



**Escola Tècnica Superior
d'Enginyeria Industrial de Barcelona**

UNIVERSITAT POLITÈCNICA DE CATALUNYA

MASTER IN NUCLEAR ENGINEERING

Department of Physics and Nuclear Engineering

Final Master Thesis

**Methodological guide to deploy Functional Analysis
into CODAC Systems for the Tritium
Processing in ITER**

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June 2018



The present Thesis has been partially funded by the Spanish Nuclear Council (Consejo de Seguridad Nuclear –CSN-) by means of a grant which for which the Author is grateful, by means of contract IDI_20150417 awarded through the CDTI entity (Centro para el Desarrollo Tecnológico Industrial), which in turn depends on the Economy, Industry and Competitiveness Ministry.

The awarded contract, offered in the frame of increasing competitiveness of companies and research centers in this case benefited the firm PROCON SYSTEMS S.A., in close collaboration of UPC and IQS Research Centers.

Each of the above mentioned entities offered its best expertise and know-how to the project in order to fulfill the tiers that were stated with anticipation.

As well it has to be mentioned that the present Thesis has been developed in order to obtain the Degree of Master in Science which is imparted at ETSEIB-UPC in the Department of Physics and Nuclear Engineering.

LE FILS DES ÉTOILES

Wagnérie Kaldéenne du Sar PÉLADAN

Dedication: Without prejudice to the practices of the great imprecators My cousins, I offer this work to my peers. Thus, and for the precedence of the examples, I do not ask for exaltation. I call down upon My guests-at-table the mercy of the Father, creator of things visible and invisible; the protection of the August Mocher of the Redeemer, Queen of Angels; as well as the prayers of the glorious chorus of the Apostles and the Holy Orders of blessed Spirits. May the just choler of God crush the haughty and the indecent! — Erik Satie

PRÉLUDE DU 1^{ER} ACTE — LA VOCATION

Thème décoratif: *La nuit de Kaldée*

E. Satie

En blanc et immobile.



The moon seen from my rooftop. "Voulez Vous la Lune?"



Acknowledgments

Thanks to my Father and my Mother, Ricard and Annie Granados, who have always been there for good and not so good situations, in whom I can be confident as we follow the good path.

Thanks to my brothers, Bernard and Ernest Granados, who are always a reference from the point of view of behavior and a good example to be followed by others.

Thanks to my Master Thesis Directors, Lluís Batet and Luis Sedano, who after a long period have been considered through the roller coaster that meant to develop the final document.

Thanks to Javier Dies, Deputy Manager of the Master Program, who has been also very considerate with the non-few problems that arose during the development of the Thesis.

Thanks to my uncle Javier Granados, who gave me a hand with understanding the physical processes proposed by ITER and also gave me some hints on control theory.

Thanks to my great uncle Manuel Garcia Doncel, to whom I ask while I write these lines pray for my soul and things to come in the future.

Thanks to Lluís Puigjaner, former Chair Professor of Chemical engineering, for talking me about inventory control in chemical plants. We had an extensive phone call about a book written partly by him and that helped me to direct my research in the good path.

Thanks also to Alfons Auguet, who also helped me with understanding how a process control strategy must be analyzed and implemented. Lesson learned.

Thanks to Carlos Tapia for his longtime friendship, and more precisely, in the present project providing a methodological proposal for the determination of the deviation of model results against measures.

Many Thanks to Lázaro Cremades and Ramón Forn i Valls for their excellent attention and giving me a good class of Functional and Value Analysis as well as explaining the correct steps by which a correct Brainstorming process must be driven.

Thanks to Cindrela Sambró and Natalia Català and Carlos Mateo for dedicating their time with me and giving their spiritual support and help in typing, giving good ideas and peer review.

Thanks to Nicolas Heumann and family for their kind attention along many years, accomodating me at their own home, being good friends, making excellent barbeques, and travelling me around the beautiful French Provence county.

Thanks to J. Abellà and S. Colomines from IQS; and also D. Marchante and P. Païs from PROCON for being polite at the initial meetings that were held at the beginning of the project and providing their own facilities in order to organize them, as well as for their technical participation in the project.

Thanks to M. Christian Jalain for its kind recommendations, being a friend, supplying FA methodology brochures and good predisposition to chat about interesting topics.

Thanks to Jean-Claude Jacquot from CASE France, for supplying information about Envision Analyst software and extensive methodological FA brochures.

Thanks to Alessandro Morbiato from SAES Italy for supplying technical information regarding heated getters for gas purification.

Thanks to Sara Latham and David Milroy from Johnson Matthey for their kind attention when asking for product information.

ABSTRACT

The present document is focused on the analysis of the ITER-TBM's Proto-CODAC system. ITER is considered to be the first nuclear fusion reactor to be energetically feasible for a sustained period of time with a rated fusion power of 500 MW.

ITER Project involves 35 countries with a total estimated budget of some 15.000 M€; being the first of its kind from the point of view of international collaboration, engineering and supply sources; where every country participate with the best of its possibilities.

The hearth of the fusion reactor is a giant Tokamak (6.2 m plasma major radius) with a series of ancillary buildings and facilities that might complete the whole project.

The operation of ITER is scheduled to operate along the next 50 years, after completion of the facilities construction and commissioning of the plant, considering first to be operated in D-D and further in a D-T modes. In this sense, the activity that supports the development of the present work was stated to be necessary to consider a tritium balance for the self-sufficient reaction and operation of the whole.

Tritium is a very scarce element being its global stocks to the present date of 2016 of some 20 kg, being produced mainly collected from the operation of Candu reactors in Canada [Raeder, 1986]. Also the operation of the ITER reactor might produce Tritium at a rate that might be able to support the fusion reaction indefinitely on a time basis.

Because of the tritium balance it is difficult to state due to its highly permeation throughout confinement of first walls and joint materials. Not to mention its highly dangerous potential to human health, according to radiological properties. This is why it is necessary to establish predictive tools that might indicate the concentration and inventory across the facility, including emissions to the environment.

In this sense, ITER Instrumentation and Control systems for Control and Data Acquisition (DACS) mainly constitute the layers between the users (Control Room) and the field Instrumentation (sensors and actuators). This is named as ITER CODAC, which is the primary global system analyzed in the present document.

The control philosophy it is stated to be predictive and from the author's point of view must include the comparison between field measurement and advanced modeling, including machine learning utility system that might be deployed in computational base.

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1 INTRODUCTION AND PRECEDENTS

In the present chapter, an overview of the ITER project is presented. Epigraph 1.1 explains roughly the ITER project and related activities. Then in the epigraph 1.2 tritium breeding cycle and the test blankets modules are explained. Epigraph 1.3 introduces the CODAC system in the framework of the ITER project. The following epigraph 1.4 explains where the present project fits in the overall ITER framework. Then epigraph 1.5 explains the environment of the main contractor (PROCON).

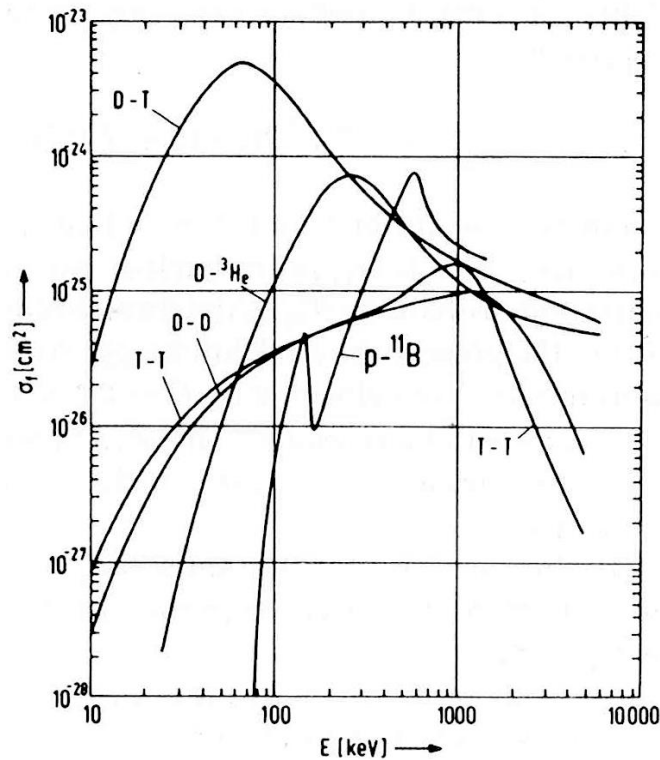
1.1 ITER PROJECT AND TBM RELATED ACTIVITIES

Nuclear fusion is sometimes regarded as a possibility to meet energy demand in a long-term future basis. The progresses towards producing fusion plasmas in current days suggests that it might be feasible to use fusion energy. Also, apart from the physical issues, technical, ecological, and economic aspects are stated as parallel problems that are being focused and studied to be solved.

The current research design of choice in the present days is a Tokamak like system. In the present document, it is assumed that the particular deuterium-tritium plasma operation campaign is of application. One has to notice that a number of campaigns are going to be followed during the life of the ITER project: sole H and D only. Nevertheless, as pictured in Figure 1-1, it is understood that the D-T fusion reaction cross sections are higher, so it should be a more efficient mode of operation of the machine and it is foreseen to be the final stage of the experiment.

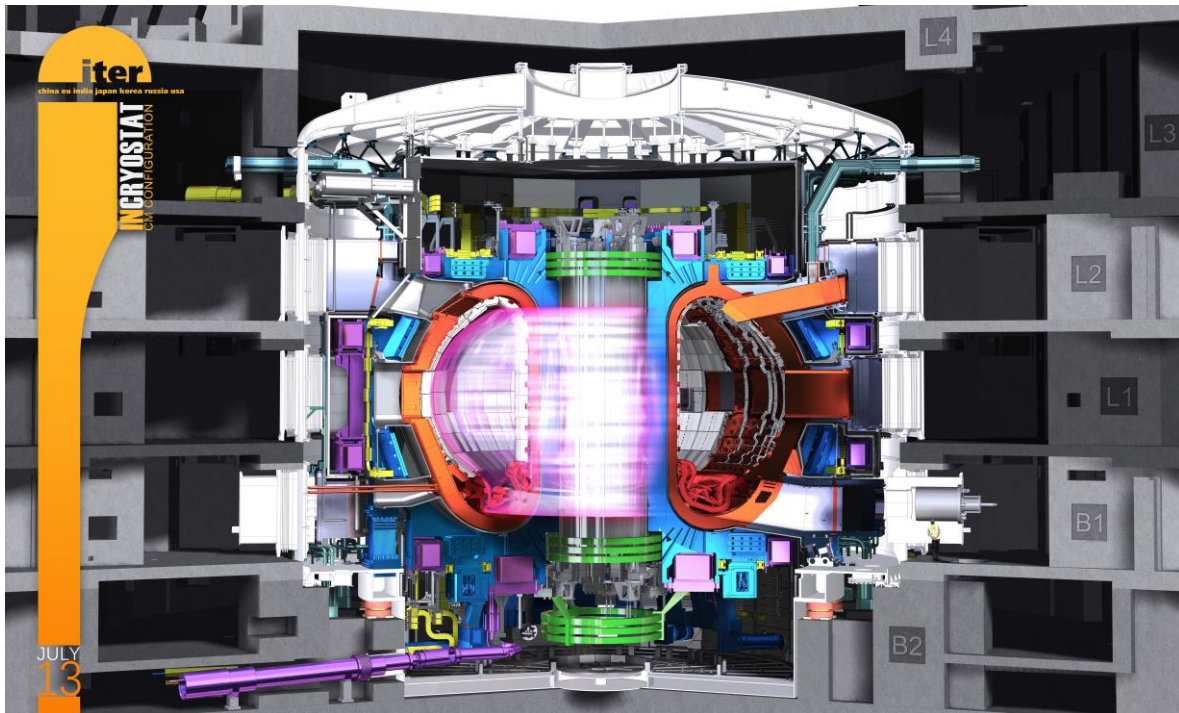
Figure 1-1 shows the cross section for the fusion reactions for some of the more common isotopes compounds.

Figure 1-1. Some isotope compounds reaction cross sections (Raeder, 1986[1])



In order to verify possible concepts to operate future DEMO reactors, a number of peripheral Test Blanket Modules (TBM) are going to be used in the current ITER project. Several countries provide different technologies and concepts regarding these TBM modules. Figure 1-2 shows the structure of the Tokamak and its main components.

Figure 1-2. ITER Tokamak reactor design. Artist's view (ITER IO, 2017 [61])



From a technical point of view, the objectives of the ITER project can be summarized as follows:

- *To demonstrate the extended burn of deuterium-tritium plasmas, reaching the reactor operation at steady state as the final objective.*
- *To achieve a power amplification $Q \sim 10$ during an inductive burnt longer than 300 seconds (The amplification factor of a fusion reactor (Q) is a concept frequently used. It is defined as the ratio of energy produced by fusion and the energy injected into the plasma.)*
- *To integrate and to test all technologies and key components of fusion power reactor.*
- *To demonstrate safety and the environmental impact acceptance of the fusion.*
- *To demonstrate safety and the environmental impact acceptance of the fusion*

Being a strategic objective, ITER is a unique device that responds, in an integrated way, all feasibility issues needed to design the next step: the nuclear fusion power plant demonstration (DEMO).

Design Principles

Based on all the foregoing, the ITER design during the EDA has adopted the following design principles: (IAEA, 2012 [62])

- *optimize the design for the objectives of the first phase of active operation and ensure flexibility and capability to accommodate the goals and constraints of following phases;*
- *within the given resources, maximize the development of the basic tokamak machine and defer that of external systems that can be changed or added later;*
- *use advanced but proven technologies, but keep the flexibility to introduce new technologies when proven;*
- *avoid irrevocable choices today if they may be made later when better information is available;*
- *for systems to be developed and designed later, reserve the maximum space available;*
- *avoid on-site production and testing as much as possible;*
- *never compromise safety of the machine operation to improve performance or decrease cost;*
- *plasma-facing components should be excluded from safety functions;*
- *emphasize passive safety in the design;*
- *maximize simplicity, fail-safe and fault-tolerant design, redundancy and diversity (wherever appropriate), independence, and testability.*

Main Plasma Parameters and Dimensions (IAEA, 2012, [62])

- *Total Fusion Power 500 MW (700 MW)*
- *Q — fusion power/additional heating power ≥ 10*
- *Average 14MeV neutron wall loading 0.57 MW/m² (0.8 MW/m²)*
- *Plasma inductive burn time ≥ 400 s*
- *Plasma major radius (R) 6.2 m*
- *Plasma minor radius (a) 2.0 m*
- *Plasma current (I_p) 15 MA (17 MA¹)*
- *Vertical elongation @95% flux surface/separatrix (κ_{95}) 1.70/1.85*
- *Triangularity @95% flux surface/separatrix (δ_{95}) 0.33/0.49*
- *Safety factor @95% flux surface (q₉₅) 3.0*
- *Toroidal field @6.2 m radius (BT) 5.3 T*
- *Plasma volume 837 m³*
- *Plasma surface 678 m² Installed auxiliary heating/current drive power 73 MW²*

1.2 Design Overview (IAEA, 2012, [62])

- *ITER is a long pulse tokamak with elongated plasma and single null poloidal divertor (Figure 1-2). The nominal inductive operation produces a DT fusion power of 500 MW for a burn length of 400 s, with the injection of 50 MW of auxiliary power.*
- *The major components of the tokamak are the superconducting toroidal and poloidal field coils which magnetically confine, shape and control the plasma inside a toroidal vacuum vessel. The*

¹ (1)The machine is capable of a plasma current up to 17 MA, with the parameters shown in parentheses) within some limitations over some other parameters (e.g., pulse length).

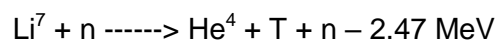
² A total plasma heating power up to 110 MW may be installed in subsequent operation phases

magnet system comprises toroidal field (TF) coils, a central solenoid (CS), external poloidal field (PF) coils, and correction coils (CC). The centring force acting on the D-shaped toroidal magnets is reacted by these coils by wedging in the vault formed by their straight sections. The TF coil windings are enclosed in strong cases used also to support the external PF coils. The vacuum vessel is a double-walled structure also supported on the toroidal field coils. The magnet system together with the vacuum vessel and internals are supported by gravity supports, one beneath each TF coil.

- Inside the vacuum vessel, the internal, replaceable components, including blanket modules, divertor cassettes, and port plugs such as the limiter, heating antennae, test blanket modules, and diagnostics modules, absorb the radiated heat as well as most of the neutrons from the plasma and protect the vessel and magnet coils from excessive nuclear radiation. The shielding blanket design does not preclude its later replacement on the outboard side by a tritium-breeding blanket constrained to the same temperature cooling water as the shielding blanket.
- The heat deposited in the internal components and in the vessel is rejected to the environment by means of the tokamak cooling water system (comprising individual heat transfer systems) designed to exclude releases of tritium and activated corrosion products to the environment. Some elements of these heat transfer systems are also employed to bake and consequently clean the plasma-facing surfaces inside the vessel by releasing trapped impurities. The entire tokamak is enclosed in a cryostat, with thermal shields between the hot components and the cryogenically cooled magnets.

1.2.1 Tritium Breeding cycle and the test blankets modules

In a Tokamak fusion reactor design an envelope to the vacuum chamber it is foreseen due to the fact that tritium breeding or reproduction functions must be provided. This envelope is called the breeding blanket and the active materials of choice are Li⁶ and Li⁷. In nature lithium is found in an abundance of 7.5% Li⁶ and 92.5% Li⁷. The out coming neutrons which come out of the plasma, due to the fact that as they are not electrically charged, the magnetic confinement does not affect on their escape outwards can develop the following reactions: (Raeder, 1986[1])



Also, apart from the breeding function the blanket must provide the means to evacuate or transfer the inside produced heat to the coolant circuit. This is done by means of a slow flux of a H₂ and He mixture which circulates throughout a structural material, which configuration depends on the design of the blanket.

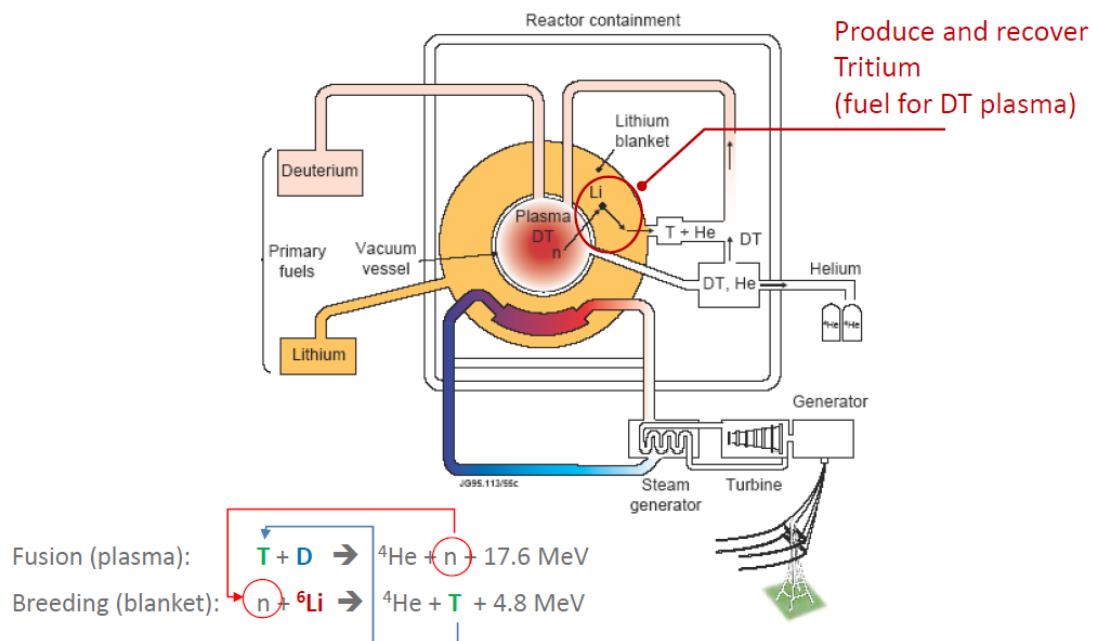
As the blanket is of outmost importance, several test blankets modules will be placed in the periphery of the tokamak, each one corresponding to each of the participants of the the project in order to test-bench the performance of each one of the concepts, for further implementation in DEMO reactors. Europe has been assigned with two positions in the peripheral equatorial ports. The two main concepts to be tested by these two test blankets are HCPB (Helium Cooled Pebble bed) and HCLL (Helium Cooled Lithium Lead).

Also the blanket must provide a mean of radiation shielding to outwards.

The issued HCPB and HCLL TBM assemblies will be installed at equatorial port number 16 and will be connected to the following ancillary systems, with which they constitute the named TBS (Test Blanket System). Figure 1-3 shows the main functionality of the breeding system.

- TBM. Consists of the properly named TBM and pipes reaching to the Vacuum Vessel raccord.
- HCS (Helium cooling system). This system is used for heat recovery, which is generated inside the Tokamak plasma chamber and transferred to TBM for the purpose of energetic feasibility demonstration.
- TES (Tritium Extraction System). This system is used for the recovery of inside system generated tritium, further concentration and return to the chamber as fuel.
- CPS (Coolant Purification System). Used for helium isolation and recovery of tritium from HCS.
- DACS (Data Acquisition and Control System). Consisting of control systems connected to the central unit that governs ITER.

Figure 1-3. Breeding blanket functions in a Tokamak (Biel, 2014 [64])



1.3 THE CODAC SYSTEMS IN ITER PROJECT

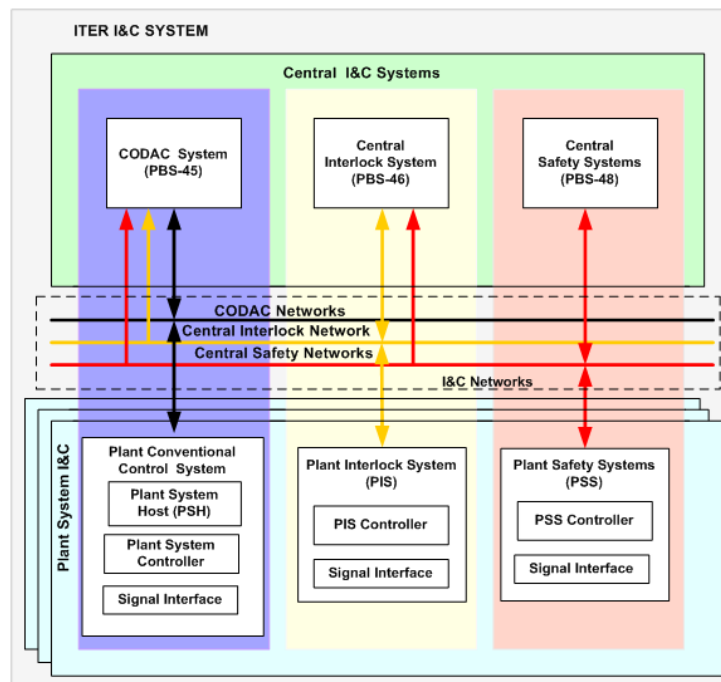
CODAC is the acronym for Control, Data Access and Communication. It is the central system responsible of operate the reactor. CODAC as a centralized system connects all the plant systems, which in turn have sensors, actuators and local and control instrumentation (I&C).

The control systems in the ITER project are split in three vertical tiers.

- **CODAC Conventional control**
- **Interlocks: Machine protection**
- **Safety: Human protection.**

The figure 1-4 shows a simplified diagram of the ITER I&C system.

Figure 1-4. Simplified diagram of the ITER I&C system (ITER IO, 2016 [54])



1.4 FRAMEWORK OF THE PRESENT PROJECT

Proto-CODAC Project (*PROCON, 2016 [63]*) has recently been launched by PROCON SYSTEMS company in collaboration with Technical University of Catalonia and Institut Químic de Sarrià (Barcelona) under partial auspices of Industrial & Technological Development Spanish Centre (CDTI). Proto-CODAC, a 10 PPY and 36 months goal-oriented Project, intends a complete CODAC prototyped demonstration implementing a dynamic tritium mass-balance control strategy for TBM systems.

The confidence on the achievement within the present ITER R&D decade of “active” tritium diagnostic solution opens, in parallel with tritium dynamic transfers proven “predictive” modeling skills (today also under development and qualification), the gate to a new continuous inventory and operation tritium control strategy not only for TBM systems and for the overall tritium plant systems. Discrete mass-balance tritium management strategy provides continued tritium mass-balance checks through integrated inventory measurements in a measuring devoted system (TMS). A drawback of static approach is that it constraints system operation flexibility, on a non-effective tritium safe control and on an inherent difficulty to provide tritium self-sufficiency demonstration, a key committed TBM Programme mission. In opposition, dynamic mass-balance tritium management approaches are considered to simultaneously provide reliable system operation flexibility, to contribute to a robust tritium management and control safety approaches and finally to support the required kinetic mass balance for tritium self-sufficiency demonstration. Similarly to the dynamic control of any other specimen in a general plant, in particular isotopes in nuclear facilities, the robustness of a continuous dynamic tritium control and management relies on three pillars: I) the achievement of continuous tritium atmosphere monitoring and T-concentration diagnostic probes at TBM effluents within the ranges of accuracy for pre-established required tritium mass-balance matching; II) the availability of a high performance predictive tritium

system models capable to anticipate tritium concentration and in-components/sub-systems inventories within the final (or assumed) range of accuracy of tritium environmental monitors and tritium forms sensing solutions in effluents; III) the final development of a proven and qualified TBM CODAC Plant System architecture fitting ITER CODAC tiers, layers and interlocks configuration and global requirements.

The confidence on the achievement within the present decade in the ITER R&D project, more specifically is the “active” tritium diagnostic solution which is to be developed, in parallel with tritium dynamic transfers proven “predictive” modeling skills (today also under development and qualification). The former constitute the gate to a new continuous inventory and operation tritium control strategy, not only for TBM systems, but also for the overall tritium plant systems.

Discrete continuous mass-balance tritium management strategy provides periodical tritium mass-balance audits, through integrated inventory measurements. The system described must be embedded in a measuring devoted system (TMS).

The drawbacks of the static approach involve system operation flexibility subject to constraints, a unsafe tritium control and an inherent difficulty to provide a tritium self-sufficiency demonstration. These concepts are meant to be mandatory objectives for the TBM Programme mission.

In opposition, dynamic mass-balance tritium management approaches are considered to simultaneously provide reliable system operation flexibility, to contribute to a robust tritium management and control safety approaches and finally to support the required kinetic mass balance for tritium self-sufficiency demonstration. Similarly to the dynamic control of any other specimen in a general plant, in particular isotopes in nuclear facilities, the robustness of a continuous dynamic tritium control and management relies on three pillars:

- I) The achievement of continuous tritium atmosphere monitoring and Tritium concentration diagnostic probes at TBM effluents within the ranges of accuracy for pre-established required tritium mass-balance matching;
- II) The availability of a high performance predictive tritium system models capable to anticipate tritium concentration and in-components/sub-systems inventories within the final (or assumed) range of accuracy of tritium environmental monitors and tritium forms sensing solutions in effluents;
- III) The final development of a proven and qualified TBM CODAC Plant System architecture must be compliant with ITER CODAC tiers, layers and interlocks configuration and global requirements.

