The possible role of the Italian Universities consortium CIRTEN for the engineering study of a fission-fusion hybrid reactor

M. Ricotti[1], A. Cammi[1], L. Luzzi[1], M. Mariani[1], E. Zio[1], A.P. Di Maio[2], G. Vella[2], B. Bozzini[3], G. Caruso[4], R. Gatto[4], S. Dulla[5], M. Ferraris[5], P. Ravetto[5], L. Savoldi[5], G. Vecchi[5], R. Zanino[5,*]

*Corresponding author. E-mail roberto.zanino@polito.it

[1] *Politecnico di Milano, Italy*

[2] *Universita' degli Studi di Palermo, Italy*

[3] *Universita' del Salento, Italy*

[4] *Universita' di Roma "Sapienza", Italy*

[5] *Politecnico di Torino, Italy*

ABSTRACT

The fission-fusion hybrid reactor (FFHR) constitutes a challenging playground for nuclear engineers. The CIRTEN consortium is responsible today for essentially all of the nuclear engineering research and education efforts in the Italian academia, with a spread of competences going from ITER, DEMO and, more generally, different fusion engineering applications, to fission applications like Generation IV reactors, ADS, SMR etc, including different enabling technologies and cultures, like materials and safety. In the paper a brief summary of the multi-disciplinary know-how inside CIRTEN is presented. It is argued that CIRTEN could give a non-negligible contribution to the further development of the FFHR concept, provided a suitable national and, especially, international collaboration framework could be envisaged.

1. Introduction

The fusion-fission hybrid reactor (FFHR) is a powerful idea [1] that attempts to combine the best features of fission and fusion towards the achievement of a multiplicity of targets, which are not limited to power production but include also nuclear waste transmutation and others. Major efforts in this field are being carried out in China [2], Russia [3] and the US [4], among others.

2. The CIRTEN consortium and the Nuclear Engineering (NE) education programs in Italy

CIRTEN is a consortium of universities, see Fig. 1, which was founded in 1994 to foster research and education in the field of nuclear technologies in Italy.

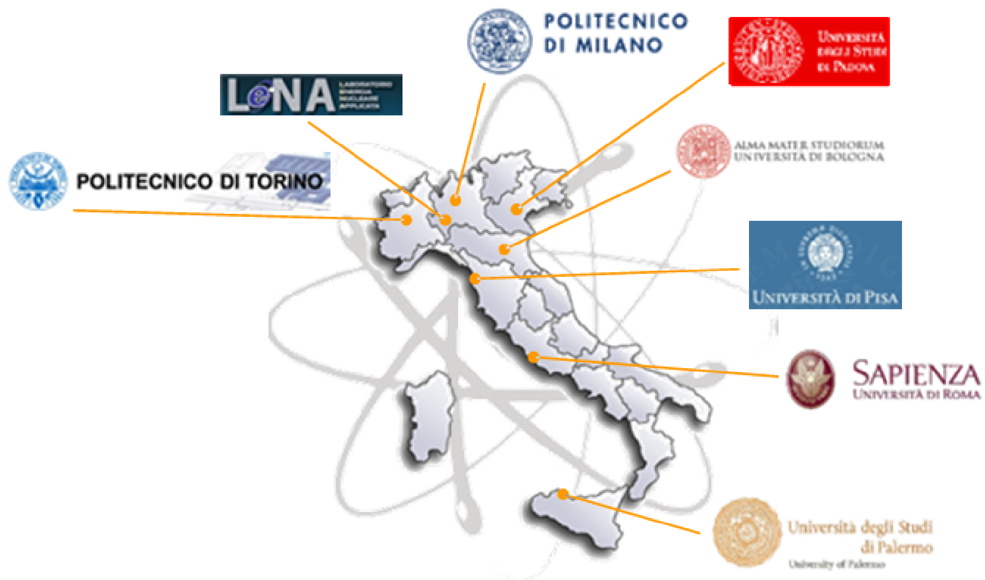

Figure 1. Italian Universities contributing to CIRTEN

Almost all faculty in the field of NE, see Fig. 2, belong to CIRTEN universities.

