Luis Fernando ROJO VIRSEDA has a Physical Science degree from the Universidad Complutense of Madrid (University of Madrid) and a Degree in Nuclear Engineering. Since 1971 in the JEN (Nuclear Energy Authority) and from 1974 at INITEC, he has developed work related to the nuclear field, participating, among others, in the projects for the Ascó Nuclear Power Plant, Vandellós-II Nuclear Power Plant and preliminary stage of the Escatrón Nuclear Power Plant, which were performed by the latter firm.
Since 1986, assigned by INITEC, he has been participating in the TJ-II Project, a thermonuclear fusion device by magnetic containment, sponsored by the CIEMAT-EURATOM Association.

COLLABORATION ON A RESEARCH PROJECT

AN ENGINEERING EXPERIENCE

L. F. ROJO

The final objective of nuclear fusion is the production of energy, but on a short and medium term basis it is a way of fostering scientific development and progressing in the field of advanced technologies. Their complexity requires a close international cooperation in order to obtain faster results. An example of this collaboration is the EEC's fusion program, to which Spain contributes within the framework of the Plan Nacional de Fusión (National Fusion Plan).

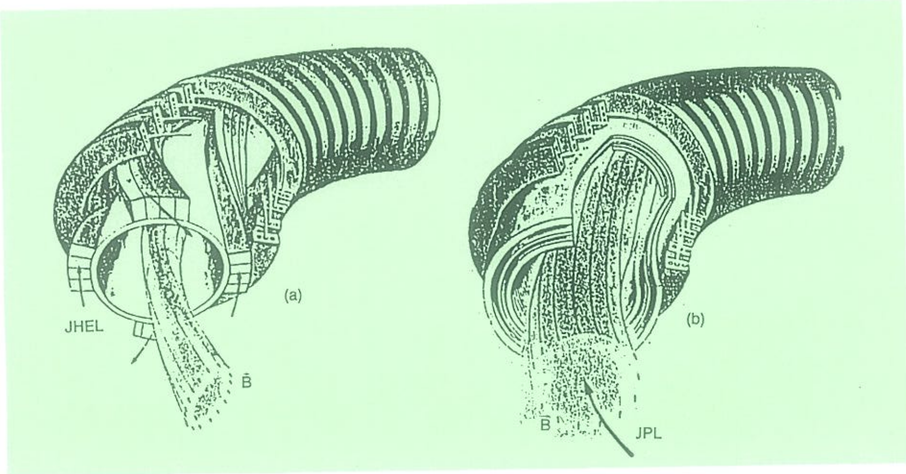
Since the signature in 1980 of a cooperation agreement between Spain and Euratom in order to foster fusion development, and more specifically since 1986, the year of our full integration in the European Community, the Centro de Investigaciones Energéticas, Medio Ambientales y Tecnológicas (CIEMAT – Energetic, Environmental and Technological Research Center) has become associated with Euratom's fusion program. This circumstance has lead CIEMAT to consider the necessity of establishing a laboratory and a fusion plan, relying on Euratom's counselling for this plan as well as on the collaboration of the Oak Ridge National Laboratory (USA), and of the Max Planck Physical Institute of Plasma at Garching and the Karlsruhe Research Center, both in Germany. In order to fulfill these objectives it was decided to start project TJ-II in 1983, defining it in principle as a plasma confinement experiment to complement Euratom's fusion program. It should be emphasized that in no case whatsoever will the TJ-II become an experimental fusion reactor, but rather, as has already been mentioned, it will be a device to study confinement characteristics, the exploitation of which could lead to conclusions regarding the future construction of electric power production plants.

Considering that the European efforts are mainly centered on the field of tokamaks, and due to the reason stated above, it was thought preferable to deal with a magnetic confinement concept other than the tokamak concept, i. e. that of stellarators.

