INTEGRATED SYSTEMS ENGINEERING APPROACH TO MANAGE THE INSTALLATION AND START UP OF A FUSION REACTOR

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Abstract

ITER is an international research and development project involving the European Union, Japan, the People´s Republic of China, India, the Republic of Korea, the Russian Federation and the USA that aims at demonstrating the scientific and technical feasibility of producing fusion power in magnetically confined plasma. The realization of the project is overseen by the ITER Organization (IO) which was established after the ratification (in October 2007) of the ITER Joint Implementation Agreement signed on the 21 November 2006. The construction activities have started with the preparation of the site, which is located at Cadarache in the South of France, and the procurement of large systems are scheduled to start at the beginning of 2009. ITER will be built and commissioned in the next 10 years and must operate for the following 20 years.
The large number of different engineering disciplines essential for its operation, the worldwide distribution of the design activities and the unusual procurement scheme based on a combination of in-kind and directly funded deliverables makes ITER one of the most challenging projects ever conceived.
The authors have been involved for several years in the definition and practical implementation of the design integration and configuration control structure inside ITER and in the management of system engineering processes.
Here they provide a brief overview of the status of the project and illustrate the systematic approach that the IO has adopted to ensure the consistency of the design with the required performance and describes the management methods, tools and working practices that are being used to facilitate the communication and manage the collaboration among the institutions and industries involved in the project.

1 Introduction

Nuclear fusion occurs when the nuclei of light elements come together at very high temperature and density and fuse together to produce a nucleus of a heavier element, releasing in the process a large amount of energy. This is the process that powers the sun and the stars and the quest to reproduce this phenomenon on the earth initiated soon after this process was first theoretically explained and then experimentally demonstrated in the middle of last century. Different types of devices have been developed and tested. and ITER belongs to the most promising family of these machines, the so called tokamak, initially developed by Russian scientists in the late 50s. In a tokamak fusion reactor a gas formed by a mixture of hydrogen isotopes (deuterium and Tritium) is first ionized (through electrical discharges similar to those in a neon tube) and then heated and compressed using large magnetic fields generated by different sets of coils. The same fields are used to confine and controls the resulting plasma, to prevent that it comes in contact with the physical walls of the device.

The current configuration of ITER is the result of a long design process. The current scientific objectives and main engineering parameters were defined in 1999, when the ITER design team was asked to develop a reduced cost option of a previous design. During this re-design phase the design solutions previously adopted were critically reviewed and areas were identified where simplifications were possible and where the requirements could be relaxed without compromising the overall mission of the project. A key decision during this phase was to exploit most of the design solutions and technologies developed and tested for the large ITER (Barabaschi, Chiocchio, 2003). This permitted an accelerated definition of the machine configuration, but had the downside to make difficult to track the design solutions adopted for each systems to clearly defined requirements.

ITER will be built largely through in-kind contribution by the 7 Parties. The sharing of the procurement scopes have been agreed already in an early stage of the design development and has led to the definition of about 200 Procurement packages with many interfaces among procurements belonging to different Parties. The IO is not directly involved in the management of the industrial contracts, but has the role to define the procurement specifications, that varies from build-to-print specifications to functional specifications and to integrate the whole process during the design and assembly phase. The procurement of such devise through such large international collaboration is an experiment in its own (Chiocchio, 2006). While in many other large industrial enterprises, such as in the nuclear industry, it is not unusual that an industrial main contractor can be selected who has the technical capabilities to deliver the whole plant turn-key, in the case of a fusion machine the number of different specialized engineering disciplines, the experimental nature of the project and the strong interplay between the design choices and the physics performance is such that the function of architect engineer and integrator cannot be entirely outsourced.

At the start of the construction phase the IO, in agreement with the Parties and the worldwide fusion community, has conducted a thorough review of the whole project, starting with the assessment of the validity of the physics objectives and selection of plasma parameters, and continuing with the analysis of safety and licensing issues and the review of the requirements and design choices of the major systems (Holtkamp, 2008). Organisational and management aspects of the project were also re-assessed. At the end of this project review the IO has been asked to re-baseline the project, defining in detail the requirements of the whole projects and of each system, and to establish an updated reference project schedule and cost baseline.

