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15.3. Design and Materials
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The role of materials R&D in the development of commercial fusion power plants [1]

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Abstract

The introduction of new materials into a commercial fusion power plant is the ultimate goal of any long range materials development program. Success requires interactive communication between the design community and materials community to ensure that the materials being developed meet the requirements of the user or customer. This communication can be in the form of participating in project meetings with the reactor designers and providing supporting data. It can also be in the form of a material properties handbook used by the designers and structural analysts. The R&D activities must also support the development of structural design criteria to ensure the reliability and long-life capability of these new materials. This paper examines the materials development issues, looks at the role of ITER and other experimental facilities in materials development, and shows how ITER can be used to develop confidence in the use of new materials in future fusion reactors. © 1999 The Boeing Company. Published by Elsevier Science B.V. All rights reserved.

1. Introduction

The long range goal of the Fusion Materials R&D Program is the successful implementation of appropriate materials in fusion power plants. Accomplishing this goal requires good communication between the customer, who in this case is the reactor designer, and the materials community. Communication is key if the materials community is to have a better understanding of the information needed by the design community in employing new materials in future power plants.

An example of the interactions that can successfully be accomplished between design and materials communities can be seen in the work conducted in the late 1970s and early 1980s. During that time there were a number of conceptual reactor designs which had sufficient design detail in the first wall and blanket structures for detailed structural analysis to be performed. Prior to this time, the life of the first wall was thought to be the time it took the radiation environment to reduce the uniform elongation of the structural material to 0.2%. Based on this information, the component lifetime of the first wall of a UWMAK-I design was defined to be two years [1]. However, a detailed structural analysis of the 2.5 mm-thick first wall determined that the dominant mode of component failure was not radiation embrittlement but rather an undetected flaw which propagated through the wall with each burn cycle resulting in a coolant leak into the plasma. Therefore, the component lifetime was decreased to less than one year for an assumed flaw of 25% of the first wall thickness [2]. This revelation identified the need for more irradiation information on the flaw growth and fatigue in stainless steel as well as hold time effects (creep-fatigue interactions). Experiments were undertaken within the US to address these issues.

Parametric studies were also undertaken by both the structural analysts and the material science community to better understand the effect of changes in property values on component lifetimes [3,4]. These studies helped to identify those material properties important to increasing component lifetimes. In some cases the properties that the materials community *thought* were important to improve first wall lifetimes actually had

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little or no impact on the structural lifetime. This close interaction between the materials and design/analysis community occurred during a time when the budgets in the US program were increasing, and there was considerable activity in fusion research. Since that time, constrained budgets and changes in direction in the approach to conceptual designs has eroded this close interface between materials research and design communities. The net result is than many of the new improvements in materials and their properties are not widely known in the design community.

The fault does not rest solely with the worldwide design community; part of the problem is in the materials community, which is frequently unresponsive to the needs of the design community. In assessing different materials, the power core designer may need information on irradiation creep or fracture toughness before considering introducing new and better materials. In discussions with a materials expert who is frequently an experimentalist, the designer may be frustrated that minimal data is available. The materials expert is not willing to make a best guess at the trend of the data without conducting experiments, which could take several years. In the meantime, the designer has a schedule to meet so he/she will either not consider the new material or will make their own guess on the behavior of the material, which can frequently be wrong. The net result is either a new material is not introduced in the design or its behavior is misinterpreted based on incorrect assumptions. The near term nature of the ITER Project is forcing a rebuilding of the relationships developed in 1970s and 1980s. However, before one can explore the interactions of ITER, one must have a better understanding of where the materials community can contribute to the design process.

2. The role of conceptual designs and materials R&D

Fig. 1 shows the various steps in the design of a fusion reactor. Initially there is a definition of high level system requirements – the pre-conceptual design. In this step the high level design requirements of a power plant (the size of the reactor, the power level, safety assumptions, economics, and societal requirements imposed by the ultimate power plant user) are identified. These requirements can be thought of as a specification. Examples of high level requirements can be found in Table 1, which was taken from the Starlite Project [5].