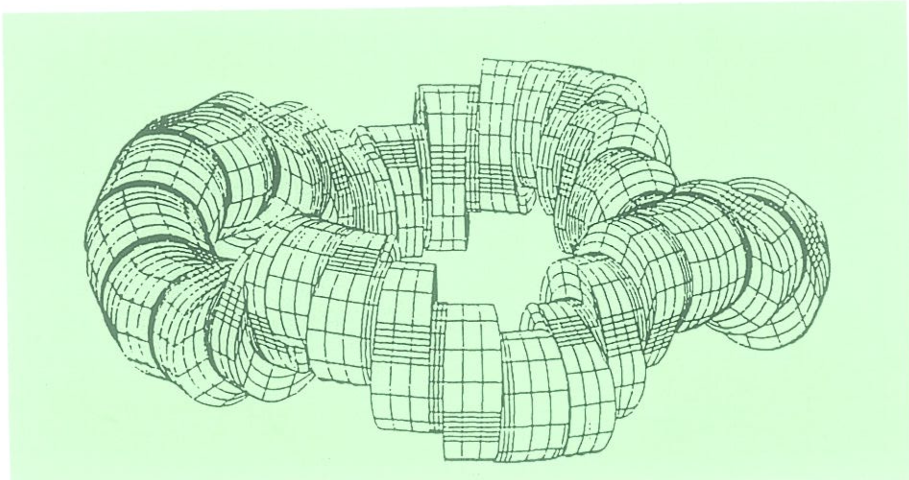
The stellarators cover a wide variety of possible configurations, of which only a limited number have become experimental devices. In the history of controlled fusion, these machines were one of the first designs, previous even to the tokamak, since they started to be studied in the fifties and sixties, but were practically abandoned in favor of the tokamaks in the seventies. Presently, the stellarators have attained confinement characteristics similar to those of tokamaks of equal size.

Since the end of 1983, CIEMAT's fusion group and ATF's design group at Oak Ridge have been collaborating on a study of torsatron and heliac configurations, both belonging to the stellarator family. Since the ATF is a torsatron and for diversification purposes, the CIEMAT settled for the heliac option. There are only two precedents of the

latter in the world, a small toroidal machine in Australia, "SHEILA", and a linear version in the United States of America.
As of last May 31, with the preferential agreement between CIEMAT and Euratom, Project TJ-II was begun under the authority of a committee formed by Euratom members and representatives from Spanish organizations, each one of which has the right to veto the activities carried out in this field, offset by Euratom's financing of 45 percent of the expenses generated by the project.
The challenge to an engineering firm on participating in a project of these characteristics with its corresponding technological innovations, as well as the opportunity to compare the different working methods involved in the task of basic research and that of industrial development, encouraged INITEC to collaborate by integrating members of its staff in the TJ-II project. The TJ-II, which is a stellarator, is different from the tokamaks in that there is an absence of net electric currents in the plasma.
As a matter of fact, in the latter devices, the torsion or helicity of the magnetic field needed for plasma confinement is obtained by means of combining toroidal and poloidal fields. This poloidal field (see Figure 1b) is created by generating an electric current in the plasma, which turns the tokamaks into devices of pulsing operation regarding this aspect, since magnetic flow variations are required in order to induce the mentioned current. However, this operating mode presents two serious drawbacks. In the first place, their pulsating character results in a greater material fatigue. Secondly, due to the existence of currents in the plasma, there is a possibility that disruptions thereof could appear on the confinement chamber walls, with the obvious risk of serious damage.
On the contrary, in the stellarators (Fig. 1A), the field helicity is obtained by means of helical coils outside the chamber, without any need of creating electric currents in the plasma. Nevertheless, in spite of being able to operate under stationary conditions, this type of machine, due to its high electric power consumption, normally operates in a discontinuous manner during this experimental stage, although both the stellarators and the tokamaks seek to operate in a continuous manner as it is suitable for future reactors.
As already mentioned, the heliac group to which the TJ-II belongs pertains to the wide range of possible configurations for the stellarators. In this type of machine, the magnetic field helicity is attained by means of a special layout of coils, which causes a torsion of the chamber itself. As opposed to the rest

