Component Testing and Materials Development for Fusion Applications Using Materials Test Reactors

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Abstract. Fusion power plant operation will strongly depend on the economy and reliability of crucial components, such as first wall modules, tritium breeding blankets and divertors. Their operating temperature shall be high to accomplish high plant efficiency. The materials properties and component fabrication routes shall also assure long reliable operation to minimize plant outage. The components must be fabricated in large quantities based on demonstrations with a limited amount of test beds. Mock-ups and test loops will, through iteration processes, demonstrate the reliable operation under reference thermal-hydraulic conditions. 14 MeV neutrons escaping the plasma dominate the nuclear conditions near the first wall. Neutron transport analyses have shown that large portions of the components near the plasma have to cope with a neutron spectrum resembling that of a fission core. MTR's, Materials Test Reactors, have been used successfully to test components for fusion power plants. Their space and availability will also ensure their role as future test bed for (sub) components such as blankets, first walls and divertors. The future generation of MTR's will allow faster testing, because of the higher neutron fluxes possible with advanced driver fuels. The strong limitation of MTR's for fusion testing will remain the limited production of helium and hydrogen, because of the lack of 14 MeV neutrons. Though large parts of the fusion components are subjected to nearly fission neutron spectra, in the domain near the burning plasma 14 MeV neutrons are dominant. IFMIF will produce the 14 MeV neutrons to fill that gap by the end of the next decade. In the meantime the MTR's will generate relevant data for fusion power plant component design. After IFMIF is operational the new generation MTR's will still have a function in testing components in a nuclear environment. The new generation test reactors will also be used for the development of component operating at high temperature in the generation-4 fission power plants. The R&D climate will be most stimulating for cross fertilization of fission and fusion component development, leading to more efficient use of the earth's resources.

1. Introduction

Fusion power plant operation will strongly depend on the economy and reliability of crucial components, such as first wall modules, tritium breeding blankets and divertors as explained by Maisonnier et al [1]. The operating temperatures shall be high to accomplish high plant efficiency. The materials properties and component fabrication routes shall also assure long reliable operation to minimize plant outage. The components must be fabricated in large quantities based on demonstrations with a limited amount of test beds. Mock-ups and test loops will, through iteration processes, demonstrate the reliable operation under reference thermal-hydraulic conditions. 14 MeV neutrons escaping the plasma dominate the nuclear conditions near the first wall. Neutron transport analyses have shown that large portions of the components near the plasma have to cope with a neutron spectrum resembling that of a fission core [2].

Present Materials Test Reactors, MTR's, offer fluxes relevant for large parts of the major components. Their mixed and fast fission spectra are not representative for all fusion conditions. The fission neutrons do not generate quantities of transmutation products He and H, as neutrons from 14 MeV sources do. The strong point of MTR's is their ability to generate sufficient displacement damage in the materials in a relatively short time. The cores of MTR's provide sufficient space for irradiation of representative cut outs of components to allow integrated functional and materials tests in a high flux neutron field.

The MTR's are the primary test bed for structural materials: reduced activation steel, tungsten, silicon carbide ceramic composites, carbon fibre reinforced carbon. In other test configurations functional fusion relevant materials: lithium ceramics, lead lithium, beryllium are being tested. MTR's provide space to accommodate standardized specimens, including fracture toughness blocks. Post-irradiation tests produce information that feeds databases for design and safety analyses for ITER and feasibility studies of fusion power plants as Van der Schaaf et al [3] show. Non-standard specimens exercises showed the benefits and limitations of sample miniaturization needed for the exposures in 14 MeV sources.

2. Blanket testing in a high neutron flux

As Maisonnier et al [1] pointed out the technical solutions of tritium production from lithium have two major paths: helium cooled ceramic lithium compounds and helium cooled lithium lead. Both approaches have conceptual designs advanced to a stage where the experimental verification of the EU design in ITER is foreseen. To verify the Helium Cooled Pebble Bed, HCPB, concept for DEMO the irradiation of Testing Blanket Modules, TBM, in ITER are foreseen. To verify the design for ITER-TBM the neutron irradiation of a Pebble Bed Assembly, PBA, has been carried out in the HFR. The HFR space and dose rates provide a valuable base line for the developments and demonstrations of such fusion key components in a neutron field. The pebble bed assembly, PBA, irradiated in the HFR, Petten, shows the feasibility of the helium-cooled concept with lithium ceramics and beryllium multiplier pebble beds. The PBA packaging, cooling and tritium purging arrangements closely resemble the design for the EU ITER Test Blanket Module, TBM. The irradiations produced a wealth of process parameters for the control of the tritium release from the pebbles.