In resume, Proto-CODAC Project explores dynamic "control" solution targeting in-prototype hardware realization integrating Proto-CODAC throughout the above mentioned three main synergistic R&D Macrotasks. The dynamic control strategy for tritium needs to be substantiated, developed, implemented, globally qualified (benchmarked) and certified according to ITER nuclear standards and regulations.

1.4.1 Development of tritium software modeling towards transfer rates and concentration predictive ability

The achievement of numerical prediction capacity of tritium transport modeling tools is a well-known challenge of nuclear fusion technology. A prospective working hypothesis of Proto-CODAC Project for new dynamic tritium control CODAC is based on the assumption that highly performant predictive tritium modeling tools will be available at the beginning of DT phase with tools and tritium CODAC dynamic approaches globally validated at previous HH, DD phases. Predictive tritium transfer system modeling tools are today being developed on the base of first-principles [Batet, et. al. 2014] [Fradera, et. al., 2011]. A large set of specific modeling packages are being developed for the so-called –unitary operations- : permeation, absorption/desorption, electrolysis, catalytic exchanges, etc with a strong physical and numerical validation. Phenomenally refined tritium modeling system tools have been developed by UPC for TBM systems (EU HCLL, HCPB and TBM and auxiliaries). The process involves the implementation and full tritium transport phenomena in reliably performant modeling tools for TBM system design based on scoping predictions and TBM experimental test parametric exploitation, aiming the determination of key transport parameters under fusion environment.

1.4.2 Tritium monitoring and final availability of continuous tritium concentration sensors in ITER TBM effluents

In connection with reliably accurate tritium ambiance monitors in TBM areas and TMS (Tritium Measuring Station) ultimate performances, active tritium control in TBM systems (i.e. a continuous confirmation of tritium mass matching between given TBM operational events) needs of reliable real-time tritium concentration sensing in the TBM effluents (pressurized helium and lead-lithium). After decades of R&D; nuclear technology has not provided reliable real-time tritium concentration sensing in the TBM effluents. However, recent years R&D developments (as new electrochemical sensors or tailored porosity diffusion membranes) anticipate final achievement of such sensing solutions with strong impact of future tritium TBM CODAC. Development of new electrochemical sensors and new porous diffusion membranes are consolidated R&D lines (IQS) (Llivina et. al. 2014, [67] [68]) showing today promising results that allow to justify a final achievement as working hypothesis and additional efforts in Proto-CODAC Project.

1.4.3 Concretion of dynamic control benefits in front of static control

As pulsed machine; diverse breeding tritium sequences will be accomplished along ITER experimental campaigns. Tritium will be bred at computed rates with pre-assessed uncertainties and local Tritium Production Rates (TPR) will be measured with uncertainties and integrated. The bred tritium will be transferred throughout the TBM systems (HCS, CPS, TES) under operation and then recovered at TRS and measured at the TMS. The experience through decades of tritium continuous measurement in irradiation experiments evidenced difficulties to match tritium balances between production and integrated measurements (in Ionization Chamber and in Liquid Scintillation) and ambiance monitors showing severe deviations. At TBMs, the matching pulse-to-pulse tritium balance with integrated accountancy methods appears as a challenge requiring, in any case, additional concentration sensing support (with the performance finally achieved) for a reliable tritium control. Proven performances of active c-probes in Helium (at vppm range) and in liquid-metal (at 0-10 Pa) opens the way to continuous tritium mass balance checking and real-time control with an expected major impact on operational availability and dose impact. Time-to-time discrete mass-balance checking between the tritium bred

and the tritium accounted after a given number of pulses requires a needed time to integration resulting on a limited operational flexibility and dosimetry safety constraints (at minimum the integration time needed to check the tritium mass-balance matching or mismatching). Additionally, such integration time is also needed to assess the mean bred tritium inventory recovery time (tritium residence time) (i.e.: ITER TBM Programme tritium self-sufficiency demonstration) after a full tritium transfer into TMS. Alternatively, balance management through c-sensor permits real-time control, a continuous mass-balance checking and residence time assessment.

1.4.4 Critical roadmap towards TBM CODAC architecture and hardware developments

The crucial CODAC architecture and hardware development focuses on the review of the TBMs design as a specific Plant System. **TBM systematic functional analysis** (by reviewing and extending previous work), ITER CODAC standardization requirement and CODAC TBM harmonization to ITER CODAC, the final implementation of dynamic control strategy for a tritium dynamic balance in CODAC TBMs includes the strategy benchmarking thorough ITER HH/DD phases and finally with a prototype demonstration that anticipates Main Control Rooms and panels detailed design.

The enounced milestones of Proto-CODAC Project are:

- ***(M1) To establish and settle the basis of conceptual design of the CODAC of ITER Test Blanket Modules (TBM) systems anticipating CODAC ITER TBM detailed engineering.***
- ***(M2) Ultimate a critical technological review of existing solutions in monitoring and Diagnostics for TBM CODAC system.***
- ***(M3) Scope of predictive tritium dynamic transfers and tritium concentration modelling with advanced tools (HYSYS/ASPEN+) in diverse TBM effluents.***
- ***(M4) Substantiation of discrete versus continuous tritium control management for ITER TBM systems,***
- ***(M5) Development of a prototype TBM CODAC hardware system with active (real or simulated signal) cross instrumentation signals simulated for a proving a new dynamic control strategy for tritium inventory control of ITER TBM systems.***

Project milestones´ are expected to be achieved through the following committed tasks:

- *Reference standards and ITER CODAC inputs critically revisited.*
- *Functional system analysis of HCLL/HCPB TBS as specific system related to ITER CODAC requirements critically revisited.*
- *Critical review of ITER-TBM instrumentation monitoring and Diagnostics requirements and present solutions; in particular for tritium sensing and monitoring.*
- *Review for ambience tritium monitoring solutions and own developments (IQS) on active tritium concentration sensing in TBM effluents*
- *Review for capacity of predictive concentrations simulation in different effluents in TBM systems (UPC)*

- *New approach to the dynamic control of the tritium systems TBM on the assumption of an active diagnosis along with obtaining final procurement of a capacity of advanced dynamic simulation of concentrations in different effluents in TBM systems*
- *In-prototype demonstration of implementation of new approach to the dynamic control of the tritium systems TBM, including Main Control Room and panel lay-out and other specifications.*

1.5 PROCON. COMPANY PRESENTATION

1.5.1 Company presentation

Founded in 1995, PROCON SYSTEMS, S.A. ("PROCON") is an Engineering company located in Badalona (Barcelona) specializing in the development of integral solutions for automation projects and in international industrial engineering projects.

PROCON develops its activities both in the domestic market and in the international market. It is DIN EN ISO 9001: 2008 certified for Design, manufacture, installation and commissioning of industrial automation projects.

Dedicated to the execution of industrial engineering projects in Barcelona, PROCON's main objective is to guarantee the total satisfaction of its customers, putting special care in the quality of its facilities.

TÜV RHEINLAND recently certified that PROCON applies a Quality System in the area of Design, Manufacture, Installation and Start-up for its projects in accordance with ISO 9001: 2000 and other Certifications.

1.5.1.1 Brief history of the firm and the holding group

PROCON SYSTEMS has a staff of 40 employees; 80% of which are engineers and technical personnel.

The invoicing of PROCON SYSTEMS, S.A. amounted to 8.2 M € during 2011, 70% was of this as an export.

As a technology-based SME PROCON SYSTEMS, S.A. has been contributing significantly to its growth since its inception to the maintenance and creation of highly qualified employment.

1.5.1.2 Activities, products, services and strategy

The traditional sectors of the PROCON SYSTEMS activity are:

- Automotive
- Large scientific facilities
- Aviation industry

The **ACTIVITIES** consolidated in the **scientific-technical markets** are:

- 1) The simulation of processes;
- 2) The design of electrical engineering;

- 3) Programming of robots and robots;
- 4) The design and analysis of systems and
- 5) High-level software programming.

With a recognized baggage of competences by large clients in:

- *Automation of industrial processes*
- *Production visualization, management and monitoring systems and test benches*
- *Large Scientific Installations*

In the area of **automation of industrial processes** in the automotive sector as well as in the aeronautical sector we can highlight the following projects:

- *Remodeling of Lines UBS 1 and 2 [SEAT, 2005-2008]*
- *Delta 3400 Project [OPEL 2007-2010]*
- *Development and Electrical Installation of Tools and Handlers for HTP and S19 of the A380 [Airbus de Illescas; 2002 - 2004]*
- *Airbus 400M Rear Stabilizer Project. (2002-2004).*
- *Project Hot Drape Forming Cell Boeing 787 (2001 - 2002).*

In monitoring, management and supervision systems of production and test benches we highlight several contracts in:

- 1) *Modification of Axis Alignment Banks;*
- 2) *Verification system of electrical elements;*
- 3) *Production Launch and Control System and*
- 4) *Traceability System of Safety and Bolted Bolts.*

As for the activities of participation of PROCON SYSTEMS in GICs (Inductance Transducers Market) are limited to:

- *Control system for DTP2 / RH; ITER*
- *People Protection System for Tunnel and Control Room in ALBA Synchrotron*
- *People Protection System for ALBA Synchrotron Laboratories*
- *Development Project of Laser Welding Technique for Different Types of Polymers.*

In relation with ITER Project and EFDA activities (2006 - 2007), PROCON SYSTEMS contributed to the design and manufacture of the electrical control system for the mechanics and hydraulics of the CMM / SCEE and CTM systems integrated in the DTP2 Tampere (Finland); specifically:

- 1) *Design and manufacture of CCS (control cabinet), extension of wiring and IWC (field wiring cabinets);*
- 2) *Development and implementation of the test protocol.*

1.5.2 Participation in the ITER project

Since the creation of the European Fusion Agency (Fusion for Energy, F4E) (Barcelona, March 2007) PROCON SYSTEMS has been having an intense relationship with the ITER Project, following and analyzing in detail the F4E and ITER IO Work Programs in terms of its own area of competence and capabilities. Special mention should be made of the areas of activity related to CODAC (Control and Data Acquisition) and Instrumentation and Control for Plant Systems and Subsystems (WDS, TBM, and Auxiliary loops), etc.

Thus, PROCON has been generating an experience of contribution to ITER and precise technological know-how of the Project together with a precise strategic vision as a Technological Base Company (EBT) for a greater scientific-technical incidence and greater commercial returns.

The presentation of this PI + D / CDTI Project: EU ITER TBM Systems: CODAC, design of main control rooms and analysis of operational strategies resulting from new developments in instrumentation is the result of the strategic analysis of PROCON SYSTEM anticipating developments of the ITER Project that mean a pre-qualification and positioning in the next years according to the WP expressed by F4E e ITER IO.

1.5.3 Quality and Environmental Certifications

PROCON is committed to effective Quality Management at all levels within the Company. PROCON's policy is to achieve and maintain the highest standard of quality in all aspects of its operation, continuously satisfying the expectations of our customers in relation to all solutions offered. PROCON guarantees the quality requirements of our customers are clearly understood and known through all the phases of contracting from the precision of specifications to the installation of the product. All the work is carried out with a high professional level and technical and commercial integration.

TÜV RHEINLAND recently certified that PROCON SYSTEMS, S.A. applies a Quality System in the area of Design, Manufacture, Installation and Start-up for its projects in accordance with ISO 9001: 2000 standards and other Certifications.

2 SCOPE OF THE WORK

In the present chapter the objectives of the work are described in two main categories: primary and secondary objectives.

2.1 PRIMARY OBJECTIVE

- a) To establish a documented base from which a further analysis of the system could be developed in order to understand the machine and its burdens. This first analysis constitutes a start point from which more detailed information can be added or well corrected by means of the detailed engineering tasks.

2.2 SECONDARY OBJECTIVES

- b) To give support to UPC throughout the technical advice given to PROCON all along the first stage of the Project.
- c) To understand based on the available information the tritium balance throughout the machine and its subsystems.
- d) To apply the Systems Engineering methodology to the ITER TBM system, giving special importance to the legal and standards research and give a standard protocol in order to develop further functional analysis.
- e) To classify the found functions by means of the nuclear standardization which have been found during the research.
- f) To better understand the ITER project as well as its advantages and drawbacks.
- g) To give the theoretical basis for the development of tritium software modeling towards transfer rates and concentration predictive ability
- h) To compile the theoretical basis for the concretion of dynamic control benefits in front of static control
- i) To establish the critical roadmap towards tbm codac architecture and hardware developments
- j) To establish a preliminary functional analysis of the dynamic inventory monitoring system
- k) To compile from the available literature inventory control methodology applied to chemical plants, making special emphasis on: interlocks and sequence control logic, physical model development, definition of model and applications, empirical dynamic models, model development process, types of models, discrete stochastic models and treatment of model results deviation from measurements.
- l) Apply the inferred functional analysis methodology to a pair of TBM subsystems of choice.
- m) Analyze the upper level mechanisms and functions. putting especial emphasis on human resources, computer resources, proposal for a data acquisition, processing and storage system database, raw materials and supply chain, raw materials, supply chain, data/documentation and maintenance and support.
- n) Analyze the upper level constraints. With special emphasis on regional opposition point of view (nimby effect), economical analysis of the outputssupporting resources and waste

3 METHODOLOGY

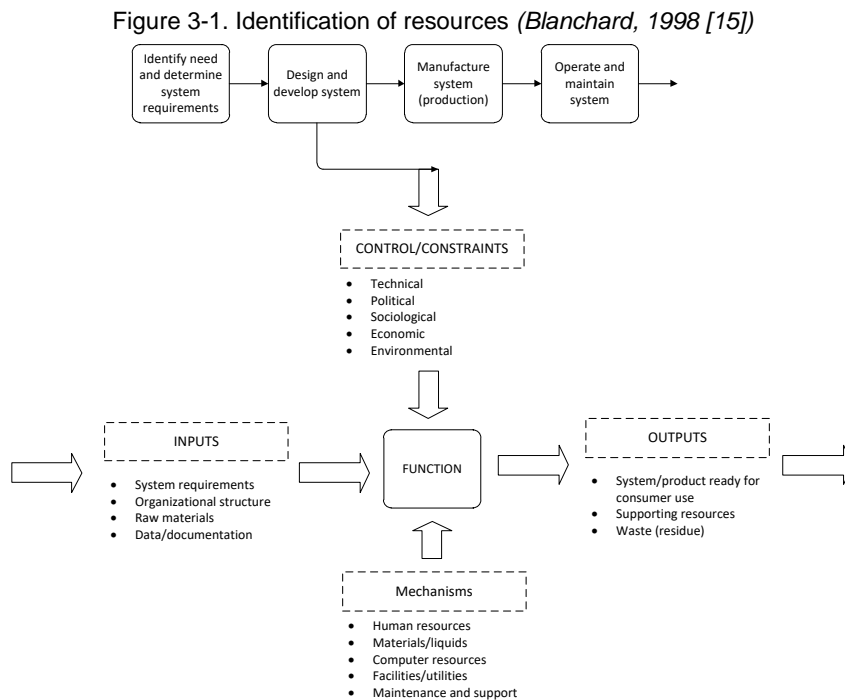
Epigraph 3.1 makes a brief introduction to the Functional Analysis methodology from the point of view of the design criteria of a product or a process. Then epigraph 3.2 develops how a design review checklist must be specified in order to include a new criterion on the list. Epigraph 3.3 deals with networking theory as per the literature of reference.

3.1 DESIGN CRITERIA

As stated in traditional system engineering manuals and references, functional analysis of the system must be one of the first steps to develop in order to compile and clarify the needs in terms of ‘whats’ and ‘hows’. The idea is to follow a top down system design architecture from the ‘what’ is needed to obtain from the system and following certain techniques as can be illustrated in selected bibliography of choice, obtain finally the ‘how’ in terms of more specifically hardware or equipment needed. Figure 3-1 shows the process to be developed in order to identify the needed resources involved in Functional Analysis methodology, as described by the literature (Blanchard, 1998 [15]).

The use of system engineering in the design phase has demonstrated to be effective in terms of feasibility, maintainability, reliability and budgetary control and is considered to the present date a best practice. The iterative nature of system engineering process during the whole product or system life cycle demonstrates the effectiveness of the methodology regarding continuous improvement, that might include as well the system decommissioning and final disposal.

In this sense, the presented methodology is deployed in order not to include from the system superfluous or unneeded equipment or system parts, so only the strictly devices that enable to perform the functionality of the system should be implemented. This means that non useful parts would be not integrated. (Blanchard, 1998 [15])



The tiers that are meant to be developed include the consideration of the needs, a feasibility study, consideration and analysis of internal and external constraints, environmental and human factors as well as the state of the art for the equipment, hardware and / or software that possibly might form part of the whole.

Also from the point of view of System Design review checklist, Blanchard establishes a series of generic aspects that must be taken into consideration. The answer to each item listed should be YES, as per the criteria shown in Table 3-1.

Table 3-1. System Design Review Checklist (Blanchard, 1998 [15])

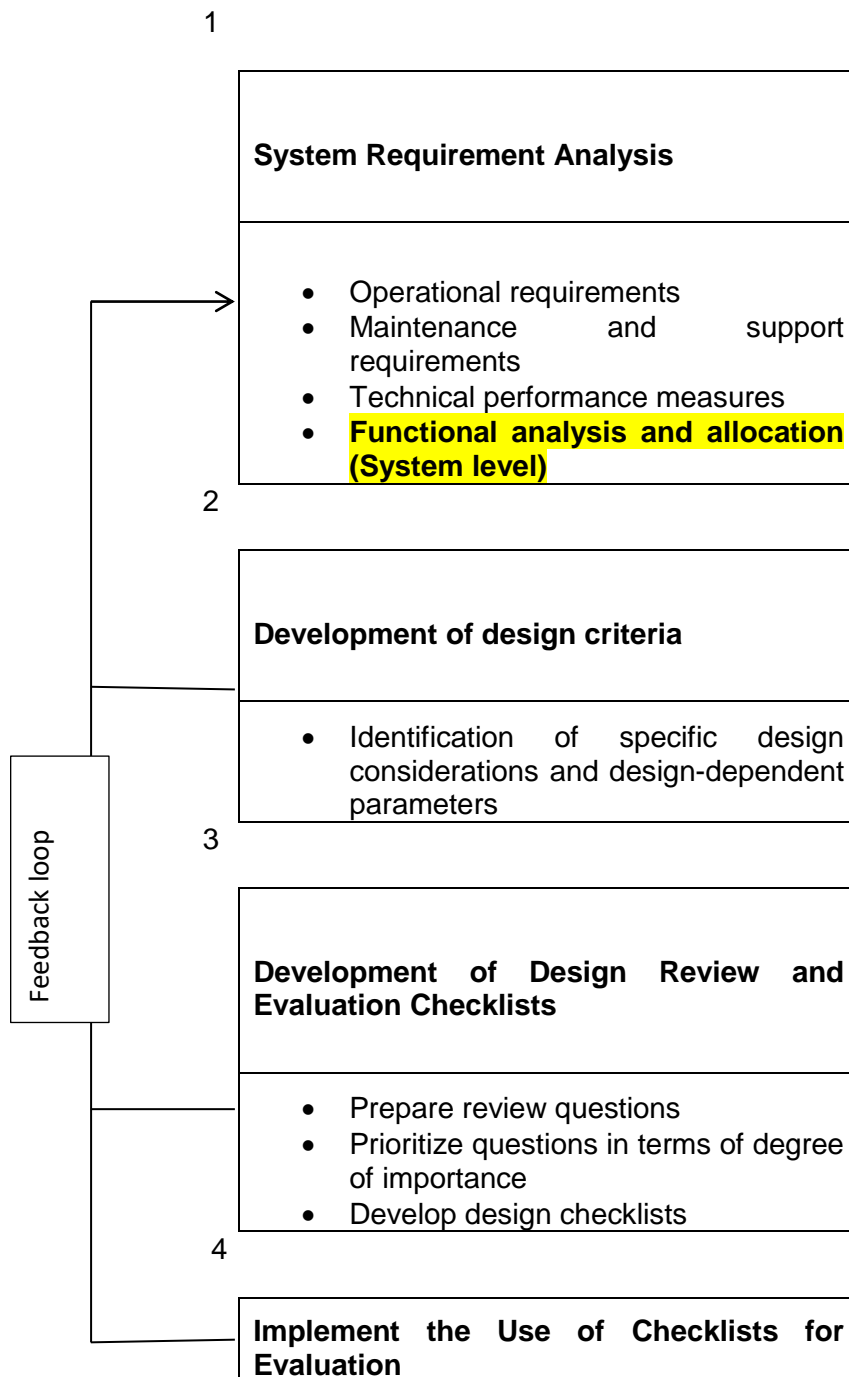
General	
1. System operational requirements defined	7. System engineering management plan completed
2. Effectiveness factors established	8. Design documentation completed
3. System maintenance concept defined	9. Logistic support requirements defined
4. Functional analysis and allocation accomplished	10. Ecological requirements met
5. System trade-off studies documented	11. Social requirements met
6. System specification and supporting specifications completed	12. Economic feasibility determined
Design features – Does the design reflect adequate consideration of	
1. Accessibility	12. Packaging and mounting
2. Adjustments and alignments	13. Panel displays and controls
3. Cables and connectors	14. Producibility
4. Calibration	15. Reliability
5. Disposability	16. Safety
6. Environment	17. Selection of parts/materials
7. Fasteners	18. Servicing and lubrication
8. Handling	19. Software
9. Human Factors	20. Standardization
10. Interchangeability	21. Supportability
11. Maintainability	22. Testability

3.2 DESIGN REVIEW CHECKLISTS

In many occasions other aspects, different from those listed above might be as well of interest. As the design review manual is mainly focused in the generalist product and process industry, the present case deals with nuclear standards that sometimes introduce different and more restrictive quality levels. This might introduce the review from these other aspects and the checklists might be developed from draft. Blanchard introduces a process to fairly develop these new checklists that may be useful in the present case. Table 3-2 shows the proposed algorithm. (Blanchard, 1998[15])

In the latter chapters, when the methodology is applied to some examples, we would see how some of the points included in the checklist are covered. It is to be mentioned that this is a non-extensive – nonrestrictive list and could be as well shortened or well include more checkpoints.

Table 3-2. Process to develop new design review checklists (Blanchard, 1998[15])



3.3 INFORMATION NETWORKS DEFINITION AND INTEGRITY

3.3.1 Information network levels definition

It is stated that for a given network there are six levels of abstraction which are common to all kind and scale of information networks. Those are presented below and are mutually related in a top down hierarchical manner: (Becker, 1977 [17])

- **I - Network level**
- **II - Processing level**
- **III - Macrofunctional level**
- **IV - Microfunctional level**
- **V - Element level**
- **VI.- Device/Technical level**

I. - Network level. This is the upper level and it is analyzed, with appliance to the proposed system, in order to determine if it is required a network. It is not considered as a network a sole batching information processor which it is off line, although it is connected to printers and/or mass storage devices or other type of peripherals. This kind of system is identified as the level II of the processing function. This is the reason why a network is a system that requires one or more information processors with and interface of one or more remote information sources and/or destination points,

II. - Processing level. This functional level divides roughly the information processing functions from the network processing functions. The functions are analyzed by their application to in order to determine if those are going to be processed in a better way by an information process or well by a network processor located in another node off the network. Lack of differentiation between both concepts is the main cause cost and performance issues arise in many systems.

III. - Macrofunctional level. A complete assessment in the level III of the required network functions leads to select or identify the group of elements that are necessary for the network equipment in order that the specific objectives are satisfied. The equipment can be acquired alternatively by its advantages and/or its drawbacks, making available for to the network designer the opportunity to better select the best equipment.

After selecting equipment, it is necessary to evaluate the control functions in order to state the group of codes and programming systems that will assure the effective control of the equipment and the network as a whole. Depending of the size of the network, and in order to achieve the decided optimization, it would be necessary to apply the codes and the control functions in more than a node of the network.

IV. - Microfunctional level. In this level it is selected a sub-group of network functions and control functions, which are necessary to implement the chosen functionality of the network. At this level the functions are still generic, and commonly it is not precise an extensive analysis to determine its applicability.

At microfunctional level IV, the following structure can be elucidated.

- Network level III functions (macrofunctional) include the following level IV (microfunctional) functions:
 - Concentration
 - Coupling
 - Distribution
 - Commutation
 - Origin/destination interface
- Control level III functions (macrofunctional) include the following level IV (microfunctional) functions:
 - Information routing
 - Network integrity
 - Database registering
 - Statistical registering
 - Usability
 - Supervisory control

V and VI. - Element level and Device/Technical level. The elements of the level IV are included and listed roughly in the following points, including the devices and techniques applicable, belonging to level VI. The inputs corresponding to level V and VI are located hierarchical are below the inputs of the control and network functions corresponding to level IV.

On behalf of simplicity the dissertation corresponding to the levels V and VI is omitted due to the complexity and extension of its development, which is actually out of the scope of the present document. Last but not least it is to be mentioned that one of the main guidelines imposed to the objectives it that the ultimate devices or techniques applicable to the system are not to be specified in a concrete manner.

3.3.2 Information network integrity

From the bibliography of reference (*Becker, 1977 [17]*), the definition of network integrity implies the situation when it are developed the necessary functions that enable the information which it is transmitted reaches is destination with precision, without distortions or errors during the distribution, as well as the same time failures could be properly detected, and it is started an appropriated procedure of rebooting. Also it is necessary that access is granted to the network from determined devices which are origin and/or destination, and authorized operators.

The integrity of the information is related to the precision and validity of the information between the origin and destination of the network. This implies certain number of functions, as it is described below through the following steps.

- Detection and error correction
- Retransmission
- Continuity
- Network reliability

- Rebooting
- Test and diagnostics.

3.3.3 Safety and security

The security of information networks is a problem to which the network designers attribute each time more importance. Huge national networks, as well as highly distributed networks, are very sensitive to many problems related to the prevention of non-authorized access to the networks and its information. A number of security measures must be implemented through several levels, and count with at the same time with a number of techniques of machines, devices, codes and programming systems.

The security functions imply the following points:

- Terminal identification
- Operator validation
- Access codes
- Distribution network

4 FUNCTIONAL ANALYSIS

Following the specified methodology a preliminary illustrative development of the data as it could have been collected from different sources is presented in the following epigraphs. Epigraph 4.1 develops the analysis of the inputs to the systems. Then epigraph 4.2 explains the TBMs design checklist. The next epigraph, 4.3, deals with 4.3 TBM subsystems and main functions. Epigraph 4.4 deals with 4.4 functional analysis of the dynamic inventory monitoring systems, which is considered to be one of the most important results in the present document. Then chapter 4.5 explains how must be developed a physical model according to the referenced literature. Epigraph 4.6 deals with the application of the described methodology: examples control strategy for two different systems constituting the TBMs. The following epigraph 4.7 explains the architecture of the codac network system, first from the point of view of the theory from the selected literature and then giving an example of the whole system as per ITER documentation. Finally epigraph 4.8 explains the controls and constraints from the point of view of nuclear standards and French legal framework.

4.1 ANALYSIS OF THE INPUTS

4.1.1 General requirements

- As all other components, the TBMs shall not put in compromise the normal operation condition of the whole machine.
- The proposed TBM shall develop its function of heat flux surface recovery within the limits of predefined deformation allowances.
- Also the irradiated TBMs shall contribute, after their extraction, to the analysis of damage produced onto the materials.
- An also important general requirement is to don't compromise the stability of the plasma.

