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The lifetime determination of ARC reactor as a load-following plant in the energy framework

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Abstract

Energy studies are interdisciplinary studies. They involve not just technical aspects, but also environmental, social and political aspects. In this framework, an advanced technological innovation as a part of simple solution for the energy problem is considered. The role of the fusion energy as new energy source and in particular the project Affordable Robust Compact (ARC) fusion reactor as new technology is presented as part of energy policy. The most innovative characteristics of ARC is its integration in the energy grid as load-following power plant. In particular, the proposed study investigates the stresses induced in the vacuum vessel, the closest component to the plasma. The performed analysis has been focused on the quantification of time in which the vessel would fail due to repeated thermal stress when it works as load-following. It has been demonstrated that the vacuum vessel lifetime can be quantified from three to five years on the basis of the thermal cycles considered (i.e. 3, 10 and 20 cycles per day).

Keywords: Fusion energy; Affordable Robust Compact; load-following capability; energy market

1. Introduction

The energy framework is a very complex field to be investigated since it does not only involve technical aspects but the effect on the human society, environmental impact and also ethical considerations. An historical growth, with the highest per capita demand concentrated in the developed countries, has characterized the behavior of the world energy needs in the last Century. Future prediction scenarios involve a trend of growing energy demand, depletion of fossil fuel, problem in the energy supply, and increasing of environmental issues. Different studies have been carried out on these scenarios. Capellán-Pérez et al. (2014) present an Economy-Energy-Environment model based on System Dynamics which integrates different aspects: the estimated peaks for oil, gas, coal and uranium, the techno-sustainable potential of renewable energy, the socio-economic energy demands, the development of alternative technologies and the net CO_2

emissions. Different authors, such as De Andrade et al. (2015), Breyer et al. (2017), etc., have proposed scenarios of energy demand in different countries and for different energy sources.

These analysis underline the relevance of the energy issue and the necessity to investigate both simple and innovative solutions. In fact, one solution to the energy problem does not exist, but sets of solutions, that are suitable to specific local context, must be investigated considering a mix of energy sources and technologies.

It is commonly accepted, therefore, that energy studies involve not just technical aspects, but also environment, society, material science, and politics. The Energy issue is strictly connected to the issues of Water, Food, Health, and to the issue of resources availability and location (Zucchetti et al., 2016): these are systemic issues that require studies on local environmental and social aspects, not just technical ones.

The following actions can be pursued to face the energy issue (Zucchetti and Testoni, 2017):

- rational use of energy;
- innovation and development of new energy sources and/or technologies.

Different studies on rational use of energy have been performed. As example, Marchais et al. (2015) investigate a quantitative approach to energy efficiency, contribution to the development of global energetic performance, promotion of the recourse to standardized approach as a support to regulation, communication based on the terminology regarding energy saving. Instead, Barea et al. (2017) study heat gain for the rational use of energy for a multi-azimuthal window as a passive solar system.

As far as the innovation and development of new sources and/or technologies is concerned, authors focus the attention on the nuclear energy. The world scientific community recognizes the role of nuclear energy (Vaillancourt et al., 2008; Apergis et al., 2010; Menyah and Wolde-Rufael, 2010) in the field of development of new energy sources. However, an open debate on nuclear energy concerns the solution of the problem of radioactive waste, reinforcing nuclear safety, developing research into reactors of the future, and nuclear fuel availability. In fact, nuclear energy is facing a crisis due to the lack of widely accepted solutions to some of its issues: radioactive waste management, health impact on population and workers in case of severe accident, nuclear proliferation, and effectiveness in solving the global warming issue. Different studies have been performed to analyze the policy of different countries on the use of nuclear energy. For example, Shim et al. (2015) have made a literature comparison on nuclear energy policy and framing, illustrating how leading policy-makers have framed nuclear energy policy in six major nuclear producers (Germany, USA, Japan, UK, France, Korea) after the Fukushima accident. They underline that all the countries had to develop their own nuclear policy frames while focusing to varying extents on three main pillars of issues: increasing public trust in government and the nuclear industry, enhancing the security of energy supplies, and meeting their own CO_2 reduction targets. At the same time, the countries had to negotiate recovery from the economic crisis. In particular, as a leader in the world renewable energy market, Germany re-emphasized the clean energy frame, abandoning nuclear power. The USA and Japan have framed the issues primarily in nuclear safety and energy security terms, although the clean energy frame is also important in the USA. The UK and France are particularly interested in the economic growth frame, and have not found necessary to emphasize the nuclear safety frame, which has priority in Korea instead. Another important producer of energy by nuclear power plants is Belgium. Kunsch and Friesewinkel (2014) have made an analysis of the nuclear energy policy in Belgium after Fukushima. The Belgian nuclear phase-out law imposes closing down in the 2015–2025 period seven nuclear power plants that used to produce more than 50% of the domestic electricity. They conclude that this creates an urgent problem in the country due to the absence of well-defined capacity-replacement plans.

On one side, the fission energy acceptance by the public is doubtful due to the risk of accidents, in particular after Fukushima and Chernobyl accidents, the safe management of radioactive waste, and the risk of nuclear proliferation. At the present, all the existing nuclear power plants are based on fission reactions, and nuclear power provides about 11% of the world's electricity (World Nuclear Association, 2018). On the other side, the use of fusion energy is under investigation. At present, there is no fusion reactor that is actively and continuously producing electric energy for usage, but the studies on the technologies based on fusion reactions are promising. In particular, the main advantages of fusion energy in comparison to fission energy are the low emission of greenhouse gases, no core melting risks, no proliferation and very low amount of radioactive waste. In addition, these improvements are also associated with the fact that fusion power plants could produce energy for long-term.

As far as the emission of greenhouse gases is concerned, few studies have been performed to compare the impact of different energy sources. In particular, Kobori et al. (2016) proposes an analysis of Life Cycle Assessment of tokamak fusion power reactors and following commercial reactors as an extension to calculate CO_2 emissions from reactor construction, operation and decommissioning that is considered as a major environmental cost. The comparison of CO_2 emission from different energy source shows that fusion contribution is 1/15 of the one resulting from a typical LNG (Liquified Natural Gas) power plant, of the same order of fission and wind power, and a little bit higher than hydro-power and geothermal. In the context that there is no unique possible solution, but it is important to consider an energy mix, fusion energy can positively contribute with a reduction of greenhouse gases.