The major result is that the basic design soundness has been demonstrated under ITER relevant neutron radiation conditions. The predictions of the analyses in terms of heat and tritium production are in line with the experimental results report Peeters et al [4]. Important issues are the heat removal changes from the lithium ceramics pebble beds and the beryllium multiplier. The gaps between the pebble beds and their containers change during irradiation because of thermal cycling end re-allocation of pebbles. Figure 1 shows a typical example of the calculated and measured temperatures in the beds.

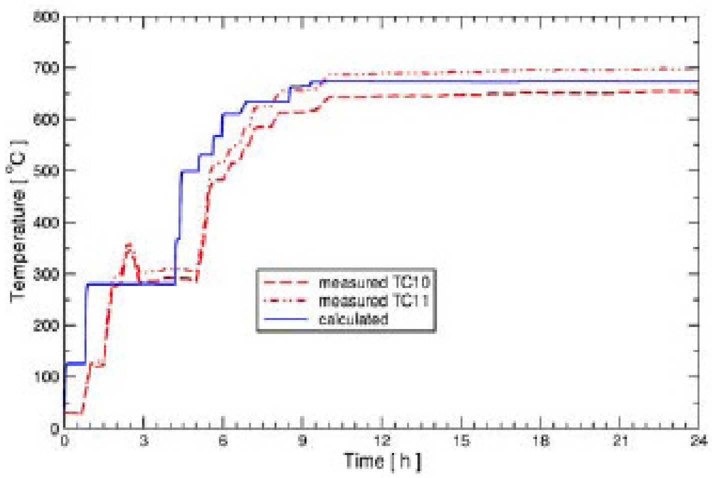


Figure 1 Predicted and measured temperatures in the ceramic breeder bed of the PBA as dependent on the time after neutron irradiation start-up.

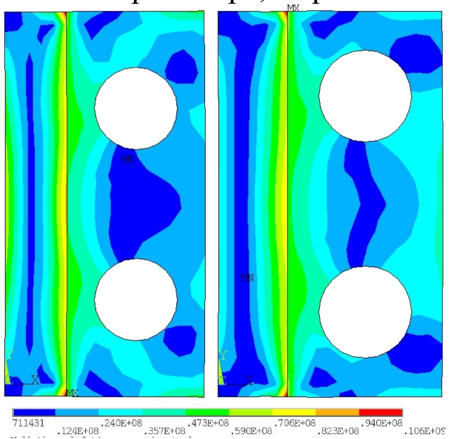
Post -irradiation testing supplements the information on the appearance and condition of the pebble beds after irradiation to about 2 dpa, a dose level relevant for the total TBM operational lifetime.
Besides the ceramic breeder concept in-pile experiments with Pb17Li breeder subcomponents are continued. The measurement of tritium permeation through the structural material steel and its control by in-situ oxidation coating of the steel during irradiation is conducted with the LIBRETTO rig. The second major subject is the effect of the helium formed in the Pb17Li on the tritium inventory and the fluid dynamics of the liquid with a similar type of rig. The resulting data, Magielsen et al [5] are of great significance for the liquid metal blanket design for DEMO and ITER test blanket modules to come.

3. Pulsed neutron radiation of first-wall mock-ups.

Another MTR experiment pertinent to the operation of fusion plasma devices is the in-pile testing of first wall ITER mock-ups. The objective is to test the thermal fatigue endurance of actively cooled first wall mock-ups in a neutron field., will provide information on the integrity of the Be/CuCrZr joints during periodic plasma burns.

The panels have beryllium armour at the plasma face and use CuCrZr heat sinks with cooling tubes inside. The heat sinks are joined to the stainless steel back plate with HIP or braze processes. Three different mock-ups will be tested to account for different approaches for the armour tiles, which will influence the ITER . The neutron irradiation will produce data on the integrity of the joints during the cyclic irradiation and thus thermal cycling in the HFR.