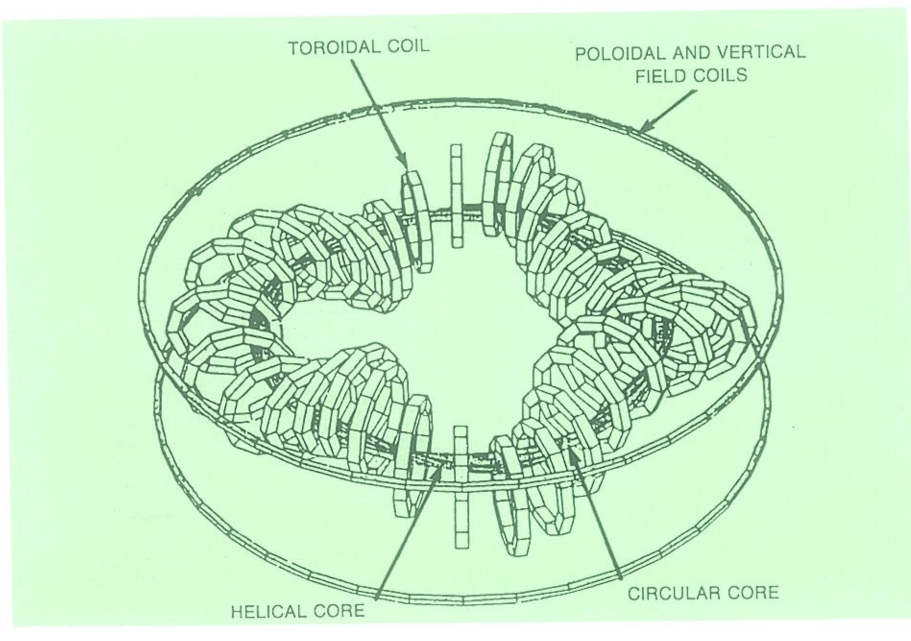


F I *Schematic representations of (A) a STELLARATOR and (B) a TOKAMAK*



F II *TJ-II Confinement chamber*

F III *Coil arrangement in the TJ-II*



of the stellarators, in which the magnetic axle, which could be defined as the approximate geometrical center of the points that join the plasma in each section along the torus, is straight toroidal, in the heliac it is helical toroidal, resulting in a confinement chamber of great geometrical complexity (Fig. II).
In an overall view, the layout of TJ-II coils is the following (Fig. III):

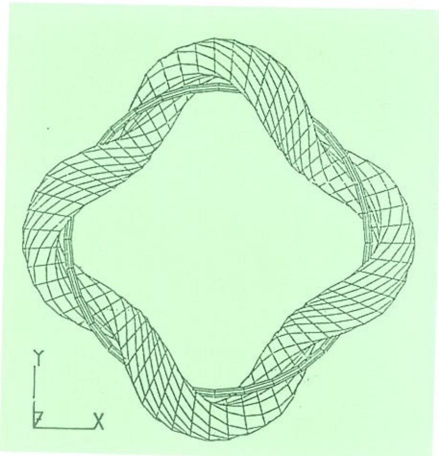
- A circular central coil or circular core.
- 32 toroidal coils whose centers form a helix around the circular core.
- Coils of vertical and poloidal fields.
- A helical coil or helical core placed on the circular core and in phase with the toroidal coil centers.

This last coil will allow a large margin of operating points to the TJ-II, for which reason the configuration receives the name of "heliac flexible".
Without going into a detailed description of the functions of each type of coil, it suffices to say that the resulting form of the plasma is that which appears in Fig. IV, which shows a plan view with the circular core as reference. Observe that, in spite of constituting a torus, the TJ-II plan view is clearly square, which produces symmetries which, as will be seen hereinafter, have their importance.
Table I below gives a summary of the components of the TJ-II system.
Firstly, the machine itself, which consists of:

- Vacuum chamber.
- Coils.
- Supporting structures.