2 An overview of the ITER design

ITER consists of 32 major systems comprising around 10 millions parts with thousands of interfaces among them that must be identified and controlled.
At the core of the plant there is the tokamak, (see Figure 1), that comprises the Vacuum Vessel (VV) , that provides the ultra high vacuum boundary and the first safety barrier of the machine, the in-vessel components, that have to

withstand the large heat and absorb the neutrons produced by the reaction, the superconducting coils used to generate pulsed poloidal fields and steady state toroidal field and to control the plasma position and shape, the thermal shields, that have to reduce the heat load on the cryogenic systems and the cryostat which provides the vacuum conditions required for the operation of the superconducting magnets. Many auxiliary devices, used to provide additional heating, to monitor and control the plasma and to perform the scientific program which is part of the ITER mission, are allocated in large ports of the VV.
Around the tokamak a number of systems are needed to supply the power and maintain the magnets at cryogenic temperature, to cool the plasma facing structure, to fuel the plasma, to create the vacuum and to control the whole plant. A schematic description of the plant configuration is depicted in Figure 2.

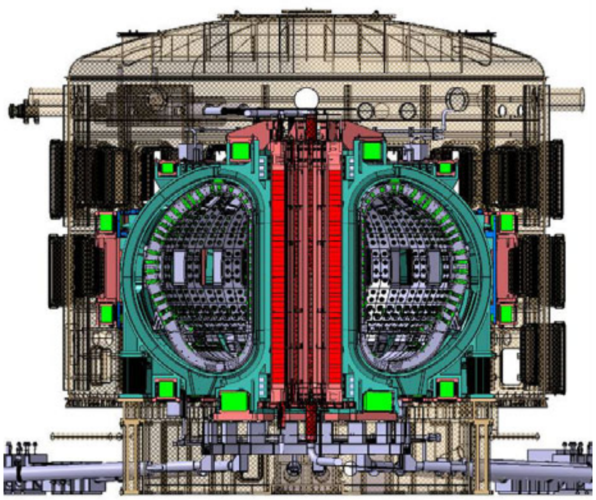


Figure 1 Cross Section through the ITER tokamak

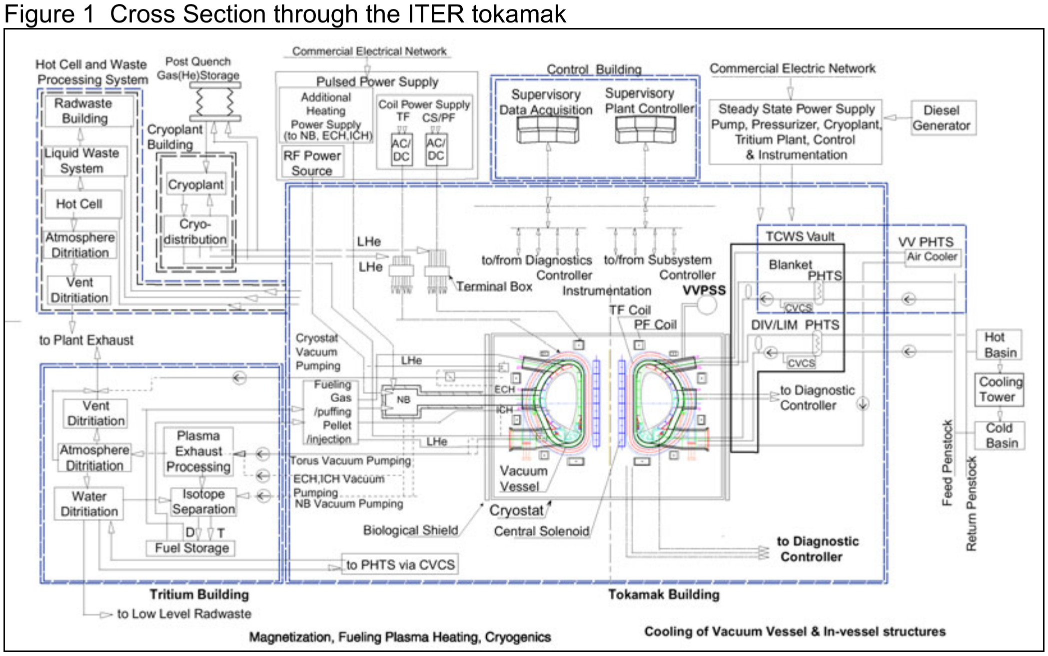


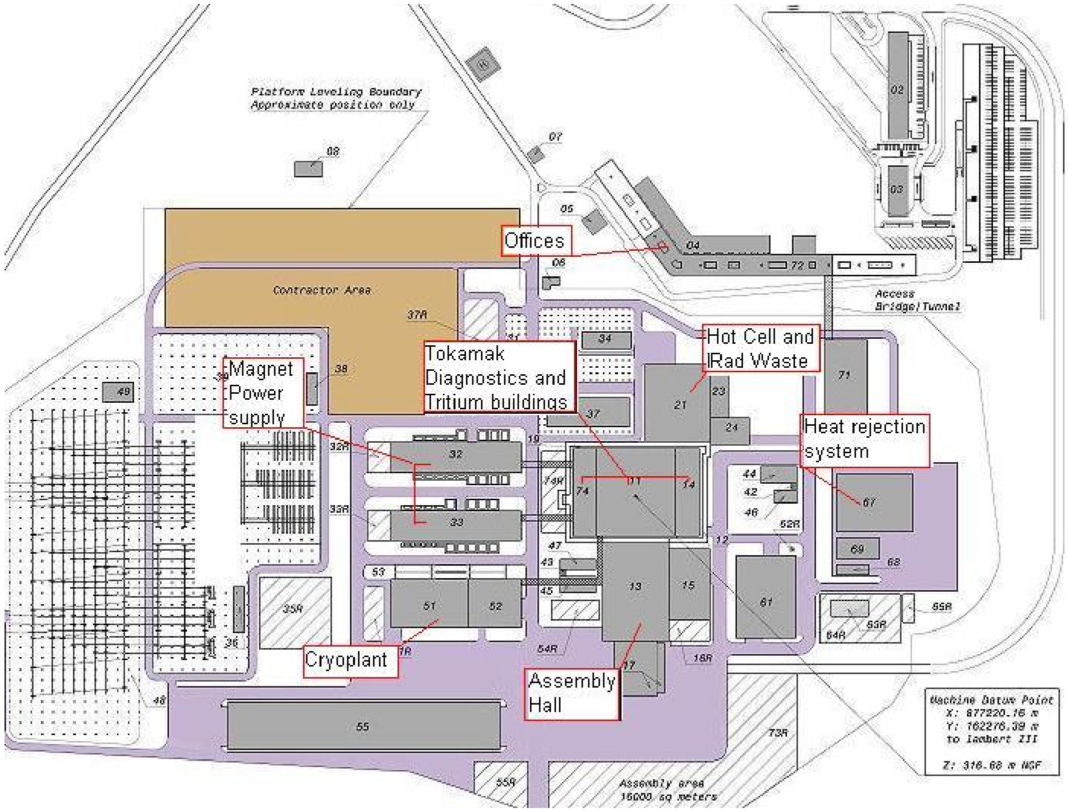
Figure 2. Plant system configuration

The core of the machine and the main auxiliary systems are located in the Tokamak Complex, that includes the Diagnostics, the Tokamak and the Tritium buildings. The 3 buildings are highly integrated and sit on a single concrete slab supported by seismic pads that reduce the effect of horizontal earthquake on the structures inside the buildings. In the inner part of the complex, the tokamak is located in a pit 30 m deep (of which 12 mm below ground) and separated by the rest of the structure by a 2 m thick concrete bio-shield. All around the bioshield, the building is subdivided in 5 levels, that are devoted to specific functions: the lowest level B2 and the highest level (L3) are dedicated to the magnets terminal boxes and to the distribution of the cryogenic fluids, while the three levels corresponding