Techno
Fusión

National Centre for Fusion Technologies

Scientific-Technical Report

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Authors and Contributions

This document has been elaborated with the enthusiastic contribution of a large group of researchers from seven Universities and Research Centres. We are enormously grateful to them for their help and support during these past two years.

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Summary

The development of nuclear fusion is rapidly becoming a vital necessity in view of the continuing rise of the world's energy demand. Nuclear fusion offers a virtually endless source of energy that is both environmentally friendly and capable of meeting any foreseeable energy demand.

The progress of fusion constitutes one of the greatest technological challenges for humanity. Indeed, this field is one of the main areas of research of the European Union (EU), as was evident in June 2005, when the final agreement to construct ITER[1] (the *International Thermonuclear Experimental Reactor*) was signed, together with the USA, Russia, China, South Korea, Japan and India. ITER is an experimental reactor intended to demonstrate the scientific viability of fusion.

As the design of ITER is already defined, over the next 20 to 30 years the main focus will be on the development of technological components for future commercial reactors, rather than on basic plasma physics. The most important challenges for fusion research are the selection, development and testing of materials and the various elements for reactors, together with the design of energy extraction systems and tritium production methods.

At present, Spain has a unique opportunity to be at the forefront of this new technological field in Europe. However, there is a need for new facilities to simulate the extreme conditions to which materials and components will be exposed inside a fusion reactor.

The project outlined in this report describes the construction of a singular scientific and technological facility (the National Centre for Fusion Technologies -*TechnoFusión*) in the Madrid region, to create the infrastructure required to develop the technologies needed in future commercial fusion reactors, and to assure the participation of Spanish research groups and companies.

The Spanish scientific community has achieved an international recognition in the science and technology areas needed for the success of this ambitious project, as is evident from the results obtained by Spanish researchers in the fusion field over the past few decades. *TechnoFusión* intends to take advantage of the existing expertise of university research groups, public research institutions (*Organismo Público de Investigación, OPI*) and private companies. The performance of materials and components under the extreme conditions of a fusion reactor is largely unknown, and this is precisely what *TechoFusión* intends to explore. For this purpose, facilities are required for the manufacture, testing and analysis of critical materials. Additional resources are planned to develop and exploit numerical codes for the simulation of

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[1] ITER (originally the International Thermonuclear Experimental Reactor) is an international tokamak (magnetic confinement fusion) research/engineering project being built in Cadarache, France.

materials in special environments, to develop remote handling technologies and other areas related to the management of liquid metals.

In summary, *TechnoFusión* focus is the creation of infrastructures for the following research areas: 1) material production and processing, 2) material irradiation, 3) plasma-wall interaction (thermal loads and the mechanism of atomic damage), 4) liquid metal technologies, 5) material characterization techniques, 6) remote handling technologies and 7) computer simulation.

Therefore, *TechnoFusión* Scientific-Technical Facility will thus consist of a complex of seven large research areas, many of which are unique in the world, with the following main technical objectives:

1) *Material production and processing*. There are still some uncertainties about the materials that will be used to construct future fusion reactors, partly because it has not yet been possible to reproduce the extreme conditions to which such materials will be subjected. Therefore, it is of utmost importance to dispose of installations capable of manufacturing new materials on a semi-industrial scale and fabricating prototypes. Top priority materials include metals such as reinforced low activation ODS type steels (*Oxide Dispersion Strengthened steels*) and tungsten alloys. To manufacture such materials, equipment is required that currently is scarce or inexistent in Spain, such as a *Vacuum Induction Melting Furnace* (VIM), a *Hot Isostatic Pressing Furnace* (HIP), a Furnace for Sintering assisted by a Pulsed Plasma Current (*Spark Plasma Sintering*, SPS), or a *Vacuum Plasma Spraying* (VPS).

2) *Material Irradiation*. Even though the exact reactor conditions are only reproduced inside a reactor, it is possible to simulate the effects of neutrons and gamma radiation on materials by irradiating by ion and electron accelerators.

The effect of neutronic radiation will be characterized by combining three ion accelerators: one light ion accelerator of the tandem type for irradiating with He, with an energy of 6 MV, one light ion accelerator of the tandem type for irradiating with H (or D), with an energy of 5-6 MV, and a heavy ion accelerator of the cyclotron type, with k = 110, to implant heavy ions (Fe, W, Si, C) or high energy protons.

Additionally, a high magnetic field, between 5 and 10 T, must be incorporated into this facility in order to study the simultaneous effect of radiation and magnetic fields on materials.

The effects of ionizing *gamma* radiation will be studied using a *Rhodotron®* electron accelerator with a fixed energy of 10 MeV that will be shared with other *TechnoFusión* facilities.

3) *Plasma-wall interaction*. Inside a fusion reactor, some materials will not be subjected only to radiation, but also to enormous heat loads in the case of plasma disruptions. In view of this, both: i) stationary conditions due to the intrinsic reactor properties: high density, low temperature and high power and ii) violent transient events (called ELMs in plasma physics literature) must be reproduced. Therefore, it is essential to dispose of a device (which it will be called "plasma gun") to study plasma-material interactions simultaneously in steady state and transient regimes, thereby allowing an analysis of the modification of the materials and their properties in fusion reactors.

The mentioned plasma gun would consist of two main elements: i) a linear plasma device capable of generating hydrogen plasmas with steady state particle fluxes of up to 10^{24} $m^{-2}s^{-1}$ (i.e., of the order of the expected ITER fluxes) and impact energies in the range of 1-10 eV, and ii) a device of the quasi-stationary plasma accelerators (*QSPA*) type, providing pulses lasting 0.1-1.0 ms and energy fluxes in the 0.1-20 MJm^{-2} range, in a longitudinal magnetic field of the order of 1 T or greater.

These devices are connected by a common vacuum chamber, allowing the exchange of samples, and their simultaneous or consecutive exposure to the steady state and transient plasma flows under controlled conditions. Both devices will operate with hydrogen, deuterium, helium, and argon.