4.1.2 Particular requirements of TBS

- **Tritium breeding**

As tritium is not available at natural state, it shall be generated in tritium breeder blankets of future DT fusion reactors. One of the primary objectives of the TBM test campaign in ITER is to demonstrate the feasibility of tritium breeding for the related blanket concept of a fusion reactor. For that purpose, tritium will be produced by neutrons capture in lithium, in particular on the lithium-6 isotope.

- The Helium Cooling System (HCS): Auxiliary systems to the removal of thermal power and tritium recovery from the blanket modules.

The primary function of the Helium Coolant System is to extract the thermal power deposited in the TBM due to the plasma radiation and neutron interaction and transfer it to the ITER Heat Rejection System (HRS).

An important design parameter is the leak tightness or the maximum allowable leak rate. Since the HCS contains tritium due to permeation inside the TBM it is required that, for all components, the leak rate should be better than 10^{-6} Pam³/s (global leak rate).

The loop has the shape of an eight with the TBM installed on the high temperature end and the helium circulator(s) on the low temperature end. A cooler, installed before the circulator, reduces the helium temperature. An electrical heater installed upstream of the TBM increases the helium temperature. Placed in the centre of the loop, a helium–helium heat exchanger transfers a part of the heat from the hot leg into the cold leg, thus, reducing the level of power that the electrical heater has to insert into the helium flow.

The most critical component of HCS is the circulator. The selected solution is the one of a single stage centrifugal turbo machine driven by a high-speed asynchronous motor. The motor of the circulator is the element that is limiting the temperature of the helium in the cold side.

The materials used for the manufacturing of the pressure vessels and piping shall be defined in order to avoid pollution of helium.

Since there will be a certain amount of tritium that will permeate from the breeder inside the HCS any material that could be a getter for hydrogen shall be avoided.

The European Union proposes two different concepts of helium-cooled blanket for testing in ITER, one with ceramic breeder and beryllium as neutron multiplier (HCPB), the second with lithium lead as breeder and multiplier (HCLL).

- HCLL/HCPB (Coolant Purification System-CPS): Auxiliary systems to the removal of thermal power and tritium recovery from the blanket modules.

The system should be composed by the following components:

Q2O Adsorption Column, Q2 Getter Beds, Economizer, Heat Exchanger, Filters, Reducing Bed, Compressor.

Q2O adsorption column based on molecular sieve was considered as the reference solution. It is foreseen to reduce the desorbed Q2O to Q2 before to send it to the tritium plant. For this purpose it is possible to use either a reducing bed, so far considered as reference option. The gas stream has to be cooled before sending it to tritium plant.

Tritium extraction is based on the adoption of getter beds, whose main advantages are compactness and operation at room temperature. The sizing of the purifier vessel has been based considering the Q2 loading in the most challenging conditions. The proposed purifier will be made with two vessels (one in absorption phase and the other in regeneration) with the getter capable to remove the Oxygen containing impurities and the remaining will be filled with ZrCo to remove Q2.

In case of HCLL the separation of water is not necessary, and the system should be simplified removing the Q2O column.

- **Heat removal and recovery**

The concept shall demonstrate the effectiveness of heat recovery, which is the other main issue of the fusion reactor for practical feasibility. This might be proved by a helium flow circulating by cooling channels which are to be integrated in the TBM structure which may provide enough heat exchange capacity.

- **Neutron shielding**

The TBM concept might be able to shield other parts of the whole machine from excessive damage produced by plasma neutron flux, secondary neutrons and gamma radiation.

4.2 TBM SYSTEMS DESIGN CHECKLIST

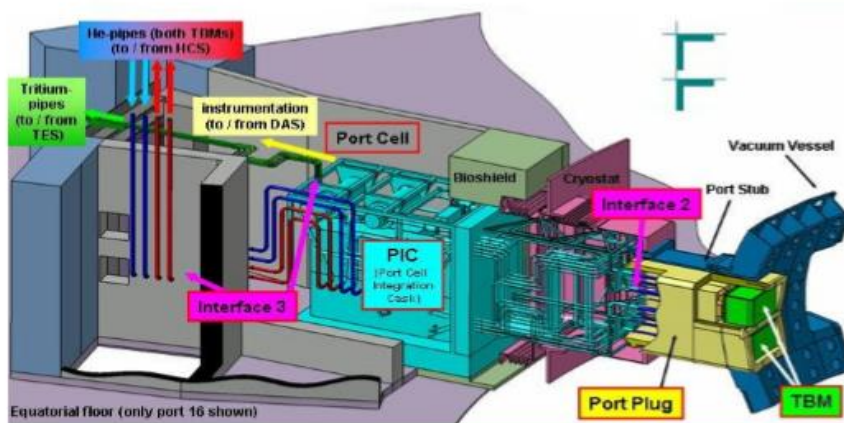
As previously stated in the present document, the systems under study are HCLL and HCPB TBMs, belonging to ITER machine. Both systems are located in equatorial port number 19 of the tokamak and differ in the principle of the tritium extraction in the following way:

Currently the systems are still in engineering design phase forming part of the orders made upon different engineering services attributed to public and private agents. As access to detailed information upon these systems has been limited the corresponding functional analysis has been developed in the basis of generic declassified data and drawings.

Meaningfully, as declared in earlier paragraphs, continuous improvement of engineering data, drawings and design parameters must be continuously improved as per applicable quality standards, involving as well local constraints from a top to bottom hierarchy (French nuclear regulatory body).

Figure 4-1 shows an axonometric view of the area around the TBM Horizontal port.

Figure 4-1. Axonometric view of the area around the TBM Horizontal port (Seki. 2007 [69])



The two basic proposals from the European consortium are named HCPB (He-Cooled Pebble-Bed) and HCLL (He-Cooled lithium-Lead).

Table 4-1 . Two main design concepts to be tested at the TBM program (Seki. 2007 [69])

	HCPB He-Cooled Pebble Bed	HCLL He-Cooled lithium lead
Structural material	EUROFER	
Coolant	Helium, 8 Mpa, 300 / 500 °C	
Tritium breeder neutron multiplier	Solid Li ₂ TiO ₃ / Li ₄ SiO ₄ , Be	Liquid Pb-15.7Li

The systems design review includes the following aspects that constitute their main functionalities:

- **Structural design.** The systems operations include the flow of strong forces created by the pressures and circulating phenomena. The review must include detailed structural definition and calculations to ensure the safety of the system.
- **Neutronics.** The nuclear nature of the system makes this point especially important for the review of the system definition. Degradation of related sub-systems and activation phenomena related to exposure to neutrons, secondary neutrons and gamma rays might be expected and its consequences predicted in order to facilitate the development of maintenance and replacement stages.
- **Thermal Hydraulics.** The Thermal phenomena related to the thermal recovery that it is expected to ensure the system for power production must be seriously analyzed, so it is related also to safety. It is to be considered that deformations might appear in the presence of high plasma temperatures and allowances must be established.

4.3 TBM SUBSYSTEMS AND MAIN FUNCTIONS

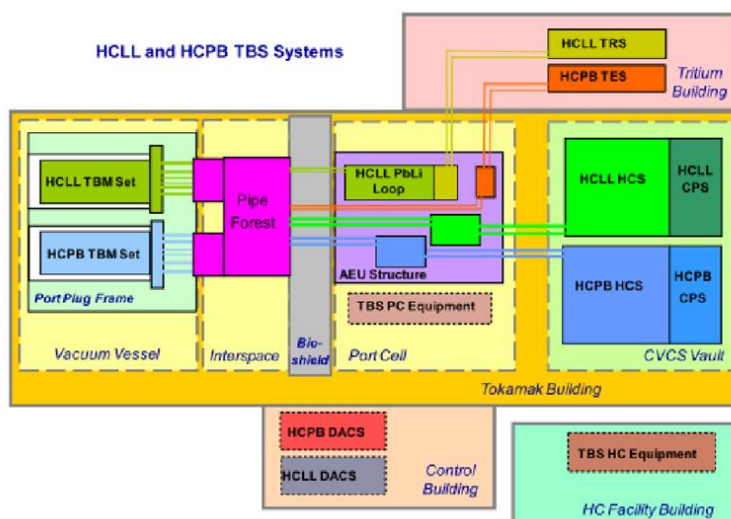
Epigraph 4.3.1 takes care of the analysis of the requirements in order to develop a proper functional analysis; the latter epigraphs 4.3.2 to 4.3.6 in their turn develop the functional analysis of the main different systems according to (AFNOR. 2012 [28]).

The system analyzed are connected and structured in the form that the following image shows schematically.

The main substances that circulate through the pipes are Helium gas and tritium, H₂ and H₂O.

In the following epigraphs the main functions of these subsystems are described, also in a schematic manner. Figure 4-3 shows the schematic diagram of the two TBMs to be tested and its ancillary interfaces.

Figure 4-2. Schematic diagram of the two TBMs to be tested and its ancillary interfaces between subsystems (Panayotov.et. al. 2011 [70])



4.3.1 REQUIREMENTS ANALYSIS

The first functional analysis are dated from after Second World War and developed at General Electric Company in 1947. The evolution of this methodology proved to increase usability, cost-effectiveness and quality in both processes and products. Years after, France also included the standards in its own corpus of industrial regulation, being as well developed in turn as European standard. Nowadays it is widely spread all over the world in the design phase of complex systems.

In France (where the issued plant is located, various standards are applicable for development of the analysis of requirements in complex systems. These are the following.

- **NF X 50-100.** Analyse Fonctionnelle – Caractéristiques fondamentales – 1996
- **NF X 50-151.** Analyse de la Valeur, Analyse Fonctionnelle – Expression fonctionnelle du besoin et cahier de charges fonctionnel – 1991
- **FD X 50-101.** Analyse Fonctionnelle – L'Analyse Fonctionnelle outil interdisciplinaire de compétitivité – 1995
- **NF EN 1325-1.** Vocabulaire du Management par la Valeur, de l'Analyse de la valeur et de l'Analyse Fonctionnelle – 1: analyse de la valeur et Analyse Fonctionnelle -1996
- **Expression du besoin et Cahier des Charges Fonctionnel.** Élaboration et rédaction. Afnor Éditions. 2^e Edition. 2008
- **Expression du besoin et Cahier des Charges Fonctionnel.** Élaboration et rédaction. Afnor Éditions. 3^e Edition. 2012

In this sense, the following paragraphs a functional analysis is developed according to the above mentioned methodology. Before that, some definitions derived from the French AFNOR Standards are given: [AFNOR, 2012].

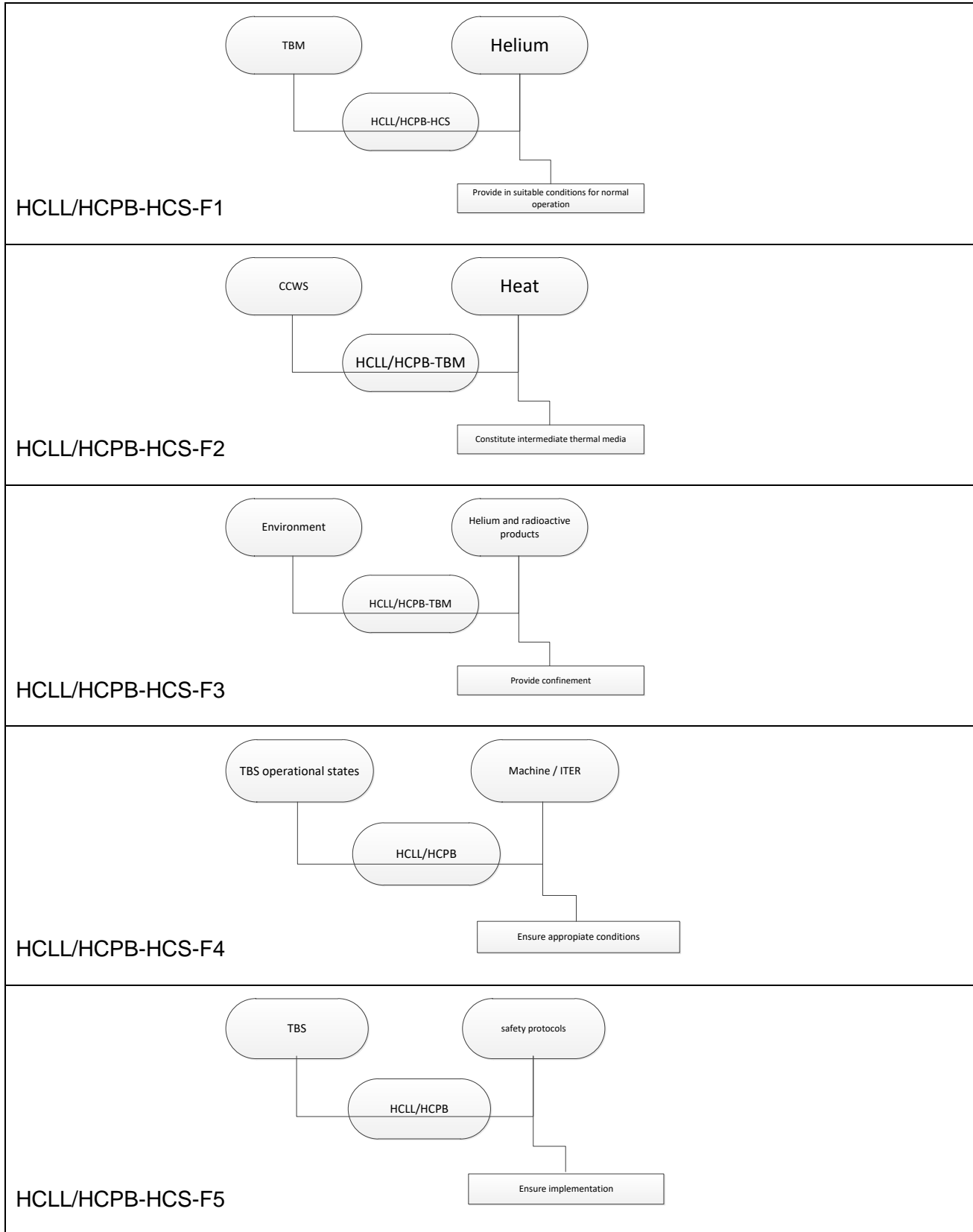
- **Function:** Action of a product or one of each component
- **Service function:** Required action to a product or developed by it, in order to satisfy a part of a requirement of the user
- **Technical function:** Action of a component or action comprising between the components of a product in order to assure the service functions

4.3.2 HCLL/HCPB-HCS

The main functions of the Helium Cooling System can be described as follows: Figure 4-4 shows the main functions of the Helium Cooling System

- **HCLL/HCPB-F1.** To ensure TBM operation by supplying helium at operating conditions
- **HCLL/HCPB-F2.** To ensure maintenance of a thermal medium between TBM and CCWS
- **HCLL/HCPB-F3.** To ensure maintaining of a confinement for Helium and radioactive products
- **HCLL/HCPB-F4.** To ensure TBS is operational by maintaining appropriate conditions and permits maintenance
- **HCLL/HCPB-F5.** To ensure TBS safety implementation

Figure 4-3. Main functions of the Helium Cooling System (Bête à cornes)

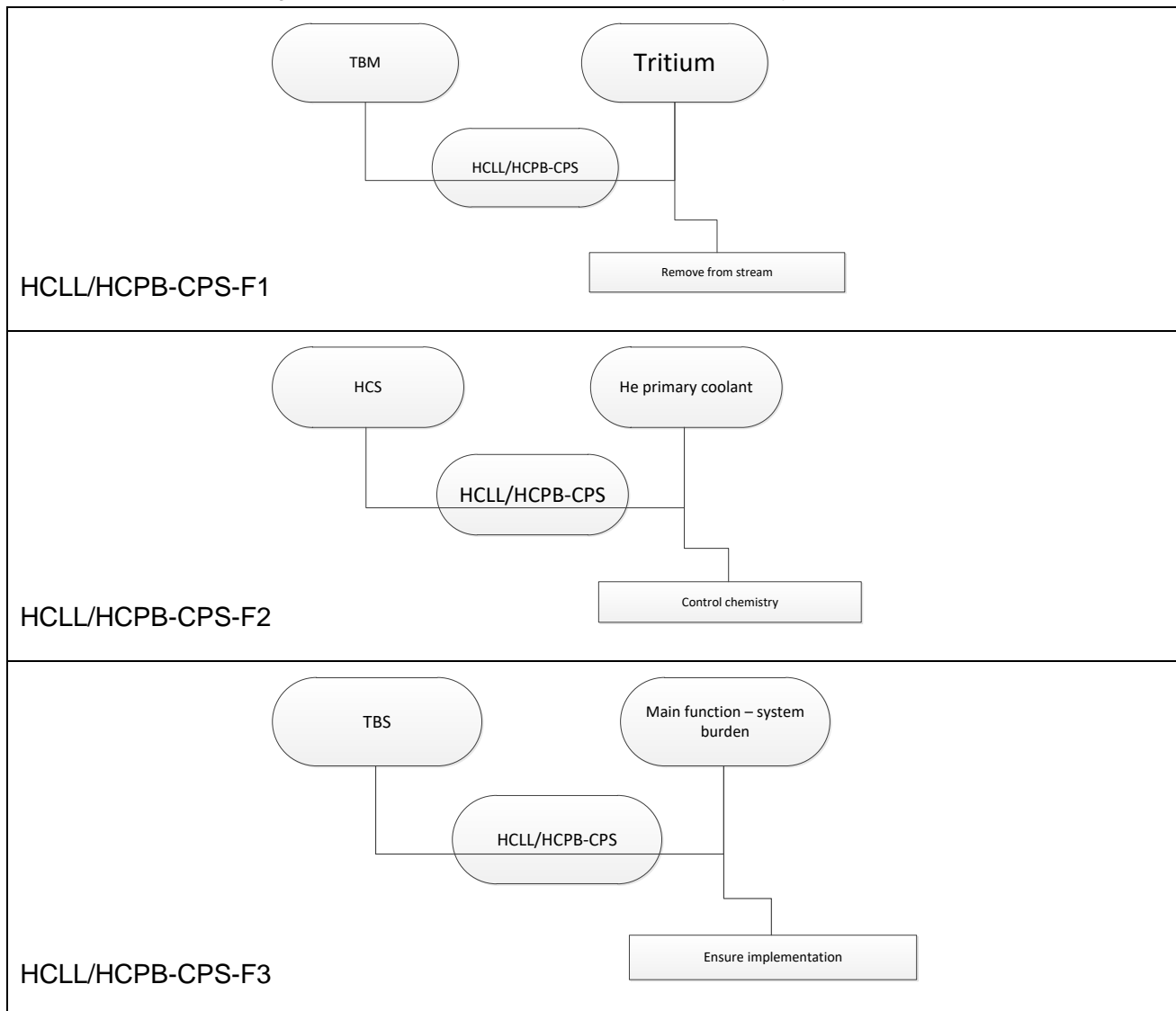


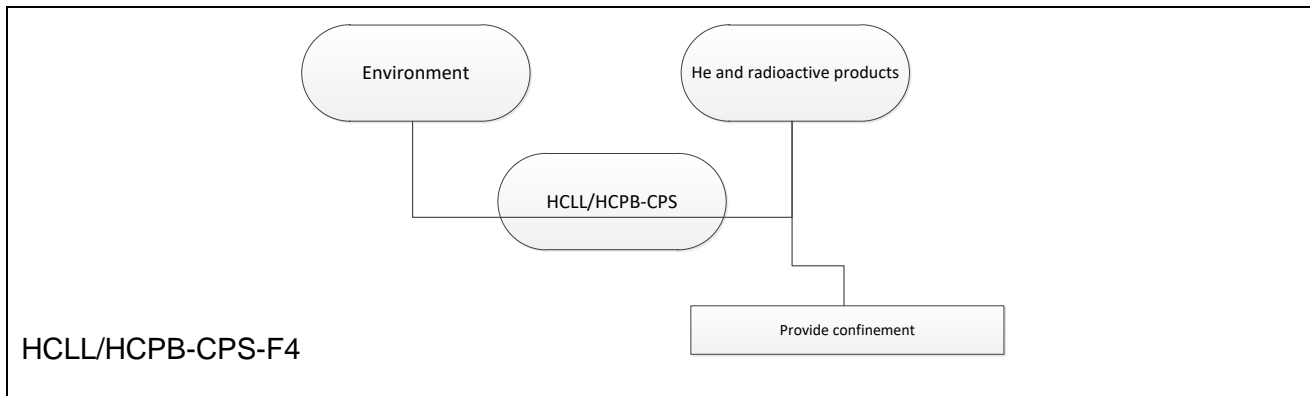
4.3.3 HCLL/HCPB-CPS

The main functions of the Coolant Purification System can be described as described in the following points. Figure 4-5 shows the main functions of the Coolant Purification System:

- **HCLL/HCPB-CPS-F1.** To enable the extraction of tritium permeating into HCS from the TBM and directs it to downstream tritium processing units in suitable form
- **HCLL/HCPB-CPS-F2.** To control the chemical conditions of He primary coolant in HCS in 2 steps:
 - F2.1: To extract gaseous impurities coming from all parts of HCS
 - F2.2: To maintain the oxidation potential of the coolant by controlling the flow of chemical species (adjusting the H₂O/H₂ ratio under normal operating conditions)
- **HCLL/HCPB-CPS-F3.** Ensures implementation of the TBS main function
- **HCLL/HCPB-CPS-F4.** To ensure maintaining of a confinement for Helium and radioactive products

Figure 4-4. Main functions of the Coolant Purification System (Bête à cornes)





4.3.4 HCLL-PbLi Loop

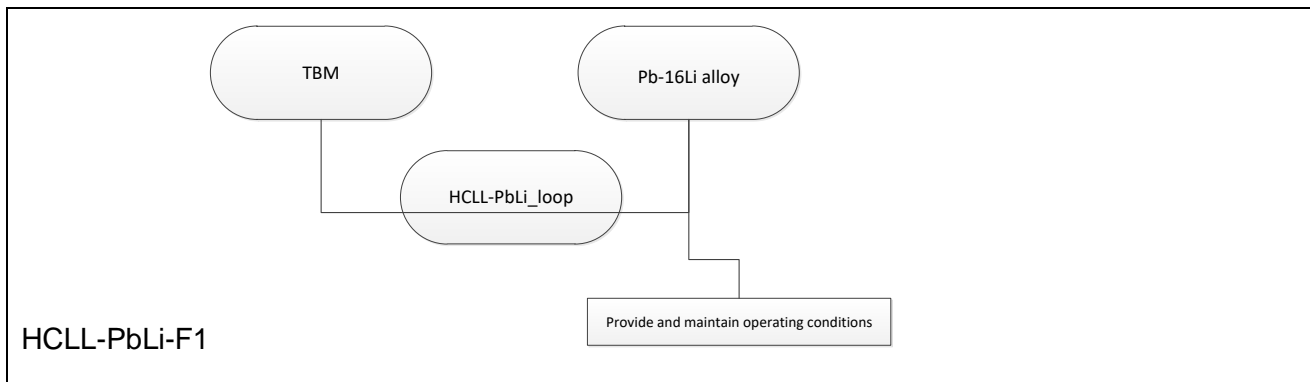
The main functions of the PbLi Loop can be described as described in the following points. Figure 4-6 shows the main functions of the PbLi Loop follows:

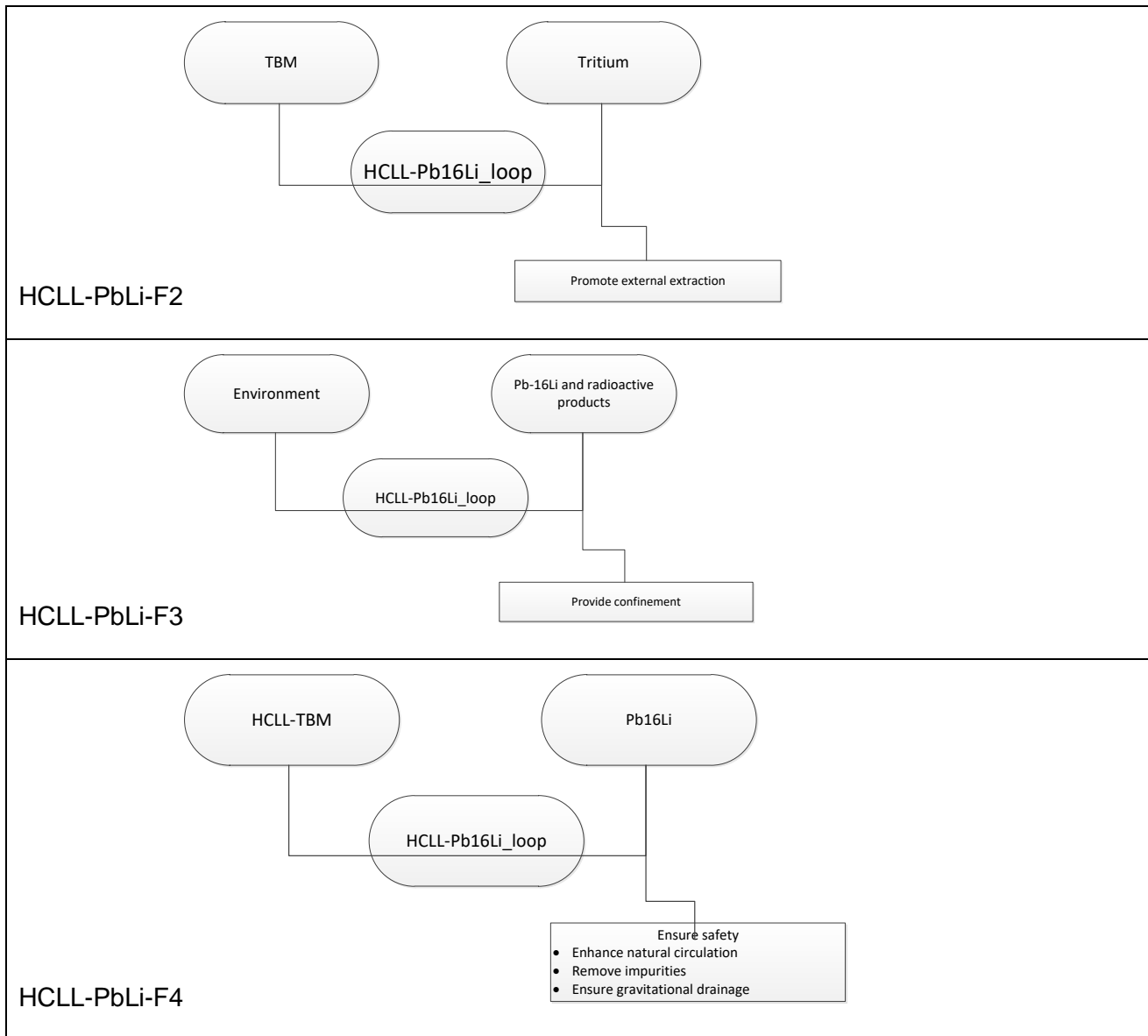
- **HCLL-PbLi -F1.** To ensure the suitable HCLL-TBM operation by providing and maintaining the Pb-16Li alloy operating conditions
- **HCLL-PbLi -F2.** To promote external tritium extraction from TBM
- **HCLL-PbLi -F3.** To ensure maintaining of a confinement for Pb-16Li alloy and radioactive products
- **HCLL-PbLi -F4.** To ensure safe conditions for HCLL-TBM deployment