Schmalz et al [6] propose an irradiation concept, using a tungsten layer about 10 mm in thickness. The layer connected to the beryllium armour generates gamma heating resembling the thermal cycles from intermittent plasma burns in the ITER torus. Cycling will be accomplished moving the mock-up in and out of the neutron radiation field produced in the HFR-PSF, poolside facility. The heating and neutron damage are in phase just as in ITER. The mock-ups with beryllium armour tiles will be subjected to 30,000 fatigue cycles at 0.5 $MW.m^{-2}$. The neutron irradiations add up to 1 dpa, displacement per atom, in the HFR, Petten.



(a) (b)

Figure 2 *(a) The reference stress distribution in the panel ITER First Wall panel*
(b) The stress distribution in the Mock-up for irradiation in the HFR, Petten.

Figure 2 shows the comparison of the heat distribution expected respectively in ITER and in the HFR-PSF intended for the irradiation. It can be concluded that the resemblance is of great technical significance, which allows the selection of the optimum connection technology for the ITER panels through demonstration. The mock-up will be fully instrumented with thermocouples and neutron dosimeters to verify the thermal cycling and radiation damage cycles. The high temperature during neutron radiation might annihilate the damage during its formation, which is expected to be beneficial for the ITER panels' integrity.

4. Neutron radiation effects on structural materials

Post- irradiation materials testing continue to feed data bases for design and safety analyses, conducted according to internationally established codes such as ASME and RCC-MR [3]. Mechanical properties results of standardized samples for strength, ductility, toughness, fatigue and crack propagation and creep are mandatory. Physical properties: conductivity, heat current, thermal expansion, density are part of the collection provided by MTR's. The theory and failure mechanism studies based on MTR results are not valid for all irradiated domains in the fusion power plant. Experimental verification of theories on radiation and transmutation product damage in materials depends on 14 MeV sources such as IFMIF.

Still in-pile MTR's experiments are essential for the experimental evaluation of component behaviour under abnormal conditions and accident sequences. Examples are quality assurance of weld repairs in irradiated steel and bolt behaviour in neutron fields more remote from the plasma can be excellently studied with in-pile experiments.

ITER first wall panels might be attached with bolting to the major structures. Two candidate bolt materials have been investigated in the HFR, Petten, by measuring the relaxation of bolts under stress during neutron irradiation up to 3 dpa at the relevant irradiation temperature of 300 ^{o} C. The remaining deformations of irradiated pre-stressed bolts and bars have been measured in the NRG hot laboratories giving the relaxation figures for both alloys. Schmalz et al [7] observed significant differences: after exposure to 3 dpa the stress relaxation of the nickel based Alloy 625+ amounted to over 80 %, whereas the alloy PH13-8Mo showed half that value: about 40 %. The difference is attributed to the effect of neutron irradiation on the solid precipitation controlling the strength of the alloys, but this has to be confirmed.

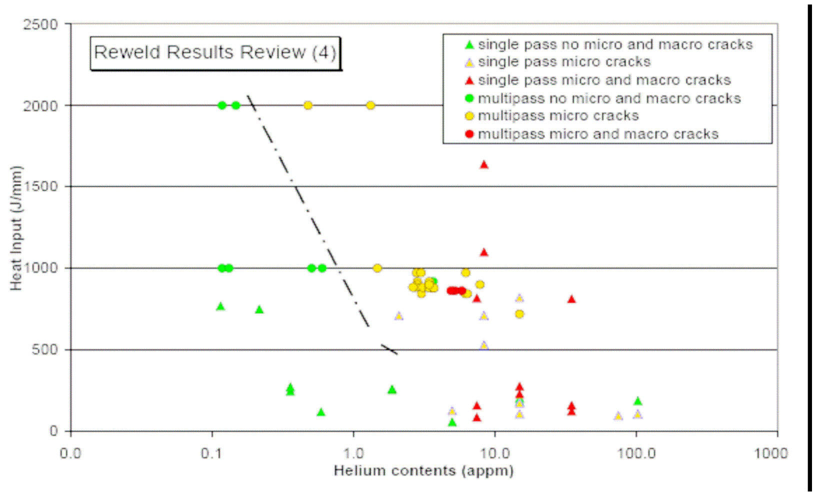


Figure 3 The appearance of cracks in welds of type 316 as dependent on welding heat input and helium content of the steel after irradiation in the HFR, Petten.