to the three sets of VV ports are allocated to the systems that interface with the plasma. Port Cells (PCs) provide confined space for the execution of remote handling and are separated from the galleries by large steel doors. The galleries provides access to the PCs and are sized to allow the movement of remote operated casks for the transport of activated components and the routing of electric, CODAC and diagnostics lines. Above the tokamak building, the crane hall extends for the whole length and width of the tokamak building and hosts a crane with a total capacity of 1500 tonnes. At the west side of the Tokamak building, the Diagnostic building is hosting diagnostic equipment and control cubicles. The levels B2 and L3 are dedicated for the coil power supply and distribution. At the opposite site the Tritium plant is entirely included inside the Tritium.

The tokamak complex is located approximately at the centre of a large site about 70 hectares that locate all other ITER buildings. (see Figure 3).

The ITER Site is arranged in such a way that all buildings, providing different kind of services to the Tokamak machine, are located around the Tokamak Complex buildings. The site north is hosting the ‘Hot Cell Facility’ with the ‘Rad-waste Building’, the ‘Personnel Access Control Building’ and the area of the ‘Neutral Beam Power Supply’. The site west is hosting the electrical facilities providing the site with electrical power and the cryogenic facilities for supply of liquid helium for the coil magnet system. It consist of the ‘Pulsed Power High Voltage Substation Area’, connecting the grid with the ‘Magnet Power Conversion Buildings 32 and 33, and the ‘Steady State Power High Voltage Substation Area’.

The site south is hosting the assembly hall for the assembly of the main components of the Tokamak machine. At the east, there are the ‘Site Service building’, ‘Control building and the ‘Cooling Water Pumping Station area’, which is connecting the Tokamak Complex with the ‘Hot and Cold Basins’.



3 Systems Engineering processes in ITER

In early 2007, soon after the signature of the Joint Implementation, we carried out an internal assessment to identify the deficiencies in the design and in the project organization and to define the processes that the IO and its partners should put in place in order to successfully execute the procurement phase of the project.