The vacuum chamber will be of modular, rigid, fully welded construction based on flat developments, since it could serve to support the toroidal coils, with possibilities of cooling and with a construction tolerance not exceeding 5 mm in some cases and also allowing easy access to the plasma inside.
The core coils must be continuous, without mechanical joints or welds in order to avoid unequally thick areas, weak points which could give rise to electric failures or areas of very high resistance which, considering the currents that run through, could cause local heating therein. Likewise, to provide for its cooling needs, the conductors will be hollow with water cooling. In the case of the core coils, which are the only ones subjected to vacuum due to their location inside the chamber, there is the additional problem of their isolation from the outside. The primary function of the supporting structures of the chamber will be to absorb the magnetic forces that are generated in the toroidal coils when the latter rest directly on the chamber.
The power supply for the TJ-II can be estimated at 140 MVA, although since its operation will be pulsating, with an expected pulse duration of 1 second, the required energy in each tripping will be 90 MJ. However, since the electric power supply at the CIEMAT does not reach this latter value in such a short period of time, it will be necessary to provide a power storage device, probably by means of an inertia wheel which, in the period between 2 consecutive pulses, should permit the accumulation of the necessary energy to be delivered to the coils. The cooling system will be in charge of extracting the generated heat in the coils after each tripping, as well as the heat that could be created in the microwave injectors, that will be used to heat the plasma, as explained below.
The vacuum system performs two functions. The first, obvious one is to make the vacuum inside the chamber, for which it is provided with the molecular turbopumps capable of obtaining 10^{-8} Torr. The second function is to inject gas, hydrogen in the first experiment and possibly deuterium in the more advanced ones, from which the plasma will be formed.
The purpose of the microwave injection system is to produce and introduce electromagnetic radiation in the plasma, the frequency of which is resonant with that of the plasma electrons moving in a magnetic field of a given intensity, which in the case of TJ-II is of 1 Tesla. Through these resonances, energy is trasmitted to the electrons which by collisions distribute it to the opposite population, ions in this case, thus fully heating the plasma. This is a necessary condition, since the higher the temperature the lower the energetic losses, and also considering that in future fusion reactors, the nuclear reaction only takes place above a threshold or ignition temperature. The elements making up the system are basically the gyrotrons (microwave producers), the waveguides and the launching devices.
It should be noted that the electric supply for the gyrotrons is independent from that of the coils, so that to the high electric power needed for the later them, it is necessary to add the not at-all negligible consumption of the microwave system.
The injection of neutrals has the same purpose as that of the microwaves, that is, heating the plasma. Essentially, it consists of introducing neutral atoms in the plasma which through collision transmit their energy to the plasma before ionizing and becoming confined by the magnetic field. Apart from producing heat, this method has the additional appeal of being able to be used to inject fuel, merely by having the element used as neutral beam coincide with that making up the plasma. The use of neutral beams in advanced stages of exploitation is planned in the TJ-II.
The fact that the plasma should remain free of impurities, given the fact that the presence thereof contributes through radiation phenomena to rapidly cool it, makes it necessary to have a cleaning system available that can eliminate any foreign elements from the chamber's inside walls in order to later remove them. It must be taken into consideration that, due to the high level of

F IV *Magnetic surfaces of the plasma in TJ-II*



T I

TJ-II SYSTEMS

MACHINE	
	- VACUUM CHAMBER - COILS - SUPPORTING STRUCTURES
POWER SUPPLY	
COOLING SYSTEM	
VACUUM SYSTEM	
	- TURBOMOLECULAR PUMPS - GAS INJECTION SYSTEM
MICROWAVE INJECTION	
	- GYROTRONS - WAVEGUIDES - LAUNCHING SYSTEM
NEUTRAL BEAM INJECTION	
CLEANING SYSTEM	
CONTROL SYSTEM	
DIAGNOSTICS	
DATA ACQUISITION AND PROCESSING SYSTEM	
ANCILLARY SERVICES	
	- ELECTRIC POWER - COOLING AND GROUNDING NETWORKS - AIRCONDITIONING - COMPRESSED AIR - WATER - LIGHTING - PUBLIC ADDRESS SYSTEM

vacuum, the slightest trace of impurity expands to considerable volumes.

