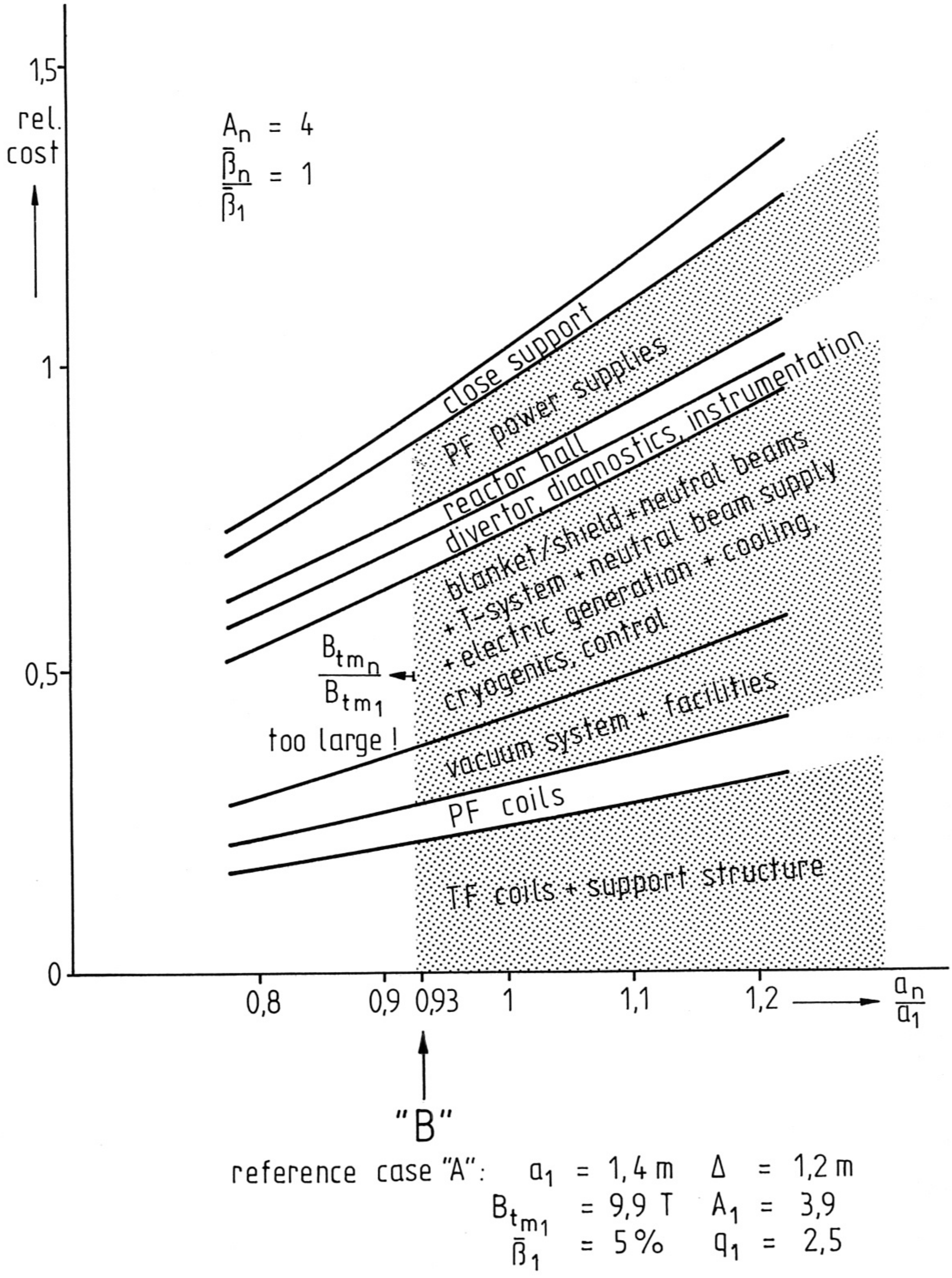

Fig. 2 INTOR cost breakdown

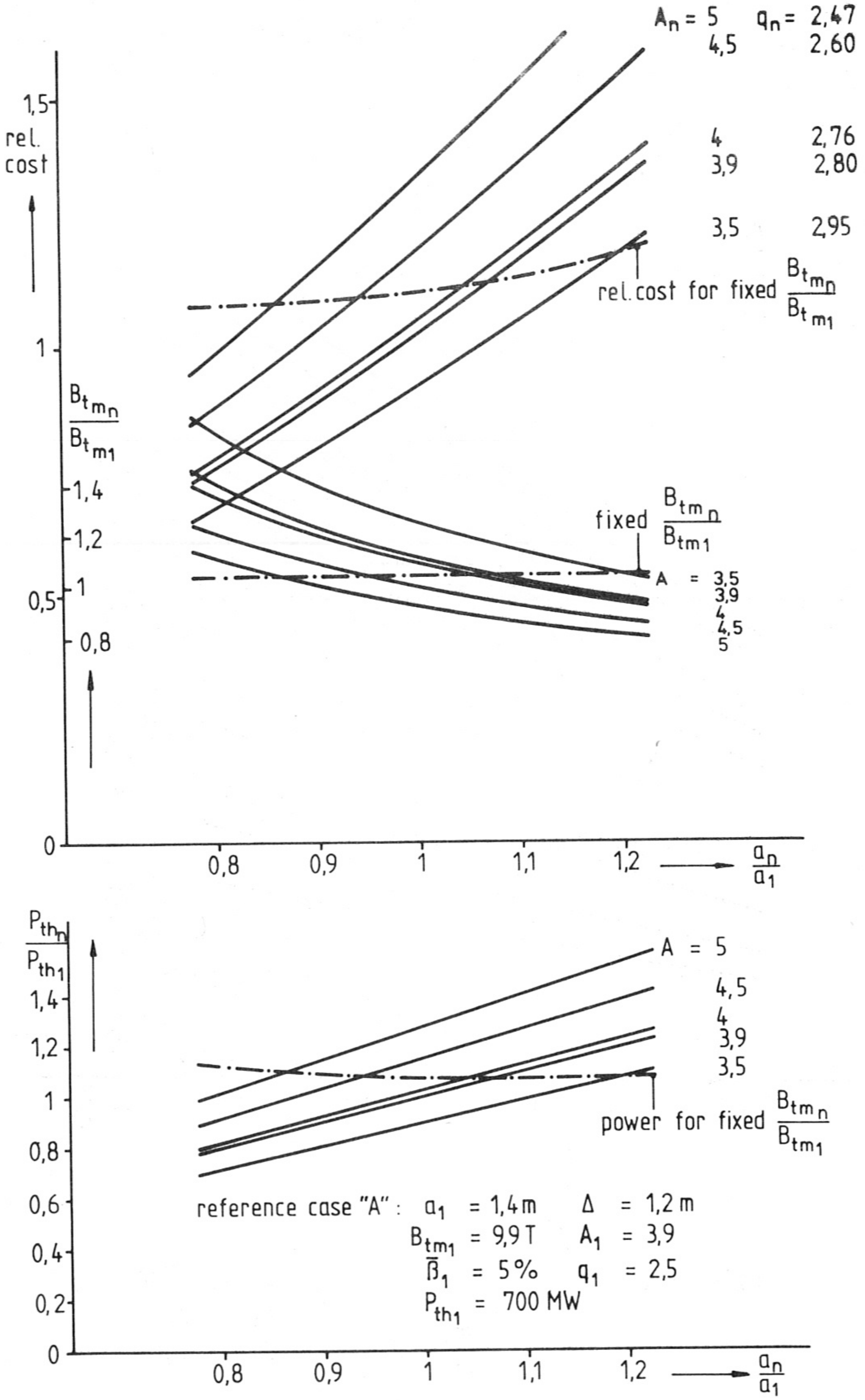

Fig. 3 INTOR cost and power scaling for X = 0,8

Enclosure 1

I N T O R - parameters

Par. set	Guid.par.July 79	Sugg.par.Oct.79 "A"	Sugg.par.Oct.79 "B"	Sugg.par.Oct.79 "C"
a_w (m)	1.3	1.5	1.4	1.5
R (m)	4.8	5.5	5.2	5.0
B (T)	5.2	5.2	5.5	5.0
a (m)	1.2	1.4	1.3	1.3
R/a	4.0	3.9	4.0	3.8
B_{max} (T)	10.5	9.9	10.6	10.4
b/a	1.6	1.6	1.6	1.6
$q_J(a)$	3.0	2.5	2.5	3.0
I_p (MA)	5.0	6.6	6.4	5.0
$\Delta\Phi$ (Vs)	75	115	110	90
$p_w(MW/m^2)$	1.3	1.3	1.3	1.6
		(1.6)	(1.6)	
S_{ch} (m^2)	(330)	435	380	(395)
P_{th} (MW)	500	700	620	800
		(870)	(760)	
ß (%)	6	5-6	5	7
		(6-7)	(6)	
kT (keV)	10	10	10	10
n (m^{-3})	$1.4 \cdot 10^{20}$	$1.3 \cdot 10^{20}$	$1.3 \cdot 10^{20}$	$1.6 \cdot 10^{20}$
		$(1.5 \cdot 10^{20})$	$(1.5 \cdot 10^{20})$	
Cost (rel.)	0.72	1	0.92	0.87
Δ (m)	1.2	1.2	1.2	1.2

Enclosure 2

Consequences of different INTOR parameter sets for INTOR cost estimates (prelim.)