Some sub-functions can be inferred from the above:

- To ensure natural circulation of the Pb-16Li alloy in the HCLL-TBS system
- To remove impurities from the circulating alloy
- To ensure gravitational drainage of the TBM module and the Lithium-Lead loop

Figure 4-5. Main functions of the PbLi Loop (Bête à cornes)



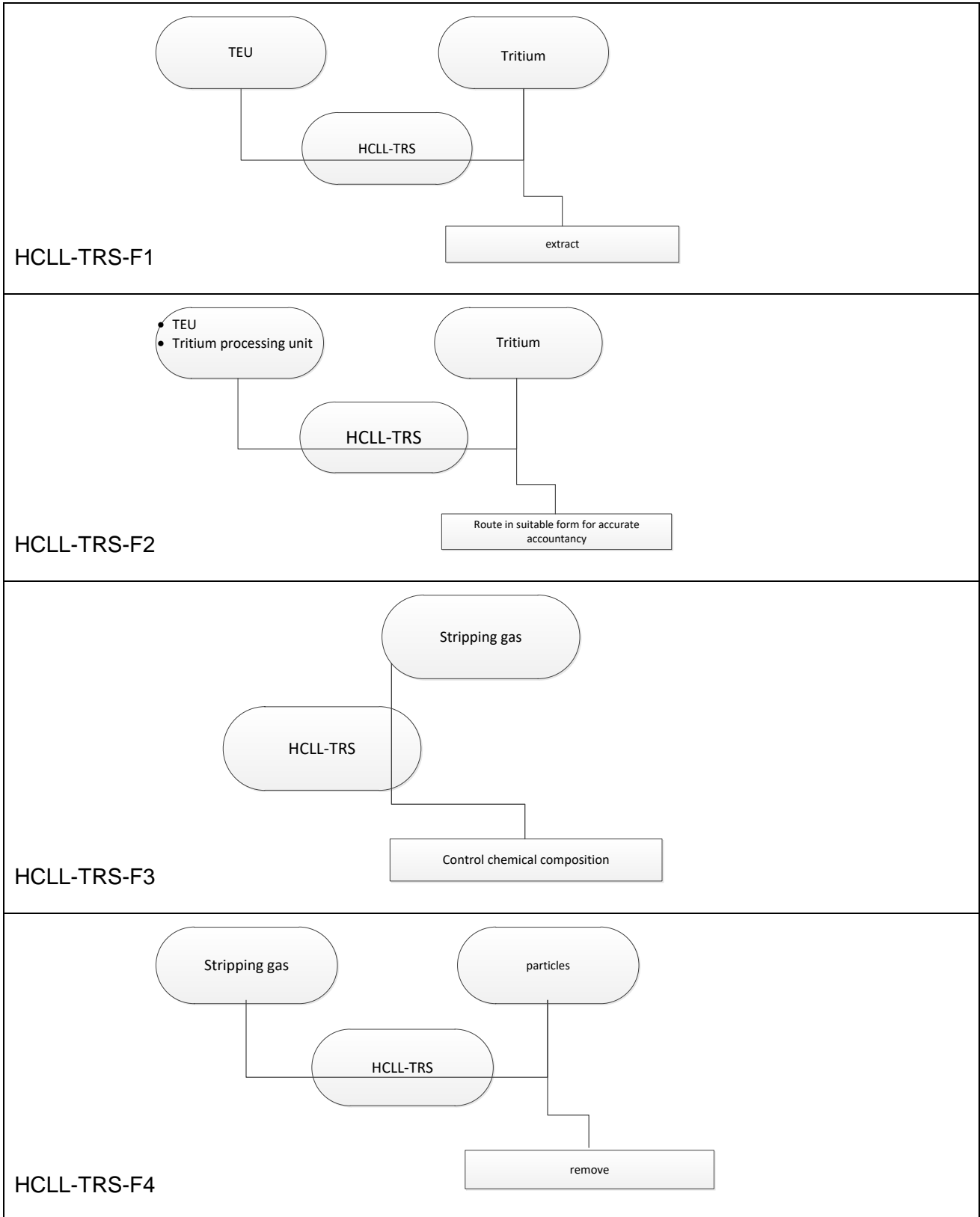


4.3.5 HCLL-TRS

The main functions of the tritium recovery system can be described as described in the following points. Figure 4-7 shows the main functions of the tritium recovery system.

- **HCLL-TRS -F1.** To extract tritium from the stripping gas coming from TEU
- **HCLL-TRS -F2.** To route the extracted tritium to the tritium processing system in the Tritium plant in a suitable form for an accurate tritium accountancy.
- **HCLL-TRS -F3.** To control the chemical composition and physical properties of the stripping gas, and in particular the H₂ content added to this gas.
- **HCLL-TRS -F4.** To remove solid particles from the stripping gas.

Figure 4-6. Main functions of the tritium recovery system (Bête à cornes)

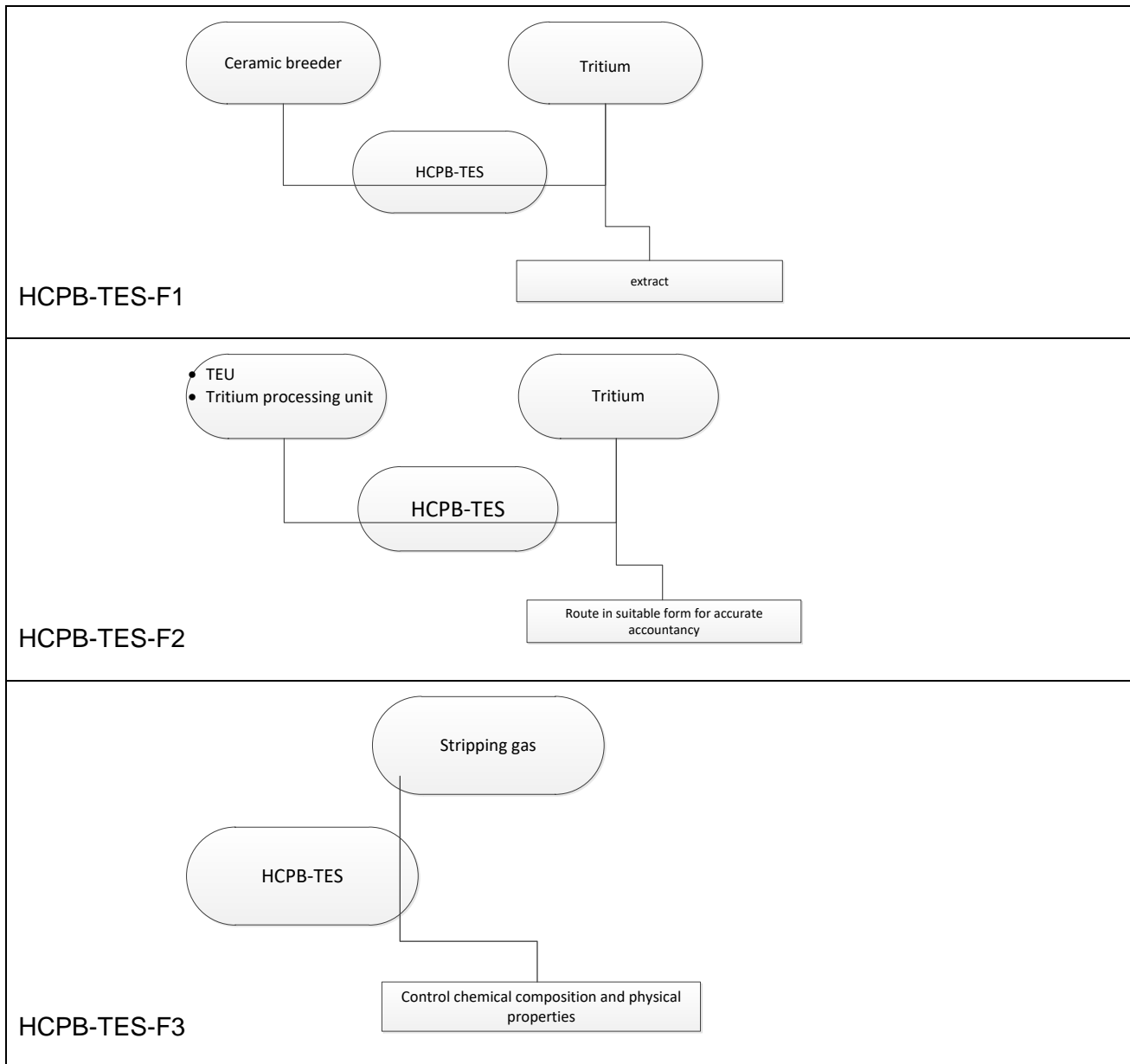


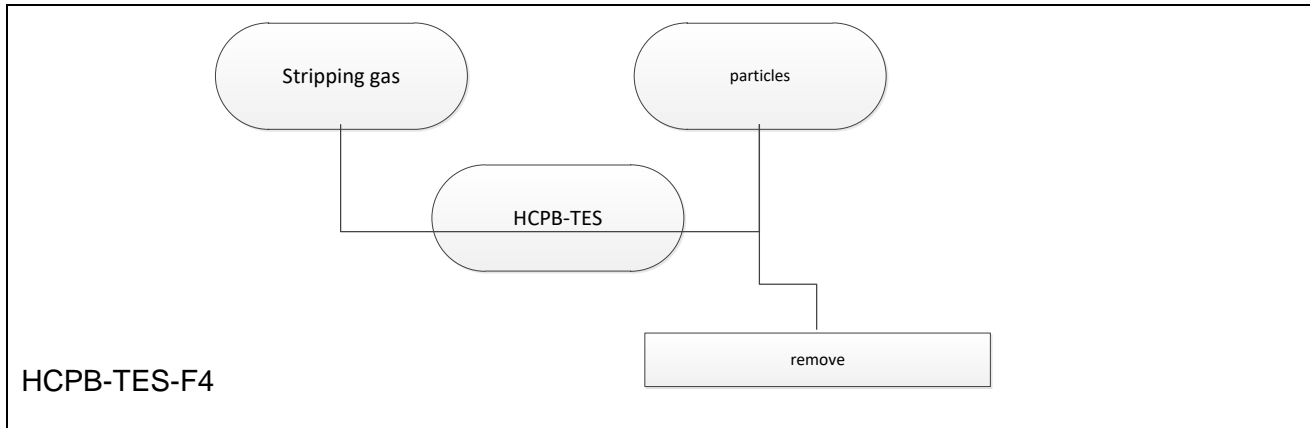
4.3.6 HCPB-TES

The main functions of the HCPB-TES are described in the following points. Figure 4-8 shows the main functions of the HCPB-TES.

- **HCPB-TES F1.** To extract tritium from the ceramic breeder in HCPB-TBM
- **HCPB-TES F2.** Ensures accurate tritium accountability by directing the extracted tritium to the tritium processing system in the tritium plant in a suitable form
- **HCPB-TES F3.** To add H₂ to the gas to control chemical composition and physical properties of the stripping gas
- **HCPB-TES F4.** To remove the solid particles from the stripped gas

Figure 4-7. Main functions of the HCPB-TES (Bête à cornes)



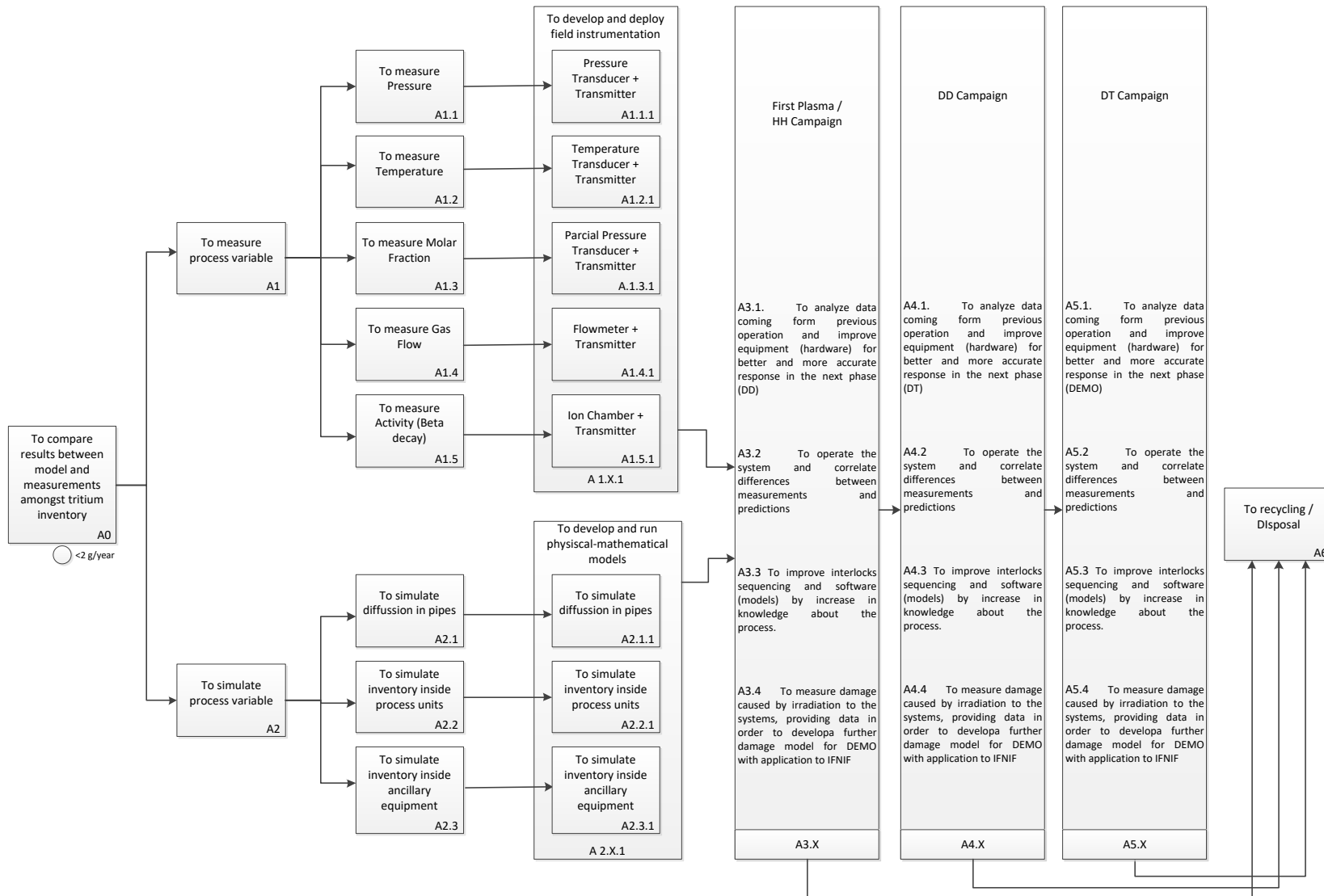


4.4 FUNCTIONAL ANALYSIS OF THE DYNAMIC INVENTORY MONITORING SYSTEM

4.4.1 Main Functions for a Tritium Inventory Monitoring System

Figure 4-9 shows depicts how the main functions of the tritium inventory monitoring system are related.

Figure 4-8. Main functions of the tritium inventory monitoring system



4.4.2 Adaptation Functions

- CODAC-AF-1. To resist the aggressive environment of the reactor
- CODAC-AF-2. To transmit signals (measurements) to the information system
- CODAC-AF-3. To obey control-command signals (actuators)
- CODAC-AF-4. To respect the facilities in order to be reusable
- CODAC-AF-5. To be locatable by the remote handling system (RFID)
- CODAC-AF-6. To respect the environment by being radioactive self contained (shielding)

4.4.3 Relationship between functions and life stage

For each service function, Table 4-1 indicates with a cross mark which are the phases or stages of the life of the product during which the mentioned function should be assured. Table 4-2 shows a matrix representation of the most representative service functions

Table 4-2. Main stages of the life cycle of the product during which the functions are to be assured

Situations: →	Design/Engineering Phase	Operation			Decommissioning/ Recycling/ Disposal
		H Plasma Phase	D Phase	DT Plasma Phase	
Service Function: ↓					
A0. Compare results		X	X	X	X
A1. Measure process variable		X	X	X	X
A1.1. Measure pressure		X	X	X	X
A1.2. Measure temperature		X	X	X	X
A1.3. Measure composition		X	X	X	X
A1.4. Measure flow		X	X	X	X
A1.5. Measure activity		X	X	X	X
A1.1.1. Develop and deploy field instrumentation	X				
A2. Simulate process variable	X	X	X	X	
A2.1. Simulate diffusion through pipes	X	X	X	X	
A2.2. Simulate inventory inside process units	X	X	X	X	

A2.3 inventory equipment	Simulate ancillary	X	X	X	X	
A2.1.1 run models	Develop and physical- mathematical	X	X	X	X	

Table 4-3. Matrix representation of the most representative service functions

For / With	Design/Engineering Phase	H Plasma Phase	D Phase	DT Plasma Phase	Decommissioning/ Recycling/Disposal
Design/Engineering Phase	A1.1.1, A2.				
H Plasma Phase		A0, A1, A2.	A0, A1, A2.	A0, A1, A2.	
D Phase		A0, A1, A2.	A0, A1, A2.	A0, A1, A2.	
DT Plasma Phase		A0, A1, A2.	A0, A1, A2.	A0, A1, A2.	
Decommissioning/ Recycling/Disposal					A0, A1

4.4.4 Inventory Control Methodology

Inventory Control involves a deep knowledge of the process, as there are a number of possibilities in order to design and deploy the related control system, which might in turn be the ultimate responsible of governing the process during operation. Nevertheless manual human maneuvers are to be foreseen in case of ultimate incidents or abnormal operation of the system.

From the selected bibliography (*Ollero, 1997 [10]*) (*Puigjaner, 2006 [13]*) three main methodologies are applicable to design control for complex processes. These are the following:

- ***Price and Georgakis***
- ***Luyben***
- ***Skogestad***

Price and Georgakis

The proposed methodology involves two levels hierarchically stacked. On the top, a supervisory control, which optimizes, start/stop, and which interacts directly with the regulatory control, which in turn interacts directly with the plant or process.

The decision sequence proposal is stated as presented below:

- Location of production control
- Design of the inventory control system
- Product specifications control
- Operation constraints control
- Design of the control which optimizes economic performance

Luyben

A second methodology is proposed by Luyben et al that develops through nine consecutive steps.

- Establish control objectives
- Determine the number of degrees of freedom
- Establish the energy management system for the plant
- Establish the production of the plant
- Control the quality of the products and satisfy the operational constraints and safety
- Establish a flow through each feedback loop and control the inventories of the total mass of liquid (level) and gas (pressure)
- Check the inventories of the components
- Control the individual process units
- Optimize the plant or improve dynamic control

Note that the methodology proposed by Luyben is an important contribution to the control systems design, but it presents some drawbacks, because in some of its points it does not explain the way

how and why the steps should be followed. This lack of concretion is due to the intrinsic difficulty to develop a general methodology which could apply to a huge variety of chemical plants.

Skogestad

The Skogestad methodology involves a series of steps. The first step is a top-down analysis in which it is decided which primary variables are going to be controlled, and in which the production of the plant is adjusted. A second stage of the design is developed down to top in which the control and regulatory level is defined, and the configuration (centralized or sparse) of the upper control level is determined.

The Skogestad methodology is complicated and is developed through the determination of economical functions and optimization, being of difficult application and actually is out of the scope of the present work. Nevertheless, two main control levels design stages are to be mentioned. These are the supervisory and regulatory levels.

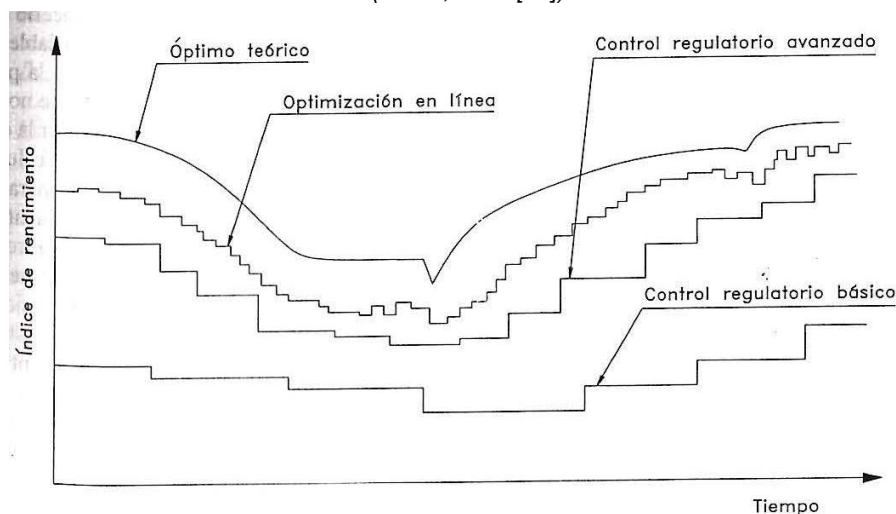
The objective of the supervisory control level of the plant is to maintain the primary control variables in its optimum set points, acting over the valves or, in its case, over the set points of the controllers of the regulatory level.

The basic regulatory level is the lowest level of automatization, consisting of the implementation of the control loops which control variables such as pressures, temperatures and flows of the plant.

The second level of automatization consists of the advanced regulatory level, which in turn it is possible to adjust the operation point or regulate the set-points of the process variables in search of the economic point which will maximize production and safety and reliability of the plant.

On-line optimization permits determine the most favorable operation conditions with which it is possible to obtain the maximum benefit in terms of any of the previous mentioned criteria. The optimum operation conditions change when determining external variables (perturbations) as could be raw materials composition, required demanded yield or quantity; or the cost at which the products are desired to be obtained. In the following Figure-4-10 it is possible to observe the performance of the various regulatory control strategies in comparison with the natural response of the plant.

Figure 4-9. performance of the various regulatory control strategies in comparison with the natural response of the plant (Ollero, 1997 [10])



The first question that is stated is if to use a centralized or a decentralized control. Obviously, the solution that finally should be implemented can be a combination of the two mentioned control strategies.

Decentralized control is clearly simpler and uses to be the option of choice when there are not significant interactions between loops and when the active constraints are always the same. The advantages and drawbacks of this kind of control are the following:

A. Advantages:

1. Controllers can be tuned directly in field
2. A complex model is not required.
3. It's easy to implement and modify

B. Drawbacks

1. It is necessary to determine the best coupling method
2. The reachable control quality is worse than using a centralized control
3. It involves a complex logic when the active constraints change

Multivariable control, also known as centralized, is used when interactions are strong or when the active constraints change from an operation point to another, this means when disturbances present different values.

Multivariable predictive control (MPC) is a good choice in the case of using centralized control. The advantages and drawbacks of this kind of control are the following:

A. Advantages:

1. Direct management of interactions
2. Easy implementation of predictive control
3. Easy to take in account changing active constraints

B. Drawbacks:

1. It requires a multivariable dynamic process model
2. Complex tuning of controllers
3. Generally it is more sensitive to modeling errors and changes in the operation conditions
4. Reliability problems could arise, since if the multivariable controller fails, all the manipulated variables signals should be frozen

4.4.5 Interlocks and sequence control logic

Many control functions in a plant included discrete steps that force a process to an end condition. When an end point is reached, it is time to repeat the steps or to start another set of discrete steps. The detection of a successful end point and initiating the next set of control actions are common control functions in batch processing. Sequencing is the time-oriented step logic of process control. Sequencing is also common in discrete-parts manufacturing, were the operations are expressed as a sequence of steps. Though traditionally not associated with process control, many otherwise continuous processes require sequential control for startup and shutdown.

Actually, the simplest form of sequence control is the interlock. The interlock is both designed to: detected an abnormal process condition, and take action to prevent an undesirable or hazardous event. After the condition clears, the consequences of the action (e.g., valve closure, loop in manual) must be reset to continue routine operation. The interlock drives process equipment through a cycle of states. This cycle of states is the essence of sequence control. (Erikson, 1999 [5])

4.4.5.1 Sequential function charts

The emerging IEC 1131 standard (*International Electrotechnical Commission, 1993*) defines a method of programming sequence control. It is derived from the IEC 848 function chart standard (*International Electrotechnical Commission, 1988*) that has been used to define sequential control logic. This format has emerged as a major programming tool in modern control systems.

4.4.5.2 Interlock Control

Interlock control is the most basic form of discrete control; in the same manner as PID control is the most basic form of regulatory control. It is widely extended the thought that the term relates exclusively to safety, but in practice, there are many discrete-control applications that require the use of interlock logic but are not safety situations. To avoid the stigma associated with the word interlock, interlocks in situations not related to safety are often labeled differently, for example, process actions and operational interlocks. It is important to understand the context of discrete control. For this reason, the 84.00.01 standard (*ISA, 2004 [37]*) deals with classifying interlock control for safety situations.

4.4.5.3 Safety instrumented system

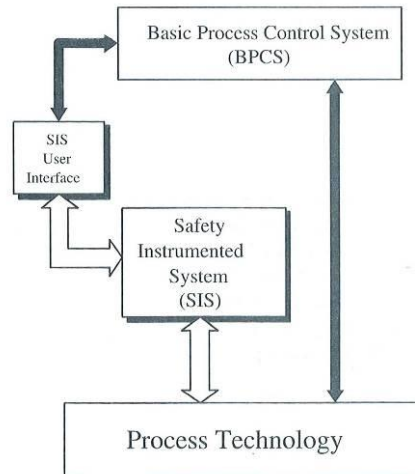
Standardization of interlock control defines control for automatic safety protection. These are called Safety Instrumental System (SIS). This implementation is required to be a separated control technology from the rest of the process control. Standard S84.01 defines the non-safety-system as the Basic Process control System (BPCS).

On the other hand, associated with the SIS there must be a user interface that provides its messaging and data monitoring. This user interface must also be decoupled from BPCS, although S84.01 recognizes the need to share safety system status between SIS and BPCS.

SIS must be composed by sensors and final control actuator elements, including an intermediate logic solver. An example of these elements includes on-off valves, limit switches, which are used to mitigate possible hazardous transients or situations in the plant.

The Figure 4-10 depicts the relationship between the plant process, different controls of the plant and the user interface.

Figure 4-10. Relationship between the plant process, different controls of the plant and the user interface (Roffel, 2004 [12])



The logic control is a mechanism that reacts to input measured signals coming from the sensors and derive and gives command to the ultimate action elements. The technology of the logic solver is not specified, but could it be an electrical/electrotechnical (Hard-Wired interlocks) unit as well as a programmable electronic system device (PES). If the case is the use of a PES it is required to be a hardened, high-reliability PLC accompanied with its corresponding I/O hardware connected to the sensors and final controls.