The remaining systems of the TJ-II satisfy either the operating requirements, control system, or the evaluation requirements of working conditions, diagnostics system or the compiling and processing of information, data acquisition system and computer, or finally the auxiliary installations involved in any experimental complex: electric power supply, cooling and grounding network, air conditioning, lighting, etc.

As a summary of the above, Figure V contains a table of the main TJ-II parameters, among which the most important are the main radius, 1.5 m, which corresponds to the central coil radius of the core, the magnetic field in the plasma center, 1 Tesla, the tripping frequency, one every five minutes, which allows returning to the initial conditions before the new pulse, the injected microwave power, 400 kW, and that of neutrals which will reach 4 or, possibly, 6 MW.

In a project of this nature specific engineering problems necessarily arise that, due to the novelty of the field of study, have probably not been undertaken previously. For instance consider the following:

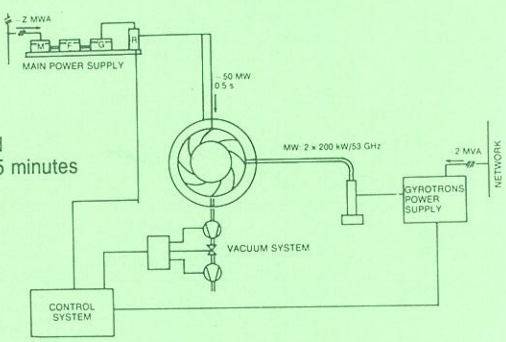
- Construction accuracy. The TJ-II magnetic configuration is very sensitive to small errors in the magnetic field caused by deformations or small deviations in the coil's correct position. This accuracy depends on the symmetry. In effect, the TJ-II is a machine of symmetry 4, that is, its magnetic configuration repeats itself exactly four times along the torus. If the deformations do not break the symmetry, construction errors up to 1 cm may be accepted, but if they do break it, the maximum accepted deviation is only 1 mm. Needless to say, this rule considerably complicates things when dealing with the electric power supply to the coils or establishing the location points for diagnostics.
- Use of magnetic materials. In order not to disturb the magnetic field of the plasma, it is necessary that both the vacuum chamber material and the welding used in its construction be of very slightly magnetizable materials. It has even become necessary to study what disturbances the existence of transformers or other ferromagnetic materials in the vicinity of the chamber could produce in the plasma.
- Pulsating nature of the operation. This paragraph fundamentally affects the need for fast switchings. It must be remembered that the total duration of the pulse is one second in the electric power systems to the coils which, on the other hand, transport high currents. This working mode likewise implies sudden temperature transients which without doubt contribute to material fatigue.
- Plasma – material medium interphare. Figure VI shows a section in which the typical bean-shape that plasma adopts in TJ II can be observed.

If consideration is given to its proximity to the inner wall of the chamber, represented by the outside circle, and the short distance that separates it from the core coils (in the figure the two small circles on the plasma), it will be understood that it is necessary to prevent an accidental contact which, more than producing considerable damage, as might happen in the case of the coils, a very undesirable occurrence, could lead to plasma contamination. This situation can be avoided by the use of limiters, devices that when suitably designed prevent the plasma from reaching the mentioned points.

