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# Discussion on fast track and impact on materials R&D strategy – fusion material issues for the energy systems in future

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## Abstract

The requirements for fusion reactor materials and the impact of reactor study on these requirements are discussed within the strategy for early generation tokamak plants, often called the 'fast track' approach. Two major features of the fusion materials, high operating temperatures and reduced activation, are considered as examples. When the entire plant is designed, the use of high temperature materials does not guarantee high thermal efficiency, and selection of reduced activation material does not necessarily lead to reduction of waste quantity. In order to achieve these goals, careful coordination of the thermal design of the blanket and generating turbine systems for efficiency, and coordination of nuclear analysis and waste management policy for waste reduction, are respectively needed. These considerations show the importance of integration of materials development and system design.

## 1. Introduction

The first generation fusion power plants that will follow the successful demonstration of burning plasma in ITER are planned in many countries. While it is generally expected that such plants are to be built around 2030s, the required features are different due to the social requirements in each countries. In the past, fusion material studies have focused on feasibility issues. However in the future energy market where fusion is expected to be deployed, additional requirements for reactor materials must be considered from view points of safety, environment, economy, social acceptance, etc.. These issues come from public selections of energy sources for the market, and fusion energy is characterized by the materials selection, blanket design and reactor concept. In the development program for fusion energy (the fast track approach), the requirement and development programs for materials should be more specific and relevant so that the product will lead to the ultimate objective – a socially acceptable and economically competitive fusion plant. Careful design and system integration are also strongly required to achieve this objective.

The development strategies for fission and fusion are quite different in the aspects of material selection and integration. In fusion, the blanket is physically separated and rather independent from the plasma, and that allows blankets to be developed and tested in programs relatively independent of the schedule of the major reactor device. For instance, ITER will accommodate at least 6 types of blanket test modules that will be developed by various parties, and be improved and replaced during the life of the plasma device. Various types of blankets can be evaluated in the same plasma confinement device, and thus blanket concepts using RAFs, vanadium and SiC composite for structural materials; water, gas, liquid metal and salt for coolants, will be studied simultaneously for possible use in tokamak power plants. This feature allows a more efficient development strategy and flexibility for fusion than was the case for fission. For fission, different types of reactor:

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liquid metal, carbon dioxide, light water, heavy water, molten salt, helium, etc., have been developed in the past. Each reactor type had different mechanisms, neutronics, fuel designs, etc., because the control of the nuclear fission reaction and the energy extraction cannot be separated.

On the other hand, this feature is one of the reasons that development of materials and blankets are still in the early phase, compared with plasma study. No existing plasma devices, even ITER, is equipped with a power producing blanket, because blankets are not required to maintain and improve the plasma performance. It should be noted that no concrete performance requirements are given for power blankets, while several development programs are implemented aiming at the first generation of fusion power plants. Operating temperature, strength, dose, safety features, economy, and all other requirements for the materials to be developed and selected, have not been defined yet, because no concrete power plant design at this level of detail is available. This paper will discuss this problem, to identify some features and considerations for the materials required for the first generation of fusion plants.

## 2. General requirements

Fusion reactor energy generation stations must be evaluated from the aspect of material balance and energy balance, which means, what is consumed and discharged as the result of construction, operation, maintenance and decommissioning. The blanket and its materials are a major part of the interface between the fusion plant and the outside society that actually provides the resources to plants, obtain the benefit energy, and accepts the emitted wastes. Briefly, the functions of the blanket are; neutron shielding, tritium breeding, and conversion of the neutron energy into a usable form. However when performance is evaluated, the measure is the benefit and cost/damage to the society in the outside world, that is sometimes called as 'externality', because it is not usually included in the direct cost of the electricity [1]. This aspect, shown in the Fig. 1 is the 'socio-economic' feature of fusion that must be considered at this stage of development. For instance, researchers tend to think a required feature of the material would be the 'reduced activity', but the public sees the results as the amount (metric tones, cubic meters or number of drums), not the activity in Becquerel, cross section or impurity concentration, etc. This leads to the recognition that the integrated blanket and materials will be evaluated not only from their technical specification but also from the eventual impacts on the market, environment and public.