Figure 2. Nuclear engineering faculty in Italy (data from http://cercauniversita.cineca.it/php5/docenti/cerca.php 05nov2016)

Notwithstanding the very significant difficulties for anything NE-related following the two referenda in Italy, a total of 100+ students a year, which for a Country without nuclear power plants (NPPs) can be considered, we believe, quite a big number, are enrolled in the educational programs either fully or at least partly devoted to NE, which are at this time the following:

- BSc level
    - NE track inside Energy engineering (UniPa)
- MSc level
    - Energy and NE (UniPa, PoliTo)
    - NE (PoliMi, UniPi)
    - NE track inside Energy engineering (UniRm1)
    - Poly2Nuc joint NE program between PoliMi and PoliTo
- PhD programs.

Of course, notwithstanding the strong involvement and success of Italian industries and agencies in the fusion field, the fact that Italy does not and also will not have any NPPs, at least in the short term, implies that our (best) students are often finding after graduation a position in some of the (best) nuclear institutions around the world, see Fig. 3 for an example. While this may be a cause of pride, as it is clearly a sign of the quality of our graduates, it also raises some questions as to the cost-benefit ratio and associated trade-off between the obvious pros of an international network of alumni and the cons associated to this brain drain for our Country.

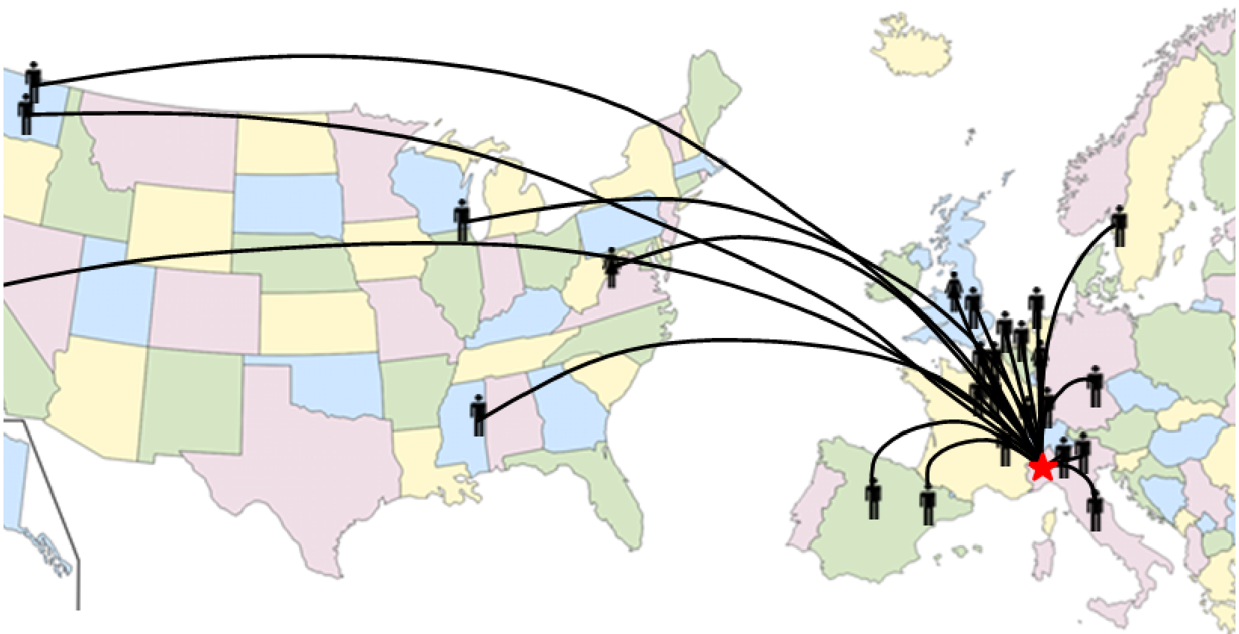

Figure 3. An example of CIRTEN "fallout": Export of PoliTo alumni towards nuclear institutions in the EU and in the US.