For what regards the no core melting risk, the magnetic confinement considering the deuterium–tritium (DT) reaction to obtain fusion, it can be realized at temperatures around 150 million °C. Fusion material at this temperature should obviously not come in contact with a material wall, otherwise the surface of the wall would melt or evaporate, and the released impurities would dilute and cool down the fusion material. At this high temperature, hydrogen gas is transformed in plasma state and the use of a strong magnetic field is envisaged with the goal to achieve durable plasma confinement sufficiently far from the wall (Ongena et al., 2016). Moreover tokamaks, unlike fission reactors, do have the fuel storage room and the reaction chamber well separated and a very little amount of fuel is available for fusion each instant of time, making a chain reaction and core melting accident physically impossible.

Concerning the nuclear proliferation, fusion technologies based on magnetic confined plasmas are of negligible relevance to the military industry. In addition, the use of neutron flux to create fissile material is not easy to achieve in fusion and requires the modification of some devices, thus the efforts will be not convenient (Zucchetti M., 2011).

Regarding the radioactive waste, fusion reactor products consist of the produced helium, which is innocuous. Instead, considering activated material and radioactivity, the only radioactive waste would be the structural materials that get activated during the life cycle of the reactor and the only radioactive fuel which would be handled is tritium. In this field, it is possible to talk about low-level radioactive waste, which can be managed in proper way. In any case, several studies have been carried out on scenarios for the radioactive waste management (e.g. Someya et al., 2015).

Finally, a working fusion energy source can provide energy for long time. In fact, at present the major fusion projects are based on the deuterium-tritium reaction, and their sources, namely water and lithium, are particularly abundant on the Planet. In detail, deuterium is present to the extent of 1 part in 6400 (156 ppm) in naturally occurring hydrogen and for fusion purposes would probably be extracted by electrolysis of heavy water (Bradshaw et al., 2011). Instead, tritium is a fast-decaying radioelement of hydrogen, which is present only in trace quantities in nature. However, it can be produced during the fusion reaction through contact with lithium: tritium is produced when neutrons escaping the plasma interact with lithium contained in the blanket wall of the tokamak (Bornschein et al., 2013). Then, lithium can be extracted from seawater, where the concentration is on average 0.17 ppm. However, considering the volume of seawater that should be handled for extraction, and the future use of lithium in the automotive application, different scenarios should be investigated. Bradshaw et al. (2011) estimate the present lithium terrestrial reserves of 9.9Mt that, if used only for fusion, would last for only 990 years under the assumptions that the demand for energy doubles by 2050 (compared to 2007), the percentage provided by electricity doubles (mainly due to electro-mobility), and the base-load provided by fusion power is 30%. On the other side, if the potential of seawater would be considered, then there will be enough lithium, at least theoretically, for the operation of 2760 power plants for 23 million years. More practically speaking way more investigations are needed to get a more accurate prediction, seeing as how there will be several limitations on sea water lithium extraction technologies due to the huge amount of water that needs to be handled per lithium gram – and consequent energy consumption - (U. Bardi et al., 2010).

Within the described framework, the deployment of fusion energy is one of the most challenging and complicated by technical point of view. Many physics and technology aspects such as plasma physics, magnets physics, reactor engineering, plasma-wall interactions, etc. need further research and development in order to achieve a mature technology. However, great hope is associated with nuclear fusion that is expected to be the ultimate environmentally friendly solution to sustainable electricity production and the elimination of the emission of greenhouse gases. The recent climate change agreement in Paris highlights the imperative to aggressively decarbonize the energy economy and develop new technologies, especially for the generation of electrical energy that are environmentally clean. In this context, the growing awareness of the impact of climate on the environment sees a call from the community to develop environmentally friendly systems, such as low ecological footprint buildings, photovoltaic farms and, most recently, hydrogen-fueled cars, buses and other transport machinery (Nowotny at al., 2018). Renewable energy offers immense opportunities in this regard, but at the present there are not available technological solution to provide energy if their immediate output cannot continuously meet the instantaneous demand (e.g. no electric storage systems available today) (Clack et al., 2017). However, the goal of fusion energy connected to the grid is supposed to lie several years from now. The main projects under investigation by the nuclear fusion community are ITER (International Thermonuclear Experimental Reactor) (Aymar et al., 2002) and DEMO (DEMOnstrating fusion power reactor) (Konishi et al., 2002). Other fusion projects exist and are under development in parallel to these megaprojects; each of them is characterized by some technical differentiating points which might allow a faster achievement of an industrial stage (both from technical and economical point of view) suitable for introduction to the market of the electricity power production.

The present manuscript focuses on one of these alternative technologies: the Affordable Robust Compact (ARC) fusion reactor (Sorbom et al., 2015). Since plasma can quickly change its power output, it allows expanding the capability of a nuclear energy facility making it theoretically suitable for a load-following power plant. Starting from this consideration, the proposed study investigates the most endangered component of ARC, namely its vacuum vessel, in the abovementioned scenario, that is a power-changing reactor, in order to prevent or predict a mechanical failure. The most relevant aspects that have to be taken into account are the possible interactions between a power-changing plasma and the structure, seen from the latter's viewpoint, this means cyclic thermal loads and neutron fluxes. For what concerns ARC, the vacuum vessel is the closest structural component to the plasma by far, seeing as how there is nothing but fluid surrounding it (Sorbom et al., 2015). Therefore, the thermo-mechanical analysis under several-cycles-per-day operation has been evaluated and verified, to estimate the lifetime of this component. From this point of view, the feasibility of ARC as a load-following power plant has been demonstrated.

2. Affordable Robust Compact (ARC) reactor

Affordable Robust Compact reactor (Fig. 1) is a conceptual design for a Tokamak conceived by Massachusetts Institute of Technology (MIT) researchers. It represents a new generation of fusion reactors, which have the final goal of tracing a new path to a clean, fast and cheap fusion energy connectable to the power grid. Its design is continuously evolving and every new idea is applied and integrated to the design; this means that the Tokamak is upgraded to the newest technology known until resources will be committed to construction of a reactor based on this design.

The idea of ARC’s concept began when a new generation of superconducting materials became available on industrial scale. In fact, ARC’s most important innovation respect to the existing fusion reactor projects is about its magnets: sets of toroidal and poloidal field coils are made of Rare Earth Barium Copper Oxide (REBCO). This material shows a relatively high critical temperature of about 80K, which is almost twenty times higher than copper’s critical temperature, and is able in a very thin tape (Fig. 2) to generate a magnetic field of tenth of Teslas.