From the study emerged that while the design of the systems making the core component of ITER, the tokamak, was well advanced, the status of the design of the other systems was very variable. Some systems have been extensively designed, while others were still at a conceptual stage. With such variability in the definition of the design of different interfacing systems, the possibility to effectively integrate the whole plant was questionable and the interfaces with the building structure could not be properly be defined.
Another reason of concern was the large number of design changes being considered as the result of the assessment of the ITER physics basis during the 2007 project review.
The conclusion of the study was that IO had to put higher priority on the finalisation of the Conceptual and Preliminary Design, prior of the commencement of the Detailed
Design for some of the lead procurement systems such as the buildings.
As a result of this assessment, the IO introduced an integrated approach to the development of the design articulated in the following points:

- Establishment of a phased design process covering the whole scope of the design and procurement activities to be carried out using a gated system of design reviews, to assess the maturity of the system design and to validate the consistency of the design with the requirements (Chiocchio et al, 2006);

- Development of a Plant Breakdown Structure, which identify the decomposition of the project in Systems;
- Definition and control the project baseline defining the functional systems requirements and the physical and functional interfaces with other systems;
- Development of a change control process to ensure that the impact of the changes on other systems, on the project performance, cost and schedule is properly assessed and tracked;
- Introduction of an interface management systems that takes into account the progressive definition of the interfaces during the project lifecycle;
- Creation of a centralized design store of the project information accessible to all ITER partners.

<u>ITER design phase definition</u>

Three main stages have been identified during the design phase of the project: conceptual design (CD), preliminary design (PD) and detail design (DD), the latter overlapping with the procurement phase of the project.