4) *Liquid metal technologies*. A number of, ITER, DEMO (*DEMOstration Fusion Power Reactor*)[2], and IFMIF (*International Fusion Materials Irradiation Facility*)[3] components will use liquid metals as refrigerants, tritium generators, neutron reproducers, moderators, etc., all of them under extreme conditions. Therefore, these applications need further research to be finally implemented in such installations.

The basic working scheme for this Facility in *TechnoFusión* is an arrangement of two liquid lithium loops, one of them coupled to the *Rhodotron®* electron accelerator to investigate the effects of gamma radiation on different conditions of the liquid lithium.

The main goals of this Facility are the studies of i) the free surface of liquid metals under conditions of internal energy deposition, and ii) the compatibility of structural materials and liquid metals in the presence of radiation. In addition, it will be possible to study the influence of magnetic fields on the cited phenomena as well as the development of methods for i) purification of liquid metals, ii) enrichment of lithium, iii) extraction of tritium, and iv) development of safety protocols for liquid metal handling.

5) *Characterization techniques*. Ambitious and well-understood research requires an accurate knowledge of the materials under study. Therefore, a range of techniques to characterize them under different situations is a key element in the global scheme of *TechnoFusión*. These techniques include mechanical testing (creep, nanoindentation, fatigue, etc.), compositional analysis (Secondary Ion Mass Spectrometry and Atomic Probe Tomography), and structural characterization (Energy Filtered Transmission Electron Microscopy, X-Ray Diffraction), as well as a number of material processing techniques (Focused Ion Beam Systems coupled to a Scanning Electron Microscope). Additional systems will be used to characterize physical properties (electrical, dielectric, optical, etc.).

Some of the above-mentioned techniques will be implemented to test the materials either in-beam –while being irradiating— or *in-situ*, inside the lithium loop. Needless to say, these techniques can also be performed before and after irradiation or before and after experiencing any other physical or chemical processes.

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[2] DEMO (DEMOnstration Power Plant) is a proposed nuclear fusion power plant that is intended to build upon the expected success of the ITER experimental nuclear fusion reactor.

[3] IFMIF is a planned high-intensity neutron reactor whose spectrum should be equivalent to that of a fusion reactor. The final design comprises two deuteron accelerators impinging on a liquid lithium target to generate nuclear stripping reactions to provide the desired neutron spectrum

6) ***Remote handling technologies*****.** The conditions inside a fusion reactor are incompatible with a manual repair or replacement of parts. Therefore remote handling is indispensable. New robotic techniques, compatible with such hostile conditions, need to be developed; while existing techniques need certification in order to be applied at installations such as ITER or IFMIF.

TechnoFusión Facility will contribute to this knowledge with: i) a large installation for the prototypes manipulation such as: *Diagnostic Port Plug* of ITER, *Test Blanket Modules* of ITER and Modules of irradiation of IFMIF, and ii) an Irradiated Room coupled to the electron accelerator –*Rhodotron*®— in order to carry out validation, certification and characterization of remote handling tools and machines in an uniform ionizing field equivalent to ITER-DEMO trying to simulate the fusion reactor environment.

7) ***Computer simulation***. To study conditions that cannot be reproduced experimentally and to accelerate the development of novel systems for a future commercial fusion power plant, *TechnoFusión* will stimulate an ambitious programme of computer simulations, combining existing experience in the fusion field with resources from the National Supercomputation Network[4]. The goals include the implementation of the global simulation of a commercial fusion reactor, the interpretation of results, the validation of numerical tools, and the development of new tools. Another indispensable goal is the creation of a data acquisition system and the visualisation of results.

Based on the existing experience of research groups at Universities, Public Research Organisations and company research departments, *TechnoFusión* proposes the development of a large scientific infrastructure in order to make a significant contribution to the development of new technologies needed for the construction of commercial fusion reactors. The project described here will permit the generation of highly relevant technological knowledge for all types of fusion reactors, irrespective of the underlying concept (magnetic or inertial confinement).

The goal of TechnoFusión is to bring together sufficient human and material resources to contribute significantly to the development of a safe, clean, and inexhaustible source of energy for future generations.

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[4] http://www.bsc.es/index.php. September 2009.

4. Material Production and Processing

4.1. *Introduction*

The main critical materials in fusion reactor are those used in the structure of the plasma facing wall, (i.e. the blanket and the divertor, which are the devices for primary heat removal), plasma purification and tritium breeding, as well as others used in the vacuum vessel, cryostat, superconductor coils, magnet shield, containment structure and auxiliary systems for plasma heating and fuelling.The interaction of the plasma and radiation with *Plasma Facing Materials* (PFMs) and other component materials of the reactor vessel will be a severe problem because these materials will be subjected to very high fluxes of energetic particles and heat. The first wall of the plasma chamber will be irradiated by energetic charged particles, a very intense flux of electromagnetic radiation and neutrons with energy up to 14 MeV. This will modify the material properties at a rate, and to an extent, that will depend on proximity to the plasma. Perhaps, this is the more urgent issue to be resolved in order to make nuclear fusion an economical and safe energy resource. Plasma facing parts and other components next to the plasma will have to perform under extreme conditions so that the plasma can achieve the operating parameters that will make the fusion reactors into profitable devices for energy production. Therefore, the structural materials for fusion applications must possess a much broader combination of properties that those so far demanded for materials used in current power generation systems or other demanding devices.

There are three groups of key materials to be developed for nuclear fusion technology:

a) PFMs used for fabricating blanket and divertor system parts.

b) Structural materials for holding the first wall components, the plasma chamber and the magnetic shield, and for building the refrigeration system and other ancillary systems.

c) Materials termed as “functional materials” because they have the capability to work as tritium breeder, refrigerant or neutron multiplier, simultaneously. The ceramic materials used in plasma diagnostic systems also fall within this material type.

The PFMs are required to possess high thermal conductivity, good mechanical strength and toughness, low hydrogen retention, reduced activation induced by irradiation, as well as being radiation hard, plasma erosion resistant and non magnetic. At present, materials complying with all the design requirements established for the plasma facing components (PFCs) are not available. However, *Carbon Fiber Composites* (CFC), Be and W, and its alloys, are being considered as potential PFMs. However the properties of these materials, and their interactions with plasmas, are very different. Therefore, a full understanding of plasma and irradiation effects on these materials is imperative for developing the PFMs required for future fusion reactors.