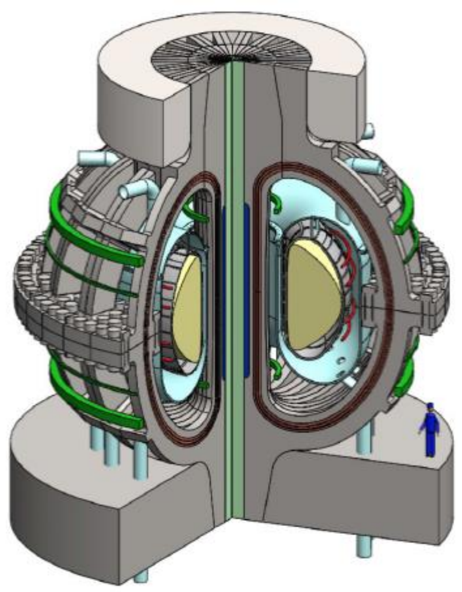

Figure 1 - The ARC Tokamak (Sorbom et al., 2015).

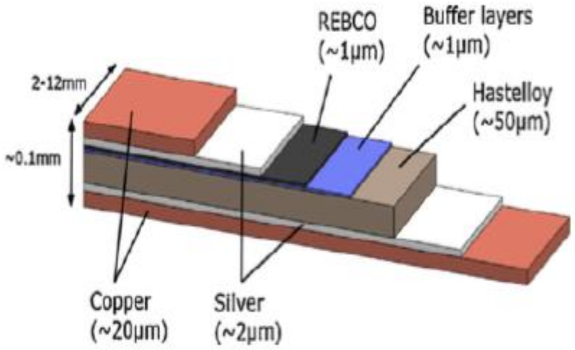

Figure 2 - REBCO tape layers example (Sorbom et al., 2015).

Another important innovation implemented in this concept is the use of a single material, Lithium Fluoride and Beryllium Fluoride (FLiBe) molten salt, which satisfies all functions done by blanket, cooling system and tritium breeder. ARC's vacuum vessel is immersed in a tank filled with FLiBe. It works as coolant for the vessel and divertors carrying out thermal energy up to the heat exchangers; in addition, it shields magnets and component from radiations and neutrons slowing them down and absorbing their energy. Since FLiBe is a mixture of Lithium and Beryllium, it works both as neutron multiplier and as Tritium breeder. It is expected to achieve a tritium breeder ratio of around 1.1.

The guidelines for the design of ARC's main components can be summarized as construction simplicity and quick maintenance. Following these concepts, this Tokamak is designed to be quickly demounted and reassembled (Fig. 3). For instance, vacuum vessel and the blanket tank are single-piece components conceived for realization by additive manufacturing; this means that the structure is not constituted by slices, thus simplifying the periodical replacing processes. Toroidal field coils are designed to be opened on their upper side so that tank, vessel, auxiliary and poloidal field coils can be removed from their position, from the top, leading to a very simple and quick process to assemble the main components of the reactor.

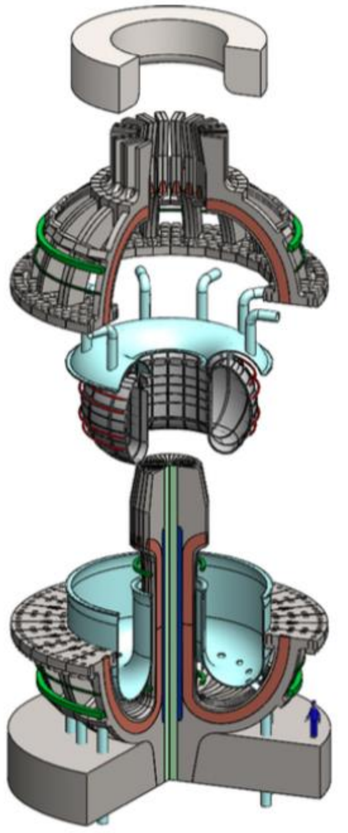

Figure 3 - ARC assembling scheme (Sorbom et al., 2015).

The vacuum vessel is one of the most critical component since it represents the containment for the plasma. Neutron flux, heat flux, thermal expansion, corrosion and deterioration make the vessel a critical component from the design point of view. The design of the supports for the ARC vacuum vessel pursued the minimization of the thermal stresses of the structure by limiting the constraints, it has its supports just on its upper side, right behind divertors (Fig. 4). Given that thermal stresses are caused by rigid constraints closing off an expanding structure rather than the expansion itself, it has been decided to let the main body of the vessel expand during the heat-up period, slightly and homogeneously hindered by just the surrounding fluid, while only the minimum sufficient amount of supports able to allow a little displacement have been set on the upper side of the chamber. In this way, the component is kept on position vertically and it is allowed to expand by slightly sliding radially.

Vacuum vessel is a double walled vessel and the minimization of the wall thickness was pursued to reduce the weight and to limit the production of activated waste. It has four layers divided in the two walls: the inner side of the first wall shows a thin layer of tungsten, the first wall, supported by a layer of structural material.

The function of this wall is to define the volume where the vacuum is generated and the plasma is confined, and to conduct the power to the FLiBe coolant which, as a third layer wide 20 mm, fully surrounds the vacuum chamber and runs all the way through it. This layer of coolant also works as first Tritium breeder medium.

Nonetheless, neutronic simulations have shown that flowing FliBe in a 20 mm channel is not enough to reach an over-the-unit tritium breeding ratio (Sorbom et al., 2015), more beryllium is then necessary in order to be sure that ARC would get a self-sustained tritium breeding cycle. Therefore, the outer wall has been provided with a first layer of neutron multiplier supported by a second layer of structural material (Fig. 4) capable to sustain the mechanical stresses generated by the containment of the FLiBe coolant. All layers of the vessel are continuous: welding and other joint are eliminated, thus hotspots and weak structural areas may be avoided. In order to increase the vessel lifetime, the divertors have been designed in order to withstand the bigger part of the heat flux, but a very little ratio of neutron flux. The latest update of the design foresee the integration of long-leg geometry divertors, able to exhaust a considerably high heat power meanwhile very little ratio of neutrons reaches their area (Vieira et al., 2015).

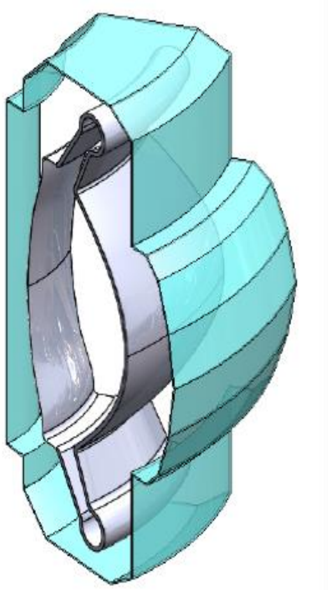

Figure 4 - A slice of ARC’s vacuum vessel, long-leg divertors and blanket tank.