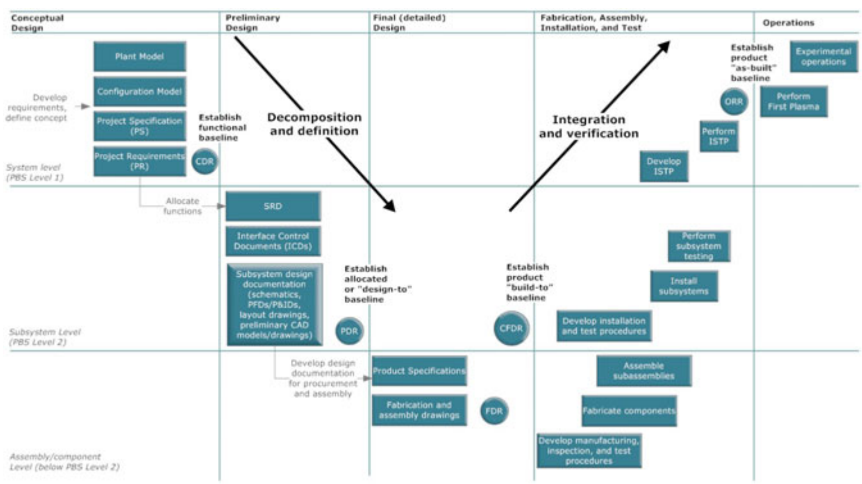
During the CD stage, the project top level functional requirements are developed and documented and trade studies are conducted to assess different configuration options. The typical activities during the CD stage include the development of the functional and design requirements, the definition of the design basis and categorization of the loads, the identification of the main interfaces, the first assessment of the cost drivers and the development of a plan to ensure that the reliability, availability, maintainability and inspectability issues are well addressed and that environmental and safety aspects are considered in the design process. At the end of this stage it is expected to have an approved functional specification, schematic of the systems (such as Process Flow Diagrams and top level Process and Instrumentation Diagrams) and the Identification of the systems recorded in Interface Control Documents (ICDs).

During the PD stage, analyses and R&D required to establish the feasibility of the design concepts are completed and verification plans for testing during manufacturing, assembly, and installation are developed. The main parameters at the interfaces with other systems are reviewed and agreed with the interfaces and reported in the ICDs. Typical deliverables include the 3D space allocation models that define the layout of the system, interface drawings, engineering analysis reports to demonstrate compliance with codes and standards, part lists with quantity of items, acceptance criteria, acquisition and installation plans and agreed quality assurance policies.

During the final design or DD stage, the designs of the hardware and software required to satisfy the development specifications are completed. Drawings are released for fabrication. Analyses needed to confirm the adequacy of the detailed designs are performed. R&D required to refine manufacturing processes is also performed. “Build-to” or product specifications are developed and placed under configuration control following a successful formal Final Design Review (FDR).

Following these design activities, the procurement phase include the development of the manufacture drawings and the definition of the technical specifications, the selection of the supplier and the award of the contract, the supervision of the fabrication activities, the on factory acceptance tests the shipping and the on-site acceptance tests. In ITER this part of the lifecycle is normally managed by the Partners in charge of the in-kind procurement, while the IO remains in charge of the integration, configuration control, integration activities on site, include the installation, system commissioning and integrated commissioning and the preparation for the plant operation.

The ITER engineering process and phases are illustrated in Figure 3.



ITER Plant Breakdown structure

The scope of the Plant Breakdown Structure (PBS) is to describe the functional breakdown of the plant in systems, sub-systems, loops, equipment and parts. It ensures that each element of the plant can be uniquely identified as soon it is created during the evolution of the design and manufacturing process, and that all relevant information can be tracked down (or linked) to the corresponding element.
The PBS is organised as a functional tree. Its elements are called “nodes”. The nodes are connected in branches and the terminal node of each branch is a “leaf”. At each level a node or a leaf correspond to a particular function in the plant.
The leaf of a tree can identify either an elementary part of the plant or an entire assembly. It is expected that the ITER PBS expands with the increasing definition of the design, so that some leaves are replaced by new branches. The ITER PBS consists of 32 major systems which are identified as first level of the PBS.

The ITER Project Baseline

The establishment of a reference baseline that is put under configuration control and can be easily identified and understood by all partners is a key element for the success of a project of the complexity of ITER. Figure 5 illustrates the structure of the ITER baseline. It should be noted that the baselines does not defines only the technical scope of the project, but also establish the costs and resources required to accomplish the task and the schedule to perform and integrate all activities.