4.4.5.4 Interlock management

Back to the interlock logic solver, it must be said that its purpose is to mitigate or reduce the possibility of hazardous events. The hazardous events are described by a HAZOP study, which is to be developed by the capital project team and constitutes the first step in identifying hazards in the process design. Measures are to be taken in order to reduce or eliminate those hazards, as can be changing the design itself, using control technologies or making use of automation. Automated hazard prevention is the base of the interlocks description. This is why a very important role of the HAZOP developing team is to describe the interlocks. (Erikson, 1999 [5])

Interlock descriptions must include the following points:

- *Hazard description*
- *Prevention strategy*
- *Safety integrity level*
- *Cause/action specification*

On the other hand the SIS must be implemented like any other control system, although that it is subject to more restrictive constraints regarding safety and regulatory issues. The former be well from the company or government. Functional testing includes startup checkout and periodic resetting during its whole lifecycle. All these tests must be documented and developed following strictly the procedures. Typical SIS functional test include the following:

- *Sensors, final elements, logic solver inspection*
- *Fault injection and results recording of SIS modules*
- *PES application software functional test*
- *Fault injection and results recording of the entire SIS*

- *Process hazardous event simulation*

Electronic databases are today excellent candidates in order to keep SIS records, which may include time, trips, event types, and others. All the desired data that must be kept must be described as well in the SIS description and may respect company and government requirements. Typical contents of an interlock database might include:

- *Interlock description information*
- *One or more interlock demand specifications*
- *One or more interlock specifications*
- *Interlock logic description*
- *Reset actions and condition*
- *Plant cell or area*
- *SIS controller*
- *Interlock test procedure, referencing a document*

Last but not least, the monitoring system of the SIS is very important and must be designed according to the same level of reliability than the solver. The main display requirements for both SIS and BPCS interlock status presentation might include process graphic display indications and interlock trip annunciation.

On-line monitoring of the SIS is almost a must in modern facilities that may make possible to operating personnel to develop actions as could be the ones presented in the following list which is not extensive and could be much more extended:

- *Monitor and record interlock events (trigger signal and action occurred)*
- *Compare event with interlock database*
- *Verify interlock action performed by application logic*
- *Verify final control element action*
- *Store event in data repository*
- *Provide predefined and temporary reports for human review and approval*

4.5 PHYSICAL MODEL DEVELOPMENT

In the present sub-chapter, epigraph 4.5.1 takes care of making a definition of the concept of model and its applications in science; epigraph 4.5.2 develops the different nature of empirical dynamic models and explains its characteristics and differences making a classification. In its turn epigraph 4.5.3 explains a methodology commonly used to implement and develop process models. Epigraph 4.5.4 explains a conceptualization of the different types of models identifying them according to the level of knowledge of the physical phenomena. Paragraph 4.5.5 explains the ideal structure of discrete stochastic mathematical models, whilst 4.5.6 treats the strategies to correct and work against deviations of the models versus the measured values.

4.5.1 Definition of model and applications

A good definition for model was given by *Eykhoff (Roffel, 2004 [12])* who said a model is “a representation of the essential aspects of a system which presents knowledge of that state in a usable form”. Modeling is an abstraction of reality and can help to understand and explain observations, and can be useful in the experimental phase by reducing the number of experiments.

A model can be more or less complicated. This has to be decided by the responsible modeler, who has to take into account which are the main elements or factors that play the main role in the idealized mechanism. The focusing in order to build a model can be from the point of view of experimental approach or well theoretical focus.

In the industry, it is possible to find mainly the following applications to the modeling practice.

- **Research and development**
- **Design**
- **Planning and scheduling**
- **Operation Optimization**
- **Prediction and control**

4.5.2 Empirical dynamic models

Most process control problems can be solved by using simple PID control. There are cases, however, where more advanced methods are required as a solution. For such situations, a process model inevitably needs to be identified in order to design a controller.

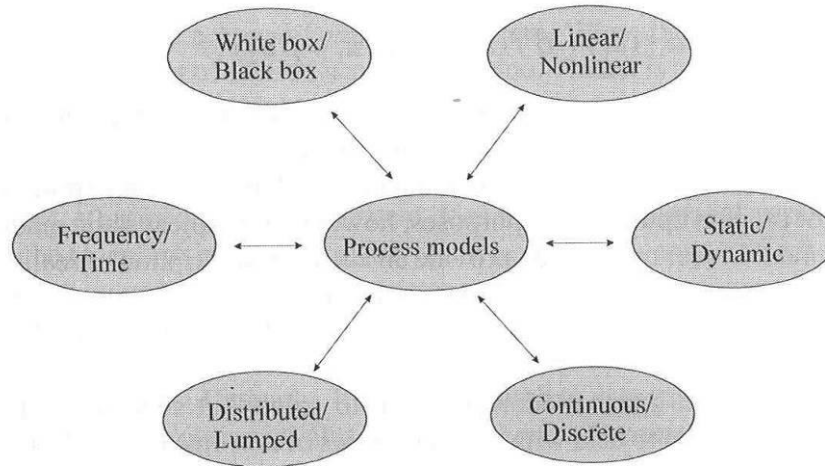
Depending on the process being investigated, one could develop first principles models (linear/non-linear (partial) differential equations) or simple linear empirical differential or difference equations built from process data only. Both types of models have their place in developing process control strategies and in analyzing process control problems; although for developing advanced control strategies often an empirical model is used.

These models are usually discrete linear transfer function (difference equation) models which provide a representation of the dynamic behavior of the process at discrete sampling intervals. They are in general much simpler to develop than theoretical models, both in their structure and parameters can empirically be identified from plant data. Structural considerations concern the order (parametric models) or the time-horizon (non-parametric models) of the model. Usually, the model is identified by minimizing the error between data and model. This can lead to over-modeling by including noise or disturbances. The common strategy is to separate data sets for model identification and for testing. Statistical tests can be applied to the test parameter significance. (*Roffel, 2004 [12]*)

These models are very useful to develop control strategies for maintaining process conditions at target. These control schemes are often simple enough that the process operators can implement them. More powerful schemes are possible if a microprocessor is available.

The major drawback of these kinds of empirical models is their limited range of applicability. Figure 4-11 shows a classification of the different types of models according to its nature. They hold quite well in the regions of operation for which they have been developed, but they could extrapolate poorly when non-linearity are present in the process. One method to reduce this effect, under changing conditions, would be simultaneously tracking the changing parameters and controlling the process. (*Roffel, 2004 [12]*)

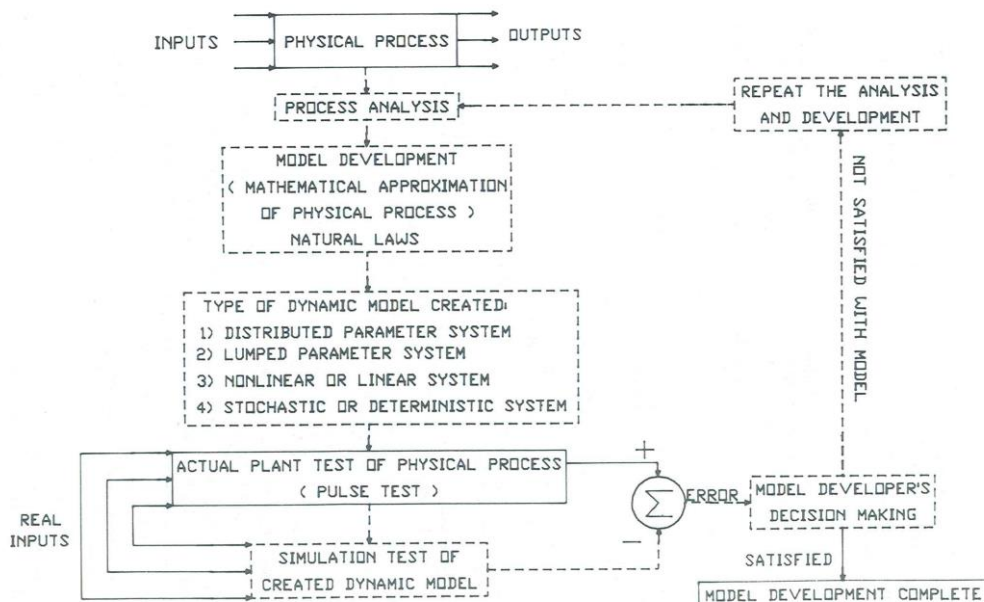
Figure 4-11. Types of models according to Roffel



4.5.3 Model development process

The development of the mathematical model of a physical process involves a priori a number of stages which can be represented by Figure 4-12 below representing the algorithm which must be followed to obtain a satisfactory result. As it can be observed, a first observation phase of the physical process is needed, while passing throughout a number of stages with mathematical approximation using natural laws and the choice between the type of dynamics that it is desired to implement in the model. This stage leads to a dynamic plant model, with which a number of simulations must be developed according to several types of inputs, analyzing the errors obtained against real inputs. At the end a decision must be taken, either the result is satisfactory or not. If the result is negative the loop branch to the first stage must be taken, until obtaining the desired feasible model. (Tsai, 1986 [16])

Figure 4-12. Model development process algorithm (Tsai, 1986 [16])



4.5.4 Types of models

Models that are based on physical and chemical laws of conservation are called white box, first principles or mechanistic models.

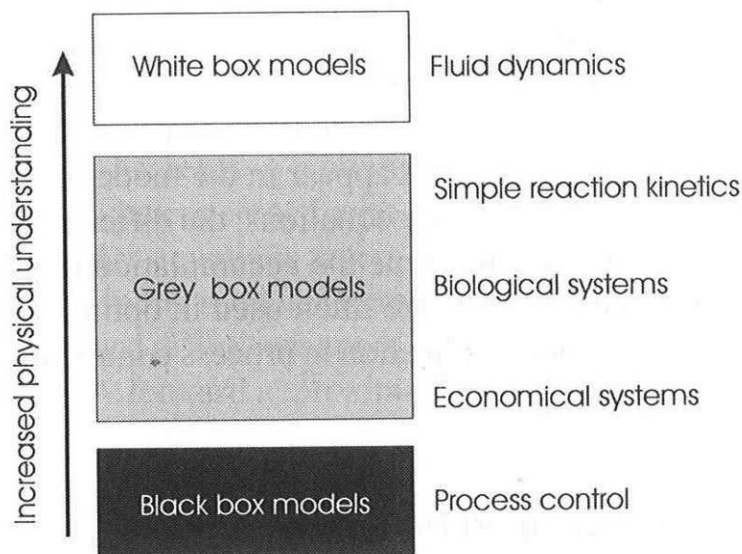
These models give a physical insight into the process and can already be developed when the process does not yet exist. In general, this type of model consists of a set of dynamic conservation balances, such as mass balance, component balance, momentum balance and energy balance. These equations are supplemented with algebraic equations describing mass transfer, kinetics and other. The effort required to build these types of models is high.

Black box models or empirical models do not reflect the physical structure of the process. They are data based and reflect the input/output relationship of the process. These models are useful when limited time is available for model development or when a physical understanding of the process is poor or incomplete. Mathematical representations include time series models, artificial neural network models, fuzzy models, partial least squares models and others.

In cases that physical insight is available, but certain information or understanding is lacking, physical models could be combined with black box models; the resulting models are called grey box models. Some of them combine physical models with neural networks or fuzzy logic models.

The level of black box techniques used in grey box models is related to the level of physical interpretation that can be given of a model. Figure 4-13 shows this concept. (Roffel, 2004 [12])

Figure 4-13. Type of models according to its level of physical understanding of the phenomena (Roffel, 2004 [12])



4.5.5 Discrete stochastic models

For computer control of the industrial processes, the discrete representation of the process model in vector difference equations is convenient. Usually the system model is represented by ad-hoc vector equations. As an example, an empirical model for hydrogen isotopes migration in a pipe is presented in Annex 1. (Batet, 2017 [58])

The process model is (Tsai, 1986 [16])

$$X(k+1) = F(k+1, k) x(k) + G(k+1, k) w(k) + P(k+1, k) u(k)$$

Where

- $k = \text{whole numbers, time sequence}$
- $x = n - \text{dimensional vector for state variables}$
- $F(k+1, k) = n \times n \text{ state transition matrix}$
- $W = p - \text{dimensional vector for disturbance}$
- $G(k+1, k) = n \times p \text{ disturbance transition matrix}$
- $u = r - \text{dimensional vector for manipulable input}$
- $P(k+1, k) = n \times r \text{ control transition matrix}$

The measurement model is

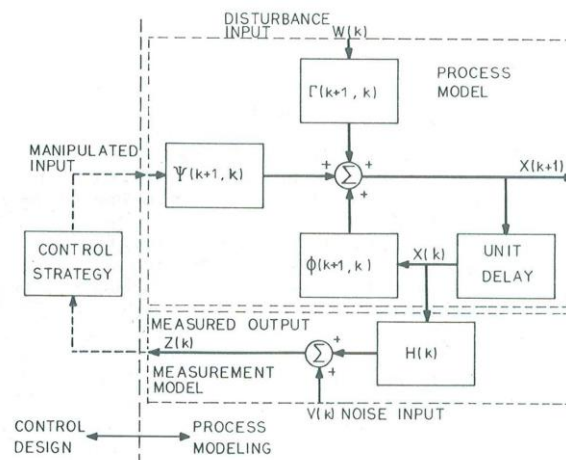
$$Z(k+1) = H(k+1) x(k+1) + v(k+1)$$

Where

- $Z = m - \text{dimensional vector for measurement}$
- $H = m \times n \text{ measurement matrix}$
- $V = m - \text{dimensional vector for noise or measurement error}$

A graphical representation of a discrete stochastic model is presented in Figure 4-14.

Figure 4-14. Discrete representation of the process model in vector difference equations (Tsai, 1986 [16])



4.5.6 Treatment of model results deviation from measurements

4.5.6.1 Failure Detection and Analysis

The main scope of a monitoring system is to assure the success of the plant operations at the same time detecting abnormal behavior while the plant is in operation.

The information provided by the monitoring system keeps operators and maintenance staff informed of the actual state of the process, also serving as a support for the decision making in order to recover normal behavior of the process. The main features that describe a monitoring system are the following:

- **Detection of a failure.** From the analysis of data measured from the process
- **Failure identification.** To identify the most relevant variables for its diagnosis
- **Failure diagnosis.** It consists of a module or device that focuses on the incurred failures and put them in contrasts with the characteristics of the plant. This is developed with a classifying method with the aim to determine the type of failure, location of the faulty element of system, the magnitude of it and the root cause.

The last step is to get rid of the failure or fault and recover the normal operation of the plant.

Some of the types of failures that can be found during the operation of industrial processes are the unexpected changes in the process parameters. These could be for example, the poisoning of a catalyzer, or well, degradation of heat exchangers due to corrosion or its unavailability.

Process disturbances , as could be excessive changes in the raw materials input concentrations of a determined system or well unexpected changes in ambient temperature, are constituent of another kind of failures. Another type of faults comes from problems associated with sensor/probes, and/or defaults in the end final active elements.

The preliminary specification for the precision of the tritium monitoring system in ITER project imposed by the ASN (Autorité de Surété Nucléaire) is of a maximum of 2 g/year.

The main strategy to be implemented in the monitoring system to be developed in the future, which is issued in the present document, aims to detect the above mentioned maximum deviation between the model and the process measurements, computing in real time (this is using on-line control techniques) all among the whole TBM system, in order to avoid the present default (exceedance of the specification over the upper tolerance level) strategy which involves to derive all the inventory to the CPS getters to make the mass balance. The last strategy is considered to be highly inefficient and involves the loss of operational flexibility and loss of time.

4.5.6.2 Simple quantitative error detection methods

Pure quantitative standard model quality assessment methods include computation and representation a number of statistical variables of choice. Most often the least squares method is used. Computing of standard deviations, means and variance are especially useful to develop this task.

As the on-line transducers (or sensors) are composed by a number of probes, the synthesis of the representative statistical value implies as well the computing of uncertainty bands at both sides of the statistical, while time series are depicted in the manner of X-R charts (comparing means against tolerance ranges), which is a practice widely extended in the common industry.

The excessive deviation of the model results from the measures or exceedance from the upper or lower limits of allowance, must generate an emergency signal, which must be transmitted and processed by the interlocks, well would it be by SIS and/or the BPCS in order to proceed according to the procedure. This means: shut-down, stand-by, regulation or well to follow a certain sequence that must return the plant to a safe condition.

4.5.6.3 Failure detection and analysis standard methods

For a monitoring system, on line measures are converted into data and consecutively synthesized into a few meaningful parameters that help the plant operators to determine the process state of operation and, if it is necessary, to make a diagnosis of the detected failures. The development of this task can be studied from three main points of view:

- **Signal based methods.** *The application of this kind of techniques in systems processes monitoring is based in the assumption that the characteristics of the values of data do not change unless a failure is produced. This implies that the statistical properties of data (as could be the mean and variance) are to be the same for equal process operation conditions.*
- **Analytic methods.** *These are methods for failure detection that use a plant model. The reason because they are used, although the sensors are different, is that the measures that they provide derive from a same dynamic state, and therefore these are functionally related.*
- **Knowledge based methods.** *This technique is complementary to the previously presented in this chapter, in the sense that it can use all the information that the other techniques can harvest in failure detection, in order to analyze the symbols and make a complete diagnostic.*

a) Signal based methods

- Alarms
- Multivariable statistical techniques
- Physical redundancy
- Analysis in the frequency domain

b) Analytical Methods

- Analytical redundancy

c) Knowledge based methods

- Expert systems
- Neural networks
- Fuzzy logic based systems
- Root cause research

4.5.6.4 Design requirements

A detection and diagnosis failure process method should include the following characteristics:

- **Low detection time interval**
- **High positive detection degree**
- **Low false alarms index**
- **Good capability of isolation.** *Capability to distinguish between the different nature of the detected failures and depends on the different type of test that are to be applied.*
- **Sensitivity to measurement.** *This property will determine the failure threshold to isolate the previously mentioned under pre-established controlled conditions. Again, this property is related to detection and the faulty element location time.*

- **Robustness.** Means the capability to counteract against failures in the presence of modeling errors and /or unknown disturbances. This is the reason why this parameter is considered to be a valuable indicator of the behavior of the diagnosis method.

4.5.6.5 Statistical model quality assessment method proposal

To evaluate the quality of the physical model used, the results obtained with it (C_p) and the concentration values recorded coming from the sensors (C_o) network are compared. In order to establish a quantitative evaluation, the methodology of (Hanna, 1994 [74]) is of application, which is based on determining four statistical parameters: geometric mean (MG), geometric variance (VG) correlation coefficient (R) and the fraction of predicted data whose ratio is between 0.5 and 2 the measured value (FAC2).

If C_{oi}^3 is the concentration measured at point i and C_{pi} is the concentration predicted by the model at the same point, the above parameters are obtained according to the following expressions:

Finally a last parameter can be defined which indicates the mean deviation of the model or bias FB. If C_{oi} is the concentration measured at point i and C_{pi} is the concentration predicted by the model at the same point, the above parameters are obtained according to the following expressions:

$$MG = \exp[\langle \ln(\frac{C_o}{C_p}) \rangle]$$

$$VG = \exp[\langle (\ln(\frac{C_o}{C_p}))^2 \rangle]$$

$$R = \frac{\langle (\ln C_o - \langle \ln C_o \rangle)(\ln C_p - \langle \ln C_p \rangle) \rangle}{\sigma_{\ln C_p} \sigma_{\ln C_o}}$$

$$FAC2 = \text{fraction of data for which } 0.5 \leq \frac{C_o}{C_p} \leq 2$$

Note: In the above formulas the subscript "i" has been deleted to simplify the notation. And the mean values of the variables are represented by the symbol $\langle \text{variable} \rangle$.

Finally a last parameter can be defined which indicates the mean deviation of the model or bias FB.

$$FB = \frac{1}{2} \frac{(\langle C_o \rangle - \langle C_p \rangle)}{(\langle C_o \rangle + \langle C_p \rangle)}$$

A perfect model would be one for which the first four parameters MG, VG, R and FAC2 are equal to 1.0, and the fifth parameter is equal to 0.0. Geometric means from 0.5 to 2.0 indicate

³ In the above formulas the subscript "i" has been deleted to simplify the notation. And the mean values of the variables are represented by the symbol $\langle \text{variable} \rangle$.

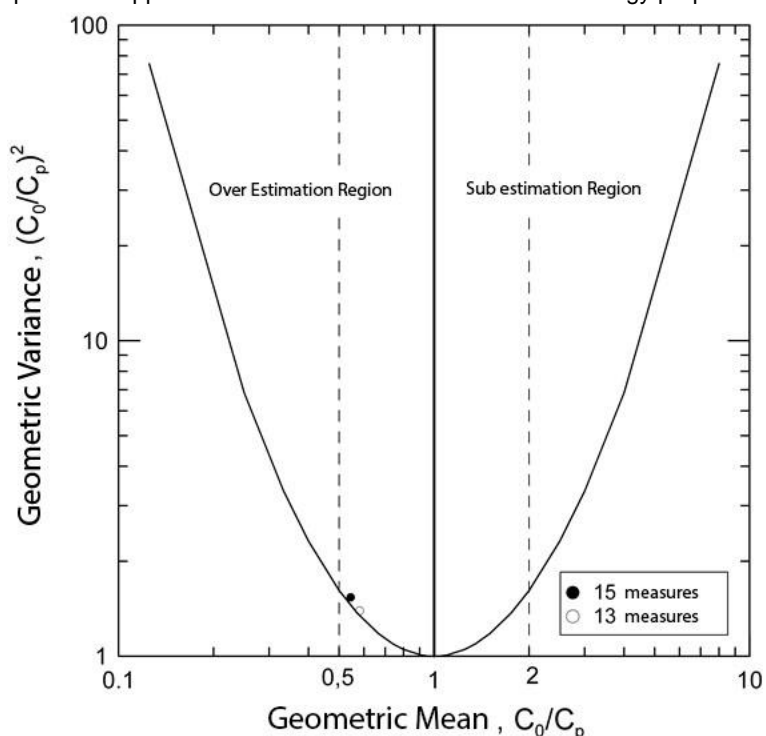
overestimation factors or underestimation of 2 above the mean. A value of the geometric variance close to 1.6 indicates a typical value of deviation factor of 2 (0.5 or 2) between observed and predicted values. If there were only a constant deviation between the measured concentrations and the concentrations predicted by the model, the ratio $\ln(VG) = (\ln MG)^2$, which defines the minimum value of VG for a mean MG, would be applicable.

If a graph represents the values of MG and VG and the function $\ln(VG) = (\ln MG)^2$, and the values of MG and VG are close to 1, and close to the previous function, the model can be considered almost perfect. If the value of MG is less than 1 the model overestimates the concentrations and if it is higher than 1 the model underestimates the concentrations. Finally, if the model has a value of R close to 1, y (MG and VG) are close to the previous curve, it is possible to establish a calibration of the model using a correction factor (s).

Below an example of the application of the model assessment methodology is presented. C_o / C_p is the quotient between the annual mean concentrations recorded in the process sensors network and those predicted by the model before its calibration.

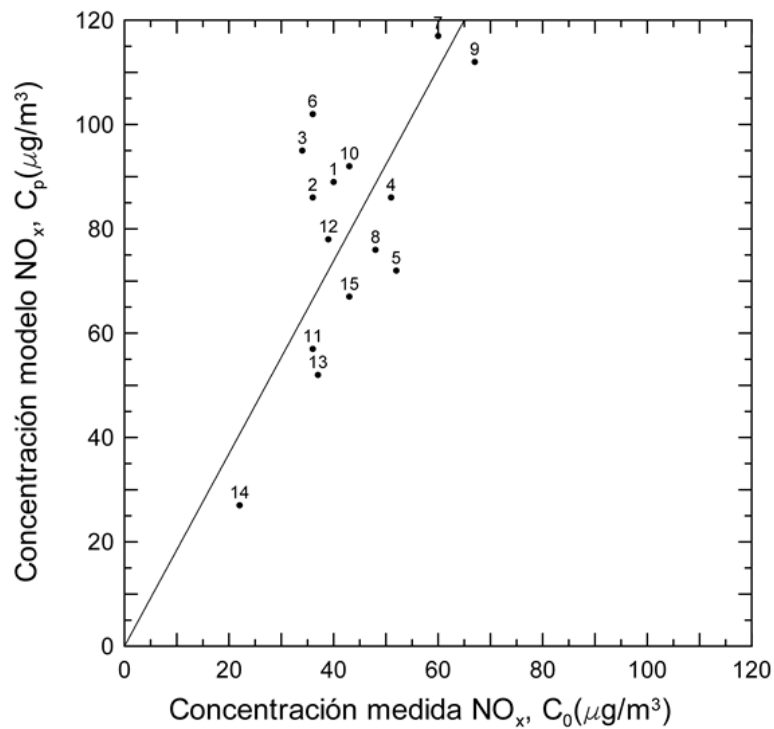
It is possible, observing the following graphs (Figures 4-15 and 4-16), that the model correlates adequately (allowing it to be adjusted) but overestimates the concentrations by an average factor close to 1.8. If two data, the more irregular ones, are excluded, the model quality is slightly improved. [Tapia, 2006]

Figure 4-15. Example of the application of the model assessment methodology proposed (Tapia, 2006 [22])



In the figure below average, an example based in an atmospheric NOx dispersion study is given for the current methodology, where concentrations at the different sensors network and values predicted by the dynamic model before calibration are presented. Note that the worst correlated model results correspond to the comparisons with the measurements coming from sensors 3 and 6, which have been discarded in the previous step.

Figure 4-16. Correlation between tritium modeled concentration against measured (*Tapia, 2006 [22]*)



4.6 APPLICATION OF THE DESCRIBED METHODOLOGY: EXAMPLES. CONTROL STRATEGY FOR TWO DIFFERENT SYSTEMS CONSTITUTING THE TBMS

As an example of application of the above described systems functional analysis and exploration two of the main TBM related sub-systems are presented below. These are the Helium Cooling System (HCS) and the Coolant Purification System (CPS).

4.6.1 HCS System description

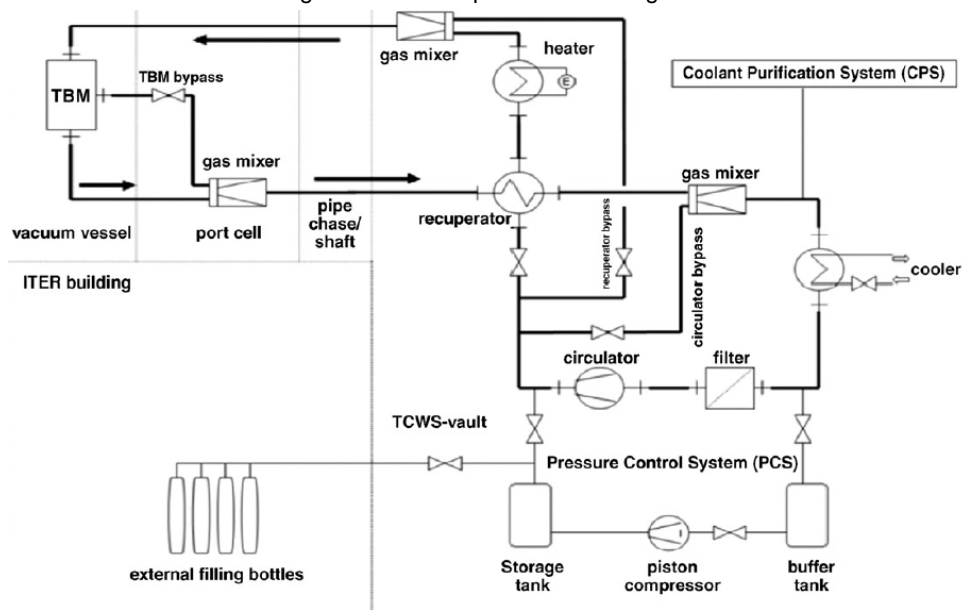
The Helium Coolant System (HCS) is an auxiliary system of the Test Blanket Modules (TBM) designed to extract the thermal power generated in the TBM due to the plasma radiation and neutron interaction and transfer it to the ITER Heat Rejection System. Also HCS shall extract the decay heat during the reactor shutdown. The coolant used for this thermal extraction is helium.