3. FFHR-relevant know-how inside CIRTEN

The FFHR can be seen as an excellent opportunity to bring together the fission and fusion research&education communities in Italy, especially considering that the most critical aspects in the design of such a reactor are likely to be related to the fission-fusion interfaces and require therefore by definition both competences.

The CIRTEN universities have built a significant experience and background in the NE field from the participation to several international projects and namely

- In fission, LFR (ELSY, LEADER), ADS (IABAT, MUSE, XADS, EFIT), MSR (MOST, ALISIA, EVOL, SAMOFAR), P&T (NEWPART, PARTNEW, EUROPART, ACSEPT, SACSESS)
- In fusion, ITER, the EU-DEMO and several of the present tokamaks, including e.g. JET and KSTAR.

The typical know-how that the CIRTEN universities could offer in the framework of a collaboration on the FFHR pertains to the following fields

- Neutronics / Thermal-hydraulics (TH) / Thermo-mechanics (fission&fusion blanket, …)
- Fusion
  - Superconducting magnets
  - Plasma-wall interactions and management of high heat fluxes
  - Radio-Frequency heating of the plasma
- Materials and nuclear fuel cycle
- Safety.

In the remaining part of this Section, a few selected contributions of CIRTEN universities in the above-mentioned fields will be briefly summarized.

In the field of multi-physics modeling, a major effort has been devoted at PoliTo, over the last 20 years or so, to the development and/or application of different, state-of-the-art computational tools, which could all be relevant in the design phase of an FFHR, e.g.

- The 4C (coil, conductor and cryogenic circuit) code [5], for the analysis of TH transients in superconducting magnets for fusion reactor applications, validated against experimental data from different machines (EAST, KSTAR, ITER Model and Insert Coils, W7-X), and also applied to several future tokamaks (ITER, EU-DEMO, JT-60SA, DTT),
- The GETTHEM (general tokamak thermal-hydraulic modeling) code, for the system-level TH analysis of the tokamak, based on the object-oriented Modelica language, currently applied to the design verification of the HCPB and WCLL solutions for the breeding blanket of the EU-DEMO [6],
- The different CFD modeling tools (ANSYS Fluent, STARCCM+, OpenFoam), applied to the TH modeling of different water cooled ITER components like the vacuum vessel [7], the first wall panels, the gyrotron collector and cavity,
- The FRENETIC (fast reactor neutronic/thermal-hydraulic) code [8], a computationally efficient, multi-physics modelling tool for liquid-metal cooled fast reactor cores, suitable for design and safety studies, recently validated against experimental data from EBR-II [9] and applied to the study of the LFR demonstrator ALFRED,
- The TOPICA code [10], for the design of ICRF antennas.

