INTOR: CRITICAL ANALYSIS OF INTOR-LIKE DESIGNS

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Abstract

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A critical and comparative analysis of existing INTOR-like designs has been made. The national designs of the four INTOR Partners and the physical and technical constraints on which they are based have been evaluated. The modelling methods used in reactor design have been further developed and compared to test their consistency. Deep insight into the cross-relations between design details and constraints and selected features has been obtained.

1. INTRODUCTION

The original INTOR work plan for the last year (1987) of the INTOR activity originally consisted of an updating of the early (1981) INTOR design concept [1] in order to introduce the results of the studies on critical issues and the evolution of the database. When the discussions on the new ITER activity started, this work plan was changed. The updating of the INTOR design concept was cancelled and replaced by a short and concise list of the changes to be made in the design concept [2], and the time gained in this way was used for a critical analysis of INTOR-like designs. This new work was performed by the INTOR Workshop with the aim of preparing valuable tools and a useful information base for future design work for an engineering test reactor.

2. DESIGNS AVAILABLE

The designs available were FER (Japan), INTOR as of Phase Two A, Part II (International Atomic Energy Agency), NET (European Community), TIBER (United States of America) and OTR (Union of Soviet Socialist Republics). The five designs are characterized by their gross parameters as listed in Table I.

During an INTOR Specialists' meeting [2] on this subject the descriptions of the five designs were converted into a common format in order to make possible a discussion and comparison of the programmatic and technical objectives, the physics and

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[2] The members of the INTOR Group are identified in Paper IAEA-CN-50/F-I-1.

TABLE I. MAJOR PARAMETERS OF INTOR-LIKE DESIGNS

	INTOR	NET	FER	TIBER	OTR
Major radius (m)	5.00	5.18	4.42	3.00	6.30
Minor radius (m)	1.2	1.35	1.25	0.83	1.50
Fusion power (MW)	585	650	406	314	500
Plasma current (MA)	8.0	10.8	8.8	10.0	8.0
Average beta (%)	4.9	5.6	5.3	6.0	3.2
Safety factor, q_I	1.8	2.1	1.8	2.2	2.1
Heating method/power (MW)	ICRH/50	TBD[a]/50	ICRH/50 LH/20	LH/10 NBI/40	ICRH/50
Number of TF coils	12	16	12	16	12
Maximum field at TF coils (T)	11	11.4	12	12	11.7
Volt-seconds	112	181	50	58	210
Neutron wall load peak/ average ($MW \cdot m^{-2}$)	1.6/1.3	1.5/1.0	1.5/1.0	1.6/1.0	1.05/0.8
Tritium inventory (kg)	3.1–4.6	2	2	TBD[a]	3.5–5.0
Test first wall area (m^2)	12	40	9	19	

[a] To be determined.

engineering design constraints, the main features that drive the design concept, and the design specifications. The critical analysis [2] of these designs should reveal the detailed causes for the differences between the designs and yield information on the impact on the design of specific decisions on constraints, features, etc.

For this analysis the designs show rather significant differences in the adopted methods or features and in the resulting parameters. The features provide for:

- Plasma performance: Q = 5 to ignited;
- Current drive method: inductive or non-inductive;
- Pulse length: pulsed ($\geq$150 s) to steady state ($\geq$1 week);
- Divertor: single null (SN) or double null (DN);
- Tritium breeding capacity (for tritium supply): none to full;
- Plasma heating: various RF schemes, NBI.

The relative span of the parameters covered by the designs is apparent from Fig. 1, and comparison of the horizontal builds in Fig. 2 provides a perhaps even clearer impression.

