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Advanced Fuel Cycles for Fusion Reactors: Passive Safety and Zero-Waste Options

Massimo Zucchetti[1], Linda E. Sugiyama[2]

[1] Politecnico di Torino, Corso Duca degli Abruzzi 24 – 10129 Torino (Italy)
[2] Massachusetts Institute of Technology, Cambridge (MA), USA

Email: massimo.zucchetti@polito.it

Abstract. Nuclear fusion is seen as a much "cleaner" energy source than fission. Most of the studies and experiments on nuclear fusion are currently devoted to the Deuterium-Tritium (DT) fuel cycle, since it is the easiest way to reach ignition. The recent stress on safety by the world's community has stimulated the research on other fuel cycles than the DT one, based on 'advanced' reactions, such as the Deuterium-Helium-3 (DHe) one. These reactions pose problems, such as the availability of ^{3}He and the attainment of the higher plasma parameters that are required for burning. However, they have many advantages, like for instance the very low neutron activation, while it is unnecessary to breed and fuel tritium. The extrapolation of Ignitor technologies towards a larger and more powerful experiment using advanced fuel cycles (Candor) has been studied. Results show that Candor does reach the passive safety and zero-waste option. A fusion power reactor based on the DHe cycle could be the ultimate response to the environmental requirements for future nuclear power plants.

1. Introduction

Nuclear fusion is seen as a much "cleaner" energy source than fission. However, the attractive safety and environmental potential of fusion can be fully realised by a design in which attention is paid to reducing the impact of materials activation and tritium inventory [1]. Activated materials, generated by neutron interactions with plant structure, will be removed from the plant during routine component replacements, and then in decommissioning at end-of-life. Tritium is a mobile and soluble nuclide with radioactive safety relevance.

Demonstration of the reactor "Passive Safety" (no need of active safety systems to control and mitigate the consequences even of the worst reasonably conceivable accidental sequences) is a key issue for showing a clear advantage of fusion versus fission power, in view of its public acceptance. Several studies in the European Power Plant Conceptual Study (PPCS) [2] and in the US ARIES [3] programs intend to assess fusion safety and also to evaluate the reactor behaviour in case of the worst reasonably conceivable accidents. Concerning radioactive waste, since most of fusion waste comes from relatively low activated material, in shielded position from the plasma, it is

[1] To whom any correspondence should be addressed

appropriate to explore solutions that minimise the use of final repositories. For this purpose, a waste management strategy must aim to:

- Recycling of moderately radioactive materials within the nuclear industry.
- Declassification of the lowest activated materials to non-active material (Clearance), based upon, for instance, on the recently issued IAEA clearance levels [4].

If all the material could be declassified according to the latter option after a relatively short interim storage, then we could have the so-called "zero-waste option" for fusion [5].
Concerning D-T fusion, it has been found that, even if feasible in theory, a zero-waste option will not be possible: a relevant amount of radioactive materials from reactor decommissioning – even if "recyclable" – should be disposed of as radioactive waste. Most probably, those materials will meet requirement for classification as Low Level Waste. The production of such waste cannot be avoided – for fusion power reactors – by means of the choice of their structural and constituting materials: it always occurs if a Deuterium-Tritium fuel cycle is used. Studies have shown [6] that it is practically impossible to reduce the long-term radioactivity of those materials to levels allowing clearance. A further step – if the passive safety and zero-waste result have to be achieved - is necessary.

2. Deuterium-Helium-3 Fuel Cycle

Most of the studies and experiments on nuclear fusion are currently devoted to the Deuterium-Tritium (DT) fuel cycle, since it is the easiest way to reach ignition. Even if physical and technological demonstration of fusion power has yet to be obtained, some of the main technological questions of future DT fusion reactors have been identified already. Among those, in particular, the radioactive inventory in such reactors is due, besides tritium, to the neutron-induced radioactivity in the reactor structures.
The recent stress on safety by the world's community has stimulated the research on other fuel cycles than the DT one, based on 'advanced' reactions, such as Deuterium-Deuterium (DD) and Deuterium-Helium-3 (DHe). With these cycles, it is not necessary to breed and fuel tritium. The DHe cycle, moreover, has a very low presence of fusion neutrons. In fact, the DHe cycle is not completely aneutronic, due to DD side reactions generating 2.45 MeV neutrons and T, and to DT side reactions generating 14.07 MeV neutrons.

DHe fusion has its own set of problems, such as the availability of ^{3}He and the attainment of the higher plasma parameters that are required for burning. However, they have also other advantages, like for instance the possibility to obtain electrical power by direct energy conversion of proton. A fusion power reactor based with DHe plasmas would not need a blanket to breed tritium, and also it would not need to produce electrical power indirectly, via the usual heating of a thermo vector fluid (such as water of liquid metal) and its use in a thermodynamic cycle with a turbine [7].
In other words, we do not find in a fusion power reactor with DHe plasmas any similarity left with nuclear fission reactors.