W, and some of its alloys, appears to be the most promising PFMs for the divertor system due to their capability to withstand high heat fluxes and to resist plasma erosion. In addition, *Oxide Dispersion Strengthened steels* (ODS), coated by a protective W layer, are considered potential materials for building PFCs. In any case, the use of W and its alloys demands improvements in their mechanical properties, and the behaviour and stability of their microstructure at high temperatures and under irradiation.

The above mentioned concerns for PFMs also arise for other structural materials that may be exposed to extreme conditions of irradiation, temperature and heat load, as well as thermal stresses, and fluids at high temperatures and pressures. These materials, as well as possessing low induced activation and very good mechanical properties, have to remain stable in an appropriate temperature range, and be radiation resistant. Some austenitic steels such as 316LN-IG (ITER Grade), specifically modified for application in ITER, *Reduced Activation Ferritic-Martensitic* (RAFM) steels, advanced ferritic steels with Cr content as high as 14 wt %, V-Ti alloys as well as SiC composites are candidate materials for such structural applications. Current research activities on these materials are focused on expanding their operating temperature window by means of improving their mechanical strength, toughness and radiation damage resistance, lowering the *Ductile-Brittle Transition Temperature* (DBTT), and stabilizing the microstructure via oxide dispersion.

Among other potential functional materials Be, Pb as well as $Be_{12}Ti$ and $Be_{12}V$ are considered for neutron multipliers, Li_2O based ceramics for tritium breeding and Li, Li-Pb and Li-Sn alloys as breeding coolants. In the case of ceramic materials for fusion applications, research program are focused on the effect of irradiation on electrical and thermal conductivity, optical properties, tritium retention and structural integrity.

At present, research and development of fusion materials are limited because effects on materials exposure to 14 MeV neutrons, as well as plasma from a power fusion reactor, are unknown due to the lack of facilities for accomplishing experiments under such conditions. A solution to this would be the build and start up of IFMIF. Another significant obstacle for fusion material development is their fabrication on an industrial scale. Currently, with some particular exceptions, materials with properties satisfying the design conditions required in fusion reactors are only produced on a laboratory scale. This occurs because industry demands precise specifications and standards before beginning their industrial production, as the costs are very high and companies are reluctant to undertake research on these materials as the current commercial demand is inexistent.

As outline above, current research and development of fusion materials falls on laboratories supported by public funds and associated with organizations responsible for the coordination of international fusion research programs. Under such circumstances, the research results obtained from materials that are produced in different laboratories usually yield discrepancies due to differences in the composition, fabrication techniques and processing conditions, as well as to a shortage of material for undertaking a rigorous and complete characterization.

The advisers and coordinators of the European Fusion Material Program bemoan the lack of interest of European industries to produce materials for fusion research laboratories. They have also highlighted the lack of research laboratories with capacity to manufacture in a single batch, a quantity of material sufficient for full characterization by the groups in charged of the investigation of the relevant material. In the European Program have been suggested the urgent need of having some European laboratories with the capability to manufacture a single batch so much material. These should be at least 50 kg per batch in the case of steels or

Fe-Cr alloys. In this sense, the **Material Production and Processing Facility (MPP)** of *TechnoFusión* will try to contribute to this part of the European Fusion Material Program.

4.2. Objectives

The present European Materials Fusion Program, in its middle- and long-term research activities, gives priority to research and development of the following materials:

1) Low activation steels for the blanket system, such as the EUROFER steel for the blanket module to be tested in ITER, and other nano-structured steels to be used in DEMO. The mid-term aim is to optimize the low activation steel for use in future reactors. The development of ODS steels is a long-term proposal. It is expected that such low-activation and radiation-hard steels can achieve a more stable microstructure with better mechanical behaviour at high temperatures than conventional steels to be used in the divertor and breeding blanket systems. Another research activity in this area is dedicated to nano-structured ferritic steel based on the Fe-14 wt% Cr alloy.

2) W and its ODS alloys for use in a divertor system cooled by He, where the operating temperature window may be 700 – 1350 ºC. The aim is to increase the microstructure stability at high temperatures, lower the DBTT and improve ductility at low temperatures.

3) SiC_f/SiC composites for advanced blanket systems cooled by Li-Pb. The aim is to develop new fibre coating manufacturing methods and techniques for optimizing the mechanical properties and thermal conductivity.

4) Functional graded materials, ceramics and coatings.

Although the guidelines of the present European Materials Fusion Program are mainly focused on the above mentioned types of materials, the corresponding programs in Japan, Russia and USA also maintain an intense long-term activity on Ti-V alloys and on an ample variety of functional materials.

Considering the guidelines of the European Materials Fusion Program, the main objectives of the MPP Facility are:

- To achieve facilities for producing batches of fusion materials within the framework of the European Program.

- To fabricate and process materials requested by users of *TechnoFusión*.

- To fabricate batches of structural materials of up to ~50 kg by means of the *Vacuum Induction Melting* (VIM) technique for fusion applications. These materials would be steels, Fe-Cr, V-Ti, and other alloys with precise control of impurities.

- To produce ODS steels, ODS Fe-Cr alloys, and ODS and non ODS W alloys by mechanical alloying and consolidation by *Hot Isostatic Pressing* (HIP) or *Spark Plasma Sintering* (SPS) techniques. It is intended to fabricate, by HIP, up to10 kg of material per batch.

- To produce nano-structured steels and alloys, or ultrafine grained, via HIP or SPS techniques.

- To achieve facilities for processing materials by thermo-mechanical treatments and severe plastic deformation techniques, such us *Equal Channel Angular Pressing* (ECAP), in order to improve their mechanical behaviour.

- To develop coating techniques with W and multifunctional ceramics layers using the *Vacuum Plasma Spraying* (VPS) technique.

The MPP Facility is planned for providing materials following the guidelines of the European Fusion Material Program and would direct its activities to develop the following materials and techniques:

1) Low activation and irradiation resistant materials for structural applications, specifically ODS and non-ODS steels and Fe-Cr model alloys.

2) ODS and non-ODS W alloys for the first wall and the divertor system.