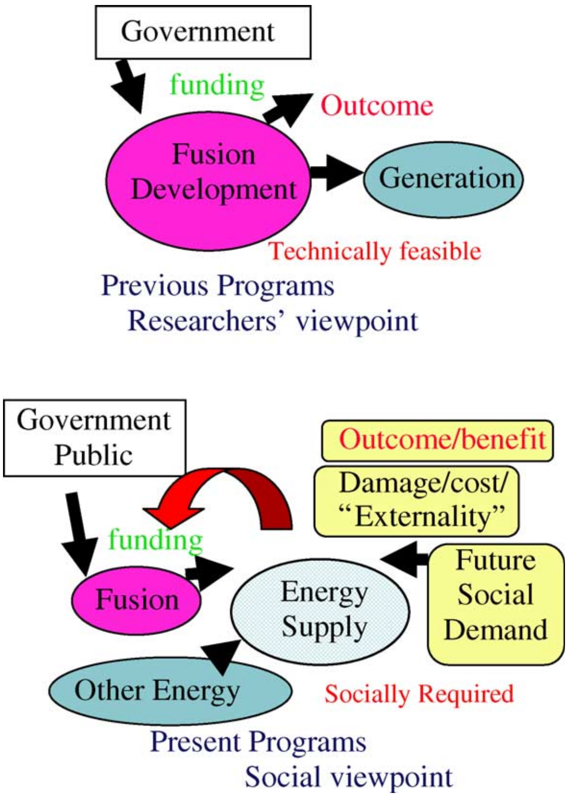

Fig. 1. Socio-economic evaluations of fusion research.

## 3. Operational temperatures of materials

It is obvious that the economy of fusion energy is strongly dependent on the temperature of coolants from the blanket, because the thermal efficiency is limited by this temperature. However, although a high temperature material is required for higher efficiency, it does not always guarantee improved efficiency. It should be noted that the state of the art generation technology of combustion-powered stations is based on supercritical water or gas turbines, that will allow limited material selections for earlier generation fusion plants because these cycles have specific temperature requirements. Steam turbine cycles for light water fission reactors are also sophisticated system, but their operating temperature is limited as these reactors use water for moderator. Due to the neutronic design, liquid water is needed for light water reactors and coolant temperatures below the critical point does not allow efficiency beyond approximately 33%. Fusion reactor blankets surrounding a burning plasma have a topologically similar configuration to combustion powered boilers and generation plants. If the material and blanket design integration do not have other restrictions, the best combustion cycle technology at the time of the fusion plant design will determine the coolant and material temperatures.

Early generation fusion plants anticipate using reduced activation ferritic/martensitic steels as primary candidate materials for blanket coolant channels. The upper temperature limit for RAFs is about 550–600 °C, that is suitable for the supercritical water cycles of the current combustion powered plants. Fusion plants in the 'fast track' approach are expected to drive this type of power plant, if they emphasize total thermal efficiency and take advantage of the current generation plant technology. Operation at either higher or lower temperature is not realistic and efficient from the viewpoint of a development strategy that takes maximum advantage of current technology.

Fig. 2(a) and (b) show examples of the plant concepts for the supercritical cycles of direct and indirect cooled fusion reactors [2]. It is obvious that the design of fusion power plants will take advantage of the knowledge of operating combustion-powered and nuclear plants. Direct and indirect cycles correspond to the pressurized water reactor (PWR) and boiling water reactor (BWR), but both fusion designs circulate 500 °C supercritical water as the primary blanket coolant. While the flow diagrams are quite similar to those of light water reactors, thermal efficiencies are 41% for direct and 38% for