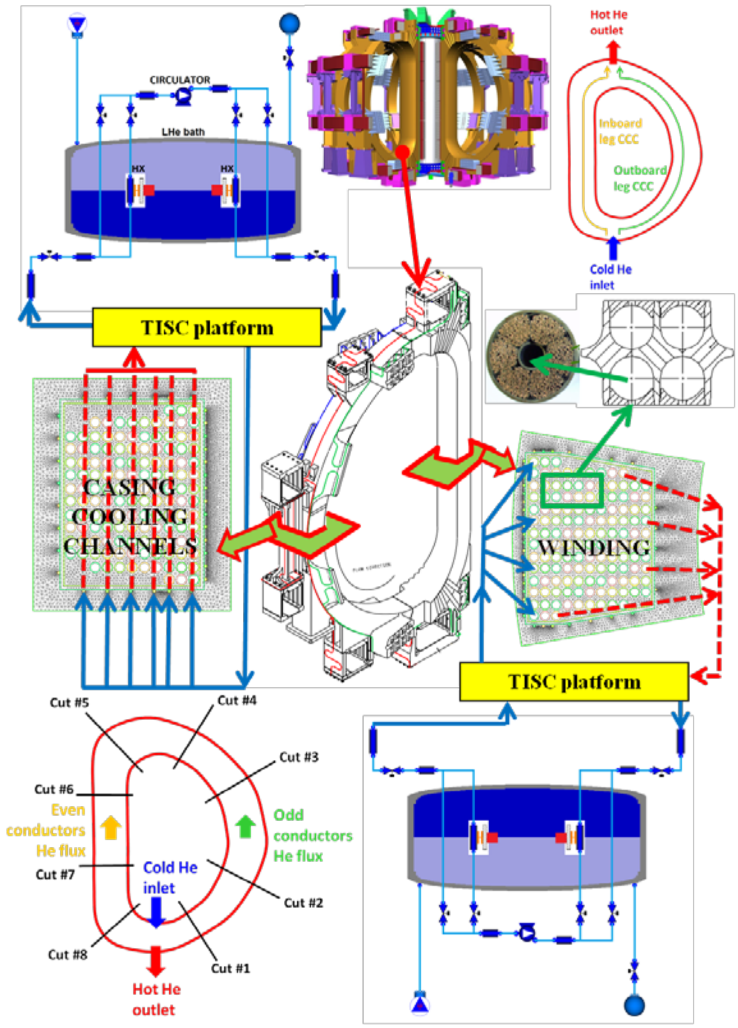

Figure 4. Architecture of the 4C code for thermal-hydraulic simulation of superconducting coils.

At PoliMi, PoliTo, UniPa and UniRm1, different models for the fission blanket could be developed

- to establish configuration, sub-criticality level and fission distribution of the subcritical system in steady-state, using the Serpent code and inverse models for reactivity monitoring [11],
- to evaluate the transmutation properties of the system, using the Fispact code, as well as the uncertainties due to nuclear data and models (using state-of the art UQ methods like GPT and reduced-order modelling),
- to compare the performances of LFR vs. MSR-like blankets, including the fluid/nuclear fuel non-linear coupling between fuel and neutron dynamics in the case of the latter [12]-[15],
- to compute the distribution of neutrons and heat load (using MCNP) [16], [21],
- to perform thermomechanical analyses (using Abaqus) [17],
- to evaluate the feasibility of selected blanket design concepts by means of preliminary TH estimates (using Relap5-3D) [18],

- to perform MHD calculations of the flow of liquid metals in a background B field for LFR-like blankets (using Ansys CFX and OpenFOAM).

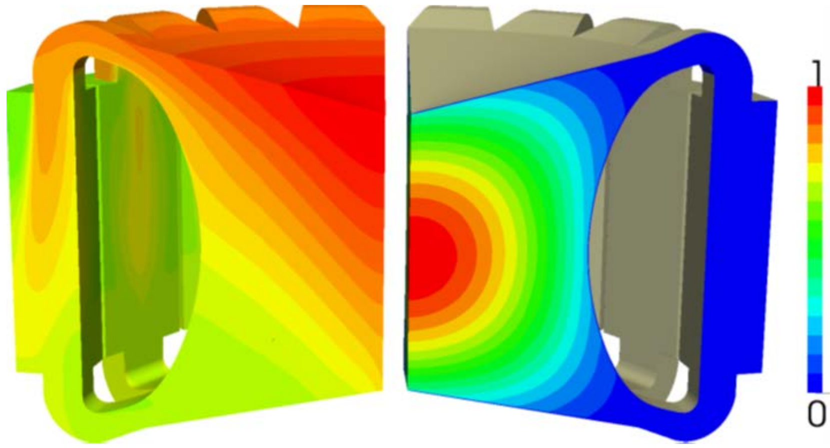

Figure 5. Spatial distribution of the delayed (left) and prompt (right) neutron sources (arbitrary units) computed with a 3D OpenFOAM simulation of an MSFR at nominal flow rate.