Each TMB is connected to a HCS circuit, which main design parameters are:

- Thermal extraction capacity: 1MW
- Coolant used: Helium4
- Design Pressure: 10.4 MPa;
- Design Temperature: 823K (550 °C).
- Nominal inlet temperature in the TMB: 573 K
- Nominal outlet temperature of the TMB 773 K

The process flow diagram is represented in the following figure

Figure 4-17. HCS process flow diagram



The HCS is a closed helium circuit that extracts heat of the TBM transferring them to the water of the Heat Rejection System. The circuit has the shape of one “eight” as is reflected in the process flow diagram.

The helium is injected to the TBM by the cold leg, at an inlet temperature of 573 K and goes out of the TBM by the hot leg, at an outlet temperature of 773 K, entering in the circuit of helium refrigeration. This refrigeration is done first by a recuperator, that made an interchange with the refrigerated helium before its injection in the TBM, and after by a main cooler that reduces the helium temperature below 323 K.

The refrigerated helium is driven by a circulator. This is the most critical component of HCS. The selected solution is a single stage centrifugal turbomachine driven by a high-speed asynchronous motor. The motor limits the temperature of the helium in the circulator inlet. Since the maximum allowable temperature of the windings insulation is 180 °C the helium temperature at the inlet of the circulator shall not exceed 50 °C (323 K).

After the circulator the helium is tempered to the nominal TBM inlet temperature level by means of the recuperator and by an electrical heater. The recuperator is a helium–helium heat exchanger, placed in the center of the loop, that transfers a part of the heat from the hot leg into the cold leg, reducing the level of power that the electrical heater

The loop has bypasses at different levels with the necessary valves and gas mixers to reintroduce the bypassed flow in the circuit.

Additionally, a pressure control system (PCS) maintains the TBM inlet pressure during pulsed operation within the allowable band around the nominal pressure. The PCS essentially consists of a low pressure and a high pressure tanks connected through a helium piston-compressor.

The operative conditions of the HCS for different operation states of the ITER plant are as presented in Table 4-3.

Table 4-4. Operational parameters for the HCLL-HCS (Aiello, 2011 [76])

Phase	P (MPa)	T_{in} (°C)	Γ (kg/s)	Notes
Plasma operation	8	300	1.3	$T_{out} = 500$ °C at steady state; $T_{out,max} = 440$ °C during pulses (1800 s repetition time, 25% duty cycle)
Short term stand-by	8	300	<1.3	e.g. Night shift
Test and conditioning	1	240	0.13	Vacuum vessel baking
Short term maintenance (upto 1 week)	1	500	0.13	Tritium out-gassing for HCPB-TBM
	1	300	0.13	Only for HCLL-TBM
Long term maintenance	1	RT	0.13	TBM set still installed in the Vacuum Vessel
	-	-	-	TBM removed, HCS stopped for maintenance

To prevent corrosion and relevant products releases the loop will be basically manufactured using austenitic steel as structural material. Since a certain amount of tritium that will permeate from the breeder inside the HCS any material that could be a getter for hydrogen shall be avoided. By this reason the material selected is austenitic steel AISI 316L.

4.6.2 Control strategy for HCS

The nature of the strategy to control the HCS operation necessarily involves several interacting loops. Loop pairing and decoupling are possible approaches to the construction of a HCS control strategy.

The primary control objectives of the HCS control are:

- **Input Temperature to TBM**
- **Output Temperature of gases coming out from TBM**
- **Flow control**
- **Head loss between ends of the filters**

The available manipulated variables are the following:

- **Power supplied to the coil based compressors**
- **Energy supplied to consumers**
- **Set point of the safety valves**
- **Positioning of the three way valves**
- **Mass flow and temperature trough economizer loops**

4.6.3 Control strategy for CPS

4.6.3.1 System Description

The Coolant Purification System (CPS) is implanted on the HCS, and treats a part of the cooled Helium flow to fulfill two functions:

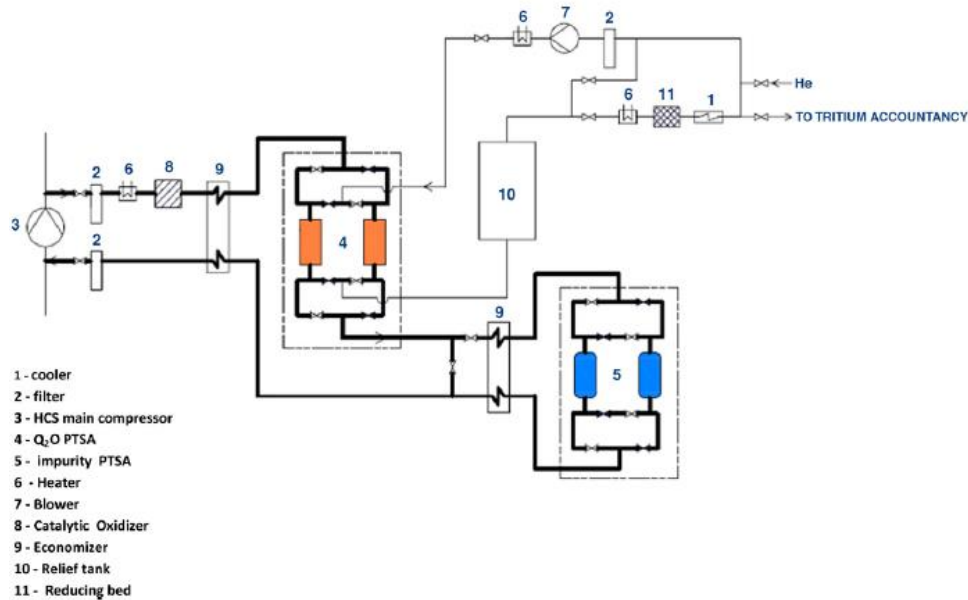
- 1.Extraction of tritium permeated from the TBM to HCS. The tritium, within an accurate accountancy, is transferred in a suitable form to the ITER tritium processing systems;
- 2.Control of the chemistry of Helium in the HCS by:

- Removing gas impurities coming from the different parts of the HCS
- Adjusting, if necessary, the oxidation potential of the coolant by a proper addition of chemical agents (normally H₂O/H₂)

The CPS extracts a part of the Helium flow upstream of the HCS circulator and returns the purified flow downstream of the HCS circulator.

The process flow diagram is represented in the following Figure 4.18.

Figure 4-18. I&CD of the Helium Coolant System (HCS) loop for HCLL and HCPB (*Ricapito, 2010 [65]*)



The Helium purification is made in three stages:

1. Oxidation of Q₂ (Q = H, D, T) and CO to Q₂O and CO₂ in a reactive-catalytic oxidizer. A metal oxide catalyzer at 250–300 °C, is used. This implies a previous phase of filtering and heating of the helium flow.

2.- Adsorption of Q₂O and CO₂ by a PTSA (Pressure Temperature Swing Adsorption) (Cu₂O–CuO). There are two beds of PTSA that operates at room temperature and 8MPa in adsorption phase. This implies a previous cooling of the flow, made by a economizer that transfer heat to the final phase of the system before reintroduce the helium flow in the HCS.

The regeneration phase is made at 573K by depressurization and heating

3. Impurity removal by a two-beds cryogenic PTSA, operated at 77K and 8MPa in adsorption phase and regenerated at 373K at ambient pressure.

A economizer transfers heat from the inlet flow to outlet flow of the cryogenic PTSA reducing the refrigeration needed in this step.

Alternatively has been proposed to substitute the cryogenic PTSA by a heated getter operating at 400°C, based on Zr alloy. This getter is not re-generable excepted for hydrogen isotopes and, once saturated, it is necessary to replace the column. Therefore it shall cope with a long CPS operation period. This alternative to cryogenic PTSA appears advantageous because of the operation simplification and space minimization.

The basic parameter for dimensioning CPS is its feed flow-rate which is a function of the tritium permeation rate from the TBM into HCS and other factors. Based in his evaluations the CPS is sized to process a He mass flow-rate of 75Nm³/h, corresponding to 0.3% of the total HCS flow-rate.

The primary control objectives of the CPS control are:

- **Input Temperature to TBM**
- **Output Temperature of gases coming out from TBM**
- **Flow control**
- **Head loss between ends of the filters**

The available manipulated variables are the following:

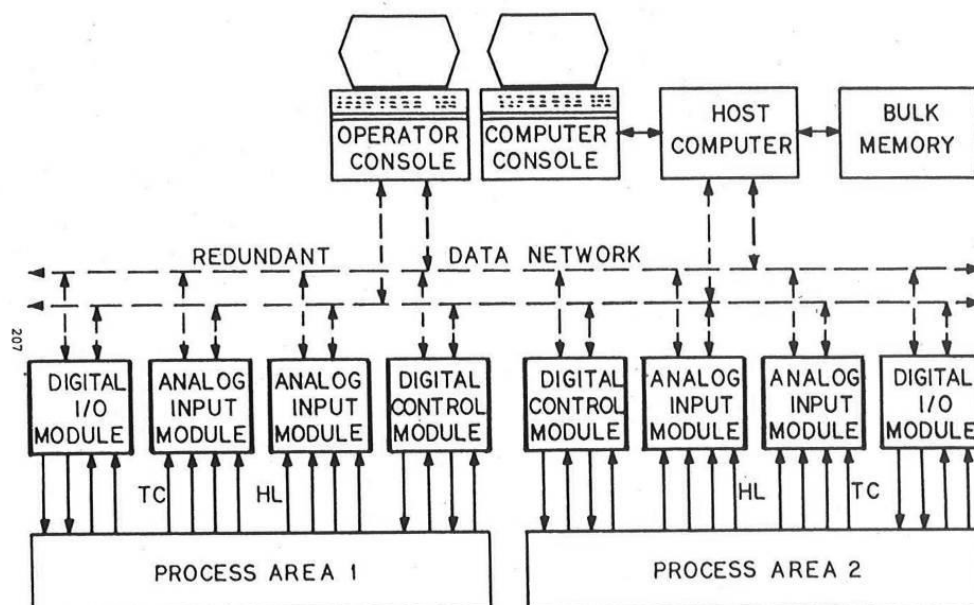
- **Power supplied to the coil based compressors**
- **Energy supplied to heaters**
- **Set point of the safety valves**
- **Positioning of the three way valves**
- **Mass flow and temperature throughout economizer loops**

4.7 ARCHITECTURE OF THE CODAC NETWORK SYSTEM

4.7.1 Networking architecture theory

All control and input modules would be connected to a digital communications network (called data highway, data bus, bus data highway or data freeway), and would share an operator's console, which would also reside on the highway. An example of this configuration is shown in Figure 4-19.

Figure 4-19. Example of a distributed process control network (Tsai, 1986 [16])



The function of the process interface unit would be solely to convert analog input signals to digital equivalents and to make these available for polling by the network. Some input signal checking might also be performed by these devices.

The process information would be displayed on the operator's console, which consists of a set of screens, keyboard, and maybe some other special displays and switches, in response to a request initiated by the operator. Control module status, set-points, and tuning constants changes would be initiated by the operator and communicated to the respective controller over the network.

The capability for communications across each vendor's data communication network (bus) varies greatly. In all cases, the operator console polls the communications network on a frequent basis to determine the status of each of the network-modules and to obtain requested data. In some cases, individual modules may initiate data transfers to other modules on the same network. This is particularly beneficial when it is desired to build complex control strategies incorporating cascade and feed-forward control, and control values need to be passed between controllers.

It should be mentioned here that, because of the extreme importance of the reliability of the data communications network, is that the normally commercially available connectors or physical interfaces between the operator and the process, systems are almost always configured with totally redundant communications channels.

The next level of design complexity for the distributed control system can follow one of several alternatives and does not just simply add more of everything. One of the most frequent alternatives is to add a host computer to enhance control system capabilities. This level of control now permits the implementation of complex supervisory control strategies, integrated or coordinated control, and complex start-up/shutdown sequences. Another alternative is to add advanced control modules to the system configuration. These are modules that support comprehensive mathematical calculations, batch or sequential control, programmable logic control, etc.

As the distributed control system configuration grows in complexity, so does the complexity of the data communication network increase. The typical network will evolve from a single dual data bus to multiple dual highways or freeways in various configurations. The configurations most frequently seen are "star", "T", "loop", and parallel hierarchy. (Tsai, 1986 [16])

4.7.2 Application to the CODAC system

Plant system controls are being procured together with the plant systems from the ITER Members, while the CODAC, central interlock and central safety systems are being implemented by the ITER Organization. This implies that the interface between the central system and the plant system I&Cs is well defined and is strictly adhered to. This also imposes a uniform standardized approach to design of the plant system controls in order to reduce overall project manufacturing and maintenance costs.

Figure 4-20 shows an schematic overview of the whole CODAC system.

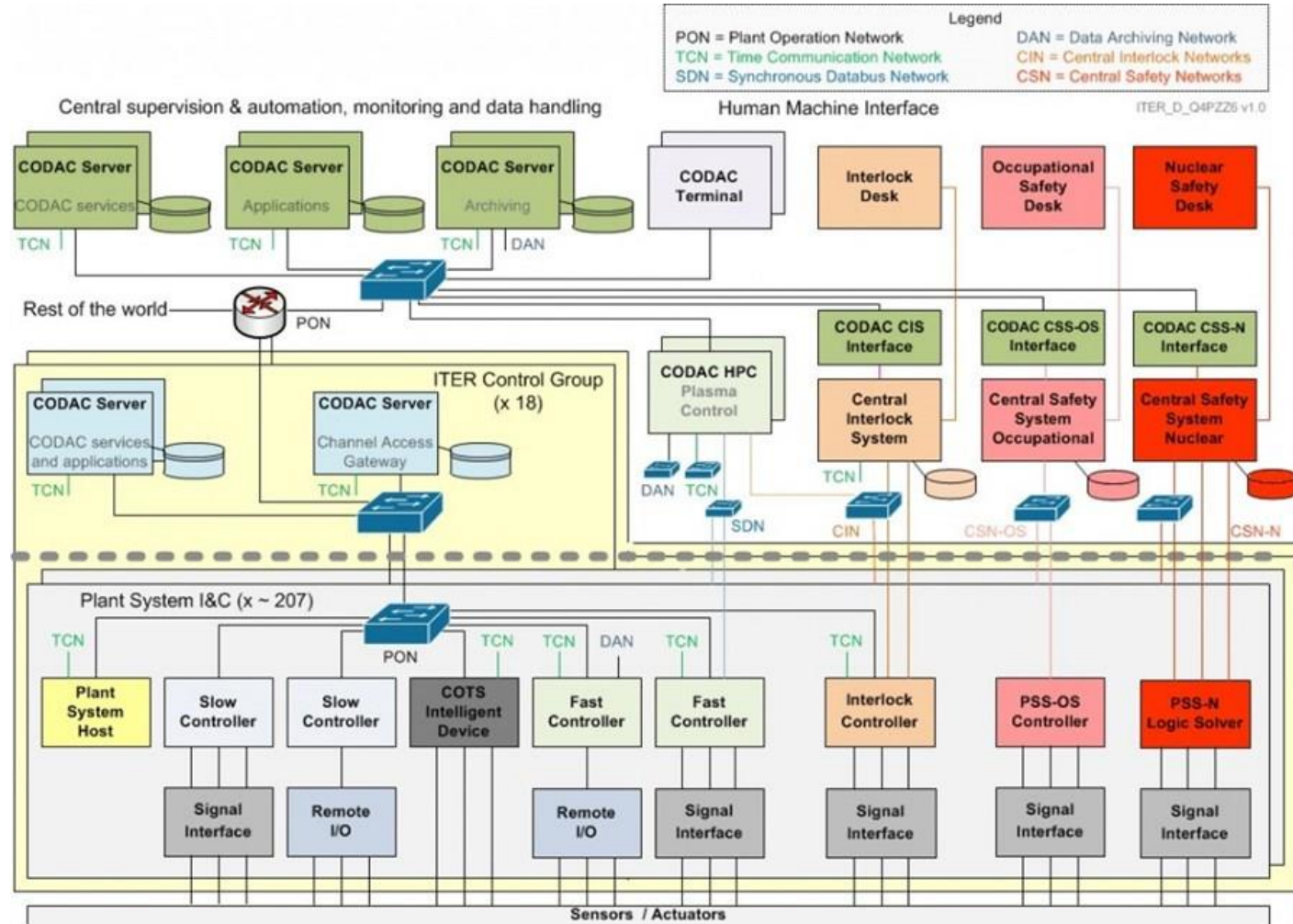
To reach these objectives, the ITER CODAC team publishes a handbook guiding all aspects of the plant system I&C lifecycle, the Plant Control Design Handbook (PCDH, 2016 [54])

CODAC Core System is a software suite for control system development. Plant system manufacturers shall use it as a template for new development, maintaining full compatibility with

the CODAC control system. **Induction training sessions** are organized regularly to allow I&C engineers learn the Core System quickly and efficiently.

The **Plant Control Design Handbook** has been finalized in 2013 and is ready for application to ITER production systems. The **CODAC Core System** is updated at least once a year throughout the construction phase of the ITER project. (*ITER IO, 2016 [54]*)

Figure 4-20. Extended ITER CODAC Architecture Diagram (ITER IO, 2016 [66])



4.8 CONTROL / CONSTRAINTS

Chapter 4.8.1 talks about the international nuclear specifications of general application, epigraph 4.8.2. talks about Characteristics of the local nuclear regulation, epigraph 4.8.3 talks about Characteristics of the local nuclear regulation, epigraph 4.8.4 talks about selected applicable Technical Standards.

4.8.1 International nuclear specifications of general application

4.8.1.1 IAEA Safety Standards series

The IAEA is authorized to establish or adopt standards of safety for protection of health and minimization of danger to life and property regarding ionizing radiation. The IAEA Safety Standards contribute to the establishment of a harmonized high level of safety worldwide.

The publications by means of which the IAEA establishes safety standards and measures are issued in the IAEA Safety Standards Series, hierarchically organized in three categories:

- **Safety Fundamentals** establish the fundamental safety objective and principles of protection and safety. Indeed, the only publication in this category is the SF-1 Fundamental Safety Principles.
- **Safety Requirements** establish the requirements that must be met to ensure safety. If they are not met, measures must be taken to reach or restore the required level of safety. Safety Requirements help Member States establish, in a harmonized manner, their national regulatory framework.
- **Safety Guides** provide recommendations and guidance for meeting safety requirements, presenting international good practices to achieve high levels of safety.

The IAEA's safety standards are not legally binding on Member States but may be adopted by them, at their own discretion, for use in national regulations in respect of their own activities.

A large number of standards have been published. In what follows, those standards more relevant for the project are described.

- **IAEA NS-R-1. Safety of Nuclear Power Plants Design – Requirements.**

It constitutes a high level document in general concepts about safety and protection which are specified, through the introduction of terms as could be Radiation Protection itself, principles about Safety in Nuclear Design and Defence in Depth.

The standard presents as well main technical requirements and plant design check items which are presented under the point of view of fission plants. Nevertheless transversal concepts are to be identified and translated by similarity into the fusion technology area for adequate application of the standard.

Management practices and recommendations are as well introduced this document and can be useful as for quality policy deployment into the ITER Project.

- **IAEA NS-G-1.3. Instrumentation and Control Systems Important to Safety in Nuclear Power Plants – Safety Guide.**

Generic document compiling top level concepts and guidelines about what are the main design features and characteristics of the I&C systems, including definition and basic classification into four main categories:

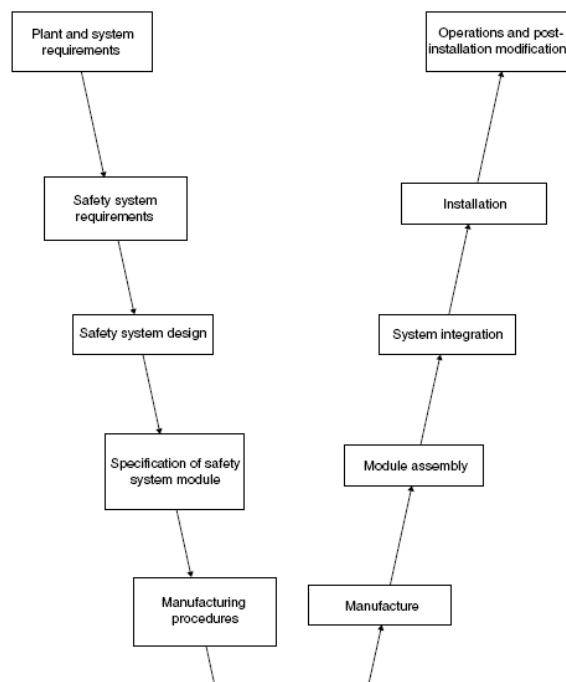
- **Protection functions**
- **Control functions**
- **Monitoring and display functions**
- **Testing functions**

These functions are to be supported by further safety strategies as can be redundancy and diversity of systems.

The same document describes the main performance and governing strategies to be implemented into the systems logic in front of different plant operational states, and, though, gives special attention to general design guidelines for ensuring reliability, introducing the concept of single failure criterion, by which the systems architecture is to be minimized over the base of a deterministic safety assessment.

In this sense, the development process is presented as taken from the same document, identifying the main stages of nuclear systems design and implementation processes, as shown in the Figure-4.21.

Figure 4-21. Development of an I&C System important to safety [IAEA NS-G-1.3]



The same document introduces as well design basis characteristics or features which might be applicable to human-machine interface systems, with extensive attention to main control rooms, emergency response facilities, control facilities, displays, monitoring, alarms and data or variables recording.

- **IAEA GS-R-3. The Management System for Facilities and Activities – Requirements.**

The document deals with general high-level aspects of the management structure within nuclear facilities, introducing at the same time the concepts of safety culture, resource and

system management and processes implementation. All this, attending to the quality principle and continuous improvement, which can be directly translated to the operational phase of the Project. Anyway, a management system based on quality is desired as well for the design and construction phases.

Special emphasis is given to planning, organization policies, definition of work actors or parties and their satisfaction assessment as well as main guidelines to structure the hierarchy of authority and responsibilities within the Project.

- **IAEA GS-G-3.1:2006, Application of the Management System for Facilities and Activities – Safety Guide**

This Safety Guide supports the **IAEA GS-R-3**. It provides generic guidance to aid in establishing, implementing, assessing and continually improving a management system that complies with the requirements in **IAEA GS-R-3**.

- **IAEA INSAG-10:1996, Defence in Depth in Nuclear Safety.**

It is a report by the International Nuclear Safety Advisory Group (INSAG). The report: (1) summarizes the historical development of safety concepts, focusing on defence in depth; (2) discusses the concept of defence in depth in terms of objectives, strategy, physical barriers and levels of protection; (3) describes the implementation of defence in depth and illustrates how its various elements interrelate; (4) indicates how defence in depth can be enhanced for the nuclear power plants that are currently operating; (and 5) proposes a development of defence in depth which could be applied systematically for plants to be built in the future.

- **IAEA 75-INSAG-3 Rev. 1 – INSAG 12:1999, Basic Safety Principles for Nuclear Power Plants**

It is, as well, a report by the International Nuclear Safety Advisory Group. The report is a revision of the original 75-INSAG-3 which was issued in 1988 to provide a statement of the objectives and principles of safe design and operation for electricity generating nuclear power plants. This revision brought the text up to date with improvements in the safety of operating nuclear power plants and identified principles to be applied for future plants.

The text presents INSAG's understanding of the principles underlying the best current safety policies and practices of the nuclear power industry.

In the same way other related top level IAEA design and safety series documents are listed below. Those could be as well of application in the current case of study:

- *Fundamental Safety principles. Safety fundamentals. SF-1*
- *Operational limits and conditions and operating procedures for nuclear power plants. Safety guide. NS-G-2.2*
- *Software for computer based systems important to safety in Nuclear Power Plants. Safety Guide. NS-G1.1*
- *Safety assessment for facilities and activities. General safety requirements Part 4. GSR Part 4.*
- *Radiation Protection Aspects of Design for Nuclear Power Plants NS-G-1.13 (2005), which supersedes 50-SG-D9 Design Aspects of Radiation Protection for Nuclear Power Plants (1985)*
- *Deterministic Safety analysis for nuclear power plants. Specific safety guide. SSG-2*

4.8.1.2 The NUREG series

The NUREG series are documents issued by the US.NRC. The NUREG series comprises:

- *Technical and administrative reports and books prepared by the staff (NUREG–XXXX) or agency contractors (NUREG/CR–XXXX),*
- *Proceedings of conferences (NUREG/CP–XXXX),*
- *Reports resulting from international agreements (NUREG/IA–XXXX),*
- *Brochures (NUREG/BR–XXXX), and*
- *Compilations of legal decisions and orders (NUREG–0750).*

Two of the documents in the first category are potentially applicable to CODAC: the NUREG-0700 and the NUREG-0711.

- **NUREG-0700. Human-System Interface Design Review Guidelines.**

The U.S. Nuclear Regulatory Commission (NRC) staff reviews the human factors engineering (HFE) aspects of nuclear power plants in accordance with the Standard Review Plan (NUREG-0800)⁴. Detailed design review procedures are provided in the NUREG-0711. As part of the review process, the interfaces between plant personnel and plant's systems and components are evaluated for conformance with HFE guidelines. This document provides the guidelines necessary to perform this evaluation.

- **NUREG-0711. Human Factors Engineering Program Review Model.**

This document is used by the staff of the NRC to review the human factors engineering (HFE) programs of applicants for construction permits, operating licenses, standard design certifications, combined operating licenses, and license amendments. The purpose of these reviews is to verify that the applicant's HFE program incorporates accepted HFE practices and guidelines.

4.8.2 Characteristics of the local nuclear regulation

4.8.2.1 General aspects

ITER handles specific requirements based on gained experience in other nuclear applications (mainly in the field of Safety and Radiological Protection), while for Qualification of the issued systems, those must be compliant both with local translation of international standards and specific Project requirements. Being the **Autorité de Sûreté Nucléaire (ASN)** the ultimate substantial Authority.

The French corpus of nuclear regulation is collected in the digital repository⁵ of the **Autorité de Sûreté Nucléaire (ASN)**. As a matter of fact, French legal framework is the source for the legal structures in Latin countries, and differs little from Spanish regulatory frame. Hierarchy principle of European legal corpus endorsement and subscription to international treaties and standards committees are considered to be the main characteristic that describes the nature of the ITER location country requirements.

⁴ The Standard Review Plan, NUREG-0800, has been prepared for the guidance of NRC staff responsible for the review of applications to construct and operate nuclear power plants.

⁵ <http://www.asn.fr>

Characteristics figures of the French body of nuclear regulation are illustrated in Table 4-5.