The schedule for the TJ-II project execution and its subsequent operation is, with some possible adjustments, as

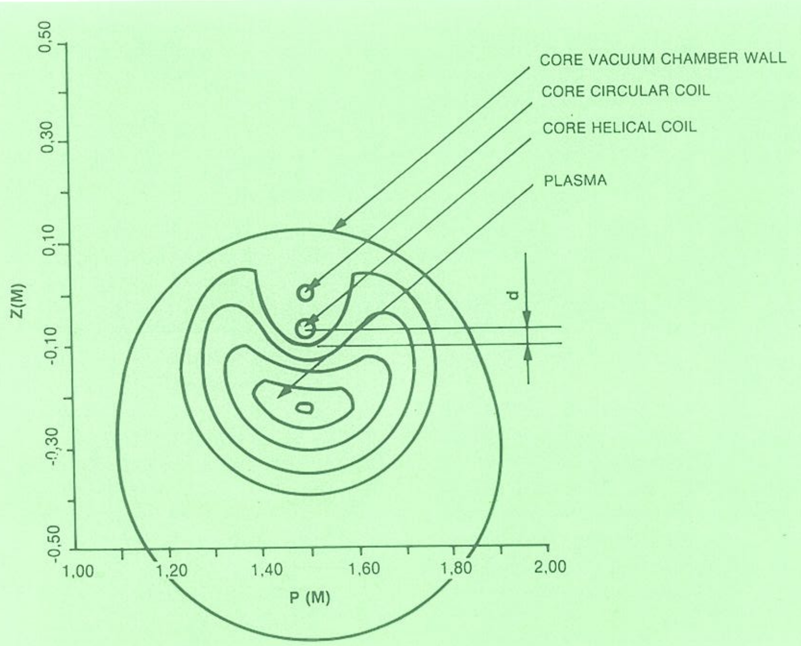
MAIN PARAMETERS

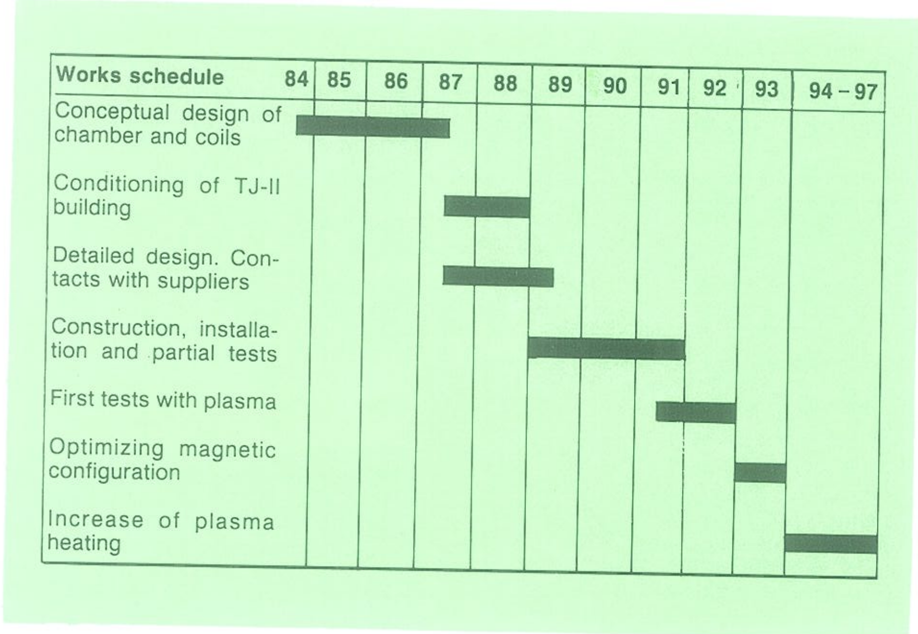
Device	heliac
Main radius	1.5 m
Mean equivalent radius of plasma	0.2 m
Magnetic field in the center of the plasma	1 tesla
Pulse length	1 second
Repetition rate	1 every 5 minutes
Microwave injected power	400 kW
Power delivered to the coils	90 MVA
Energy consumed in each pulse	50 MJ
Power taken from the network	
– Main power source	2 MVA
– Gyrotrons power source	2 MVA
Neutrals injected power	2-6 MW
Vacuum system pressure	10^{-8} torr



F V *TJ-II Scheme*

F VI *Poloidal section of TJ-II. Plasma shape*





F VII *TJ-II Project Schedule*

shown in outline form in Figure VII and detailed below in the text.