Some of the relevant TH features could also be studied taking advantage of the DYNASTY facility (first test end of 2016) developed at PoliMi for studying the stability of a closed molten salt loop with distributed heat generation.

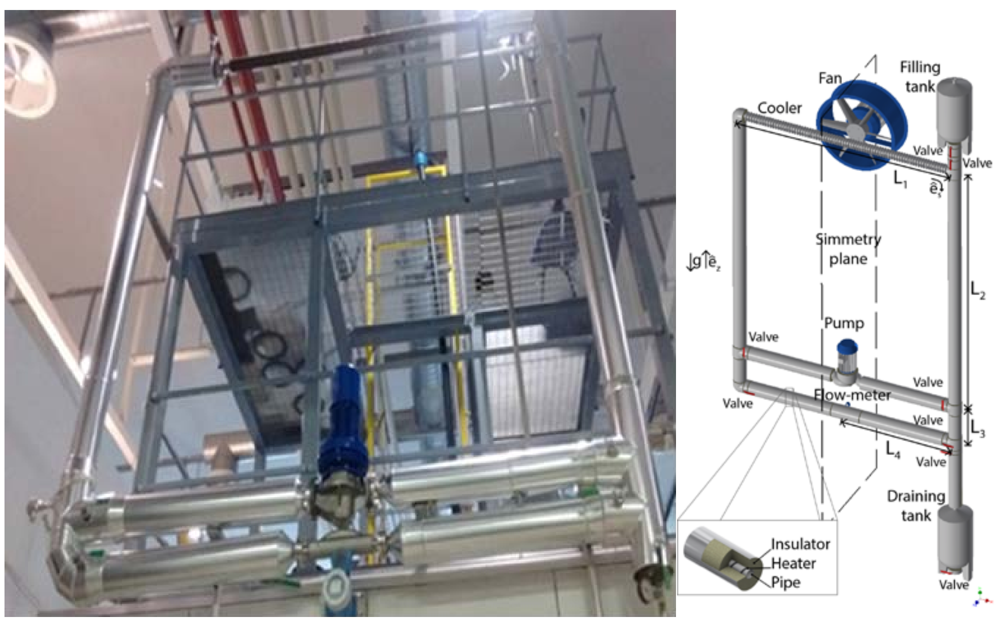

Figure 6. The DYNASTY facility at PoliMi.

In the field of nuclear materials several efforts are ongoing in the CIRTEN or related universities, among which some of the most FFHR-relevant ones include

- The analysis of chemical compatibility between MS and structural components, where a computational approach combining DFT simulations and Molecular Dynamics is coupled to (and partly validated by) an experimental approach, combining in turn the synthesis of compounds, thermal analyses, X-ray diffraction and solubility experiments, performed in the New Integrated Nuclear Laboratories at PoliMi [22],

- The study of pyrometallurgical reprocessing [23] and waste confinement [24], again in the same PoliMi laboratories,
- The development of joined or coated components and their experimental characterization at PoliTo, in collaboration with a series of international institutions [25]-[27],
- The experimental study of the corrosion of structural metallic components in contact with MS at UniSalento, where preliminary tests on W corrosion in molten NaCl have been performed [28]-[30].