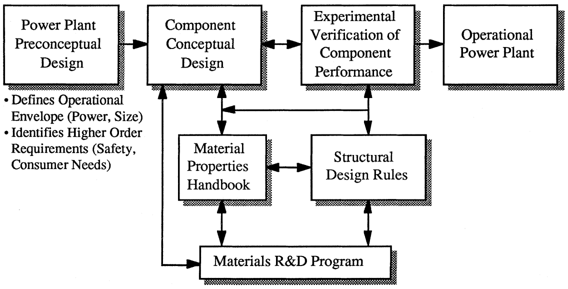


Fig. 1. Technology flow and interfaces in designing a commercial fusion reactor.

Table 1
Requirements for an attractive fusion electric power source

1	Cost advantage over other available central station options
2	Eased licensing process
3	No evacuation plan needed
4	No high-level waste produced
5	Reliable, available, and stable electrical power production
6	No local or global atmospheric impact
7	Closed on-site fuel cycle
8	High fuel availability
9	Plant capability of load-following
10	Availability in a range of unit sizes

Three of the requirements shown in Table 1 are specifically related to materials. These are: (1) materials used in the plant will produce no radioactive waste greater than Class C; (2) no evacuation plan will be needed; and (3) the cost of electricity will be competitive with other approaches. To maintain a ‘Class C’ level of radioactivation, the choice of structural materials for the high flux/high spectrum energy regions of the reactor (primary wall, divertor, etc.) is limited to three classes. These materials are low activation ferritic steel (9Cr–1W–V), a V–Cr–Ti alloy, or an SiC composite. In order to gain public acceptance and support, fusion must demonstrate that it does not disturb the day-to-day life of the public; fusion power plants must be perceived by the public as inherently safe. To support this notion, a criterion was established that the power plant does not need an evacuation plan in case of an accident. This requirement makes the design significantly more challenging and severely restricts the use of materials. For example, the power core must passively accommodate all probable accidents such as loss of coolant. Toxic materials such as beryllium, even though they have short half-lives, should be avoided or minimized. Materials with high melting points or low vapor pressure are preferred for off-nominal events such as loss of coolant. The third challenge is that a fusion reactor must be competitive in the cost of electricity to be accepted by the utilities. This requirement imposes one of the most difficult challenges with regard to design and operational constraints on the materials because the cost of electricity is not only a factor of material cost but also thermal conversion efficiency, component reliability, component life, and system maintainability.

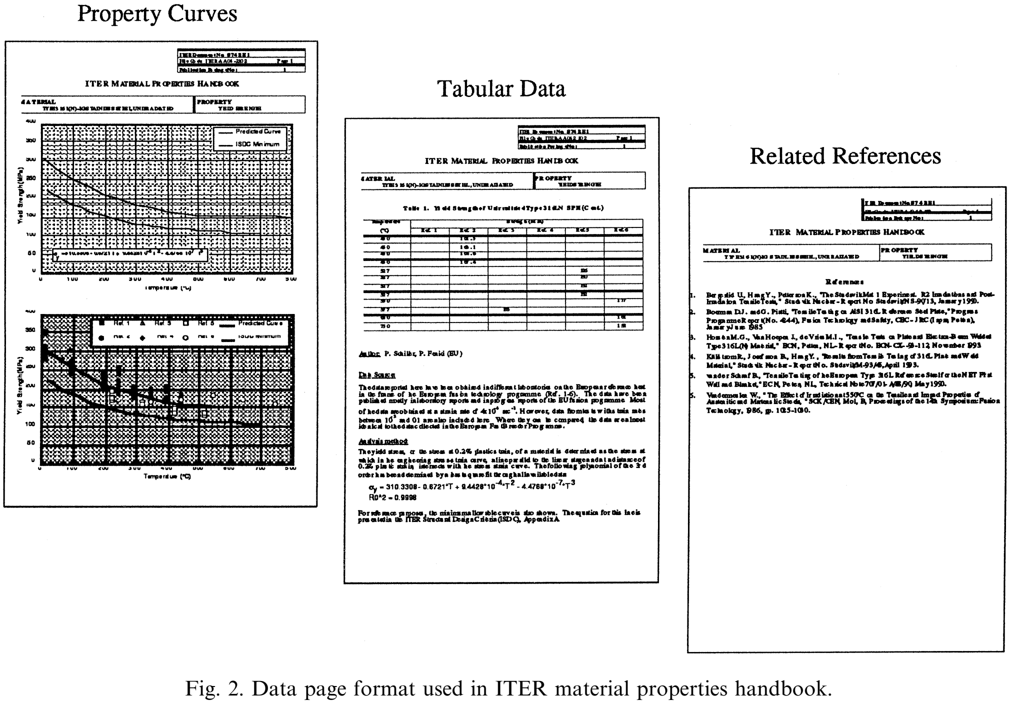
Once the high level requirements have been identified, the next step in the design process is to begin actual detailed design of the various components. At this point the materials community needs to begin interacting with designers. The materials community can directly provide information to the design community in the form of graphs, tables, or by attending the project meetings with the designers. However, designers frequently need more information than the materials experts traditionally provide. The materials community needs to provide the thermal physical properties and equations on material behavior that can be used in finite element equations.