3. The desirable role of Nuclear Fusion Energy within the electricity grid

The current electricity grids are characterized by different power mix according to the specificities of each country, such as economic activities, population amount and distribution, population life-style, etc. Their common technical requirement is to satisfy the relatively variable power demand, which fluctuates during the whole day (e.g. Fig.5), and changes in amplitude and shape according to the period of the year. The power demand curve, in a country where nuclear energy is also used in the energetic mix, is commonly split into two contributions (e.g. Fig.6): base power load and peak power load. The supply of the base power load is conventionally provided by means of traditional power plants (i.e. based on the steam Rankine cycle), fed by fossil fuels such as coal and natural gas, or by nuclear fission reactors. These plants are characterized by slow responsiveness to the power load variation, especially nuclear power plants for which many physics issues and safety policy considerations force to keep a stable production level. The size of the base power load plants is normally big because of high investment, but low fuel cost. Many of the above-mentioned power plants show severe troubles when facing the load-following need, i.e. when trying to change their power output sufficiently promptly.

Obviously, an ideal load-following power plant should be able to change its power output in a wide range and in a short time: the prompter and the wider the capability to change power production is, the more reliable and affordable the grid is. The peak power load is covered by a mix of simple gas turbines and combined cycle power plants often supported by hydroelectric power plants, whose hydraulic basically works as an energy storage to be filled overnight thanks to the base power capacity surplus. These technologies are characterized by a fast responsiveness and small or medium power capability. Most of these plants have a limited power range in which their efficiency is economically suitable; therefore, a change of power out of their design point might results in a more expensive energy cost (e.g. gas turbines).

The above described situation is partially changing with the introduction of the renewable sources (mainly windmill and photovoltaic fields) quickly growing in the last decades in some countries (Leite da Silva et al., 2010; Carpinelli et al., 2015). This means of production introduces an intermittent and only partially foreseeable power source. This effect complicates the management of the peak power production for the Energy Provider Authority.

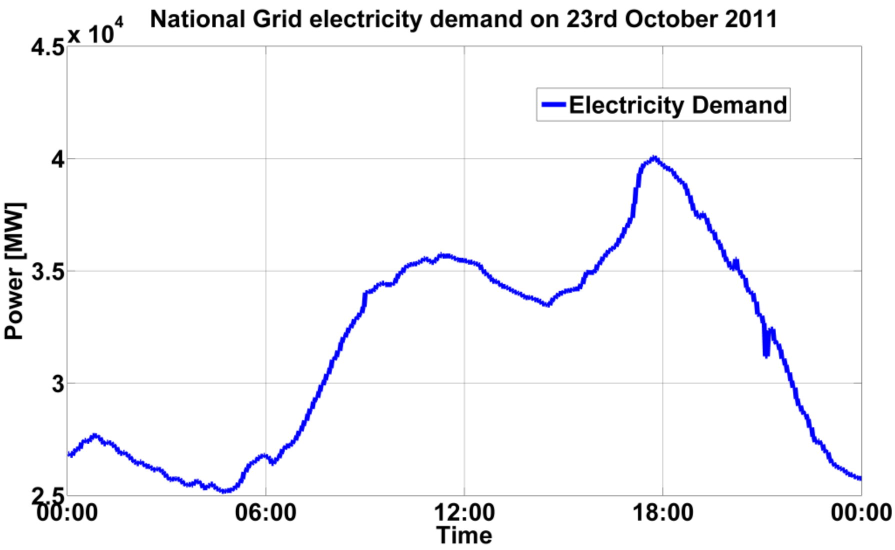

Figure 5 - Example of daily electricity demand in Great Britain (University of Glasgow, 2018).

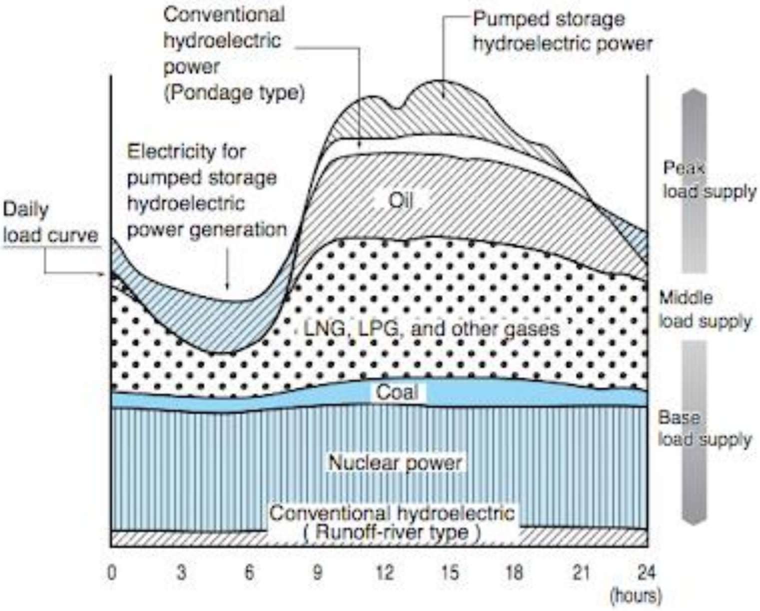

Figure 6 - Example of electric energy stratification divided by type of plants and their role in Japan (Inside Power Station, 2018).

As previously explained, big and complicated plants work as base load; while the more flexible ones work as load-following.

In this framework, historically nuclear power plants are used to provide the base load. Nuclear fission power plants have difficulties changing power quickly, since there are many issues to take into account: a power variation could be translated in a variation of coolant flow rate and coolant's temperature as well; both of those type of variation cause problems such as reactivity insertion and feed-back, loss of heat sink, change of heat transfer coefficient, etc. and each of them affects fission power as well. This means that an even small power change needs an accurate study of each power level and transient evolution.

Now, the role of fusion energy in a potential future grid is not yet defined; however, from the physical point of view the fusion reaction does not have the same constrain as the fission reaction in terms of control speed. The fuel is a gas brought in plasma state, and it has to be fed continuously to the Tokamak in order to have continuity of the fusion reaction, thus the dynamic of the reaction itself is very fast. The purpose for fusion researchers and engineers should be to properly design all the other systems of a power plant based on nuclear fusion energy to let it work as load-following power plant. These features are mandatory in a scenario where the renewable sources continue to increase their share in the power grids: they must be flanked by highly responsive power production means, which can compensate the jagged behavior of wind, sun and users. This would turn it into one of the most versatile type of plants in the whole energy overview.