From 1983 to 1987, Stage 1, and more specifically in the second half of this period, conceptual design of the chamber and the coils, including:

- Selection of configuration.
- Theoretical studies of the confinement characteristics of the selected configuration.
- Determination of magnetic parameters, of transport, and of equilibrium and stability of the plasma.
- Basic engineering design.

In 1987, Stage 2, arrangement of the building for locating TJ-II and detailed design, which comprises, among others, the following activities, to be performed up to and during 1988:

- Preparation of drawings and specifications for construction of the machine (chamber, coils, supports).
- Drafting of specifications for materials, welding and surface finishing.
- Cost estimate.
- Alternative studies for coil supporting.
- Specifications for testing and quality control.

For the reasons given below, all of these activities will take place in close collaboration with the industry that is awarded the construction contract.

From 1989 to 1991, the construction, erection and partial tests of the machine will take place, as well as the development and layout of its associated systems, among which the following can be mentioned:

- Power sources for the gyrotrons.
- Main power sources.
- Microwave system (gyrotrons, waveguides, etc.).
- Vacuum and control systems.
- Cooling system.

From 1991 to 1992, after the operating tests of the systems, the first tests with plasma will be performed, verifying that the geometric configuration of the magnetic field conforms with the projected one.

In 1993, a study of the confinement properties of the heliac configuration will be performed, optimizing it as much as possible.

During the period 1994-1997, the plasma heating capacity will be increased by putting the neutral beam injectors into operation.

As indicated at the beginning of this paper, after the preferential agreement between CIEMAT and Euratom for development of the TJ-II project was signed in May of last year, the Euratom-CIEMAT Association was constituted, answering to a Steering Committee formed by six members, three from Euratom and three Spanish. The latter are the General Manager of CIEMAT, the Administration Manager of the same center and a representative of the Ministry of Education and Science. The present Director of the project is Agustín Grau and, as shown in Figure VIII, its structure comprises three large sections. The last section, Experimental Physics, presently contributes to the project through its experience in the location and design of diagnostics derived from knowledge acquired in the operation of an existing small tokamak.

The Theory and Simulation Section, which could be called conceptual development, is entrusted with everything related to the magnetic configuration and the study and optimization of all parameters involving plasma. Logically, the personnel in this Section are mainly physicists.

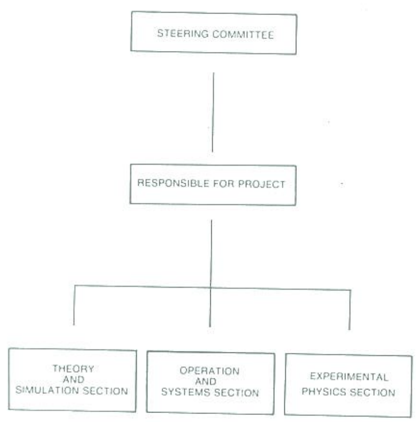
Finally, the Operation and Systems Section develops engineering work related to specific problems of the project and construction of the machine, mainly mechanical, electrical, layout, etc. The technical personnel from INITEC who presently collaborate in the project are in this Section.

Due to the fact that the author deals more with the field of project engineering, a somewhat more detailed explanation of the tasks that are developed in this field are given below.

In the first place, it could be asked how a project of this type is engineered and what difficulties there are confronting it. Some technical problems arising from the uniqueness of the machine were previously touched on, but without dealing with such specific facts, there are other more general conditioning factors. The first one of them arises from the novelty of the design, and in spite of the existence of periodic exchanges of information among the groups working on fusion projects, the experience and the documents from them are only partially applicable.

Another hindrance is the non-existence, in some cases, of official design and manufacturing standards, considering the exceptional conditions to which the components and materials of these experimental devices are subjected, which makes it necessary to carry out

F VIII *TJ-II Project Organization*



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