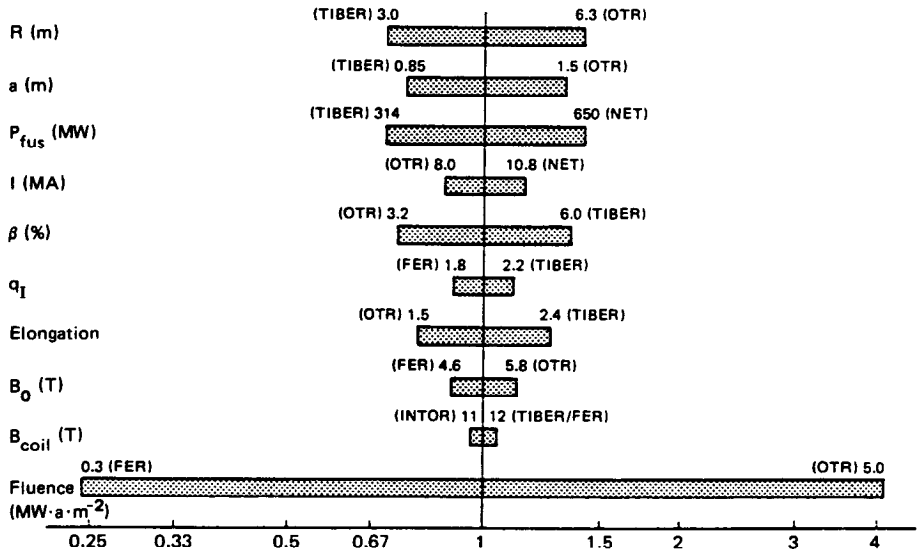


FIG. 1. Relative span of the parameters covered by the designs.

3. CRITICAL ANALYSIS

The analysis is aimed at determining the detailed reasons for the rather large differences between the designs. The reasons might fall into the following categories:

- Objectives,
- Design philosophy,
- Physics assumptions and constraints,
- Engineering design constraints,
- Others.

The results of the study will yield quantitative information on design drivers which have a large impact on the design. For these items a careful assessment of the determining constraints and parameters is important and expansion of the related database by R&D should be particularly rewarding.

Comparison of the objectives as formulated by the leaders of the individual design teams shows that all the designs have in common the purposes of providing an essential step forward, leading to a well balanced point between the present generation of large devices and DEMO, aiming at reactor relevant operating conditions, applying reactor relevant technologies and providing for engineering testing. Differences in the objectives mainly result from strategic considerations and differences in expected budget availability. Thus the differences express themselves mainly as differences in the fluence goal (which also concerns the operating cost) and in the