Re-welding of the ITER vacuum vessel involves the welding of the neutron irradiated steel shell of about 60 mm in thickness by low heat input processes such as narrow gap Tungsten Inert Gas welding, electron, and laser beam welding. Due to the formation of helium from boron in the austenitic Type 316 steel inter-granular cracking can occur depending on the amount of helium and the welding process, in particular the heat input. To verify and validate the intended welding processes on irradiated vessel wall steel the HFR produces as thick as feasible steel plates welded in the NRG hot laboratory under ITER relevant conditions. There are limitations to the plate thicknesses to be irradiated and part of the verification leans on finite element analyses of the larger thicknesses. Van der Laan et al [8] show, Figure 3, based on experimental evidence from the HFR the major fields in the welding domain as dependent on helium content and welding heat input. The latter is important for the selection of the final welding process for irradiated Type 316 steel.

5. Radiation effects on functional materials

The HFR has a long experience of providing the environment relevant for the irradiation of lithium ceramics to measure the decisive properties of the different contenders. Crucial in the comparative experiments are the tritium release behaviour of individual pebbles and their integrity. The EXOTIC series deliver the data that the developers of lithium ceramic pebbles require to improve their products, Casadio et al [9]. Power densities and purge gas conditions and composition are the main variables from the irradiation process conditions. Figure 4 shows the tritium residence times for a wide spectrum of lithium meta-titanates.

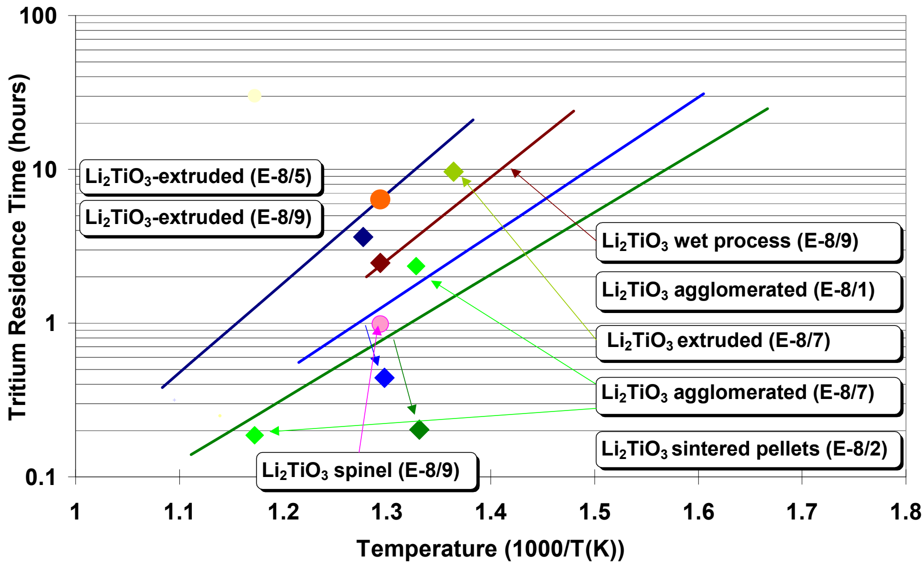


Figure 4 Tritium residence times for lithium meta-titanate Li_2TiO_3 pebbles irradiated up to about 17 % total lithium burn-up in the HFR, Petten.

Similar comparisons have been produced on the basis of experiments in EXOTIC rigs with lithium silicates and zirconates. For safe and economic production of tritium from lithium short residence times are preferred. In this way the tritium reaches the plasma as fast as possible with a low tritium inventory in the blankets during plasma operation.

Additional irradiation experiments on lithium ceramics and beryllium pebbles are underway in the HFR, aiming for long-term high dose level, 20 dpa, behaviour of complete pebbles beds. Partners from Japan, the RF, and the EU have provided the pebble materials being irradiated now. The radiation effects on the pebble bed configuration get special attention, because the geometrical stability of the beds determines the heat transfer, and thus the blanket thermal behaviour, Hegeman et al. [10]. Swelling and creep depend on the ^{6}Li burn-up and displacement damage, hence the HICU rig has drums which are shielded with cadmium to harden the neutron spectrum, resulting in a quite different ratio of tritium production and displacement damage. Figure 5 shows the tailoring of the spectrum accomplished in the HICU rig.