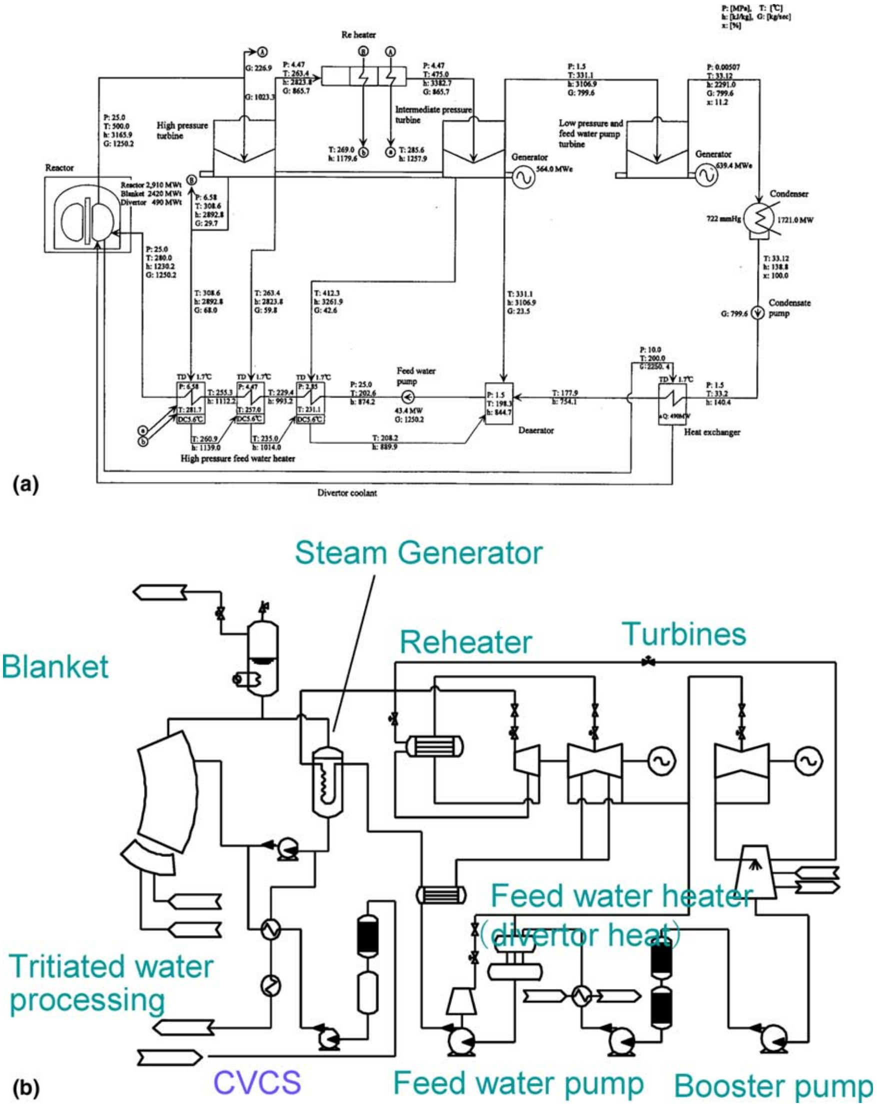

Fig. 2. Flow diagrams for fusion power plant generating systems. (a) Direct supercritical water system. (b) Indirect supercritical water system.

indirect cycle because of the high vapor temperature. In order to develop these systems, however, managing water contaminated with tritium, and compatibility of the material with supercritical water, are major feasibility issues to be solved. In the integrated design of the thermal plant, effective use of the heat from divertor is another problem. The divertor will have to handle a far higher heat flux than will the blanket, and thus the coolant temperature must be relatively low, so that effective use of that energy is difficult.

Gas cooled systems were also designed and evaluated for the same temperature range. With gas cooled blankets, either a gas heated steam generator, or a direct cycle turbine with gas near 500 °C can be designed, but it was found that the direct cycle gas turbine showed very poor efficiency. Therefore the only possible choice for a gas cooled blanket at 500 °C is a gas heated steam generator, that has efficiency lower than the water cooled systems. Table 1 summarizes the efficiency of the power plant of these three cycles. As far as the efficiency is concerned, the direct water cycle in the best, but the tritium concentration in the coolant is anticipated to be the highest.

In order to take advantage of the efficiency of high coolant temperatures, 900 °C or higher is needed to drive gas turbines [3]. For such a plant, SiC composite materials, closed cycle gas turbines and other novel technologies will be needed. For coolant temperature between 650 and 900 °C, there is no proven power plant technology available and applicable for fusion. If such a coolant is chosen, generation technologies specific to fusion must be developed. In any case, energy utilization systems for fusion should be compatible with the future energy market, which may be quite different from that of the present times. For instance, hydrogen production and use of high temperature heat may be one of the major energy demands and could be far larger than electricity demand in the future when consumption of fossil fuel and emission of carbon dioxide is strongly discouraged. Material and blanket development will have to take this fact into account.

Table 1
Comparison of generation system parameters for three for fusion plant concepts

| | Direct cycle water | Indirect cycle water | He gas |
|---|---|---|---|
| Main steam pressure (MPa) | 5 | 16.3 | 10 |
| Turbine temperature (°C) | 500 | 480 | 500 |
| Coolant flow rate (kg/s) | 1250 | 1260 | 1865 |
| Vapor flow rate (kg/s) | 1250 | 1037 | 908 |
| Total generation (MW) | 1200 | 1090 | 1028 |
| Thermal efficiency (%) | 41.4 | 38.5 | 35.3 |
| Technical issues | Tritium in coolant | Steam generator | Expansion volume |

Thermal efficiencies in other thermal Plants: BWRs – 33%, PWRs – 34%, Supercritical Fire – 47%.

## 4. Reduction of radioactive wastes

Use of reduced activation materials is required from safety and waste issues. Solid wastes can be evaluated by various methods. Amount, either volume or mass, may be even more important than activity or contact dose for economic and social acceptance reasons, because the physical quantity and the classification are the visible result of waste generation and disposal. Activity is, however important when ‘clearance’ of the waste is attempted [4]. Contact dose is the essential measure to evaluate recycling or reuse of components, intended for waste reduction.