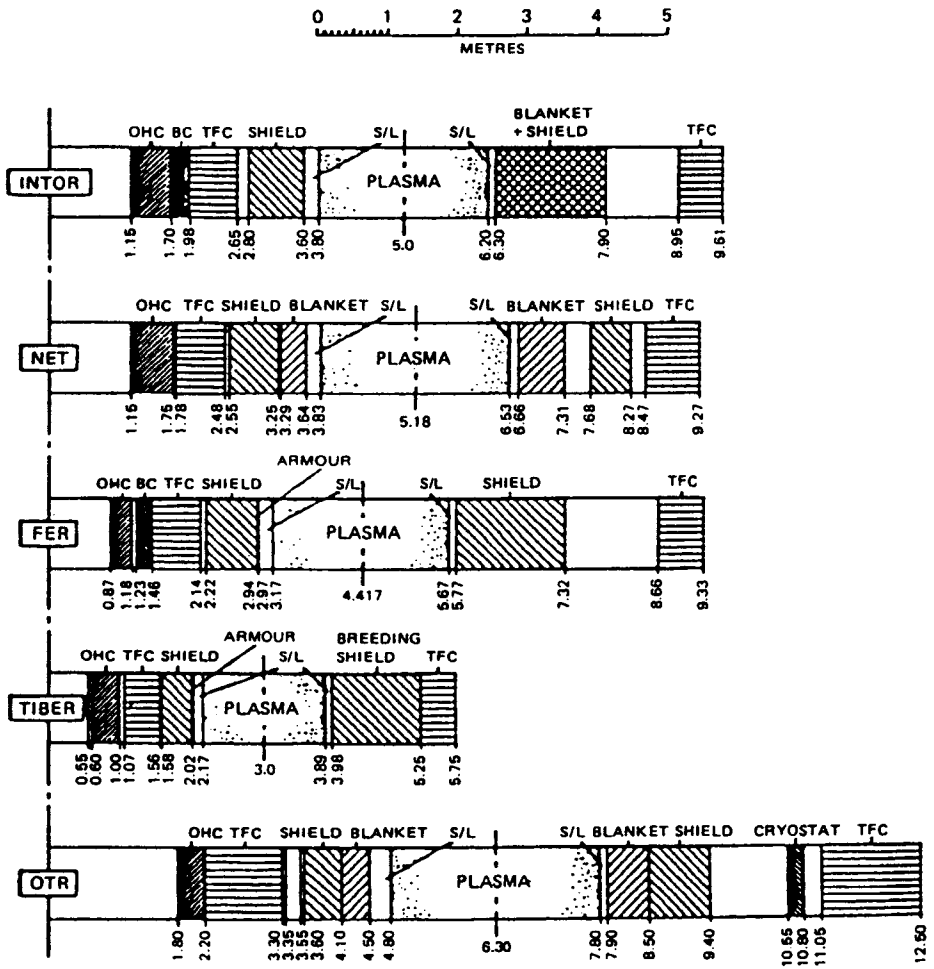


FIG. 2. Comparison of horizontal builds.

intended tritium breeding capability, which is related to the fluence goal. Within the depth of this analysis the fluence target has only a moderate influence on the design and only affects the thickness of the shield. Thus, a difference in objectives is not the prime cause for the differences between the designs.

The other categories require a more detailed analysis. System codes were the tools used for this purpose. Such codes are in use by all INTOR Partners. They are rather elaborate and designed to replicate a design in very great detail. The prevailing design philosophy is a built-in property of these codes. The codes were tested by comparisons between them. This was done by applying them not to their own design but to the design of a Partner, replacing their own input assumptions and constraints

TABLE II. PHYSICS CONSTRAINTS

	INTOR	NET	FER	TIBER	OTR
I_p (MA)	8	10.8	8.74	10	8
K (at 95% of magnetic flux)	1.6	2.05/1.7	1.7	2.4	1.5
$\tau_{E,\ required}$ (s)	1.4	1.9	1.7	0.44	1.7
$\tau_{E,\ ASDEX\text{-}H}/\tau_{E,\ required}$	2.9	3.0	2.3	6.8	3
n (10^{20} m^{-3})	1.6	1.7	1.14	1.06	1.7
Murakami parameter[a] (10^{19} $T^{-1}\cdot m^{-2}$)	19	23	15	8	25
Beta required (%)	4.9	5.6	5.3	6	3.2
Troyon coefficient (%)	4	3.5	3.5	2.8	3.5
Impurity control, divertor type	SN	DN/SN	SN	DN	SN
Pulse length (s)	150	350	800	55	600
Heating	ICRF	TBD[b]	ICRF (LH for ramp-up)	LH + NBI	ICRH

[a] Estimated using line average density.
[b] To be determined.

by those of this Partner and then comparing the result with the Partner's design. After some minor improvements all of the codes were able to replicate the designs of any Partner if the input assumptions were adjusted accordingly. This means that:

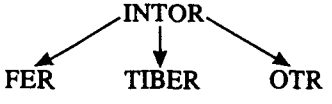
— The predictive powers of the system codes of the Partners are very close to each other.
— The design philosophies on which the codes are based are more or less the same.

It thus follows that the differences between the designs are the consequence of the differences in the decisions on the constraints determining the designs and in the selection of design features. It thus becomes possible, by comparing the designs, to directly study the reaction of a design to a variation of the constraints and features. Tables II–IV list the physics constraints, the engineering design constraints and the design features for the five examples.