3. Ignitor and Candor

To begin to explore the possibilities of DHe plasmas, a DT burning plasma experiment at high field and plasma densities, which can be much closer to the required parameters than present-day experiments, is particularly attractive [8].
Compact high-field experiments were the first to be proposed in order to achieve fusion ignition conditions on the basis of existing technology and the known properties of high-density plasmas. Good confinement and high purity plasmas have been obtained by high field machines Alcator/Alcator C/Alcator C-MOD at the Massachusetts Institute of Technology [9] and Frascati Torus Upgrade (FT/FTU) at ENEA in Italy [10].

Ignitor is a proposed compact high magnetic field tokamak, and it is aimed at reaching ignition in DT plasmas and at studying them for periods of a few seconds [11-13]. However, the plasma density limit in Ignitor is well above the optimal density for DT ignition, and it is suitable to the higher densities required for DHe burning. In fact, Ignitor has been also designed to satisfy conditions where 14.7-MeV protons and 3.6-MeV alpha particles produced by the DHe reactions can supply thermal energy to a well-confined plasma [14]. In particular, Ignitor can sustain plasma current exceeding that required to confine proton orbits at birth, and has more than sufficiently high densities so that the slowing-down time of both the protons and alpha particles is shorter than the electron energy replacement time of the thermal plasma in which they are produced. Preliminary analyses show that a fusion power $P_F \cong 2$ MW may be reached [15]. In particular, as a start, Ignitor can allow initial studies at the level of approximately 1 MW of power in charged particles from the DHe reaction in a mostly DT plasma [14-16].
A design evolution of Ignitor in the direction of a power reactor using a DHe fuel cycle has been proposed. A feasibility study of a high-field DHe experiment of larger dimensions and higher fusion power than Ignitor, however based on Ignitor technologies, has brought to the proposal of the Candor fusion experiment [8,14]. The main characteristics of the Candor machine are the following: the major radius R_o is about double than Ignitor, plasma currents up to 25 MA with toroidal magnetic fields $B_T \cong 13$ T can be produced. Unlike Ignitor, Candor would operate with values of poloidal beta around unity and the central part of the plasma column in the Second Stability region. The toroidal field coils are divided into two sets of coils and that the central solenoid (air core transformer) is placed between them in the inboard part.
The DHe ignition regime can be reached by a combination of ICRF heating and alpha particle heating due to DT fusion reactions that take the role of a trigger. Thanks to this fact, and unlike other proposed DHe fusion experiments, Candor is capable of reaching DHe ignition on the basis of existing technologies and knowledge of plasma. With this method, the need for an intense auxiliary heating, which is one of the main technological drawbacks of DHe ignition, would be considerably alleviated, becoming feasible with the present technology. However, this method has the disadvantage of using tritium and of presenting a higher neutron flux (due to DT reactions) than 'pure' DHe plasmas, and a neutron flux transient when passing from the initial DT trigger reaction to the final DHe burning plasma.
The characteristic times over which the plasma discharge can be sustained are longer by more than a factor of 4 than those of Ignitor.

4. Safety assessment

Tritium inventory in Candor is expected to be very small and not to be a problem from the safety viewpoint.
As far as neutron-induced radioactivity is concerned, neutron transport calculations to determine its neutronics were performed for Candor, and the results are available in [17]. Neutron activation has been calculated in [17] also: activity concentrations and dose rates are the main output of the simulation. Table 1 shows activation data at end-of-life (maximum) irradiation.
The main result of the study is that neutron activation is quite moderate. For instance, the maximum dose rate of the most radioactive component is 600 times lower than that for Ignitor after the end of DT operation.

Concerning demonstration of the reactor passive safety, it would be necessary to evaluate the reactor behaviour in case of the worst reasonably conceivable accidents. Those assessments have yet to be completed for Candor, however a preliminary evaluation can be carried out in terms of consequences of an environmental release of activated reactor material in case of accident.
We may evaluate the dose to Most Exposed Individuals (MEI) of the population around the reactor site, due to the release of a given quantity of activated material, say 1 kg of the most activated

component at the end of machine's life (higher activation case). A short-circuit in the reactor magnets could lead to partial meltdown and vaporisation of that component, and – in absence of any active or passive mitigation – to the release of the radioactive vapour to the environment.
However rather conservative, this scenario is useful for a first assessment. We used the GENII population dose code [18] for our estimates. Results show that the airborne release of 1 kg of activated material from the internal toroidal magnets (at their highest activation, that is, about 4.3 10^6 Bq/kg with no interim cooling), would cause an Effective Dose Equivalent (EDE) to the MEI of about 5.2 10^{10} Sv, all pathways included, committed EDE due to an acute release, no mitigation. Cu64 is the main nuclide contributing to the EDE. This value is practically irrelevant from any radiological viewpoint. However, if we think to a conservative amount of the Candor most activated components that could be accident-prone in theory (say, 100 tons), our results permit us to determine that, even if all those Candor machine components were instantly vaporised and released via atmosphere to the environment, the committed EDE to the population's MEI would be insignificant, no more than a few microSieverts committed in 50 years. One can compare this value to the annual natural background radiation level (around 2000-3000 microSievert). This means complete passive safety from the radiological viewpoint for Candor, in case of any conceivable accident.