3) Fabrication of nano-structured materials, metal-ceramic joining via the HIP and SPS techniques.

4) ECAP processing of steel and Fe-Cr alloys.

5) W and ceramic coatings produced by the VPS technique.

4.3. International status of the proposed technologies

4.3.1. Techniques of production and processing of fusion materials

(I) Vacuum Induction Melting furnace

VIM is the fabrication technique of metal alloys via melting and refining of metal components under high vacuum in an induction furnace. The metal components are melted in a crucible inside a vacuum chamber and the melt is then poured into moulds. This technique produces alloy ingots with a homogenous composition and extremely low content of interstitial impurities: e.g. O, N, H and P. VIM is the most successful technique for the fabrication of high purity steels and alloys that have metals such as Zr, Ti and V with a very high oxygen affinity. Compared with traditional steelmaking furnaces, modern VIM furnaces have several advantages:

1) Extremely pure steels and super alloys, as well as alloys containing reactive metals, can be produced.

2) Very precise control of temperature, composition and residual atmosphere.

3) Extraction from the melt of gasses and other impurities in solution.

4) Electromagnetic stirring for melt homogenization.

5) Very easy and safe operation.

The importance of the VIM technique in the production and processing of the materials is shown in Figure 4.1.

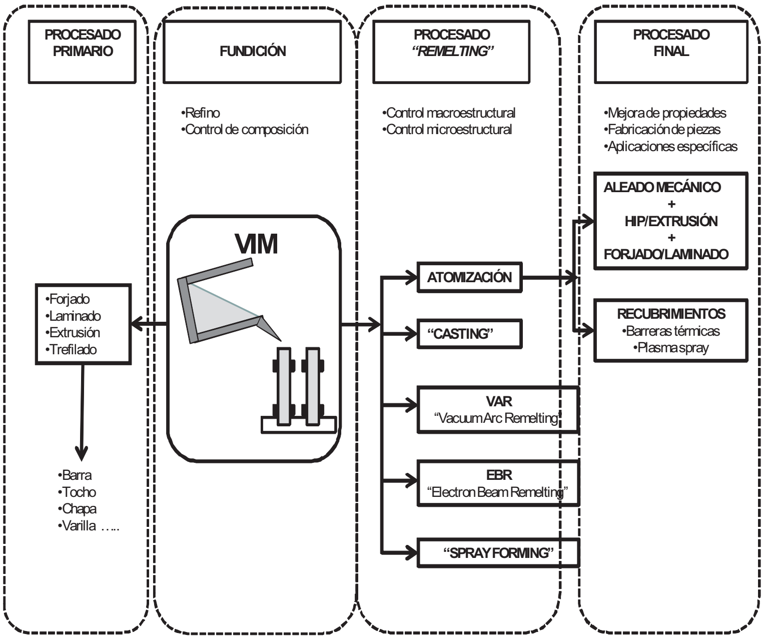

Figure 4.1. Applications of the VIM technique to fabrication and processing of materials.

(II) Hot Isostatic Pressing Furnace

The HIP technique consists of the simultaneous application of high pressure and heat to a material in order to achieve consolidation, sintering, shrink, densification and removal of internal porosity. Typically, temperatures and pressures above 1000 ºC and 90 MPa are employed. The pressure fluid is usually argon or nitrogen, and heating is by electric current. HIP can be used for processing any material: metals, ceramics, polymers, composites and polymers. This technique is successful for producing advanced alloys having a specific composition or microstructure, as well transparent ceramics, which cannot be developed by other techniques. Moreover, it is used to diffusion bond similar and dissimilar materials that cannot be bonded otherwise.

The HIP technique is of great interest for fusion material development. It was originally developed for nuclear technology to join materials difficult to bond by diffusion, but its use has been extended to all fields of material production and processing. In the case of a starting material such as a mechanical alloyed powder, or a simple powder blend, it is encapsulated into steel cans or glass ampoules. After the process of HIP consolidation, the material should be fully dense, isotropic and porosity free, these being significant advantages compared to traditional sintering techniques or others such as consolidation by extrusion. The technique permits the fabrication of ingots of materials whose composition and microstructure is unattainable by casting from melt and subsequent forging or extrusion, as well as components with a complex geometry and precise dimensions.

At present, large furnaces with capabilities for operating at temperatures and pressures as high as 2200 ºC and 400 MPa, respectively, can be built. This has enabled HIP to be successfully applied in research and development of materials and processing techniques of interest for fusion technology, e.g. ODS steel and alloys, nano-structured materials, advanced composites and ceramics, as well as techniques of joining and coating.

(III) Spark Plasma Sintering Furnace

The SPS technique has appeared as an alternative consolidation and sintering technique to HIP and traditional sintering. Recent improvements in the SPS systems have converted this technique into the most suitable, among current techniques, for fabricating nano-structured and functionally graded materials, metallic and ceramics. During the SPS process material is consolidated very quickly by means of Joule heating produced by Direct Current (DC) pulses of very high current density that are applied maintaining an applied uniaxial pressure. The DC current pulses stimulate sintering of the material by virtue of plasma generation and electromigration induced by the high current density developed at the contact points between powder particles.

A SPS system equipped for the fabrication of advanced ceramics, functionally graded materials, and refractory alloys is proposed for the MPP Facility. This system will also have the capability to perform coating and diffusion bonding experiments.

(IV) Vacuum Plasma Spraying System

Protective coatings on PFCs or on other parts of the plasma chamber of a fusion reactor could be developed by projecting droplets of molten material at high velocity onto the substrate. The molten droplets form injecting powder of the protective metal or ceramic into a jet of hot plasma. An electric arc between a finger-like W cathode and a cylindrical Cu inner anode contour, or more simply a cone-shaped nozzle anode, creates the plasma, i.e. the VPS torch. The high droplet impact velocities and low oxidation associated with VPS permit the fabrication of ~100% dense coatings with thickness ranging between 20 µm and 2 mm or more. During spraying the system chamber is maintained at a low pressure of inert residual gas, typically 50 – 200 mbar, in order to avoid oxidation of the coating. An additional advantage of VPS for protective coating is the possibility of performing surface treatments of the substrate, while inside the chamber, immediately before the coating process for improving adhesion of the coating to the substrate. Vacuum plasma spraying is preferred to atmospheric plasma spraying for oxidation sensitive materials such as W alloys, and/or where improved adhesion and density is required.