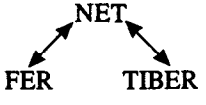
This study was performed by starting from one design and then replacing successively the physics picture, the engineering picture and the features by those of another design and by checking the outcome. This was done for

TABLE III. MAJOR ENGINEERING DESIGN CONSTRAINTS

	INTOR	NET	FER	TIBER	OTR
Field ripple at edge (%)	1.2	1.5	0.75	0.8	1.0
Impurity control	SN	DN/SN	SN	DN	SN
Plasma elongation (at 95% of magnetic flux)	1.6	2.05/1.7	1.7	2.4	1.5
Maximum radiation to TF coil insulator (rad)	10^9	5×10^8	3×10^9	10^{11}	10^9
Allowable TF coil stress	ASME	600 MPa	600 MPa	600 MPa	600 MPa
Maximum first wall heat flux ($MW \cdot m^{-2}$)	0.4	0.4	0.4	0.3	0.4
Allowable first wall stress	ASME	RCC-MR	ASME	ASME	200 MPa
Directed peak heat flux ($MW \cdot m^{-2}$)	5	5	2	3	5



and for



As an example the transition from NET to FER is shown going from top to bottom in Fig. 3. The figure shows the radial build, starting from the axis of rotation on the left, followed by the regions of the OH central coil, the inner leg of the TF coil, the inboard shield, the inboard blanket, the plasma, the outboard blanket, the outboard shield and the outer leg of the TF coil. The figure starts from the NET-DN configuration. The first step, A-1, replaces the NET physics picture by that of FER, but does not yet change the radius of the OH transformer coil. The FER physics is more optimistic than the NET physics and thus leads to a smaller plasma radius and, simultaneously, to a longer burn time. The latter is corrected in step A-2, where the central bore is reduced such that the reduction in volt-seconds corrects for the excess in burn time. This case represents a NET with FER physics. The next step

TABLE IV. MAJOR DESIGN DRIVING FEATURES

	INTOR	NET	FER	TIBER	OTR
Operating mode	Ignited	Ignited	Q > 20–30	Q > 5	Q > 5
Pulse length (s)	150	>200	800	CW	600
Current drive	Inductive	Inductive	Hybrid	Non-inductive	Inductive
Fluence ($MW \cdot a \cdot m^{-2}$)	3.0	0.8	0.3	3.0	5.0
Tritium breeding rate	0.6	0.3	0.0	1.0	1.05
Plasma heating method	ICRH	TBD[a]	TBD[a]	NBI + LH	ICRH
Impurity control	SN	DN/SN	SN	DN	SN
Access for maintenance	Horizontal	Vertical	Horizontal	Horizontal	Horizontal
Weight of largest replaceable component (t)	300	60	250	32	300
Availability/period	25%/10 a	8%/11 a (25%/1a)	7%/6 a	30%/12 a	50%/9 a

[a] To be determined.

introduces the FER engineering: the current density in the TF coils is increased together with the thickness of the outboard shield, which simultaneously leads to the reduction of the field ripple from 1.2 to 0.75%. Then, in step C-1, some of the features are modified. The NET double null divertor is replaced by the FER single null divertor. The elongation is reduced from 2.0 to 1.7 and a bucking cylinder is introduced to support the TF coils, the number of which is reduced from 16 to 12. This change leads to a more circular plasma with a correspondingly larger diameter and requires a larger neutral bore for obtaining the needed volt-seconds. With only 12 TF coils their outer legs have to extend rather far in radius to keep the field ripple down to 0.75%. The final step, C-2, removes the blanket, introduces the low FER fluence target and assumes some RF support in generating and driving the plasma current. A comparison with Fig. 2 demonstrates that the introduction of the FER physics, engineering and features into the NET design leads in fact to the FER design. This means that the impact of the various modifications is understood quantitatively. There is no need for qualitative changes of the system codes. The results can be considered to be rather accurate. They also show that each of the three categories — physics, engineering and features — has considerable influence, although there is some difficulty in defining conclusively what item belongs to which category.