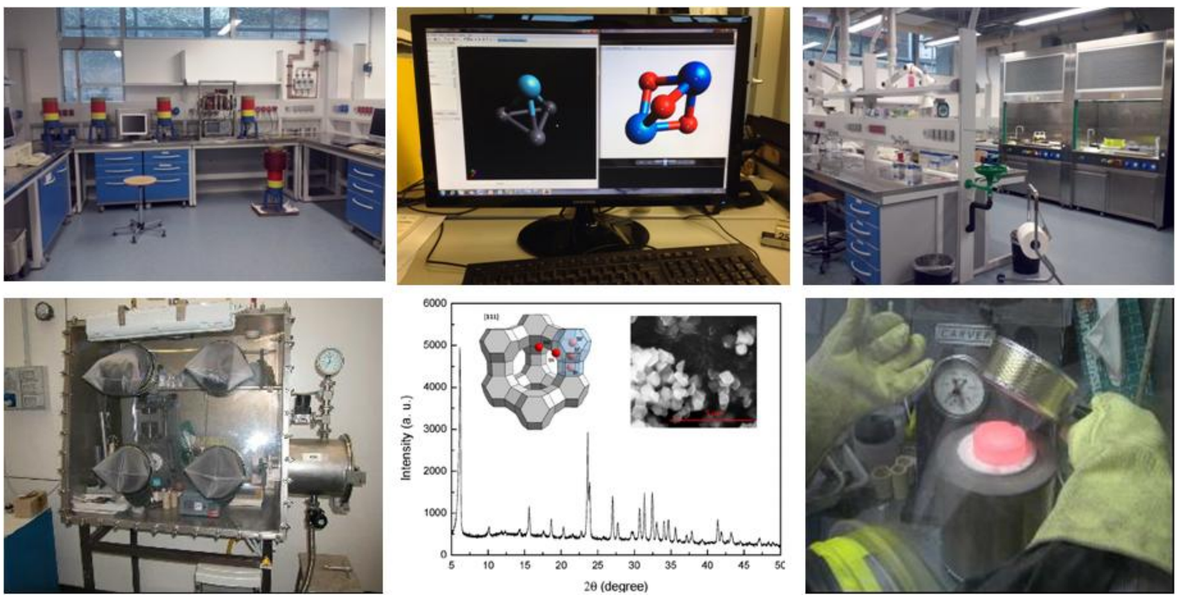

Figure 7. The Integrated Nuclear Laboratories at PoliMi.

Last, but definitely not least, the CIRTEN universities could contribute to the safety assessment of the FFHR different, complementary points of view, namely the analysis of operational transients at different power levels, the identification of the Postulated Initiating Events, based on the peculiar characteristics of the subcritical assembly, and the ensuing accident analysis of the most relevant scenarios, using for the operational/accident transients both TH and multi-physics codes (like FLUENT, RELAP, FRENETIC, CONSEN [20]), or dedicated codes (like MELCOR 1.8.6-FUS and 2.1) in the case of severe accidents, and the integrated deterministic and probabilistic risk assessment of the entire system [31]-[33].