The general features of the SPS process are:

- Produces extremely clean coatings that are nearly fully dense
- Rapid processing times
- Spraying of refractory metals is possible
- Very thick coatings are possible
- Creation of near-net shapes is possible
- Superior control of coating thickness and surface characteristics. High deposition rate
- High bond of a coating to the substrate
- In-chamber final cleaning using *Reverse Transferred Arc* (RTA) process
- Coating of complex geometries
- Fully automated processes
- Flexible system configurations such as:
    - High volume, continuous-operation system configurations using one or more load lock systems and transfer chambers
    - Batch processing system configurations using robotics and other dedicated manipulation methods

The above characteristics allow development of functionally graded W coatings onto ODS steels for PFCs, thereby reducing concerns about thermal expansion coefficient mismatches between W and steel substrates.

4.3.2. Laboratories of reference in production and processing of fusion materials

As mentioned above, a laboratory for the production and processing of fusion materials with the herein proposed features is an urgent requirement for the European Program for Fusion Materials Development. At present, there exists a very limited number of fusion materials research centres with facilities to produce and process, using the proposed techniques, the quantities of material required for planned characterization programs and irradiation experiments within existing international collaborations. These are:

- *Oak Ridge National Laboratory (Materials Science and Technology Division)*, Oak Ridge (USA).
- *Forschungszentrum Karlsruhe FZK (Institute for Materials Research I, II and III)*, Karlsruhe (Germany).
- *Commissariat à l´Energie Atomique (CEA)/ Direction des Sciences de la Matière*, en Grenoble, (France)

4.4. *Projected techniques*

It is envisaged that the MPP Facility of *TechnoFusión* would have three separate areas, each of which with different facilities. These are listed below together with their proposed facilities.

- *Metal casting and processing*
  - A VIM furnace
  - Machines for material processing and for thermo-mechanical treatments: swaging, ECAP, rolling and forging.
- *Powder metallurgy and ceramic materials*
  - A HIP furnace
  - A SPS furnace
  - A VPS furnace
  - A cold isostatic press
  - Atmosphere controlled and vacuum furnaces
- *Control and analysis*
  - Equipment for control and analysis of raw and processed materials.

4.4.1. Vacuum Induction Melting Furnace

This facility will be dedicated to the production of special steels, Fe-Cr alloys and super-alloys.

VIM and casting is the usual method for fabricating high purity steels and alloys having an accurate composition as well as an effective reduction of interstitial impurities and oxide formation that are detrimental to their mechanical properties. The basic required features for such a furnace are:

- Crucible volume: ~ 3 - 8 l
- Maximum steel capacity: ~ 50 kg
- Power supply for melting: ~ 100 kW
- Base vacuum: 1x10^{-5} mbar
- Pumping rate: 6 m^3/min

Accessories:

- Vacuum chamber for pre-heating mould and for casting in vacuum.
- Electromagnetic stir for melt homogenization.
- Automatic loading system.
- Systems for temperature and pressure measurements..

VIM systems with the above features will be built to order by specialized companies that will design and assemble these systems. For instance, ADL (Germany) design VIM systems that might fulfil our requirements. To date, two VIM designs from ADL have been considered for the MPP Facility:

a) A two chamber design VIM-VMC with a vertical mould chamber (Figure 4.2).

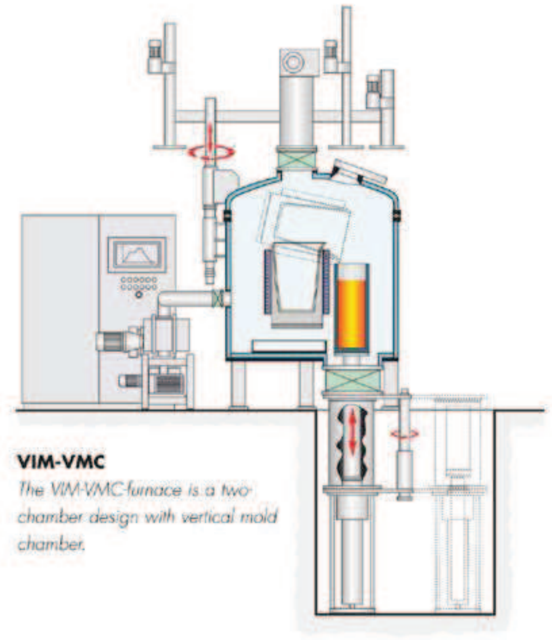

Figure 4.2. Two-chamber VIM-VMC design with vertical mould chamber.

b) A two chamber design VIM-HMC with a horizontal chamber for mould pre-heating and casting in vacuum (see Figure 4.3)

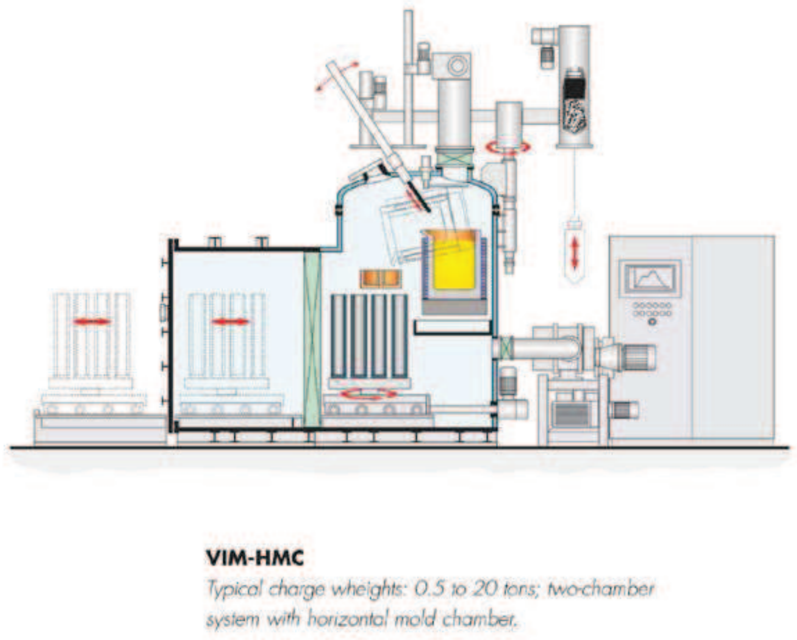

Figure 4.3. Two-chamber VIM-HMC design with horizontal chamber for mould pre-heating and casting in vacuum.