These investigations also allow conclusions to be reached on which items have the highest or the lowest impact on the design. In this connection it is necessary to remember that the impact is the product of the sensitivity times the potential variation

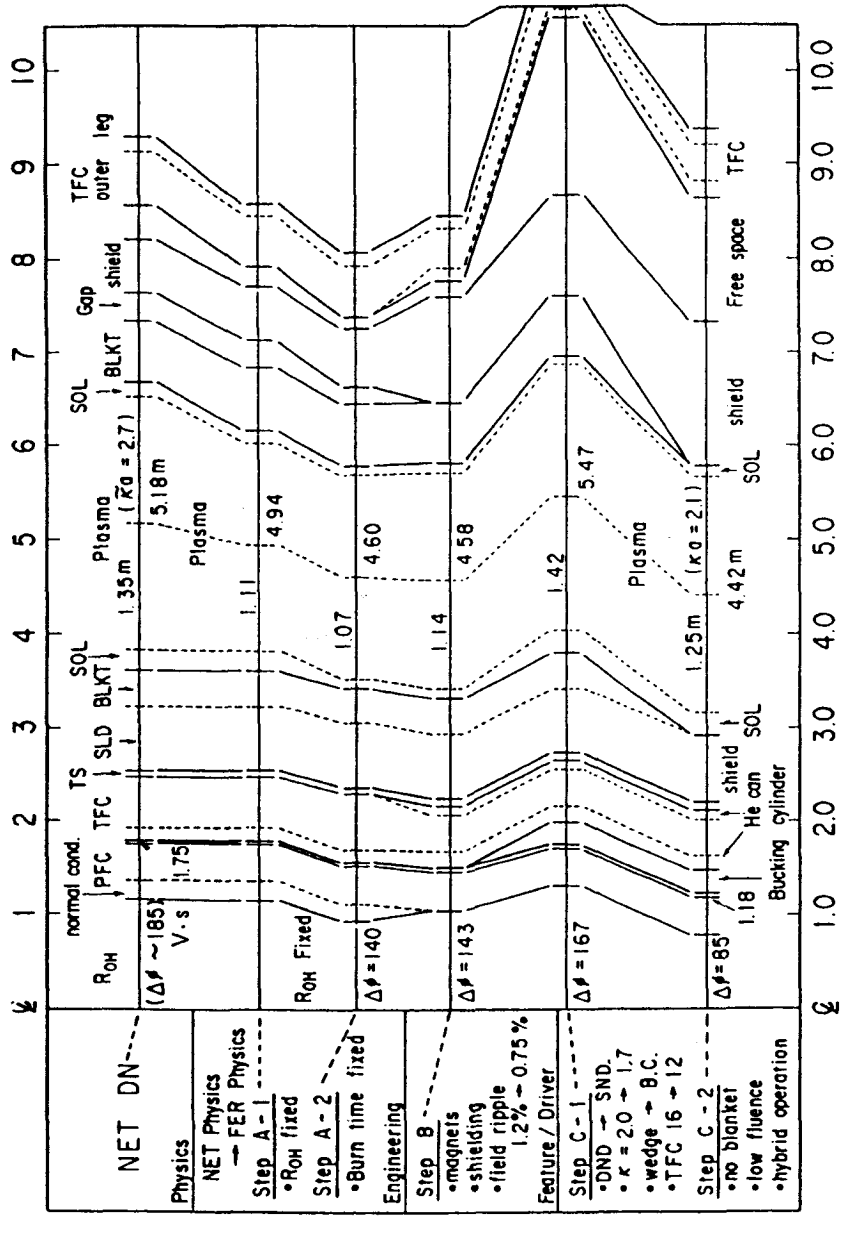


FIG. 3. Radial build. Transition from NET to FER by successive replacement of the NET constraints by the FER constraints.

of the parameter under study. The sensitivity can be deduced from the above studies. The potential variation of the parameter relates to the degree of knowledge and either constitutes a risk for achieving targets or requires the introduction of safety margins which might be expensive. This is related to the quality of the database and the corresponding R&D. On the other hand, considerable uncertainties can be accepted where the sensitivity is low. From the results of such evaluations the following were determined:

— Items with the strongest sensitivity to changes:
  Ignition margin or Q [1]
  Safety factor (q)
  Elongation
  Shield attenuation[1]
  Z_{eff} and reactivity[1]
  Neutron wall load
  Beta scaling coefficient (Troyon factor)
  TF coil stress.