Table 4-5. Overview of the French regulation corpus related to the use of nuclear energy

French nuclear Legal Framework	Number of Items ⁶
International conventions	18
European Communitarian Directives	19
National French Codes	31
Laws (Those applicable to the fields of nuclear safety and radiation protection)	19
Decrees	99
Technical regulations (Arrêtés)	156
Circulaires, directives, instructions, guides	47
Avis	6

After extensive screening of the nature of these regulations, its development can be represented by means of the following conceptual categories:

- **Transport (Tr).** *Radioactive material transportation issues. Mainly regarding Safety and Security.*
- **Environment (Env).** *Constraints and limitations regarding anthropogenic use of nuclear energy with respect to natural systems.*
- **Radiological Protection (RP).** *Constraints and limitations regarding anthropogenic use of nuclear energy with respect to human health.*
- **Radioactive Waste (RW).** *Regulations about radioactive waste classification, management techniques and disposal methods.*
- **Safety and Emergency Planning and Prevention (S&E).**
- **EU Strategic Planning (EU).**
- **Internal organizational specific decree (Org. Int.)**

Main characteristics regarding specifications of I&C and CODAC in this case might be compliant with local translation of the CE and international technical standards (see IEC, IEEE, and so on) as described in the Norme Française (NF) document series relative to nuclear compatibility and system's safety.

Since I&C and CODAC systems involve a series of technological subsystems, including sensor technology, signal processing, data transmission, as well as human-machine interface through visual display monitoring and command from control room, the documental research has been focused on these topics.

Most of the referred regulations are issued for nuclear fission industry, although some of them can be a starting point for the ITER expected integration standards

⁶ According to ASN web repository.

Regarding the standards, the nuclear requirements applicable to ITER does not differ substantially from the common international regulation standards, since French regulation endorses directly the international standards.

The main item of the French nuclear regulatory corpus that is listed as applicable in the reference document **Plant Control Design Handbook for Nuclear Control Systems (PCDH-NCS)** is the *Arrêté du 7 février 2012 fixant les règles générales relatives aux installations nucléaires de base* (English translation is available as an ITER document). This Decree lays down general rules for basic nuclear facilities. It defines the general rules applicable to all basic nuclear facilities. The order contains the essential requirements in the areas of safety management, public information, accident risk control, control of the impact on health and the environment, waste management or emergency situations. It has been slightly modified by the *Arrêté du 26 juin 2013 modifiant l'arrêté du 7 février 2012 fixant les règles générales relatives aux installations nucléaires de base*.

4.8.2.2 ITER TBM Legal Framework integration.

A kick off meeting was held in Cadarache between ITER responsible Officers for TBM with delegations of the seven ITER Members with the aim to establish a common legal and standards framework. As a result of the interview, Luciano Giancarli⁷ declared:

"The aim of the meeting was to converge on some outstanding issues in the definition of the template for the TBM Arrangements, so that the Members will have a common legal framework for working with the ITER Organization during the development and construction of the Test Blanket Systems," [Griffith, 2012]

In this sense, as stated in the **ITER ORGANIZATION 2014 ANNUAL REPORT**, the granted Framework legal advisory contracts for construction issues are currently held by **Gide Loyrette Nouel, Norton Rose and Bird & Bird** firms.

- ***Note of interest for PROCON SYSTEMS in the scope of PROTOCOAC: In the eventual case a system was to be delivered to the ITER project, having the advice of these firms, through the ITER TBM responsible, would be of valuable help.***

4.8.3 Selected applicable Technical Standards

Applicable standards for I&C systems are issued by the International Electrotechnical Commission (IEC), a worldwide organization for standardization in the electrical and electronic fields. IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides.

Preparation of these publications is entrusted to technical committees. The activity of one of these committees is relevant for this project, the **IEC technical committee 45: Nuclear instrumentation**. More precisely, the **subcommittee 45A: Instrumentation and control of nuclear facilities**,

⁷ ITER responsible officer for the TBM Program

IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense.

IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. In this sense, in the scope of this project, CENELEC, the European Committee for the Electrotechnical Standardization, and AFNOR (French) standards [www.afnor.org] correspond to IEC standards.

The applicable identified IEC Standards regarding I&C compliance with nuclear safety requirements deal with the following topics:

- *Surveillance testing of I&C systems important to safety*
- *Qualification of electrical equipment of the Safety System*
- *Design of control rooms design, interfaces, controls, VDUs and alarms, under the scope of functional analysis.*
- *FMEA Analysis techniques for systems reliability*
- *Software aspects for computer based systems performing functions important to safety*

4.8.3.1 Description of the most relevant IEC standards attaining to the project.

4.8.3.2 IEC 61513

Introduction

IEC 61513:2011 Nuclear power plants – Instrumentation and control important to safety – General requirements for systems sets out requirements applicable to instrumentation and control systems and equipment (I&C systems) that are used to perform functions important to safety in nuclear power plants (NPPs).

The standard highlights the relations between:

- The safety objectives of the NPP and the requirements for the overall architecture of the I&C systems important to safety;
- The overall architecture of the I&C systems and the requirements of the individual systems important to safety.

To be used by designers, operators of NPPs (utilities), systems evaluators and licensors

Scope

I&C systems important to safety may be implemented using conventional hard-wired equipment, computer-based (CB) equipment or by using a combination of both types of equipment. IEC 61513 provides requirements and recommendations for the overall I&C architecture which may contain either or both technologies.

This standard highlights also the need for complete and precise requirements, derived from the plant safety goals, as a pre-requisite for generating the comprehensive requirements for the overall I&C architecture, and hence for the individual I&C systems important to safety.

The standard introduces the concept of a safety life cycle for the overall I&C architecture, and a safety life cycle for the individual systems. By this, it highlights the relations between the safety objectives of the NPP and the requirements for the overall architecture of the I&C systems

important to safety, and the relations between the overall I&C architecture and the requirements of the individual systems important to safety.

The standard defines requirements for the I&C functions, and associated systems and equipment, derived from the safety analysis of the NPP, the categorization of I&C functions, and the plant layout and operational context; and structures the overall I&C architecture, dividing it into a number of systems and assigning the I&C functions to systems.

4.8.3.3 IEC 61226

Introduction

IEC 61226:2009 Nuclear power plants – Instrumentation and control important to safety – Classification of instrumentation and control functions responds to an IAEA requirement to classify nuclear power plants instrumentation and control systems according to their importance to safety. With distributed computer based I&C systems now being used for NPP instrumentation and control systems, the functions important to safety are distributed over several systems or subsystems. Therefore, it is the intent of this standard to

- Classify the I&C functions important to safety into categories, depending on their contribution to the prevention and mitigation of postulated initiating events (PIE), and to develop requirements that are consistent with the importance to safety of each of the categories;
- Assign specification and design requirements to I&C systems and equipment concerned which perform the classified function

The standard establishes the criteria and methods to be used to assign the I&C functions of a NPP to three categories A, B and C, which depend on the importance of the function for safety, and an unclassified category for functions with no direct safety role. It outlines generic requirements for each category, and specifies basic technical requirements for matters such as QA, reliability, testing and maintenance.

Scope

IEC 61226 establishes a method of classification of the information and command functions for nuclear power plants, and the I&C systems and equipment that provide those functions, into categories that designate the importance to safety of the function. The resulting classification then determines relevant design criteria.

The design criteria are the measures of quality by which the adequacy of each function in relation to its importance to plant safety is ensured. In this standard, the criteria are those of functionality, reliability, performance, environmental durability (including seismic) and quality assurance (QA).

The standard follows the general principles given in IAEA **NS-R-1** and **NS-G-1.3**, and defines a structured method of applying the guidance contained in those codes and standards to the I&C systems that perform functions important to safety in a nuclear plant.

The following table lists the ITER standards of choice for the issued systems according to the categorization, which is established by **IEC 61226**.

Table 4-6. Main standards concerning the CODAC System

Applying to all systems of any category		
Category A function systems	Category B function systems	Category C function systems
<ul style="list-style-type: none"> • IEC 61226, Nuclear power plants – Instrumentation and control systems important for safety – Classification • IEC 61513, Nuclear power plants – Instrumentation and control for systems important to safety – General requirements for systems • EC 60709, Nuclear Power Plants – Instrumentation and Control systems important to safety – Separation • IEC 61000-4 (all parts), Electromagnetic Compatibility – Testing and measurement techniques • IEC 61000-6-2, Electromagnetic compatibility (EMC) – Part 6-2: Generic standards – Immunity for industrial environments 	<ul style="list-style-type: none"> • IEC 60780, Nuclear power plants – Electrical equipment of the safety system – Qualification. • Seismic events: IEC 60980, Recommended practices for seismic qualification of electrical equipment of the safety system for nuclear generating stations. (ITER specific) 	<ul style="list-style-type: none"> • IEC 62138, Nuclear power plants – Instrumentation and control important for safety – Software aspects for computer-based systems performing category B or C functions • IEC 61513. (systems for which specific environmental qualification is required) • IEC 60780. (might be required under certain circumstances)
<ul style="list-style-type: none"> • IEC 60780, Nuclear power plants – Electrical equipment of the safety system – Qualification. • IEC 60812, Technical Analysis for system reliability – Procedure for failure mode and effects analysis (FMEA). • IEC 60980. Seismic events. (ITER Specific) 		

4.8.3.4 Standards for I&C systems. ITER specific.

The reference document **SRD-45 (CODAC) from DOORS**, lists a large number of International standards as potentially applicable to CODAC, some of them with nuclear implications. Most of them are included in one or another of the lists above, except:

- **IEC 60231** *General Principles of Nuclear Reactor Instrumentation (original from 1967; supplements up to 1977)*
- **IEC 60232** *(it must be an error, the number and the title doesn't exist as IEC)*
- **IEC 61227** *Nuclear power plants - Control rooms - Operator controls*
- **IEC 61963** *(it must be an error, the number and the title doesn't exist as IEC)*
- **IEC 62241** *Nuclear power plants - Main control room - Alarm functions and presentation*
- **IEC 62247** *(it must be an error, the number and the title doesn't exist as IEC)*

The reference document **Plant Control Design Handbook for Nuclear control systems** lists as references a number of International standards that have been listed above: IEC 61513, IEC 60709 (by error numbered 61709 in the PCDH-N), IEC 61226, IEC 60780, IEC 60980, IEC 61000-4 (all parts), IEC 61000-6-2, IEC 60812 and IEC 62138.

5 UPPER LEVEL MECHANISMS AND FUNCTIONS

The present chapter deals with the mechanisms and functions that are considered to be at an upper level, considering that are not directly related with the TBMs systems or well act over a higher level of abstraction in the organization. Epigraph 5.1 deals with human resources, as stated per ITER public documentation. Epigraph 5.2 considers the expected computer resources that are to be needed and makes a proposal of a preliminary design of a relational database which is to be developed in the future and must be embedded within the I&C systems. Epigraph 5.3 explains the ITER project organizational structure taken from ITER documentation. Then, epigraph 5.4 makes a rough product materials breakdown and explains which are the main suppliers and their nationality. After that, epigraph 5.5 explains upper level constraints, including economic and social issues. Finally epigraph 5.6 talks about the main project outputs as could be electricity and the expected produced waste.

5.1 HUMAN RESOURCES

The best answer to this issue is provided by Fusion for Energy (**F4E**) text and is transcribed below in the following paragraphs.

As Host Member to the ITER Project, Europe has the responsibility to build nearly all of the 39 buildings and technical areas of the ITER platform. The Domestic Agency for Europe (Fusion for Energy) is thus charged with managing the tender offers for the building projects entrusted to Europe and awarding the related contracts (principally to European companies).

Fusion for Energy has put into place a rigorous qualification process for companies. Companies must prove:

- **Conformity with laws and regulations and contractual requirements.** *In terms of security (companies must submit valid security and occupational health policies).*
- **Technical conformity.** *The contractor must prove that it has the technical capacity to carry out the work demanded.*

Meeting these conditions is a requirement for any company hoping to be awarded a construction contract with Fusion for Energy. Fusion for Energy can exercise its right of audit at any time during the execution of contractual works.

According to the European Domestic Agency construction contracts, a maximum of two tiers of subcontracting is permitted. Accordingly, no part of the contracted works may be subcontracted to a third tier unless otherwise approved by Fusion for Energy. Compliance with this clause is closely monitored and up to now this requirement has been complied with strictly.

The construction of the ITER facility is estimated at 18 million man hours. The number of workers is expected to reach a peak between 2020 and 2022, with close to 2,000 people involved with the construction activities.

5.2 COMPUTER RESOURCES

The projected I&C configuration takes into account different layers which include servers and slave computers and cells which respond to a logical structure which enables the connectivity of all sensors and actuators at the lowest level to the main servers of Proto-CODAC at the top.

The inferred logical structure includes fast and slow information treatment devices including microprocessors for quick response signals and PLCs for the slow branches.

5.2.1 Proposal for a data acquisition, processing and storage system database.

Also the foreseen logical CODAC I&C structure might be able to feed a dynamic relational database which mimics the data structure in order to implement the plant model data structure which might include machine learning techniques in order to enhance better responses at each campaign, so each time the operator must be able to respond in a better or least harmful way to the transients. Also, as this is an experimental facility, the procedures must be improved each time with learned lessons for improved safety and optimized power output.

The proposed database mainframe is to be tied directly with the CODAC system and embedded within it, acquiring digital and analog data from process sensors and probes and transmitting them to upper levels in the data processing network.

Obtained data, which can be obtained also from redundant measuring probes, are, after being adequately conditioned, passed to a data processor system, which could be based in machine learning techniques based on neural networks. This level makes a preliminary computation of the tritium inventory and it is related at the same time, and in both senses, giving feedback to the data command and control system server, which is to be located at the same layer of abstraction.

This mutual interaction provides two functions at the same time: increase knowledge about the process, both to human operators and letting them configure the machine to learn for future control operation campaigns; and to develop the actual inventory computation with better accuracy, along the on-line control operation.

The database related to the command and control operational system is related in a lower section below with a series of sub tables or databases that account for the inventory in the different sub-systems, making possible to use the various models implemented and making possible the communication with the end active elements or actuators which constitute the automation system of the processes.

This same scheme is replicated to all the TBM layers (all of the involved in the aim of the HCLL and HCPB Proto-CODAC Project Proposal), converging to an upper abstraction layer which consists on the main data server which includes ancillary data storage and monitoring to operators, also making data available for further analysis to be developed by the process specialist and data analyst ITER staff.

Both expert system and neural network enhanced AI approaches are to be developed in order to increase the knowledge and improve controllability of the process. This task can be developed in a first stage by one single team, as while the products increase in complexity probably will require more developers and analyst staff, which might contribute to the creation of new highly-skilled and experts job positions creation.

Figure 5-1 depicts Preliminary Data and Signals Acquisition, transmission, processing and Storage system roadmap.

As M. Mitchell Waldrop wrote in his book *“Man-Made Minds. The Promise of Artificial intelligence”*, dating from 1987, Part II, Visions of a new generation, where he talks about Hidden AI, databases were already foreseen to be developed as the main core of AI systems in the future. Today, this has been proven and almost everywhere in our technical-electronica devices and Operating Systems (OS) we find some kind of AI, DB enhanced, that are running in the background of the machine and interacts with the user by the main interface. [Waldrop, 1987]

5.2.2 Multidimensional *model development and treatment of errors*

As treated in point [4.5.4. Types of models], modeling is developed using different techniques depending on the level of knowledge of the physical process being studied.

In our case, the accounting of tritium among the different process units and pipes can be subjected to certain level of uncertainty, which must be well assessed. Multiple are the methods of treatment of errors and and uncertainty, as declared in point [4.5.6.3 Failure detection and analysis standard methods], where it has been treated the errors that could come from the same process, but we must take into account as well probable numerical errors, and son on, establish high and low tolerance limits for the task to make decisions. This means stop the plant or take the corresponding corrective actions in order to return as soon as possible to normal operation.

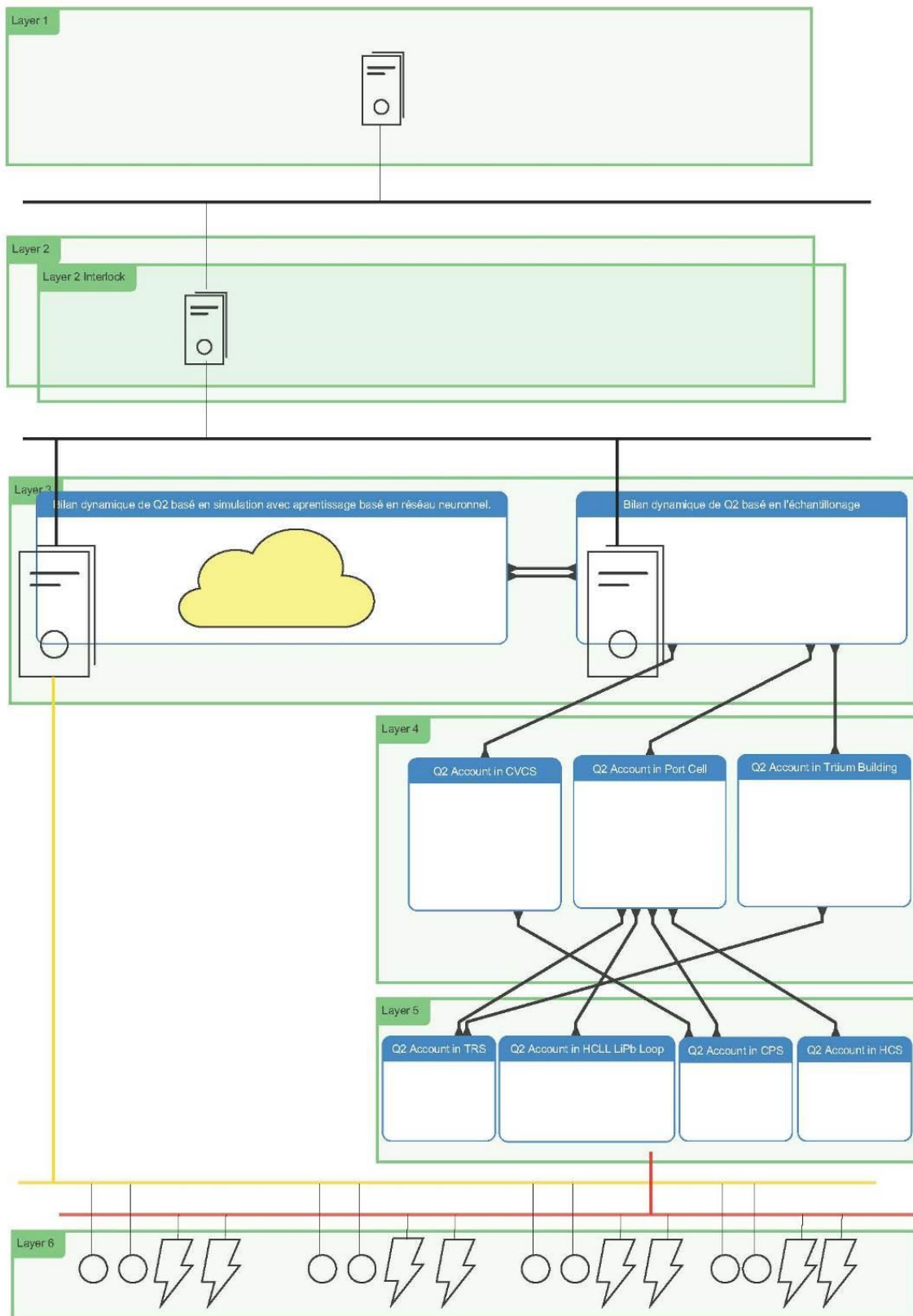
In this sense, we must take into account the work developed by Elisabeth Mas de les Valls and collaborators dealing with highly complex models, actually using open source Open Foam software as well as other coding protocols (Li. Batet, et al, 2004 [75]). Also Mr. Lluís Batet inherent developments include different kind of models based on the known as condensed parameters (As presented in Appendix 2, by direct communication of Prof. Dr. Lluís Batet). Which could be identified as the white and black types of models described by (Roffel, 2004 [12]).

Both types of models will be run simultaneously on the central monitoring machine, so as to evaluate the differences between both, as benchmarking of these models in order to improve them, and as well put them in contrast with the empirical data coming from sounds and probes installed in the pilot plant or mockup. All the retrieved data will be stored for further analysis which will represent a high volume of data and volume consumption.

The final objective of retrieving all these data is to sum or compose the total tritium amount in all the TBM systems (as it is described in the Main Objectives of the project, see point 2). Many techniques of interpolation, extrapolation, and correlations are available nowadays, as could be the following, non-extensive list:

- Least Squares method
- Splines
- Global Polynomial Interpolation
- IDW (Inverse distance weighting)

Figure 5-1. Preliminary Data and Signals Acquisition, transmission, processing and Storage System (AI and Databases) – Applicable to BPCS and SIS separately



5.3 RAW MATERIALS AND SUPPLY CHAIN

5.3.1 Raw materials

Table 5-1 presents a non-exhaustive checklist in which materials used in the project are compiled with indication of its location. A further task of compilation of the quantities (which are not well specified yet) is meant to be developed in order to know the quantities of activated materials to be treated as waste and also in order to compute administrative taxes related to waste.

Table 5-1. Main materials composing the ITER Tokamak (*ITER IO, 2015 [4]*)

Material	System
Pb	Shielding
Li ⁶ – Li ⁷	Breeder blanket
Li ₄ SiO ₄	Tritium breeding material
Li ₂ TiO ₃	Tritium breeding material
Be	Neutron multiplier
Nb ₃ Sn	Central Solenoid Toroidal field coil
Nb-Ti	Poloidal field coil
316LN Steel	Structural material
EUROFER-97 (X10CrWVTa9-1)	Structural material
Cu alloy	Heat sink
C	Components near plasma
W alloy	Divertor
Fiber Optics	I&C
Cu Cable	I&C

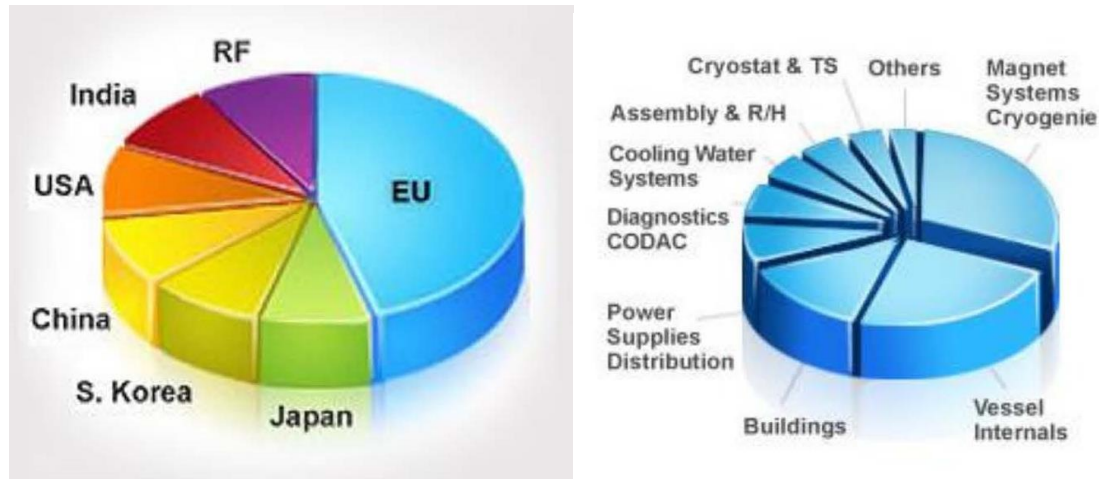
5.3.2 Supply chain

The structure of the procurement strategy in the ITER project involves world class manufacturing and distribution to converge finally at the site for assembly.

Domestic agencies and central team develop and deliver different ITER components. While Europe is the main contributor, accounting for barely half of its components.

Figure 5-3 shows budgetary contribution from the point of view of the contracts awarded to the different participating countries. (*ITER IO, 2015 [4]*)

Figure 5-2. Budgetary contribution from the point of view of the contracts awarded to the different participating countries (left) and expenditure in the different systems composing the Tokamak (right) (ITER IO, 2015 [4])



The procurement contracts are awarded following the main directives that can be described as presented below.

- **Contracts according to transparency, proportionality, equal treatment and non-discrimination**
 - No mandatory geographical distribution
- **Best value for money (cost effective design)**
 - Cost and quality awareness
 - Risk Management rather than Risk Avoidance
- **Tenders competed to all European economic operators**
 - Tender worldwide if necessary
 - Negotiate directly if justified
 - Share information with other Domestic Agencies and IO

5.3.3 Data/Documentation

Publicly available data for the ITER project includes websites and devoted issues written by the communication department of the same organization. Also a number of scientific papers are written on a periodic basis, including the progress and new findings that are obtained from the research.

5.3.4 MAINTENANCE AND SUPPORT

The materials and equipment inside the vacuum chamber are exposed to ionizing radiation and extreme temperatures. This is the reason why it will be necessary to make continuous and periodical maintenance (also known as predictive and corrective maintenance).

As shown in Figure 5-4, the design of the Tokamak includes robotized systems to change the in-vessel parts, as well as the TBMs cell ports and other equipment.

The parts which are extracted from the chamber will be disposed transferred to the waste area, from which will be adequately treated and directed to its corresponding waste management agent.