Therefore, although low activation materials are needed, they do not always result in reduction of waste quantity. Blankets made of reduced activation materials will be classified as ‘mid level’ waste, despite the significant improvement in activity reduction in such materials. Blankets will be heavily irradiated with fusion neutron, and it is impossible to avoid the blanket materials becoming highly activated wastes. Fig. 3 shows a typical radial build of a fusion power plant. This shows that the components behind the blankets; including the shield, superconducting magnet, and coil cases; have much larger volume of material than the blanket, and thus have larger impact on waste quantities. This suggests that it is efficient to enhance the performance of the shielding to reduce the waste quantity, because such a shield may keep these outer components below the ‘clearance’ level [5]. Once waste is classified into a certain category, the activity level has little impact on the cost or public acceptance of the solid waste, because handling and disposal procedure are essentially set by the category. Of course ‘clearance’ is not commonly implemented yet in many countries, categorization of wastes to be considered exists in most

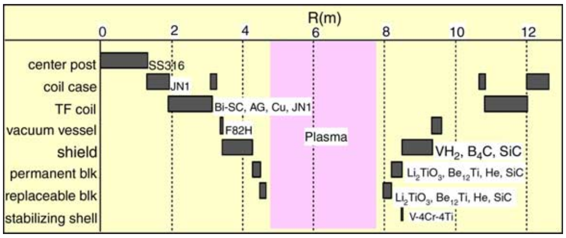

Fig. 3. Radial Build of a high temperature gas cooled reactor A-SSTR2 designed to the minimum waste concept [5].

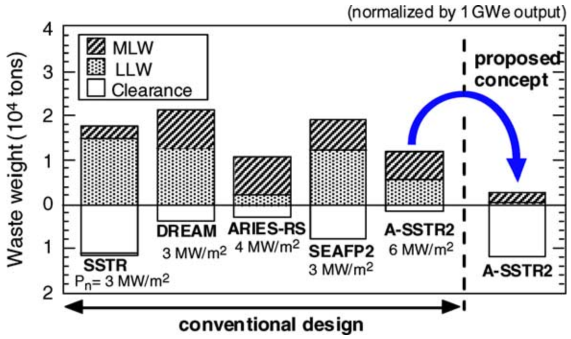

Fig. 4. Effect of the waste minimization design applied to A-SSTR2, and comparison to waste quantities in other conceptual designs.

countries. In Fig. 3, a new shielding material, vanadium hydride, is specified because of its higher hydrogen density than in any other conventional shielding materials. Fig. 4 shows the result of such a waste minimizing design. The weight of the waste can be reduced by one order of magnitude down to about 2000 metric tons through the lifetime of a 1 GWe plant. This methodology must be considered in fusion plant design and system integration, so that waste generation be minimized. Any fusion machine will be analyzed by neutronics and nuclear analysis for tritium breeding, activation, shielding and heat generation. Nuclear assessments will provide guideline for radiation damage and activation for each component. This analysis eventually determine the requirements for materials; i.e. lifetime neutron fluence, irradiation temperature, composition and impurity concentration. Solid wastes will be either cleared, classified to lower level groups, or if it is unavoidable, to become waste. Reuse or recycling must also be considered. In these latter cases, materials will be controlled for lower surface contact dose, because this is the essential metric for component handling in the reuse or recycling processes. Recycling may cost more than disposal of used materials and production of new components, but may be more effective to reduce radioactive emission from fusion energy, and thus more important for public acceptance of fusion. Such a feature must be considered for early generation fusion plants, because it will determine the environmental friendliness and public acceptance of fusion energy.

## 5. Other safety and environmental concern and materials

The ultimate measure of the safety of fusion energy is the potential public dose caused by the radioactive emissions from the facilities to the environment. While the majority of the activity caused by activation due to the fusion neutrons comes from solid nuclides, the environmental impact is evaluated from emission of volatile forms of nuclides such as tritium and carbon-14. Blanket materials are major sources of these nuclides, and are the path for release through various mechanisms such as permeation, contamination, leaks, and chemical reactions. Even if the activity of the blanket from activation of the original elements would be low, contamination of secondary coolant during operation, and slow release of dissolved tritium from solid waste could be more important. For instance, carbon-14 from steel could be a significant source of public dose in the long terms beyond 100 years, and requires more attention.

Emission of carbon dioxide is another key issue of the environment and socio-economics because of its impact on global warming. Since one of the major incentives for earlier deployment of fusion (‘fast track’ approach) is its carbon-free feature, carbon dioxide generation including the mining and processing of raw materials of the plants, and its contribution to the reduction of green house gas must be accounted for.

## 6. Conclusions

Some of the issues identified in this report are not new, but have not been considered seriously in the development of materials and their integration into the study in fusion. Fusion material studies are now in a new phase, to investigate a strategy to develop first generation power plants. Requirements and target specifications for materials must be determined from close interaction with plant design. In addition to operational temperatures and radioactive wastes, there are some other features of fusion such as supply of resources and safety, that are important characteristics that will be evaluated by the future society. There are no definitive criteria to select materials at this stage. The evaluation of the performance of materials and systems require not only the physical values, but also the total cost paid by the public, including environmental damage, and the benefit to be received by the public.

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