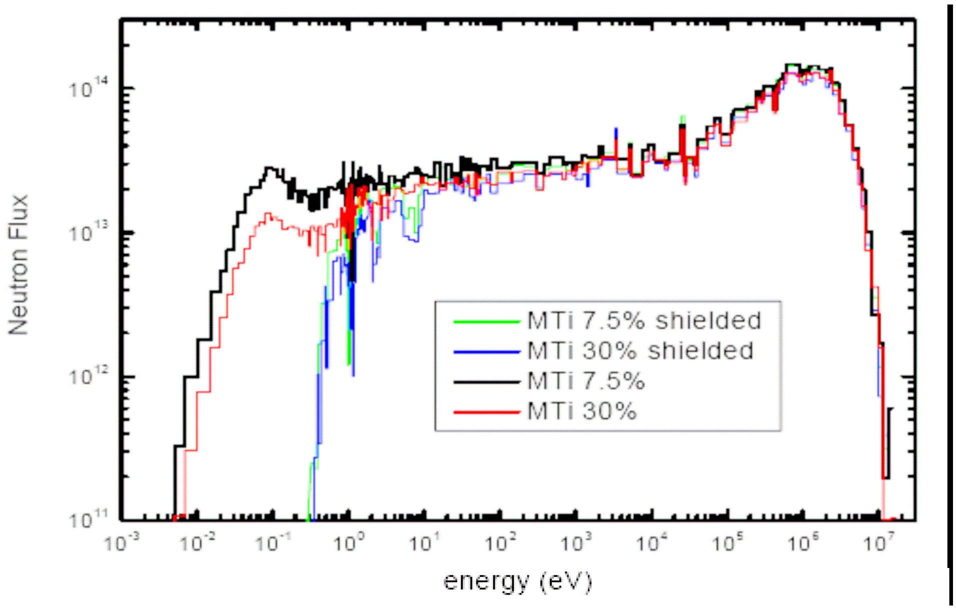


Figure 5 The effect of shielding on the neutron spectrum exposure of meta-titanate with different ^{6}Li contents.

6. Functionality of 14 MeV neutron sources

For this decade and most of the next decade only MTR's will provide the environment for bulk testing of materials and components for fusion devices. In the second half of the next decade 14 MeV sources such as ITER, IFMIF and will start the crucial demonstration of components under near fusion plasma nuclear conditions. These sources have limitations in accumulated total damage (ITER) irradiation volume (IFMIF) and control. In itself the operation of IFMIF is the first of a kind, Moeslang et al [11]. MTR's are needed to provide the demonstration of the integrity of the capsules to be irradiated in IFMIF. The very dense packing of specimens in the small capsule volume, with additional heaters and temperature sensors, requires a complex design that has to be validated under neutron irradiation. MTR's can provide an environment, that is not one to one similar to the IFMIF beam conditions, but the cores of MTR's can approximate the harsh environment to a useful degree.

The limited space in IFMIF will necessitate the use of MTR's to supply essential facts on more bulky component behaviour and materials in parallel to 14 MeV sources. The lack of 14 MeV neutrons is a severe limitation for the prediction of long-term behaviour of armour and first zone of blankets near the plasma. For the volume of fusion power plants not directly exposed to 14 MeV neutrons the MTR's will help out to predict and demonstrate lifetimes and select the right materials. It must be born in mind that in the zone near the plasma, such as the case for blankets about one third is exposed to significant fluxes of 14 MeV neutrons. The other two third encounters neutron spectra more resembling the fission reactor spectrum.

7. Next generation materials en components test reactors

The first generation of MTR's will be closed in this and next decade, because they reach their end of economic and technical life. The new MTR generation will be utilised for 4 major areas of nuclear interest: energy, science, health and environmental issues. Fusion and the next generation fission (Generation 4) power plant development will share the areas energy and science in the next decades. The concept and design of the new MTR's will centre on faster development cycles, thus higher fluxes.

The successor to the HFR, PALLAS, will start operation at the end of the next decade. It is intended as an integral part of the EU nuclear research infrastructure. The new isotope and materials test reactor definition is an initiative by four parties: JRC-IE, Mallinckrodt Medical, Technical University Delft, and the lead by NRG. Bergmans et al [12] indicate that the key element in the specification is the doubling to tripling of the fast and thermal neutron flux of the core to about $5*10^{18}$ $n.m^{-2}$, keeping position volume comparable at least to the present. New fuels like UMo will make the higher fluxes possible, with acceptable fuel manufacturing cost. Flexible reflector designs will allow adjustment of a particular reactor cycle with a thermal power in the range of 40 to 80 MW. Flux boosting for particular experiments remains a possibility to obtain the required irradiation specifications.