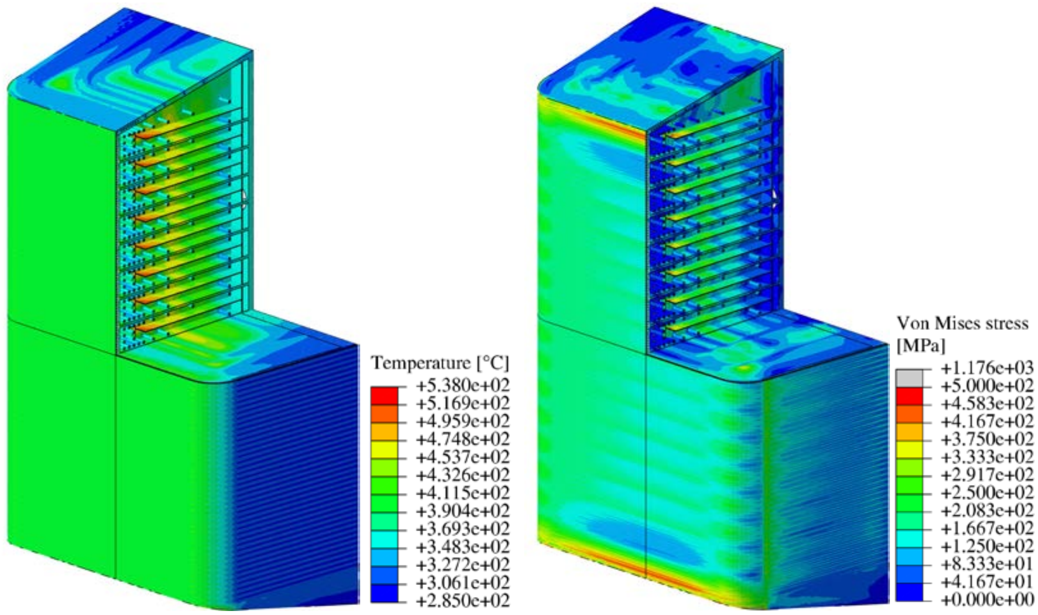

Figure 8. Temperature (left) and Von Mises equivalent stress (right) field distributions in the WCLL equatorial outboard blanket module.

4. Conclusions and perspective

NE programs in CIRTEN universities were born more than 50 years ago and are still alive and quite active, notwithstanding three major NPP accidents in the US, Ukraine and Japan, and two referenda against nuclear power production in our Country, over the last 40 years or so.

The competences of the Italian academic NE community inside the CIRTEN consortium could be interestingly applied to the FFHR, if/when a suitable collaboration framework will be established with the major national and international players.

Considering the long-term nature of all nuclear endeavors (FFHR included …), it is crucial for the survival of any program not only to confirm but also to increase the support for the education and training of the future generation of nuclear engineers and scientists.

References

[1] H. A. Bethe, The fusion hybrid, *Physics Today* (May 1979) 44-51.

[2] Y. Wu, et al., Fusion-Fission Hybrids Driven Research in China, *Fusion-Fission Research Needs Workshop*, Sept. 29-Oct.1, 2009, Gaithersburg, Maryland, USA.

[3] B. V. Kuteev, et al., Development of DEMO-FNS tokamak for fusion and hybrid technologies, *Nucl. Fusion* **55** (2015) 073035 (8pp).

[4] J. P. Freidberg, et al., Fusion–fission hybrids revisited, *Nature Physics* **5** (2009) 370-372.

[5] L. Savoldi Richard, et al., The 4C code for the Cryogenic Circuit Conductor and Coil modeling in ITER, *Cryogenics* **50** (2010) 167-176.

[6] A. Froio, et al., Dynamic thermal-hydraulic modelling of the EU DEMO HCPB breeding blanket cooling loops, to appear in *Progress in Nuclear Energy* (2016).

[7] R. Zanino, et al., CFD analysis of a regular sector of the ITER vacuum vessel. Part II: Thermal-hydraulic effects of the nuclear heat load, *Fus. Eng. Des.* **88** (2013) 3248-3262.

[8] R. Bonifetto, et al., A full core coupled neutronic/thermal-hydraulic code for the modeling of lead-cooled nuclear fast reactors, *Nuclear Eng. Des.* **261** (2013) 85-94.

[9] D. Caron, et al., Full-core coupled neutronic/thermal-hydraulic modelling of the EBR-II SHRT-45R transient, *Int. J. Energy Res.* (2016) DOI: 10.1002/er.3571.

[10] V. Lancellotti, et al., TOPICA: an accurate and efficient numerical tool for analysis and design of ICRF antennas, *Nucl. Fusion* **46** (2006) S476-S499.

[11] S. Dulla, et al., A method for the continuous monitoring of reactivity in subcritical source-driven systems, *Annals of Nuclear Energy* **87** (2016) 1-11.

[12] S. Dulla, et al., Random effects on reactivity in molten salt reactors, *Annals of Nuclear Energy* **64** (2014) 353-364.

[13] M. Aufiero, et al., Development of an OpenFOAM model for the Molten Salt Fast Reactor transient analysis, *Chemical Engineering Science* **111** (2014) 390-401.