4. Thermo-mechanical stress in vacuum vessel

Since plasma can quickly change its power output, ARC technology is supposed to work as load-following plants. The vacuum vessel component separates plasma from the energy carrier (FLiBe), it is therefore one of the most critical components of ARC in a load-following scenario: in particular, it is the structural component in which the highest thermo-mechanical stresses are induced.

A variation of fusion power could be mainly modeled, from vacuum vessel's point of view, as changing thermal load on the vessel; this leads to several issues, but the problem expected to be the most concerning is the thermal fatigue on the chamber, which in order to be technically and economically acceptable needs to survive for a minimum time before replacement or failure.

4.1 Methodology and data

To perform a lifetime prediction for the vessel, fatigue and creep data must be accurate and realistic. A likely normal plant operation cycle has been selected. ARC is supposed to run normally at around 500 MW_{th} of fusion power, connecting to the grid and giving around 200 MW_{el}. Moreover, in order to cover daily peak demand, ARC should be able to change its power up to about 750/800 MW_{th} of fusion power, and therefore more or less 300 MW_{el}. The expected thermal efficiency is 0.4 (Sorbom et al., 2015). However, ARC is supposed to run even at lower powers (250/300 MW_{th}), if necessary.

Once the model geometry of the vessel's main chamber has been determined, mechanical and thermal simulations using Finite Elements software have been carried out, with the aim to understand, from a thermo-mechanical point of view, the following main issues:

- Mechanical static loads;
- Thermal static loads;
- Steady state conditions;
- Creep analysis;
- Thermal transients;
- Thermal fatigue analysis.

Thermal fatigue should take into account several effects usually present in the models, namely stress concentration geometries and hotspots, frequency and especially mean stress. Since reactor vessel has a relatively simple geometry there are no stress concentration spots shown by simulations. The operating frequency of the thermal cycle for a load-following reactor concept does not affect FEM thermo-mechanical results since the power fluctuations may be conservatively quantified in tens per day. However the model of life prediction that has been used in this paper takes into account cycle's frequency. The only parameter that could heavily affect the results of the present study is the mean stress, since thermal cycles cause the vessel to be always stretched: a quite safe assumption in this study is that the component, during simulations, is referred to room temperature for stress and displacement, this means that the vessel, in normal operating conditions, which means a surrounding temperature of above 800 K, is considered as always expanded and thus, taking into account the above described supports as well, stretched. In this context increasing and decreasing the thermal load in a still very high temperature, would just change the magnitude of the related stress keeping it always in traction with respect to the same component kept at room temperature.

Once the model has been set up ten simulations based on finite elements analysis have been run by means of COMSOL Multiphysics®; each peak fusion power has been simulated from 100 MW_{th} up to 1 GW_{th} in steps of 100 MW_{th}.

The boundary conditions have been set on the FLiBe fluid temperature evolution and on the convective coefficients so as to keep them within the allowed FLiBe's working range. In particular, the boundary condition of the outer vessel facing the bulk tank has been chosen to be a film with low turbulence and a temperature equal to the highest level experienced in the FLiBe's loop, that is tank's outlet one. This makes the assumption quite conservative from a thermo-mechanical point of view. The main outputs of the simulation were vessel's temperature, monitored to stay below the upper limit set at 930 K; and stress behaviour of inner and outer vessel.

In Table 1, the main loads and boundary conditions used for the simulations are reported. In particular neutron energy deposition changes for each layer of material, according to MCNP simulations (Sorbom et al., 2015). Neutron flux, first wall thermal load and coolant's temperatures change with fusion power. Fluids convective coefficient have been decided and validated in separated, small scale CFD simulations. Simulations have been implemented with temperature dependent material properties.

Table 1 Main loads and boundary conditions used for the simulations.

Loads & B.C.	Mechanical module	Heat exchange module
Toroidal symmetry	Yes	Yes
Roller	Behind upper divertor	-
Channel fluid pressure [MPa]	0,2	-
Tank fluid pressure [MPa]	Hydrostatic	-
First wall load [MW/m^2]	-	0,5 @500 MWth
Neutron flux [MW/m^3]	-	Depending on material (16,5 for inconel's inner wall)
FliBe T [K]	-	Depending on fusion power
Channel convective coeff [W/K/m^2]	-	50000
Tank convective coeff [W/m^2/K]	-	5000

4.2 Results and discussion

First simulations showed that during transients the vacuum vessel did not experience any sort of stress and temperature hotspot nor anomalous peak, this is due to its relatively easy geometry: symmetry, single-piece with no welding and joints as well as thin enough walls help avoiding this type of issues in thermo-mechanical scenarios.

It has also been possible to notice that the stress and temperature depend on fusion power, this means that the higher goes the power, the higher the temperature and the stress get. This observation allows to conclude that to set up a creep and fatigue study it was possible to start with a chosen fusion power cycles, run its relative simulation and record the resulting stress, temperature and displacement that corresponded to the cycle's points of main interest, namely the lower, the mean and the higher peak power. This procedure got to simplify the study.

Figure 7 shows examples of Von Mises stress resulting from a 500 MWth and 1 GWth of fusion power. As stress is almost proportional to power, it is interesting to get an idea of the stress field value at the most likely mean power of a power cycle, that is supposed to be about 500 MWth and at the highest stress caused by thermal loads in normal operating conditions, namely the stress related to 1 GWth. Then, the stress in the right picture of Figure 7 is the maximum one that the vessel would experience. Focusing on the color scales, that show the entire spatial range of stress, the inner wall experiences the highest stress of 270 MPa and 450 MPa of peak respectively for 500 MWth and 1 GWth of power; while the lowest stress is recorded on the component's outer wall, that is around 50 MPa. The inner wall is also the one that experiences the highest stress change during a thermal cycle. In particular, for 1 GWth of power, the vessel gets to a maximum stress of roughly 450 MPa, and to a minimum of less than 200 MPa at about 200 MWth. This seems promising since the maximum stress recorded is way lower than Inconel's 718 yield strength, which is around 900 MPa at about 800 K (Bast and Boyce, 1995). This investigation has been carried out on the basis of design conditions. Future works should also analyze the level of uncertainty of the simulation, by performing a sensitivity analysis.