4.4.2. Hot Isostatic Pressing Furnace

This facility will be use for compacting metallurgy processed powdered alloys as well as structural and functional ceramics, and for joining and improvement of cast alloys. The required basic features are:

- Maximum working pressure: 400 MPa
- Maximum working temperature: 2000 ºC – 2200 ºC
- Hot zone dimensions: ~200 mm Ø×800 mm; minimum 140 mm Ø ×250 mm

There are two companies that offer HIP designs that incorporate these features with the required standards:

a) The model AIP10-60H furnace by American Isostatic Presses[17] (Figure. 4.4.) This furnace features a 140 mm Ø x 254 mm hot zone, a maximum working temperature and pressure of 2200 ºC and 414 MPa, respectively.

Figure 4.4. The AIP10-60H HIP furnace from American Isostatic Presses.

b) The model QIH21 furnace by Avure Technologies[18] for research and pilot production manufacture (Figure 4.5). It is a high capability furnace with a ~250 mm Ø x 900 mm hot zone, which allows processing of steel ingots of up to 12 kg. A layout of the system configuration is shown in Figure 4.6.

Figure 4.5. Avure Technology HIP furnace QIH21 for research and pilot production.

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[17] http://www.aiphip.com/WebPages/hip.htm.
[18] http://www.hasmak.com.tr/tozpdf/Avure-HIP-Brochure.pdf.

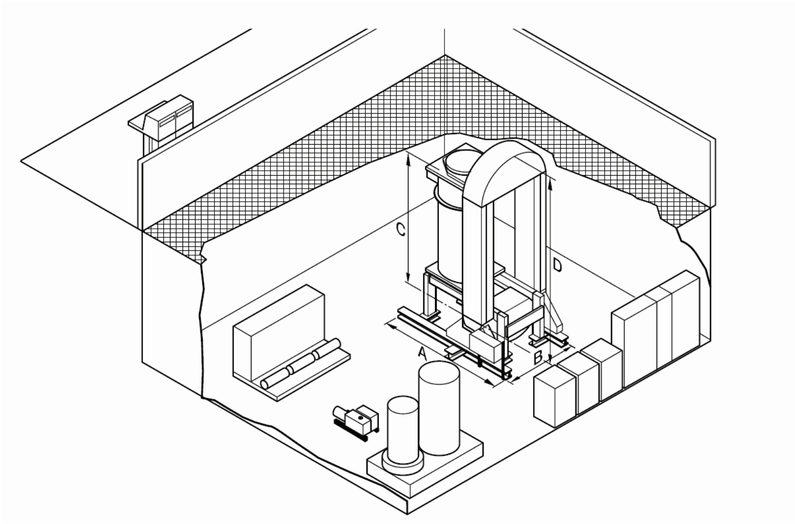

Figure 4.6. Dimensions of the HIP furnace QIH21. A = 1.9 m; B = 1.4 m; C = 2.7 m; D = 3.5 m.

4.4.3. Spark Plasma Sintering Furnace

Such a facility would be used for fast sintering, joining, fabrication of nano-structured materials such as ODS alloys and functional ceramics, as well as coatings of functionally graded materials. The required basic features are:

- Maximum working temperature: ~ 2200 ºC
- Maximum pressing force: ~ 1.250 kN
- Maximum current: 30 kA DC
- Power supply: 350 kVA
- Pulse duration: 1 – 255 ms
- Double wall chamber for sintering in vacuum and controlled atmospheres
- System for working in hydrogen
- System for working in vacuum

The model FCT-HPD 125 furnace by FCT System GmbH[19] (Germany) satisfies these requirements. It can mount moulds as large as 350 ∅ mm x 300 mm and can achieve a maximum working temperature of 2400 ºC. The furnace is shown in Figure 4.7.

Figure 4.7. SPS model FCT-HPD furnace by FCT System GMBH.

4.4.4. Vacuum Plasma Spraying Facility

This facility will be dedicated to developing protective surface coatings for PFMs, thereby permitting the desired operation of PFCs in the plasma chamber of a fusion reactor. The VPS system recommended for the Facility of MPP should have the following capabilities:

- A revolving stage for handling components for coating.
- A chamber for large work pieces.
- Manipulators for work pieces and plasma gun.
- Reverse transferred-arc for substrate cleaning.
- Plasma guns that give rise to minimum heating of the substrate under coating conditions.

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[19] http://www.fct-keramik.de

- Variable operation conditions.

- Growing rates as fast as 10 µm/min.

- Power up to 180 kW

- Coating thickness in the range 20 microns – 2 mm.

Sulzer Metco[20], the leading company in the development and construction of VPS systems, has recently improved the VPS technique by the development of a new *Low Pressure Plasma Spray* (LPPS) system, whose advantages and chamber configuration are shown in Figure 4.8. Such a system fulfils the above requirements for PFM protective coatings, in particular for the reliable coating of large surface areas with complex surfaces such as those of PFCs. The characteristics of a Sulzer Metco LPPS system are:

1) A large (4 m^3 volume) vertically oriented chamber that permits protective coating of large surfaces.

2) The use of a tungsten insert in the copper anode that allows torch operation with electrical currents exceeding 2.5 kA thereby achieving input powers well above 100 kW.

3) Adjustable positioning of the axial and radial positions of the plasma jet by means of linear movements of the gun along the torch (z-position) and/or perpendicular axis (x- and y-positions).

4) Fast charge and discharged without alterations in the chamber pressure.

5) Variable projection distance, between 15 and 135 cm, to allow different coating conditions.

6) Capability for coating surfaces, with complex geometries, as large as 70 cm x 70cm.