— Items with the weakest sensitivity to changes:
  Fluence
  Burn time
  Presence/absence of bucking cylinder[1]
  Presence/absence of inner blanket[1]
  Shield thickness
  Scrape-off layer (inboard)
  Edge ripple[1]
  Plasma inductance[1]
  Plasma profiles
  Volt-seconds
  Radiation dose to insulator[1].

This list is still subject to some scatter between the results obtained by the individual Partners. This is not so much a consequence of the quality of the codes but rather is caused by differences in what is kept constant and what is allowed to change.

4. CONCLUSIONS

Because of the large spread in the parameters of the available INTOR-like designs, a deep insight into the impact of the various design determining properties has been obtained. This was made possible by the utilization of system codes describing the design in rather elaborate detail. These codes have been checked for their

[1] Studied by only one delegation.

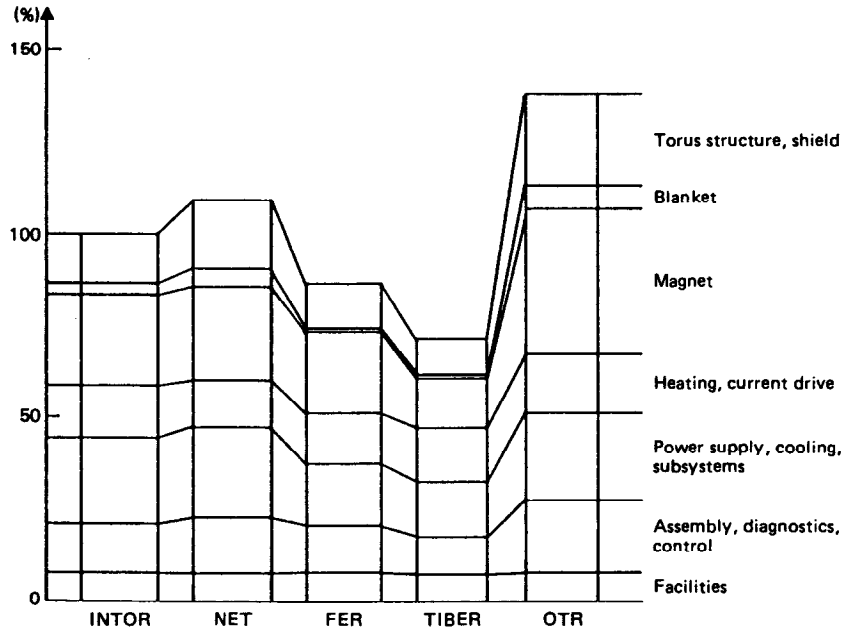


FIG. 4. Comparison of the costs of the individual designs.

predictive power and their degree of accuracy. The results obtained have qualified these codes as fast and reliable aids both for designers and in the definition of R&D programmes. The degree to which the various constraints or features impact the design has been analysed and a list has been established. This list shows items where R&D is particularly rewarding and others with only a small impact on the design. The amount of the potential influence is best demonstrated by a comparison of the direct capital cost of the compared designs, for which calibrated codes also exist. An example is given in Fig. 4, which shows a breakdown of the direct capital costs relative to those of INTOR. These analyses scatter by about 5–15% between the Partners because they also reflect the national traditions with respect to how large projects are organized in their relation to industry. Keeping this in mind one can conclude that in comparison with INTOR the direct capital costs

— Of NET are about the same,
— Of FER are about 10% lower,
— Of TIBER are about 35% lower, and
— Of OTR are about 25% higher.

These are non-negligible factors, indeed.

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