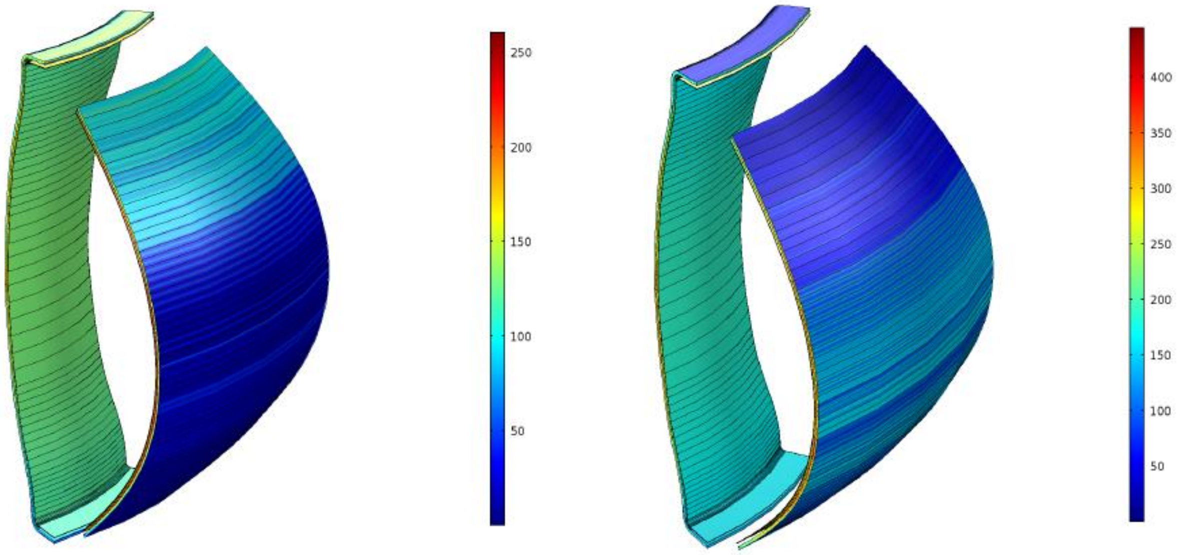

Figure 7 - Von Mises stress for 500 MWth (left) and 1GWth (right).

To better understand how the stresses are distributed along the thickness a zoom of the simulations has been done and reported in Figure 8. The scenarios of 500 MWth is reported as example. The left one depicts the Von Mises stress, while the right one shows the 3 principal stresses of a simulated thermal cycle ending at 500 MWth and reaching the steady state. It is possible to notice that, from a thermo-mechanical point of view and in normal operating conditions, the most endangered region of the vessel is the inner wall, which experiences a wide range of stress along its thickness, caused by the high temperature gradient. However the wall, compared to the main chamber cross-section, is thin enough to take the assumption of thin shell and then properly compute the average stress over its thickness for further analysis.

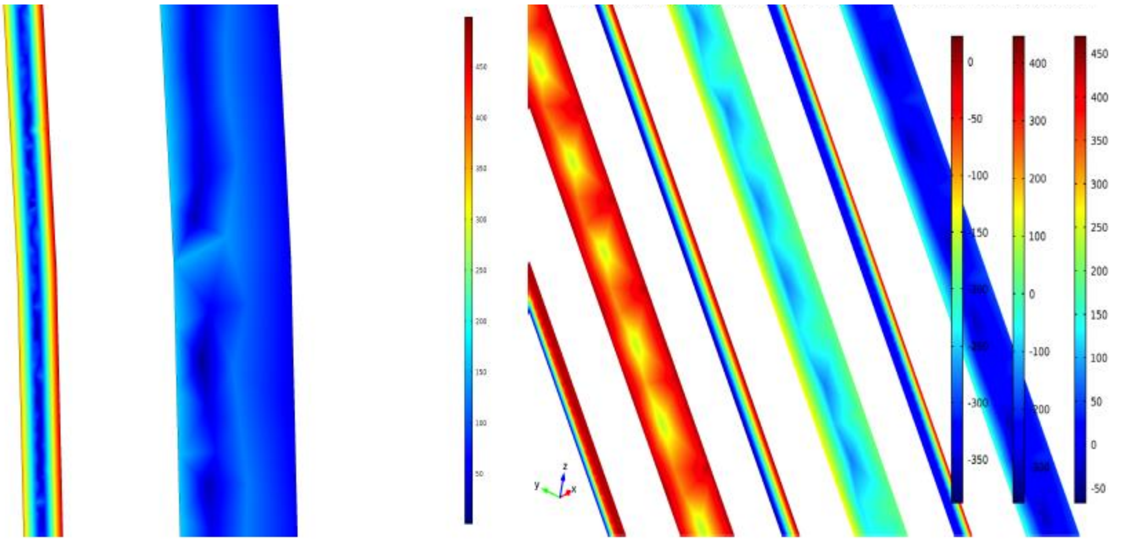

Figure 8 - Zoom in of the Von Mises stress at 500 MWth (left picture). Principal stresses and their relative color scales organized from the left to the right (right picture), picture taken at the end of a thermal cycle with mean power of 500 MWth. For both the images the zoom in has been done on the outer poloidal side of the vessel. All the stress reach their maximum, about 450 MPa, in the FliBe's side of the inner wall. The first principal stress is the only experiencing a compression of almost 450 MPa, on the plasma's side of the inner wall.

This stress is typical of a flexion. Bending is due to thermal expansion of the entire section, in fact the wall with the higher toroidal radius, which tends to distance the most from supports, experiences more stress: this is combined to stress due to temperature gradient through the wall itself. In fact, vessel's layers closer to plasma, which are the hottest ones and hence tend to expand the most, are compressed because of layers close to FLiBe, which are hundreds of Kelvin colder and therefore expand way less. They hinder expansion of hotter layers and experience a stretching because of them. This behavior is quite promising seeing how stretched walls, which are the most endangered and subjected to cracks, are the coldest and furthest from plasma too.

The only actual problems for thermal-mechanical resistance seem to be creep and thermal fatigue.

Before the beginning of the creep and fatigue analysis, the finite element model has been implemented with one last improvement: up to now neutron flux has been modeled as a volumetric heating source in the material, but it has been furthermore approximated as constant in the poloidal section. However even if ARC development team has not exact data about poloidal behavior of neutron flux, it is generally considered as acceptable the assumption that neutrons field in Deuterium-Tritium fueled D-shaped plasma shows a peak at half of the vessel's height, and the flux continuously decreases up to the divertors area, where roughly half of the peak flux is reached. From a thermo-mechanical point of view, a parabolic behavior of neutron flux in the poloidal section, with an overall power equal to the constant approximated one, seemed to be quite acceptable. Neutronic works are under development at the Massachusetts Institute of Technology, in particular, the parabolic assumption has been validated and assumed as realistic.