In the following table the European cost breakdown (revised version as used in the group 17 report of the 3rd session INTOR workshop October 1979) is used to show the influence of different parameter changes on component and overall cost. (All cost figures in arbitrary units.) Set 1 = reference.

Parameter set	1=Guid.P.	2="C"	3="A"	4="B"	(scaling assumed)
Cost of Reactor					
TF coils	150	180	220	210	$\cdot(\frac{R_n \cdot B_{maxn} \cdot r_{maxn}}{R_1 \cdot B_{max1} \cdot r_{max1}})$
PF coils	40	50	70	60	$\cdot(R_n \cdot I_{pn}/(R_1 \cdot I_{p1}))$
Vacuum system	50	60	70	60	$\cdot(R_n \cdot a_n/(R_1 \cdot a_1))$
Blanket/Shield	40	80	50	50	$\cdot(R_n \cdot a_n \cdot p_{wn}/(R_1 \cdot a_1 \cdot p_{w1}))$
Divertor	10	10	10	10	constant
Support structure	10	10	15	15	$\cdot(\frac{R_n \cdot B_{maxn} \cdot r_{maxn}}{R_1 \cdot B_{max1} \cdot r_{max1}})$
Neutral beams	80	80	90	85	$\cdot(R_n/R_1)$
Tritium system	20	20	25	20	$\cdot(R_n \cdot a_n \cdot p_{wn}/(R_1 \cdot a_1 \cdot p_{w1}))$
Reactor hall	40	40	50	50	$\cdot((R_n+a_n)/(R_1+a_1))$