7) Advanced control of the chamber and plasma jet.

8) Plasma gun operation at spay pressures as low as 1 mbar.

9) Possibility for developing multi-coatings.

A schematic arrangement of the gun inside the LPPS chamber is shown in Figure 4.8, along with the installed plasma jet and particle diagnostics.

Figure 4.9 shows a Sulzer Metco VPS system with the above characteristics that would be successful for coating of large PFCs.

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[20] www.sulzermetco.com

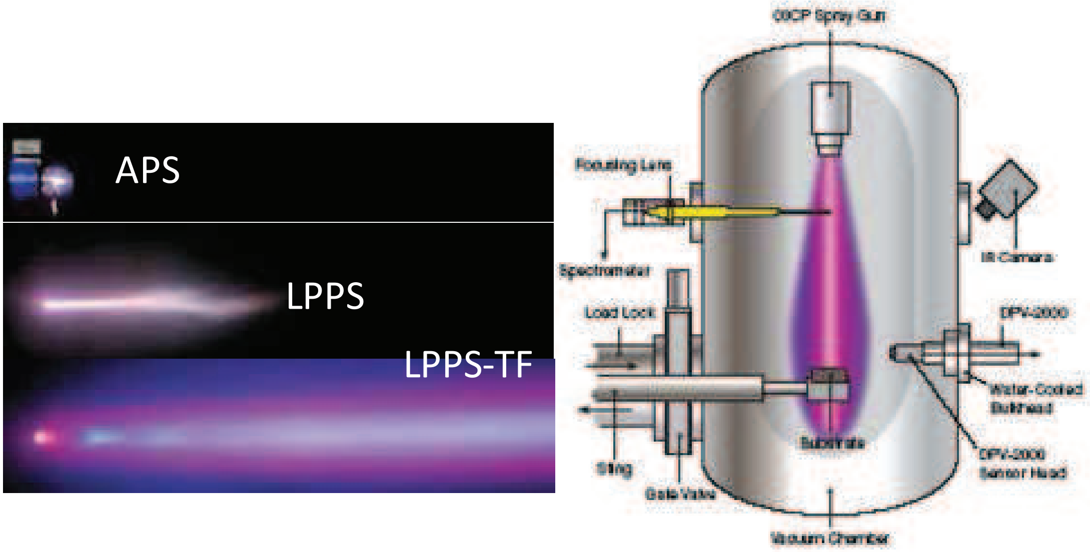

Figure 4.8. (Left) Comparative images of a plasma beam in (APS) an air plasma spray system at 1 bar and in a LPPS system operating (LLPS) at 50 mbar and (LPPS-TF) 1 mbar. (Right) Schematic layout of the Sulzer Metco LPPS-TF system for fast growing of extremely dense and thin coatings.

Figure 4.9. Sulzer Metco VPS system suitable for protective coating of large PFCs

4.4.5. Attritor and Planetary Mills

It is also considered that the MPP Facility should be equipped with a high capacity attritor for powder processing in controlled atmospheres, at least, and several types of high-energy planetary mills for mechanical alloying as well as their corresponding sets of jars for proper powder processing. The characteristics of such equipment are detailed in: *Union Process*[21] y *Retsch*[22] .

The attritors and planetary mills will be installed in an area with the following services utilities:

- Temperature and humidity control in the range 5 – 25 ºC with maximum humidity below 60% at 25 ºC.
- Soundproof capability for a sound level of about 90 dB.
- Electric power supply and closed circuit water cooling.
- Supply of gasses (Ar, He, H, etc.)
- A cabinet for safe powder handling.
- Two glove boxes with controllable atmospheres.
- A system for air displacement detection.

4.4.6. Cold Isostatic Press

The MPP Facility should have a CIP system for compacting powders before sintering. The required specifications for this system are:

- Compacting vessel dimensions, (minimum): ~75 mm x 300 mm.
- Maximum pressure: ~ 400 MPa
- Automatic control of pressurization and depressurization.
- A quick-fill reservoir and electrohydraulic pumping.
- A two-stage letdown system.

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[21] www.unionprocess.com/pdf/lab_attritors.pdf
[22] www.retsch.com/dltmp/www/36276-acdd0376481f/brochure_ball_mills_en.pdf

The model AIP3-12-60C CIP system by American Isostatic Presses[23], shown in Figure 4.10 could fulfil the requirements.

Figure 4.10. The model AIP3-12-60C CIP system for American Isostatic Presses

4.4.7. Vacuum and controllable atmosphere furnaces

Several furnaces for thermal treatment under high-vacuum and controllable atmosphere conditions will be needed in the MPP Facility. In addition, tubular furnaces suitable for degassing cans containing processed powders will be required.

4.4.8. Rotary swaging machine

Rotary swaging is a process for the precision formation of metal bars. The finished shape of a formed workpiece is obtained without, or with only a minimum amount, of additional final processing by machining. Swaging dies, usually formed by four die segments, perform high frequency radial movements simultaneously with short strokes. To prevent the formation of longitudinal burrs at the gaps between the dies, a relative rotational movement is applied between dies and the workpiece. The swaging dies rotate around the workpiece, or alternatively the workpiece rotates between the dies. The major advantages of rotary swaging processing as compared to other techniques are:

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[23] www.aiphip.com/

- It is an incremental forming process where the oscillating forming takes place in many small processing steps.

- It allows the development of fully homogenous material formation compared to a continuous process.

- It allows very high forming ratios in only one processing step as the deformability of the material is uniformly distributed over the cross-section.

The MPP Facility would have a rotary swaging machine for processing steel and alloy bars with improved mechanical properties. The technical characteristics of the swaging machine would be:

- A stroke frequency variable in the range 1.500 – 10.000 strokes per minute.

- Total stroke lengths ranging from 0.2 to 5 mm.

- A heating system for hot swag processing.

- Operation via the infeed method.