Figure 5-3. In vessel transporter for blanket maintenance (ITER IO, 2016 [71])

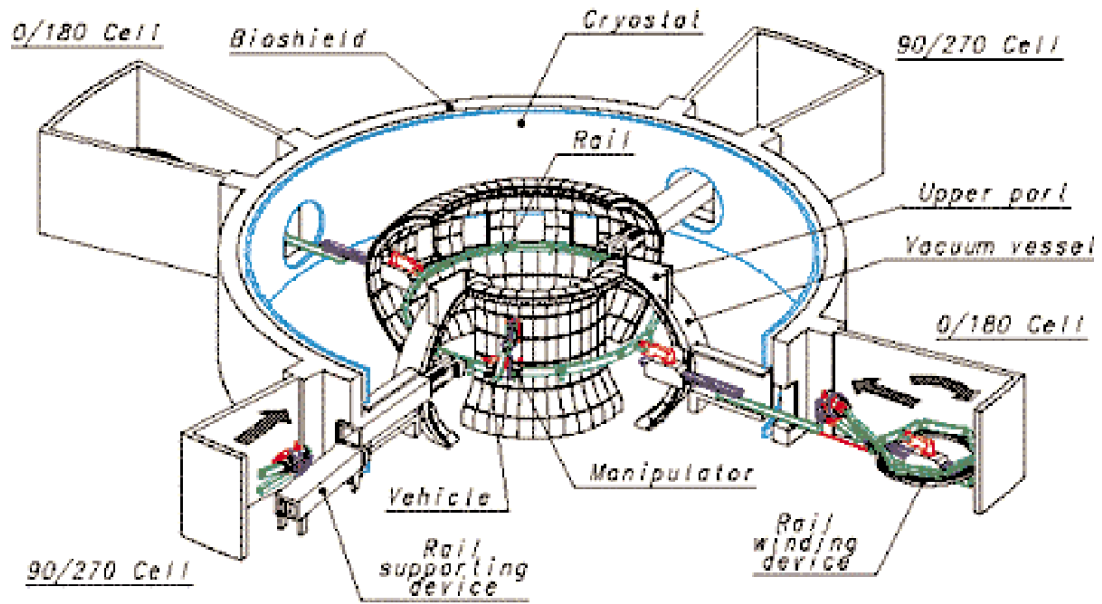
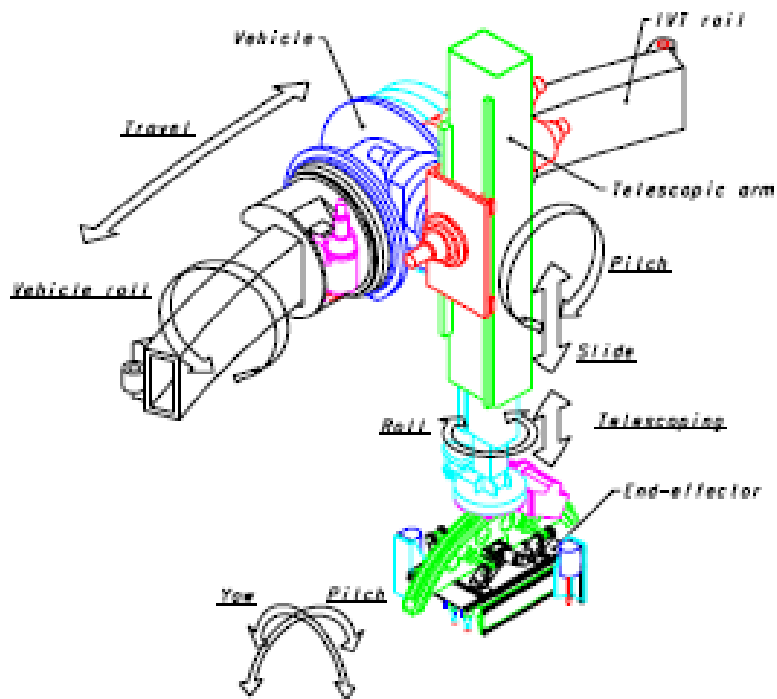


Figure 5-4. Rail-mounted vehicle and telescopic arm. (ITER IO, 2016 [71])



5.4 UPPER LEVEL CONSTRAINTS

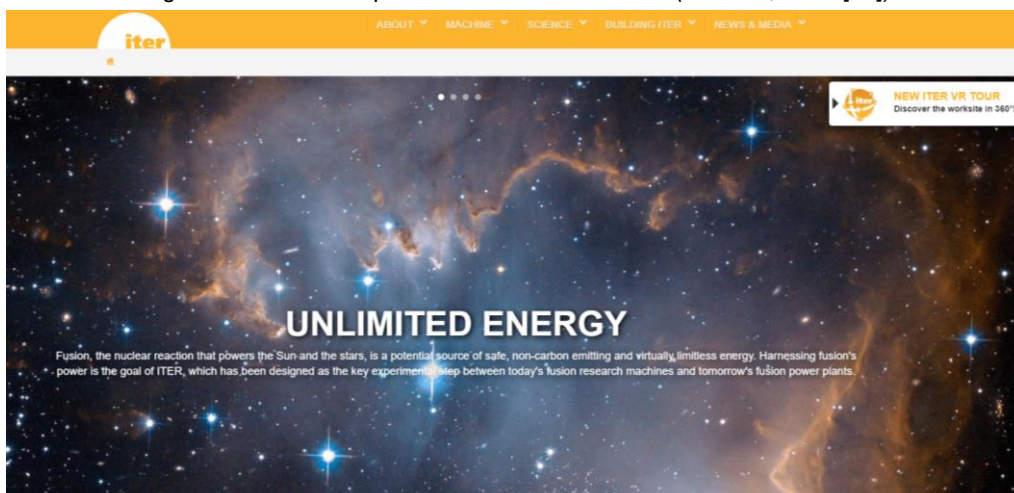
5.4.1 Regional opposition point of view (Nimby effect)

Already, many centuries ago, the wise scientific *élite* have tried to search for the perpetual movement, this means, a machine which would turn always, eternally to the limit without energy consumption. They imagined that energy could be generated without needing a source. After Carnot in the 19th Century enounced the laws of thermodynamics this extreme was obviously rejected. More specifically, the second law of thermodynamics enounces that in a system following a cycle, a part of the energy is degraded to lower quality or more diffuse forms by any kind of alternative mechanisms. This is the main concept of entropy.

More than 50 years after the WW II we can still see how nuclear promoters make promises of having it all without anything in change or return. If it is true that the energy industry plays an important role in society, by means of producing electricity and many other positive externalities, we cannot turn our back to the obvious drawbacks that also it might generate nuclear power, although understood with pacific commitment. Negative effects are and will be produced by the nature of the anthropological technical systems. Those negative externalities are to be taken seriously into account as well at the time that decisions are to be discussed, moreover when the sites of the huge machines or energy producing plants are to be located nearby populated areas. (Barrillot, 2005 [32])

According to Bertrand Louart in its article entitled "ITER, la fabrique de d'Absolu, Seconde Partie" (Louart, 2006 [33] [34]), dated from 2006: ITER is the same type of technological solution which comes with the same kind of problems of political, social and ecological nature. Instead of recognizing the huge obstacles that the nowadays industrial society presents, it is expected to pulverize them to the punch of nuclear reactions, ideally controlled. Instead of putting over the table and criticizing the life style of the consummation society and the dictatorship of the economy founded over competitiveness, which means the accumulation and unlimited growth and centralization of power, an economical based society doesn't learn the lesson and still tends to accumulate and increase both wealth and energy consumption and waste. Even though in recent years a more sensitive attitude with the environment has been observed in most countries (mainly Europe), with remarkable exceptions.

Figure 5-5. Screen capture taken from IO website (ITER IO, 2017 [61])



The nations consortium invest millions in a scientific continuous leak inside a cult to a technology that will give a response ideally to all the questions of mankind. Figure 5-5 shows a screen capture taken from the ITER IO website, which promotes the opposite ideal as the one described among these thoughts.

Back in the 1920's, Czech writer Karel Capek was suddenly interested in the scientific innovation being developed during its time. He popularized the word "robot", which was invented by his brother, with his theatre play Rossum's Universal Robots (R.U.R.). He developed the issue that was widely extended by science-fiction of the turn back of the machine against humans. In year 1922 he published the novel "La fabrique d'Absolu", in which he explains how an experienced inventor discovers the mechanism to disintegrate matter and use the unleashed energy to turn a motor. The invention is popularized after it is patented and people starts to believe in mysticism because it seems like magic. Although several philosophers have treated the issue of the presence or absence of a God in the hearth of matter. The epilogue of the novel foresees the total war and annihilation because of belief and will for power. Indeed in its time the novel was no more than a prank directed to the clerical status. Nowadays, Capek it would not be a progressist as we consider it today. **The recurrent issue that he treated in his texts was basically that it is not possible to obtain all without anything in exchange and that the excessive ambitions generate the worst consequences.**

5.4.2 Economic

The answer to this issue is best found in proprietary documentation released by ITER, which is transcribed below.

First, consider the R&D and fabrication activities that are going on for ITER around the world. In 2014, the ITER Domestic Agencies estimated the number of contracts awarded related to the development and procurement of ITER systems, components and infrastructure at over 1,800—the direct beneficiaries of these contracts are the laboratories, universities and industries in ITER Member countries. (Contracts are also awarded directly by the ITER Organization.) These contracts—many of which demand skilled contributions in engineering—are significantly more labor-intensive than conventional industrial manufacturing. An estimated EUR 3 billion are engaged in ITER manufacturing around the world.

It is estimated that over three-fourths of the total European construction contribution to ITER will be directed to industry, a proportion that is similar in other Members.

Since 2007, 1,200 people have worked on the preparation of the ITER site, the construction of the Provence-Alpes-Côte d'Azur International School, and the ITER Itinerary. A further 2,500 people have been in ITER construction (for the period mid-2010 to 2014). Today, approximately 1,400 people work for the ITER Organization in Saint Paul-lez-Durance (ITER staff, contractors, temporary agents, European Domestic Agency staff and subcontractors); these employees contribute, with their families, to the economic life of the region.

During the peak of construction and assembly works (2017-2019), 3,000-4,000 workers will be employed on the ITER site.

Contracts totaling EUR 4.77 billion have been attributed since 2007 by the ITER Organization, the European Domestic Agency for ITER (responsible for the in-kind contribution of Europe to ITER,

including all buildings), and Agence Iter France. Within this total, French companies have been awarded EUR 2.52 billion worth of contracts, of which 71% (worth EUR 1,8 million) were attributed to companies based in the PACA region (statistics for the period ending 30 June 2016). [IO, 2016]

5.5 ANALYSIS OF THE OUTPUTS

5.5.1 System product ready for consumer use

The final product of the ITER project is electricity injected into the grid, by means of a dedicated substation. ITER rates a fusion power around 500 MW (50 MW electrical) means approximately 400 MWh of energy for the whole year campaign taking into account a load factor of 91.3%.

5.5.2 Supporting resources

The supply chain for the ITER project includes the manufacturing and transport from almost all of the participant countries. In the case of poloidal and toroidal coils, because of its size, the manufacturing is developed in a dedicated building located at the same site. A non-exhaustive list of the most important supplies is presented below.

Additionally it is possible to find references about this issue in ITER publications. The paragraphs below clarify a bit more about supporting resources.

Electrical supply to the ITER site will be assured by an existing network that feeds the Tore Supra Tokamak—part of the adjacent CEA Cadarache research facility. The French electricity provider RTE completed a 4-hectare switchyard on the ITER platform and the connection to the main network in June 2012. Operating the ITER Tokamak will require from 120 MW to up to 620 MW of electricity for peak periods of 30 seconds. No disruption to local users is expected.

Concerning water supply, approximately 3 million cubic meters of water will be necessary per year during the operational phase of ITER. This water will be supplied by the nearby Canal de Provence, and transported by gravity through underground tunnels to the fusion installation. The volume of water needed for ITER represents only 1 percent of the total water transported by the Canal de Provence. The combined effect of the ITER installation and the adjacent CEA facilities remains below 5 percent of the total volume of water transported by the Canal de Provence.

5.5.3 Waste (residue)

Fusion reactors, unlike fission reactors, produce no high activity/long-lived radioactive waste. The "burnt" fuel in a fusion reactor is helium, an inert gas. Activation produced in the material surfaces by the fast neutrons will produce waste that is classified as very low, low, or medium activity waste. All waste materials will be treated, packaged, and stored on site. Because the half-life of most radioisotopes contained in this waste is lower than ten years, within 100 years the radioactivity of the materials will have diminished in such a significant way that the materials can be recycled for use (in other fusion plants, for example). This timetable of 100 years could possibly be reduced for future devices through the continued development of 'low activation' materials, which is an important part of fusion research and development today.

Also, in words of ITER publications it is possible to find more accurate information. Excerpt from original text is found in the following paragraphs.

The activation or contamination of in-vessel components, the vacuum vessel, the fuel circuit, the cooling system, the maintenance equipment, or buildings will produce an estimated 30,000 tons of decommissioning waste that will be removed from the ITER scientific facility and processed.

ITER, as operator, will bear the financial responsibility for the temporary and final storage of operational radioactive waste. Host State France will be in charge of the dismantling phase and the management of the waste resulting from this dismantling; the cost for these activities will be provisioned by ITER during the operation phase and shared by the Members. France will also be responsible for providing temporary storage for part of the operational waste, pending its final disposal; this will be financed through ITER operation cost. [IO, 2016]

6 CONCLUSIONS

The present document states a proposal for a functional analysis design review of the CODAC / Proto-CODAC ITER Systems, following a series of methodologies that are of application to the different subsystems according to their nature and functional specifications.

The general and secondary objectives have been covered over the text, including:

- *Understanding of the Tokamak and TBMs*
- *Understanding of how a dynamic tritium monitoring system should be implemented*
- *Application of Systems Engineering methodology to the case study*
- *Classification of functions*

Also, as stated in the objectives, the document helps to a better understanding of the ITER whole project, its advantages and drawbacks.

The functional analysis, as it is formerly understood comprises the major part of the text, and it is developed through chapters 4 and 5.

Chapter 4 entitled as the formal “Functional Analysis” covers the review of systems inputs, system design checklist, TBMs subsystems and their main functions. Also the formal FA of the proposed dynamic inventory monitoring system it is stated. The remainder of this chapter deals with the methodology on physical models theory, based on the referenced literature. An overview of the CODAC network system is developed, as well as its identified control variables and constraints.

Finally, Chapter 5 deals with the upper level mechanisms and functions, most of them taken as excerpts from public IO documentation.

Least but not less, future work is proposed for the development of a global CODAC embedded relational AI enhanced neural network based database, for its interest both in the improvement of the process knowledge, at the same time that the physical models are being developed, and increase in operational performance of the dynamic tritium inventory monitoring system.

7 FUTURE DEVELOPMENT

In order to make a sufficient correct assessment of the overall tritium balance a number of highly complex techniques are being used, involving, as has been stated previously, different departments in Universities and enterprises. As told before there include UPC, IQS, FUS-Alliance and Procon; all under the auspice of CSN and Ciemat, all Spanish entities.

The presented work stated in the present document constitutes the rules and explains a personal approach to the philosophy of different types of models to develop the tritium monitoring in the future TBM subsystems of the real ITER and DEMO plants, and has covered a number of literature references in order to provide a methodological guide which has to be enlarged or more well precised in the future, so as the project advances the technical specifications and specific components could be defined or well discarded. For, as stated first in the text this is the main goal of a Functional Analysis.

On the other hand, the development of the specific models include nowadays two UPC-proprietary models: one deterministic model which works with condensed parameters (which could be considered as 1D) and a second type of models, more complex indeed in its implementation and which considers certain degree of variability in its inputs and results and allows modeled disturbances, represented as noise. This second type of models can be considered or called 1.5D.

Meanwhile IQS works in its virtual models of parameterized instrumentation which at the present days want to detect pure Hydrogen and in the near future should include Helium and furtherly Tritium.

Procon works hardly on plant automation, while the other tasks are being developed as well as it co-directs the project.

The main issues to be solved in the future, and in which the efforts should be directed are the following:

TASK	Responsible
<ul style="list-style-type: none">• Consideration of variability and error reduction on measurements and model results• Develop concise models	UPC
<ul style="list-style-type: none">• Obtaining hardware specifications and parameterization of the detectors	IQS
<ul style="list-style-type: none">• Determine Optimal Plant control Strategy for the TBM Supervisory control	PROCON

8 GLOSSARY

- [1] AFNOR. Association française de normalisation
- [2] AI. Artificial Intelligence
- [3] ASN. Autorité de Surété Nucleaire
- [4] BPCS. Basic Plant Control System
- [5] C&ID. Control and Instrumentation Diagram
- [6] CCWS. Component Cooling Water System
- [7] CDTI. Centro para el Desarrollo Tecnológico Industrial
- [8] CEA. Commissariat à l'Énergie Atomique (French: Atomic Energy Commission)
- [9] CENELEC. Comite Europeen de Normalisation ELECtrotechnique (European Committee for Electrotechnical Standardization)
- [10] CIEMAT. Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
- [11] Co. Concentration values recorded coming from the sensors
- [12] CODAC. COntrol, DAta Access and COmmunication
- [13] Cp. Results obtained with the model
- [14] CPS. Coolant Purification System
- [15] CVCS. Chemical & Volume Control System
- [16] DACS. Digital to Analogue Converter System
- [17] DEMO. Demonstration Reactor
- [18] DOORS®. Dynamic Object-Oriented Requirements System. IBM Trade Mark
- [19] ECWG. ITER's Export Control Working Group
- [20] EFDA. European Fusion Development Agreement
- [21] EMC. Electromagnetic compatibility
- [22] F4E. Fusion for Energy. Domestic Contractor Agency
- [23] FA. Functional Analysis
- [24] FAC2. Fraction of predicted data whose ratio is between 0.5 and 2 the measured value
- [25] FMEA. Failure Modes & Effects Analysis
- [26] HAL. Hardware Abstraction Layer
- [27] HAZOP. HAZard and OPerability
- [28] HCLL. Helium Cooling Lithium Lead
- [29] HCPB. Helium Cooling Pebble Bed
- [30] HCS. Helium Cooling System
- [31] HDF. Hierarchical Data Format
- [32] HF. Human Factors
- [33] HFE. human factors engineering
- [34] I&C / IC. Instrumentation and Control
- [35] IAEA. International Nuclear Safety Group
- [36] IBM. International Business Machines
- [37] IEC. International Electrotechnical Council

- [38]INSAG. International Nuclear Safety Group
- [39]IO. ITER Organization
- [40]IQS. Institut Químic de Sarrià
- [41]ITER. International Thermonuclear Experimental Reactor
- [42]LOCA. Loss Of Coolant Accident
- [43]MAC. ITER's Management Advisory Committee
- [44]MG. Geometric Mean
- [45]MPC. Multivariable Process Control
- [46]NPP. Nuclear Power Plant
- [47]NS. Nuclear Standard
- [48]NUREG. US Nuclear Regulatory Commission Regulation
- [49]PACA. Provence-Alpes-Côte d'Azur
- [50]PAS Publicly Available Specifications
- [51]PCDH. Plant Control Design Handbook
- [52]PCDH. Plant Control Design Handbook
- [53]PCS. Passive Control System
- [54]PES. Programmable electronic system device
- [55]PID. Proportional-Integral-Derivative controller
- [56]PROCON Systems. Engineering company specialized in the development of projects for body assembly lines and robotic solutions, surface treatments for the automotive industry, as well as the development of sophisticated control, personal safety and access control systems for large scientific facilities
- [57]Proto-CODAC. PROCON R&D project in the field of the nuclear fusion technologies related with control, data acquisition, monitoring and diagnostic systems
- [58]PTSA. Pressure and Temperature Swing Adsorption
- [59]R&D. Research and Development
- [60]R. Correlation coefficient
- [61]RFID. Radio Frequency Identification
- [62]SIC. Standard Industrial Classification
- [63]SIS. Safety Instrumental System
- [64]SRD. System Requirement Document
- [65]STAC. ITER's Science and Technology Advisory Committee
- [66]TBM. Test Blanket Module
- [67]TBM-PC. ITER's Test Blanket Module Program Committee
- [68]TES. Tritium Extraction System
- [69]TRS. Tritium Recovery System
- [70]UPC. Universitat Politècnica de Catalunya
- [71]VDU. Visual Display Units
- [72]VG. Geometric Variance

9 REFERENCES

- [1] Controlled Nuclear Fusion. Fundamentals of its Utilization for Energy Supply. J. Raeder et al. 1986.
- [2] Cahier des charges des automatismes. Analyse fonctionnelle. Techniques de l'ingénieur. M. Roux
- [3] Cahier des charges d'un produit informatique. Techniques de l'ingénieur. J-P. Zanin
- [4] ITER Organization 2015 Annual Report
- [5] Plantwide Process Control. K. T. Erikson et- al- Wiley series in chemical Engineering. 1999
- [6] Engineering Design. A systematic Approach. Third Edition. G. Pahl et. Al. Springer 2007
- [7] Análisis funcional de redes de información. Enfoque estructurado del medio de comunicación de datos. H. B. Becker. Limusa. 1977
- [8] Metodología del Análisis Estructurado de Sistemas. J. B. de Areba. Universidad Pontificia Comillas Madrid. 1994
- [9] Process Automation Handbook. A Guide to Theory and Practice. J. Love. Springer. 2007
- [10] Control e instrumentación de procesos químicos. P. Ollero de Castro, et. Al. Ediciones Síntesis. 1997
- [11] Modern Methods of Systems Engineering. J. Jenney, et. Al. 2010
- [12] Advanced Practical Process Control. B. Roffel, et. Al. Springer. 2004
- [13] Estrategias de modelado, simulación y optimización de procesos químicos. L. Puigjaner, et. Al. Ed. Síntesis. 2006
- [14] Process Control. Designing Processes and Control Systems for Dynamic Performance. 2nd. Edition. T. E. Marlin. Mc Graw Hill. 2000
- [15] Systems Engineering and Analysis. Third Edition. B. S. Blanchard, et. Al. Prentice Hall Int. Series in Industrial and Systems Engineering. 1998
- [16] Modern Control Techniques for the Processing Industries. Marcel Dekker, Inc. T. H. Tsai. 1986
- [17] Ullmann's Encyclopedia of Industrial Chemistry. Sixth Completely Revised Edition. Processes and Process Engineering. Wiley. 2003
- [18] Perry's Chemical Engineering Handbook. 8th Edition. Don W. Green et. al. 2008
- [19] Functional Analysis in System Engineering: Methodology and Application. N. Viola, S. Corpino, M. Fioriti, F. Stesina. Politecnico di Torino. Systems Engineering – Practice and Theory. INTECH 2012.
- [20] NASA Systems Engineering Handbook. NASA/SP-2007-6105 Rev1
- [21] Man-Made Minds. The Promise of Artificial intelligence. M. Mitchell Waldrop. Walker and Company. 1987
- [22] Estudio de los niveles de emission e inmisión de óxidos de nitrógeno en el área de Barcelona. C. Tapia. AUMA. 2006.
- [23] Systems Engineering Fundamentals. US Department of Defense. 2001.
- [24] Competitive Engineering. A Handbook for Systems Engineering, Requirements Engineering and Software Engineering Using Planguage. Elsevier. 2005.
- [25] Control System Advanced Methods. W. S. Levine. CRC Press. 2011.
- [26] Essentials of Project and Systems Engineering Management. H. Eisner. John Wiley & Sons, Inc. 2002.
- [27] FD X50-101 Décembre 1995. AFNOR
- [28] Expression du besoin et Cahier des Charges Fonctionnel. Élaboration et redaction. Afnor Éditions. 2e edition. 2008
- [29] Expression du besoin et Cahier des Charges Fonctionnel. Élaboration et redaction. Afnor Éditions. 3e edition. 2012
- [30] Safety and Environmental Impact of Fusion. CEA, et. al. 2001
- [31] ITER ou la Fabrique d'Absolu. Bertrand Louart. 2006
- [32] Le complexe nucléaire. Bruno Barrillot. CDRPC / Observatoire des armes nucléaires françaises. 2005
- [33] La Fabrique d'Absolu. B.L. 2006. Archipel, journal du Forum civique européen.
- [34] ITER, la Fabrique d'Absolu (Seconde Partie). Bertrand Louart. 2006 . Archipel, journal du Forum civique européen.

- [35] IEC 61513 standard “Nuclear power plants – Instrumentation and control for systems important to safety – General requirements for systems”.
- [36] Nuclear Safety Control System - Overall Quality Plan.
- [37] Functional Safety: Safety Instrumented Systems for the Process Industry Sector - Part 1: Framework, Definitions, System, Hardware and Software Requirements. ANSI/ISA-84.00.01-2004 Part 1 (IEC 61511-1 Mod)
- [38] IEC 61513 standard “Nuclear power plants – Instrumentation and control for systems important to safety – General requirements for systems”
- [39] IEC 61226: 2010
- [40] IAEA INSAG-10: 1996, Defence in depth in nuclear safety
- [41] IAEA 75-INSAG-3/Rev.1 - INSAG 12: 1999, Basic safety principles for nuclear power plants
- [42] IAEA SSG-2, Deterministic Safety Analysis for Nuclear Power Plants
- [43] IAEA SSR-2/1, Safety of Nuclear Power Plants: Design. Specific Safety Requirements
- [44] IAEA GSR Part 4 Safety Assessment for Facilities and Activities
- [45] IAEA GS-R-3: 2006, The management system for facilities and activities - Safety requirements
- [46] IAEA GS-G-3.1:2006, Application for the management system for facilities and activities - Safety Guide
- [47] IAEA NS-G-1.1 Software for Computer Based Systems Important to Safety in Nuclear Power Plants
- [48] IAEA NS-G-2.2 Operational Limits and Conditions and Operating Procedures for Nuclear Power Plants
- [49] IAEA NS-G-1.3: 2002, Instrumentation and control systems important to safety in nuclear power plants
- [50] ISO 9001:2008, Quality management systems – requirements
- [51] Order dated 7 February 2012 relating to the general technical regulations applicable to basic nuclear installations
- [52] Arrêté du 7 février 2012 fixant les règles générales relatives aux installations nucléaires de base.
- [53] Technical Specification for the technical and regulation assistance services by an “autorité de sûreté nucléaire” agreed notified body on nuclear pressure equipment for the test blanket modules. f4e_d_25sn43 v.1.2
- [54] Plant Control Design Handbook for Nuclear control systems (PDCH) IDM -UID 2YNEFU-
- [55] ITER Project Management and Quality Program – ITER Quality Assurance Program.
- [56] HCLL-TBS System Design Description. Reduced Version. Conceptual Design Review Document. September 2014. F4E_D_22K8LA v.1.0.
- [57] HCPB-TBS System Design Description. Reduced Version. Conceptual Design Review Document. September 2014. F4E_D_22CU2 v.1.2.
- [58] Internal document of PROTOCODAC, by L. Batet, 2017
- [59] Batet L, Mas de les Valls E., Sedano L.A., Mathematical models for tritium permeation analysis in liquid metal flows with helium bubbles, Fusion engineering and design, Vol. 89, num. 7-8, p. 1158-1162, DOI: 10.1016/j.fusengdes.2014.04.031
- [60] J. Fradera, L. Sedano, E. Mas de les Valls, L. Batet, Implementation of two-phasetritium models for helium bubbles in HCLL breeding blanket modules, J. Nucl.Mater. 417 (2011) 739–742.
- [61] <https://www.iter.org>
- [62] ITER EDA DOCUMENTATION SERIES No. 24. International Thermonuclear Experimental. Reactor (ITER). Engineering Design Activities (EDA). ITER TECHNICAL BASIS. IAEA, VIENNA, 2002
- [63] POSTER ID 5-19. CDTI. Tritium 2016. 11th International Conference on Tritium Science & Technology
- [64] Tritium Breeding and blanket technology. W. Biel. DPG School “The Physics of ITER” Bad Honnef, 26.09.2014
- [65] The ancillary systems of the European test blanket modules: Configuration and integration in TIER. I. Ricapito, et. Al. Fusion Engineering and Design 85 (2010) 1154–1161
- [66] ITER CODAC Architecture . <https://www.iter.org/mach/codac/architecture>

- [67] L. Llivina, S. Colominas, J. Abella. Evaluation of the response time of H-concentration probes for tritium sensors in lead–lithium eutectic alloy. *Fusion Engineering and Design*, vol. 89, no 7–8, pp 1397-1401,2014.
- [68] L. Llivina, S. Colominas, J. Abella. Development of a hydrogen permeation sensor for future tritium applications. *Fusion Engineering and Design*, vol. 89, Issues 7–8, pp. 1209-1212, 2014.
- [69] ITER activities and fusion technology. M. Seki. 2007 IAEA, Vienna
- [70] System engineering approach in the EU Test Blanket Systems Design Integration. Panayotov et. al. *Fusion Engineering and Design*. Volume 86, Issues 9–11, October 2011, Pages 2241-2245
- [71] ITER Engineering Design Activities. 2016.R & D ITER-In-Vessel Remote Handling
- [72] European testing blanket modules auxiliaries design. Aiello. *Fusion Engineering and Design* 86 (2011) 602–606
- [73] Guidelines for Use of Vapor Cloud Dispersion Models. Second edition. Center for Chemical Process Safety of the American Institute of Chemical Engineers. 1996
- [74] Mathematical models for tritium permeation analysis in liquid metal flows with helium bubbles
- [75] *Fusion Engineering and Design*, Volume 89, Issues 7–8, October 2014, Pages 1158-1162. L. Batet, E. Mas de les Valls, L. A. Sedano
- [76] Development and validation of a simplified tritium migration simulation tool for its dynamic monitoring at ITER. MASTER’S FINAL PROJECT. April 2018.
- [77] PROTOCODAC. Análisis de las Experiencias del Montaje de Permeación. JM Sojo. June 2018