8. Discussion

MTR's can do more than their name suggests. Of course large amounts of standardized coupons are irradiated under application relevant environmental and temperature conditions in-pile or afterwards tested to obtain the information needed to soundly base a reliable design. The present paper shows that for the development of the blankets and first wall designs valuable information can be obtained from the nuclear environment MTR's offer. The results produce insight that is improving the designs of blankets, divertors, and first wall and capsule design for IFMIF.

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Several MTR replacements in the EU are in different design stages such as the Réacteur Jules Horowitz, RJH, in France as described by Guidez [13] and PALLAS in the Netherlands. The conceptual design of the replacement for the HFR, Petten, named PALLAS, envisages a fruitful co-operation of the experimenters for advanced fission power reactor (Generation-4) and fusion plant components. Both areas will benefit from the expertise, lay out, and facilities for post- and in-pile testing for advanced fission reactors and fusion power plants. The fission spectrum (or lack of 14 MeV neutrons) does not produce the He and H in the amounts relevant for fusion power plants. Thus a 14 MeV source is essential for the determination of their impact on materials. Before IFMIF is completed MTR's are the source of test results relevant for fusion power plant design. After IFMIF operation the contribution of the new generation MTR's such as PALLAS and RJH will be essential for the integrated test of components in a neutron field. The new generation of MTR's will also be instrumental for the development of high temperature components for generation-4 fission power plants. The designs and materials development will serve both the new fission and fusion power plants to develop for the middle of this century.

9. Conclusion

1. A long list of successfully completed (sub) component irradiations and irradiations presently launched and on the drawing boards show the importance of MTR's for the development of tritium blankets, first walls and divertors.
2. Until IFMIF is available the present generation MTR's will provide materials test results of irradiated materials for ITER building and fusion power plant development.
3. After IFMIF is operational MTR's will be needed for testing and evaluating components for fusion power plants. MTR's provide the volume and neutron damage to complement IFMIF materials testing with small size specimens.
4. The new generation MTR's can be operated economically with higher core neutron fluxes and the potential to used boosters for special tests to shorten irradiation times.
5. The new MTR's will serve both fusion development and the fourth generation fission reactors. The R&D environment resulting from this MTR utilization will enhance strongly the cross-fertilization taking place. Both fusion and fission communities aim for application of materials in components to be operated at high temperature in a strong neutron field. This will be to great benefit for the use of the worlds' resources.

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10. References

[1] MAISONNIER, D. et al, DEMO and fusion power plant conceptual studies in Europe, Fusion Engineering and Design **81** (2006) 1123-1130.
[2] TAYLOR, N.P., The impact of materials selection on long-term activation in fusion power plants, JNM **283-287** (2000) 28-34.
[3] VAN DER SCHAAF, B. , Structural materials development and databases, Fusion Engineering and Design **81** (2006) 893-900.
[4] PEETERS, M.M.W. et al, In-pile operation of the HCPB Pebble Bed Assembly irradiation, NRG report 71082, Petten, December 2005.
[5] MAGIELSEN, L., LIBRETTO 4/1 and 4/2 design and safety report, NRG report 66792, October 2005.
[6] SCHMALZ, F. et al, Design for in-pile thermal fatigue of first wall mock-ups under ITER relevant conditions, Accepted contribution to SOFT-23, in preparation .
[7] SCHMALZ, F. et al, Irradiation stress relaxation of ITER candidate bolting materials, Contribution to ICFRM-13, December 2005, Paper submitted for publication in the JNM.
[8] VAN DER LAAN et al, Assessment of the feasibility of demonstrating the reweldability of irradiated 60 mm thick SS 316(N), NRG report 61526, August 2004.
[9] CASADIO, S. et al, Tritium release kinetics from Li_2TiO_3 pebbles as prepared by soft-wet-chemistry, JNM **329-333** (2004) 1252-1255.
[10] HEGEMAN, H. et al., Status of the high fluence irradiation of ceramic pebbles in the HICU project, appearing in the Proceedings of CBBI-13, Santa Barbara, December 2005.
[11] MOESLANG, A. et al ., The IFMIF test facilities design, Fusion Engineering and Design **81** (2006) 863-871.
[12] BERGMANS, H., PALLAS, NRG presentation, Petten, August 2005.
[13] GUIDEZ, J., 2005 Review French Research Reactors, C.E.R., CEA, Bagnols, 2005