[14] A. Pini, et al., Analytical and numerical investigation of the heat exchange effect on the dynamic behaviour of natural circulation with internally heated fluids, *Chemical Engineering Science* **145** (2016) 108-125.

[15] A. Cammi, et al., The influence of the wall thermal inertia over a single-phase natural convection loop with internally heated fluids, *Chemical Engineering Science* **153** (2016) 411-433.

[16] P. Chiovaro, et al., Study of the helium-cooled lithium lead test blanket module nuclear behaviour under irradiation in ITER, *Fus. Eng. Des.* **84** (2009) 2178-2186.

[17] P. A. Di Maio, et al., On the optimization of the first wall of the DEMO water-cooled lithium lead outboard breeding blanket equatorial module, *Fus. Eng. Des.* **109-111** (2016) 335-341.

[18] S. Kim, et al., Draining and drying process development of the Tokamak Cooling Water System of ITER, *Fus. Eng. Des.* **109-111** (2016) 272-277.

[19] R. Gatto, et al., Self-consistent electron transport in tokamaks, *Phys. Plasmas* **14** (2007) 092502.

[20] G. Caruso, et al., Modeling of a confinement bypass accident with CONSEN, a fast-running code for safety analyses in fusion reactors, *Fus. Eng. Des.* **88** (2013) 3263-3271.

[21] N. Burgio, et al., Monte Carlo simulation analysis of integral data measured in the SCK-CEN/ENEA experimental campaign on the TAPIRO fast reactor. Experimental and calculated data comparison, *Nucl. Eng. Des.* **273** (2014) 350-358.

[22] M. Cerini, et al., DFT-GGA Prediction of Thermodynamic Parameters in Solid Phase for Binary Compounds of Actinides and Fission Products, *Proceedings Global Nuclear Fuel Cycle for Low-Carbon Future* **5451** (2015) 1361-1366.

[23] G. De Angelis, et al., Pyroprocess Experiments at ENEA Laboratories, *JNFCWT* **13** (2015) 19-27.

[24] E. Macerata, et al., Immobilization of radioactive isotopes in fluorapatite matrices, *MRS-Symposia* **1193** (2009) 95-102.

[25] L. Gozzelino, et al., He-irradiation effects on glass-ceramics for joining of SiC-based materials, *Journal of Nuclear Materials* **472** (2016) 28-34.

[26] Y. Katoh, et al., Radiation-tolerant joining technologies for silicon carbide ceramics and composites, *Journal of Nuclear Materials* **448** (2014) 497–511.

[27] M. Ferraris, et al., Effects of neutron irradiation on glass ceramics as pressure-less joining materials for SiC based components for nuclear applications, *Journal of Nuclear Materials* **429** (2012) 166–172.

[28] B. Bozzini, et al., Corrosion of Stainless Steel Grades in Molten H2O/KOH 50% at 120°C: AISI304 Austenitic and 2205 Duplex, *Mater. Corros.* **64** (2013) 988–995.

[29] B. Bozzini, et al., Corrosion of Stainless Steel Grades in Molten NaOH/KOH Eutectic at 250°C: AISI304 Austenitic and 2205 Duplex, *Mater. Corros.* **63** (2012) 967–978.

[30] B. Bozzini, et al., Numerical modelling of MCFC cathode degradation in terms of morphological variations, *Int. J. Hydrogen Energy* **36** (2011) 10403-10413.

[31] E. Zio, Challenges in the vulnerability and risk analysis of critical infrastructures, *Reliability Engineering and System Safety* **152** (2016) 137-150.

[32] E. Zio, Some challenges and opportunities in reliability engineering, *IEEE Trans. On Reliability* **PP (99)** (2016) 1-14.

[33] E. Zio, Integrated deterministic and probabilistic safety assessment: Concepts, challenges, research directions, *Nucl. Eng. Des.* **280** (2014) 413–419.