The ITER baseline schema also indentifies the approval authority over the elements of the baselines. The top level ITER programmatic objectives (which form the ITER Project Specifications), the Overall Project Cost and Overall Project Schedule are under the responsibility of the ITER council, that represents the ITER stakeholders.at the lower level, the engineering requirements for the whole project, the PBS and WBS, the Integrated Project Schedule and Integrated Project Cost are under the responsibility of the ITER Director General, that has a delegation to approve changes to the baseline that do not impact the overall ITER objectives.

To expedite the management of the changes and non conformance notifications, the baseline defines lower level class of configuration items that are under the responsibility of the technical departments or the Domestic Agencies established by the ITER Parties.

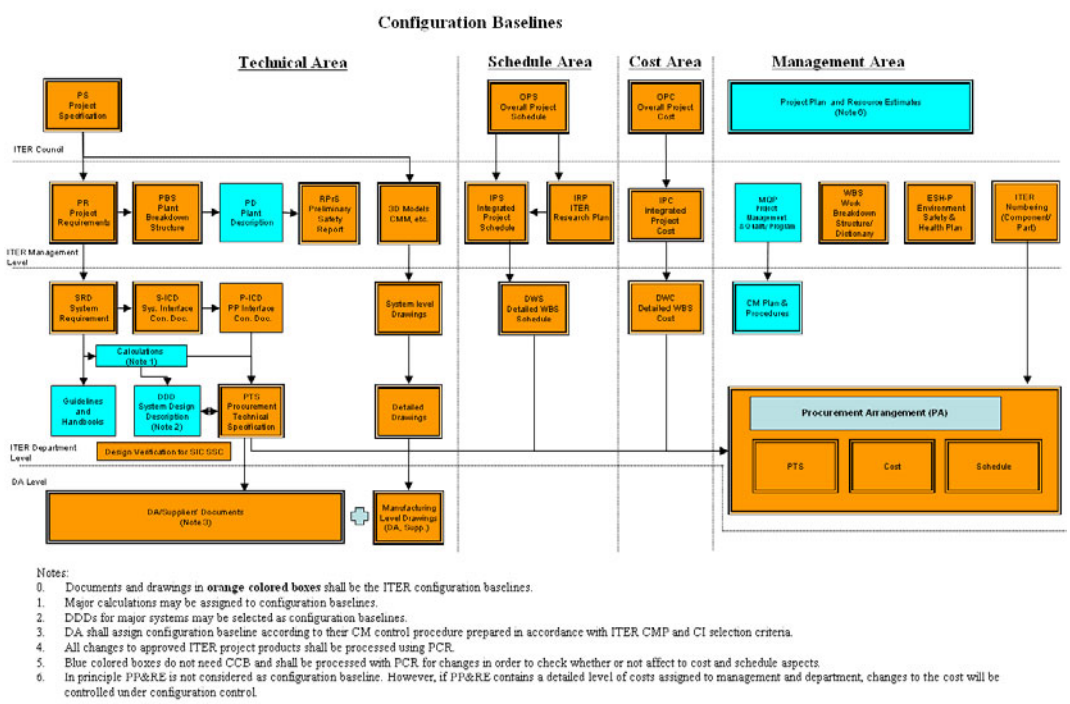


Figure 5 Structure of the Configuration Baselines

The physical configuration of the plant is represented in a large number of models and drawings that are managed through the ENOVIA LCA (Dassault Systemes, 2008) database. This allows the navigation of the database through geographic or functional based tree structures. It also defines the roles of the different partners and allows the establishment of rules to control the access to the data and the versioning of the models and drawings. In the current phase of ITER, the fast pace of evolution of the design of many systems makes difficult for the engineers accessing the database from remote locations, to identify the current valid configuration. To overcome this difficulty, we have introduced a type of models (Configuration Control Models, CMMs) that define the space envelope and the main interfaces of each systems. These models do not describe the detailed inner structure of the components, and thus they are updated only when modification of the outer boundaries of the component are introduced. The CMMs are also very practical for the detection of clashes and for the graphical representation of large assembly of the ITER plant.