Creep is a phenomenon that occurs when a metallic material experiences constant high temperatures (it usually becomes not negligible at temperatures higher than roughly half of metal's melting point) and constant stress. It leads to a plastic, permanent deformation due to its grains sliding one on each other. It strongly affects a component's lifetime, which operates at high temperature conditions.

Thermal fatigue rises its issues in a component subjected to time dependent thermal loads and temperature cycles, this leads to changing temperature gradients and cycles on thermal expansion rates. If a component shows any type of structural constraint thermal expansion is translated in stress on the component; therefore a thermal load and temperature cycle lead to a stress cycle. This phenomenon is a key characteristic of a load-following power plant that, by definition, changes its power during its normal operations, almost cyclically, considering that it mainly follows the daily peak demand.

For the studied thermo-mechanical phenomena, namely creep and thermal fatigue, it has been decided to follow a probabilistic material strength degradation model proposed by NASA (Bast and Boyce, 1995). The proposed model should be able to deal with many phenomena present in structures; namely high temperature, high-cycle fatigue, low-cycle fatigue, creep and thermal fatigue. It is an interesting model not only for its flexibility but also because it is based on many experiments conducted exactly on Inconel 718, indeed the model and its main coefficients provide a calibration possibility for this super-alloy.

It is interesting to mention that phenomena such as thermal fatigue and creep are very tricky and hard to deal with; and even for the same component it is possible to experience very different results by changing just a working parameter such as, for instance, frequency or temperature. Luckily, Nasa's model also suggests how to deal with component's working conditions that differ from the ones set for the experiments that have been used to build the model itself. For ARC's vacuum vessel this is the case of the cycle frequency and the temperature. For instance, here for frequency no calibration was needed, since the expected frequency for ARC's load cycles is quite similar to the experiments' one (that is roughly 10^{-4}- 10^{-3} Hz); on the other hand, the average temperature experienced by the vacuum vessel during the load cycles is quite higher than the one reported in Nasa's experiments. This needed an adjustment to the model, which is translated in an additional element in the product structure of the equation that follows.

The paper indeed proposes a unified equation of which coefficients are calibrated for each above-mentioned effect:

$$\frac{S}{S_0} = \prod_{i=1}^{n} \left[\frac{A_{iU} - A_i}{A_{iU} - A_{i0}}\right]^{a_i}$$

Where n is the number of effects which component is subjected to; A_i, A_{iU} and A_{i0} are the current, ultimate, reference value of a particular effect; a_i is an empirical material constant for the i^{th} product terms of variables in the model; S and S_0 are the current and reference value of material strength. For what concerns this study, A is a temperature for the high temperature model, a time for the creep model and a number of thermal load cycles for thermal fatigue model; a is an empirical exponent which takes into account other important parameters in the single model, for instance in the creep model it deals with average temperature of the component. For creep effect, Inconel's strength degradation is mostly affected by the exponent, which is temperature dependent: it indeed could decrease the strength by a factor of 5-6 for very high operating temperature and after years of lifetime. This is why a maximum allowed temperature of 930 K - way lower than the melting point of 1570 K - has been set for the structure; since exceeding around 930 K Inconel's stress limits start decreasing relatively quickly, too much with respect the order of magnitude of time requested, which is the units of years (Brinkman et al, 1991). To ensure that the structure would not exceed the chosen temperature heat exchange equations have been computed for each of the plasma power step previously set, namely from 100 MWth to 1 GWth with the aim of coming up to the FLibe's requested temperatures. A dynamic system able to change coolant's flow rate and inlet temperature while the plasma changes power would allow the vessel's temperature not to get above the chosen temperature threshold; several FEM simulations have been done for checking the right FLiBe's temperature for each power step.

Once the model has been calibrated, it has been possible to put the A_i value required for the desired lifetime, study each effect present in the model and analyze the information obtained on the component resistance.

Following the strength degradation model proposed by NASA it has been possible to carry out a first evaluation study for the component's lifetime. Since the proposed equation's coefficients depend on time for the creep's factor and on the number of cycles for the thermal fatigue factor it has been possible, by choosing the most likely number of cycles per day, to compute a safety factor that compares the resulting stress from the simulations and the resulting one from the computations. It follows that the vessel is supposed to fail when the safety factor rises above 1. Seeing as how the first results of 3 cycle per day, which is believed to be a likely frequency for the major cycles, got promising, it has been decided to compute also less probable scenarios, such as 10 and 20 cycles per day, in order to assess the behavior of the component and its lifetime. Figure 9 shows some results of this investigation. It shows that the vessel is quite able to allow ARC to change its power in complete safety from a thermo-mechanical viewpoint.

The investigation focused on the quantification of the time needed for the vessel (and as a consequence the Tokamak) to fail due to repeated thermal stress when working as load-following: it can be observed that the vacuum vessel's lifetime may be quantified from three to five years according to the frequency of the thermal cycles.

However, because of the physical effects such as neutron embrittlement and neutron induced activation in the Tokamak structures, the vacuum vessel of ARC Reactor is thought to be replaced no later than two years of operation. Therefore, the main conclusion of this modeling activity is that thermal fatigue, which is the most concerning phenomenon in a load-following scenario, is not the most challenging issue for the design of the ARC vessel. Additional investigation in particular concerning a sensitivity analysis must be performed in the future to validate this preliminary considerations.