Figure 4.11 shows the rotary swaging machine model FELLS FR 25V[24] that fits the MPP Facility requirements

Figure 4.11. Rotary swaging machine model FELLS FR 25V

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[24] www.felss.de

4.4.9. Severe Plastic Deformation Facility

Grain refinement down to submicron sizes, or even below 0.1 micron, can be attained by means of *Severe Plastic Deformation* (SPD) techniques. It has been demonstrated that the ultrafine grained microstructures induced by SPD processing can induce a remarkable improvement in the mechanical and tribological properties of metals. Among SPD methods the ECAP technique appears to be the most promising for fusion materials since: 1) it can yield an effective pure shear strain as high as ~1 per processing pass without significant changes in the dimensions of workpieces; 2) after several ECAP passes, extremely high cumulative strains and an ultrafine microstructure can be achieved in workpieces suitable for preparing bulk samples for mechanical testing.

The MPP Facility should be provided with an ECAP machine for processing fusion alloys. It would be an optimised prototype whose design would be based on results from ECAP experiments on low activation steels that researchers from this project are presently undertaking.

4.4.10. Equipments for analyses, control and mechanical testing of materials

The chemical composition and microstructure of materials processed in the MPP Facility, as well as of the starting raw materials, need to be accurately determined in order to know the effectiveness of the methods applied. As a minimum requirement, this Facility would be equipped with analysis systems for interstitial impurities: e.g. O, N, C, and S, in addition to facilities for performing structural characterization by X-ray diffraction, metalography and micro-hardness:

The MPP Facility should be provided with the following equipments:

- A model LECO THC600 analyser for simultaneous determination of O/N/H by IR and thermal conductivity.
- A model LECO CS230 analyser for simultaneous determination of C/S.
- A model LECO GDS-850A glow discharge atomic emission spectrometer for bulk analysis of metal alloys.
- An X-ray diffractometer
- A scanning electron microscope (SEM)
- Mechanical test machines
- Micro-hardness
- A metallographic microscope

- A helium ultrapycnometer.
- A grindosonic instrument for the non-destructive measurement of elastic properties of materials.

The above listed facilities will be integrated into an auxiliary laboratory associated with the laboratories for casting and processing of materials.

In addition, the MPP Facility will have auxiliary equipment and tools for material cutting and preparation, e.g. precision balances, fast and precision cutting machines, various types of polishing machines, a sand blaster, oxyacetylene and arc welding sets, plus work benches equipped with a wide range of tools. These latter equipment and tools would be integrated in a sample preparation laboratory attached to the above mentioned auxiliary laboratory.

4.5. Experimental capacity

As mentioned previously in section 4.2, the main activity of the MPP Facility will be the pilot production and processing of promising fusion materials required by the research programs. Specifically, these materials will be:

- Steels, Fe-Cr and W alloys, ODS and non-ODS, via mechanical alloying and consolidation by HIP or SPS.
- Low-activation and radiation-resistant steels and alloys produced by the VIM technique.
- Functional materials and ceramics produced by SPS and HIP.
- Protective coatings created by means of the VPS technique.
- The joining of dissimilar materials by HIP or SPS.

The facilities proposed will allow producing and processing:

- Sufficient material for proper characterization by the different research groups involved in the material development.
- Materials specifically requested by *TechnoFusión* users for irradiation experiments.
- Up to 40 - 50 kg of cast materials.
- Bulk materials severely deformed by ECAP.
- A wide variety of functional materials and protective coatings.

4.6. *Layout, supplies and safety requirements*

(I) Rooms and utilities

The estimated space requirement for the MPP Facility is as follows:

- One plant of 400 m^2 for the following facilities: VIM, SPS, HIP, VPS, ECAP and rotary swaging. This plant would also contain a soundproof room for the attritors and mills used in powder processing, and separately, an enclosure with two glove boxes, a safety cabinet for powder handling plus containers for storing treated powders. The floor of this plant would be required to support weights up to about 500 kg/m^2 at the locations of the SPS and VIM. In addition, an overhead crane would be installed to service the area where the VIM, SPS and HIP are to be installed.
- One 40 m^2 laboratory for housing the mechanical testing machines.
- One 30 m^2 laboratory for housing material analysis and control equipment.
- One 30 m^2 laboratory for installing auxiliary equipment and machines.
- One 30 m^2 room to house a scanning electron microscope and X-ray diffractometer.
- One 20 m^2 room for workshop and tools.
- One 30 m^2 storeroom divided into two sections.
- 200 m^2 dedicated to offices and common areas.
- One 30 m^2 meeting room.

Related to the required supplies:

(a) Power supply:

- At least, 2 independent 3x400 V±10% lines for ~300 kVA plus 2 additional lines for 3x400 V ±10% to provide ~200 kVA in the plant.
- 4 three-phase lines with 15 kVA capacity for the plant.
- 2 three-phase lines with 10 kVA capacity for the SEM/x-ray laboratory.
- 2 three-phase lines with 15 kVA capacity for the mechanical testing laboratory.
- 1 three-phase line with 19 kVA capacity for the analysis and control laboratory.
- Conventional installation of 20 kW in the plant, laboratories and workshop.

(b) Water supply:

- A refrigeration system with closed circuit circulation and outdoor cooling tower.
- Required flow: At least 300 litres/min at 4 bar of pressure, for when the VIM and SPS furnaces operate simultaneously.

(c) Gas and compressed air supplies:

- A refrigeration system with closed circuit circulation and outdoor cooling tower.
- Required flow: At least 300 litres/min at 4 bar of pressure, for when the VIM and SPS furnaces operate simultaneously.H_2.

(II) Safety

The room and enclosure for powder processing will be properly prepared for the safe manipulation of powders. This will include: a system for air displacement detection; a fireproof cabinet for chemical storage and a radioactive materials will not be processed or stored in the laboratories.

The installation of an oxygen displacement detection system will be required. In addition, in locations where equipment using H_2 gas is located, leak detection systems for this gas will be installed. In addition, a safety cabinet with an alarmed H2 detection and air extraction system will be needed for conducting mechanical alloying experiments with an attritor mill.

For certain equipment, such as attritor and planetary mills, additional safety measures will be required, e.g. soundproofing the room (noise level ~85 dB per system), installation of anti-vibration mounts given the high speeds that can reach (up to 500 rpm, etc.), etc.

Finally, there are no plans to work with radioactive materials or radiation sources, thus radiological safety measures will not need to be implemented.