<u>Configuration Management (CM) and Project Changes Procedure.</u>

Two aspects make the management of changes in ITER particular complex. One is the large number of interfaces among the systems; the other, related to the in-kind procurement scheme, derives from the fact that changes to one system under the responsibility to one of the ITER Party often translates in modifications (and extra-cost) that must be taken over by other Parties. The ITER Parties are very sensitive to the need of limiting the number of changes and properly assess their implications.

The ITER change management procedure ensures that all ITER Parties are constantly involved in the assessment of the technical impact of the changes and they participate in the calculation of the related cost and schedule modifications.

The procedure is in place since the creation of the ITER organisation, and to date about 175 Project Change Requests have been processed. Recently we have also introduced a web based system that allows all participants to review the status of all project changes, and be automatically notified when actions are required.

<u>Interface management</u>

The interface management systems in use at ITER is based on the definition of interface control documents (ICD) for each pair of interfacing systems. These documents comprise a scope description, a control table that summarises the status and pending actions for each identified interfaces and a set of Interface Sheets (IS). The IS provides for each interface the:

- *Interface Function*, that specifies “what” the interfacing system must perform;
- *Performance Interface Requirement*, that specifies “how well” a function must be performed (e.g., parameters such as pressure or temperature);
- *Design Interface Constraint*, that specifies applicable codes and standards, specific design requirement for operation and maintenance and essential features;
- *Physical Interface Requirement,* that specifies physical characteristics for components at the interface boundary such as materials, dimensions, tolerances, finish size, weights.;
- *Interface control parameters,* that defines the status of the interface definition (draft, accepted, approved) and the link to the project schedule milestones.

All the ICD and IS are organised in a database that allows the automatic search and control of interfaces. A status report of the interface can be automatically generated by system (listing all interfaces affecting one system) or by pair of interfacing systems (listing of interfaces between them)

Centralised Engineering Database

The IO has already in place an object oriented database called ICP (ITER Collaboration Platform) that covers many of the functionalities of modern Project Lifecycle Management (PLM) tools. The Change Management System and the Interface Management System described above are already implemented in ICP and can be linked to any other "object" defined in the ICP (documents, actions, equipments, people and organizations, etc.).
In parallel the IO is conducting pilot projects to test the functionalities of commercial software that are not implemented in ICP. At present three options are considered, migrate the current functionalities of ICP into a commercial PLM, continue the development of ICP as a full PLM or to integrate the two to reduce the development costs and to cover the entire spectrum of ITER needs.
An example of the ICP functionalities, beside the already mentioned Change management and interface management systems, is the definition of the ITER room database.
The room-book is a centralised tool accessible for everyone working in the ITER Organisation as well as for external contributors via the ITER Technical web page. Its scope is to publish all buildings related information such as concrete outline drawings, general arrangement drawings as well as radiological zoning drawings or magnetic field maps. Each room contains data like volume, wall-, ceiling-, and wall surface, hazards zoning in the different phases and the room environmental conditions such as pressure, temperature or humidity. The room-book also provides the function of a database in terms of retrieving data based on a defined search. Information such as Control Cubicles, magnetic field sensitive components or ferromagnetic objects can be extracted for buildings, levels or rooms of interest.
Different applications, which are configured for the engineering departments, are supported by the room-book such as the 'Steady State Electrical Power Network database' to manage the different electrical loads in the buildings or the 'CODAC database' for identification of the different signals.

4 Conclusions

The management of design activities of a large number of systems to be carried out through a world wide collaboration requires that engineering processes are deployed to control the coherent development of the design and the prompt identification and resolution of issues at the interfaces. Also it is important that efficient and easy to use tools are deployed that improve the communication among all participants.
The ITER organization has recognized the importance of these aspects and has involved the industrial expertise in the definition of systems engineering approach. Also the involvement of all ITER Parties in the definition and assessment of the design processes have been considered a key elements for the success of the international collaboration.

The systematic approach that has been developed and applied and the tools that we have deployed compare favourably with those in use in similar large projects.

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