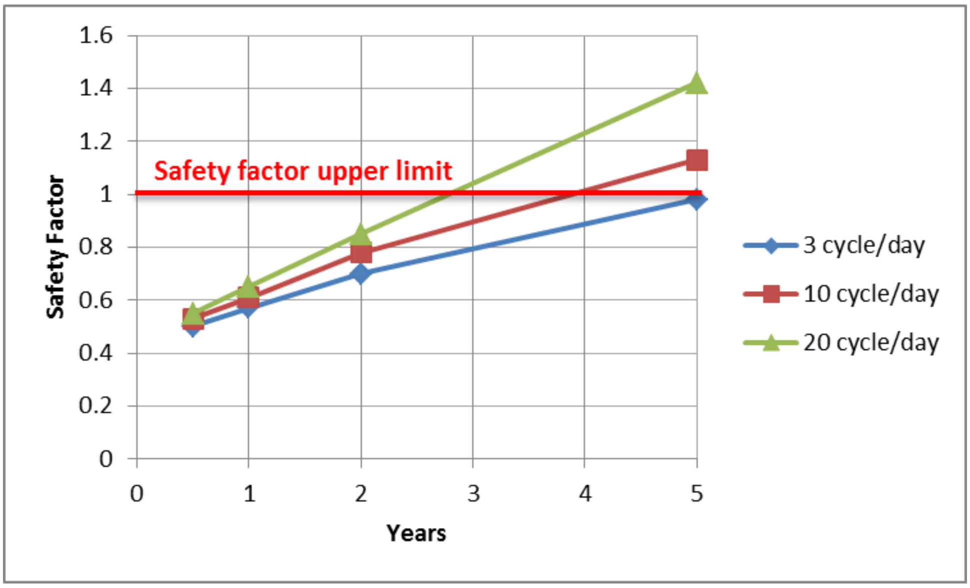

Figure 9 - Vessel's lifetime prediction for cycles from 300 MW_{th} to 800 MW_{th} of fusion power.

5. Conclusions

In the Twenty-First Century, energy is no longer just a technical issue. The discipline that studies energy has rapidly expanded its sphere of competence and an interdisciplinary research is fundamental to face the energy problem. Hence, addressing the issue of energy means now consider also environment, society, materials science, and political aspects.

The main energy-related problems that the world experiences even in everyday life are the air pollution and the climate change, directly caused by combustion products and CO2 emissions. Because of that ecosystems are changing, glaciers are melting and seas' level rising, while incidence of human's health diseases increases.

There are also several other problems related to today's energy sources: fossil fuel's story accounts for environmental disasters such as, for instance, Vertical Horizon's platform or tanker sinking. Nuclear fission has lost public consensus and caused several damage to the environment after Chernobyl and Fukushima's disasters. In the meanwhile energy demand rises year by year and it is not supposed to decrease or stabilize, trying to focus on short term solutions such as improving efficiency and reducing emissions and waste of energy and materials in existing plants and technologies is not sufficient. Cutting edge technologies are required in order to solve the mentioned issues.

In this framework, the investigation of new energy sources and/or technologies can be a part of solution to face the energy problem. One of these new energy sources is represented by the fusion nuclear energy. This source in particular is recognized by Scientific World Community as one of the candidates for long-term solution, for developed countries; great hope is associated with nuclear fusion, which is considered an environmentally friendly solution to sustainable electricity production.

Generically speaking, once this technology will be commercially available, it would be able to substitute partially or entirely fossil fuels, reducing the problem of greenhouse gases and environment pollution, that are to this day the most concerning and harmful issues in energy and environment fields. In this context it is easily foreseeable that energy industry would change face and get revolutionized: energy companies would start a run to make their own reactor designs and licenses, while there will probably be a new gold rush for lithium. Moreover they would reroute funds from enhancing existing energy sources to reaching and improving fusion energy.

Researchers would be more interested in nuclear technologies and would aim to solve the problems that fusion still have, such as tritium handling, reactor material activation and electricity cost lowering.

Furthermore it will be necessary the creation of new nuclear energy policies, for installation site choices, safety policies for workers and environment, new rules for tritium handling and policies for the decommissioning as it will be the most concerning for the public.

In the meanwhile, other industries would adapt themselves to the new energy source, for instance electric transports and electric house heating would be promoted in order to avoid city-centre’s pollution: as cleanly-produced electricity would be available, there would be no reason to keep polluting with internal combustion engines and similar technologies.

Nuclear fusion would be able to take fission’s place too; its public consensus is dropping even faster than uranium’s supplies on Earth and, as previously mentioned, it would be superfluous to deal with fission’s radioactive waste.

It is very likely that fusion will not erase the mentioned sources, at least for the first decades, as they have been made more reliable for the electricity grid by experience, fusion will probably make their use decrease far enough to get a cleaner atmosphere.

However, the connection of fusion energy plants to the grid is supposed to be reached decades from now (ITER, 2018).

In the specific of this field, a study has shown a new technology that can be proposed in the energy market. This project is the Affordable Robust Compact (ARC) fusion reactor, a new generation of fusion reactor born thanks to the advent of high temperature superconductors, additive manufacturing, new diagnostics and materials. In this context, a research group of scientists and engineers of Massachusetts Institute of Technology began to design ARC. It represents a cheaper, smaller, but even more powerful, faster way to achieve fusion energy with respect to the existing projects on fusion energy. In terms of energy policy, the adoption of the ARC concept would permit to move nuclear fusion from a far-future energy source to a short-term solution for peak electricity production in developed countries.

One of the most innovative characteristics of ARC, in fact, is the load-following capability. Since plasma can quickly change its power output, a load-following power plant, based on the ARC concept, can be connected to a grid characterized by several other intermittent energy input, such as solar and wind based power plants. In this case, the ARC reactor could be not only the base-load energy producer, as all the other fusion projects are supposed to be, but also a load-following one, capable to cover peak requests and other plant shutdowns.

This aspect of ARC would not only revolutionize the electricity grids, but also will get them more reliable and efficient, allowing scientists and technologists to better develop renewables to integrate the grid itself. It would be indeed not discouraged a grid made only with renewables and a set of ARC-like reactors, letting the tokamaks change their power as renewables increase or decrease their output.

Furthermore as ARC is affordable and compact would easily fit in a very copious quantity of possible sites, allowing stranger’s energy dependent countries (e.g. Italy) more independency.

In order to highlight and provide evidence of the load-following capability the proposed study has been carried out and it has shown that one of the main stressed component of ARC is the vacuum vessel. The performed analysis has been focused on the quantification of the time in which the vessel would fail due to repeated thermal stress when it works as load-following. It has been demonstrated that the vacuum vessel lifetime can be quantified from three to five years on the basis of the thermal cycles considered (i.e. 3, 10 and 20 cycles per day). However, there are several more aspects to take into account and study in order to be perfectly sure that the vessel would survive for the desired time. From a thermo-mechanical viewpoint, it has been demonstrated that a load-following working condition is not an extreme issue for the vessel, and this allow us to go ahead and take the next step in the investigation. Indeed, it will be also interesting to study which would be the effect of neutrons on the structure, they have been taken into account here as a heat source, but neutrons could also embrittle the material causing a faster-than-expected degradation of the mechanical as well as thermal properties of the structure. There is therefore a possible interplay between the neutron's effect and thermal effect, for this reason it has been decided to replace the vacuum vessel every couple of years, while waiting for more data about the effect of neutrons in this type of component in such operating conditions.

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