Diagnostics	20	20	20	20	constant
Assembly	70	90	90	80	prop. like case 1
Design	170	210	230	215	prop. like case 1
Cost of Close Support	60	70	80	70	$\cdot(R_n \cdot a_n/(R_1 \cdot a_1))$
Cost of Balance of Plant					
Electric supplies	130	130	210	190	$(\frac{70 \cdot I_{pn}^2 \cdot R_n}{I_{p1}^2 \cdot R_1} + \frac{60 \cdot R_n}{R_1})$
Electric generating	20	30	30	25	$\cdot(P_{thn}/P_{th1})$
Cooling,cryogenics,constr.	30	50	40	35	$\cdot(P_{thn}/P_{th1})$
Instrumentation	30	30	30	30	constant
Facilities	30	30	40	35	$\cdot(R_n \cdot a_n/(R_1 \cdot a_1))$
Design	80	90	120	120	prop. like case 1
Assembly	40	50	60	50	prop. like case 1
Indirects, Allowance for Indeterminates	280	340	390	360	prop. like case 1
TOTAL	1400	1690	1940	1790	

With respect to the lack of detailed definition for the sets 2, 3 and 4 only the following rough cost figures should be quoted:

TOTAL	1400	1700	1900	1800

For definition of parameter sets see Enclosure 1.

In the cost scaling a lower TF ripple than in case 1 is anticipated.