Concerning radioactive waste, the quantity and quality of radwaste from the machine exercise and decommissioning has been estimated: total radioactivity concentrations in Table 1, nuclides concentrations and gamma dose rates show that no Candor spent material will need to be disposed of as permanent waste in underground repositories. All materials will be able to be recycled, if convenient, after a short interim decay. Most of the components far from the plasma, on the other hand, could be declassified to non-radioactive waste and released from regulatory control. In practice, all the components - even those closer to the plasma chamber - if a longer interim decay is accorded, can be eligible for clearance, according to the IAEA limits. In particular, all components but internal magnets may be declassified after less than 10 years of decay. For internal magnets, 20 years of interim decay are necessary. Candor does reach the zero-waste option, without the need of any materials selection, low-activation materials, or shielding.
The final design of a fusion power reactor with DHe plasmas has yet to be conceived. However, the passive safety and the zero-waste option is a reachable goal for such reactors, as the results for Candor have indicated.

Table 1 - Neutron activation in Candor main components. Activity concentration (Bq/g) at different decay times after maximum (end-of-life) irradiation.

Component	**Zero**	**1 day**	**1 week**	**1 month**	**1 year**	**10 y**	**25 y**
Internal Toroidal Magnets	4.3 10^6	8.0 10^5	9.2 10^2	5.1 10^2	3.9 10^2	1.3 10^2	40
Transformer Coils	3.0 10^5	5.9 10^4	5.1 10^1	2.4 10^1	1.7 10^1	5.0	1.7
External Toroidal Magnets	9.7 10^4	1.9 10^4	1.3 10^1	5.4	2.8	0.47	0.18
Structure (C-Clamp)	1.4 10^3	9.6 10^2	2.6 10^2	4.2 10^1	2.0	0.21	0.023

Conclusions

This paper concentrates upon the safety and radioactive waste issue for fusion. Innovative solutions in those areas could be a clear advantage of fusion power versus fission, in view of its ultimate safety and public acceptance. Concerning waste, clearance (i.e., declassification to non-radioactive materials) of all reactor components, after a sufficient period of interim decay, should be the final goal for an environmentally acceptable reactor. Demonstration of the reactor passive safety it would also be necessary: this concept may be translated as negligible doses to population even in case of the worst conceivable accidents with radioactive environmental release.

Even if feasible in theory, a zero-waste option for fusion reactors using the Deuterium-Tritium fuel cycle will be difficult to obtain: a relevant amount of radioactive materials from reactor decommissioning – even if recyclable within the nuclear industry – should be disposed of as radioactive waste, mainly due to economic reasons connected with the excessive interim decay time that is necessary to allow their recycling. Most probably, those materials will meet requirements for classification as Low Level Waste.

As a further step towards the zero-waste and passive safety options, the features of fusion reactors based on alternative advanced fuel cycles have been examined, to assess whether those goals could be reached with such devices.
In fact, fusion reactors with advanced Deuterium-Helium-3 (DHe) fuel cycle have quite outstanding environmental advantages, such as the quite low presence of Tritium, neutrons and activated materials. Ignition in DHe plasmas, however, is much more difficult to obtain than for DT plasmas. Compact ignition tokamaks can be designed in order to achieve DHe ignition without excessive auxiliary heating, if a DT plasma is used as a 'trigger' for the DHe reaction. Ignitor, a compact ignition experiment aimed at studying DT plasmas, may also be used in that direction. The extrapolation of Ignitor technologies towards a larger and more powerful experiment using advanced fuel cycles (Candor) have been described too.

Results obtained for the Candor study show that no environmental problems will arise from such reactor, from the radiological point of view, even with the presence of DT plasmas triggering. Candor does reach the zero-waste option. Concerning safety, we have shown complete passive safety from the radiological viewpoint for Candor, in case of any worst conceivable accident.
Studies for the development of compact ignition tokamaks and advanced fuel cycles must be carried out in parallel with the current mainstream development line, which deals with larger tokamaks and DT plasmas, i.e. the ITER (International Tokamak Experimental Reactor) and DEMO designs.
We think, in fact, that a fusion power reactor based on the DHe cycle could be the ultimate correct response to the environmental requirements for future nuclear power plants.

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