Early in the ITER project it was recognized that designers and analysts need a single source of information which would contain these properties along with predictive equations. Thus the ITER Material Properties Handbook (IMPH) [6] was created. This Handbook satisfies two needs. First, it provides the information in an easily understood form for the designer and analyst. As illustrated in Fig. 2, the IMPH contains graphs and predictive equations to show data trends, tabular data to show the actual data points, a description of the analysis methods, and references. The IMPH is frequently updated with results from the ITER R&D program so that the Handbook serves as an interface between the design and materials community. Second, the Handbook is useful in identifying data voids to the materials community. For example, ITER currently needs information on the thermal and irradiation creep of copper alloys. A survey of the literature, along with discussions with the international materials community, revealed that this information does not exist for Cu–Cr–Zr in the heat treated condition desired by ITER. As a result, experiments are in progress by the materials community to develop this data. The same has occurred with regard to radiation damage of copper alloys.

3. Design rules identify material properties needs

An effective interaction between structural analysts and the materials community is in the development and use of design rules. Currently design rules do not exist for components used in either near-term fusion experiments or longer term devices such as DEMO. Existing design codes such as the French RCC-MR [7] and the US ASME Boiler and Pressure Vessel code [8] are based on metallic systems. There are no design rules for ceramic materials such as SiC and no activities planned either in analysis or experiment to develop a design criteria for composite materials. The aerospace industry is in the process of developing some design rules for composites, but this is for two-dimensional carbon fiber composites which are adhesively bonded, not three-dimensional ceramic composites. Until such rules are developed for SiC/SiC, it will be difficult to incorporate this class of material into a reactor.

Use of existing design rules such as RCC-MR or the Boiler and Pressure Vessel code on metallic structures can give different results on fusion component lifetimes using the same set of material properties. Because of varying assumptions regarding the treatment of material


Property Curves

Tabular Data

Related References

Fig. 2. Data page format used in ITER material properties handbook.

properties in developing design allowable, the ITER Project decided to develop its own design code. These requirements are defined in the ITER Interim Structural Design Criteria (ISDC) Appendix A (Material Design Limit Data) [9].

The ISDC essentially uses the organizational format of both the RCC-MR and the ASME Boiler and Pressure Vessel code to define the use of allowable. Where the ISDC differs is in the modification of thermal ratcheting rules as they apply to plasma disruptions and in the use of embrittled materials (materials with low uniform elongation).

The base material properties for the ISDC come from Appendix A, which contains the design allowable such as minimum tensile strength. Appendix A does not contain all of the material properties and therefore is not a duplication of the IMPH. Instead it uses key properties obtained from the IMPH that are needed to define which rules apply in the structural analysis. Examples of the type of information contained in Appendix A are minimum time for stress rupture, minimum creep ductility, cyclic stress–strain curves, fatigue curves, and isochronous stress strain curves. In providing information for use in Appendix A, the material properties data voids are readily apparent, suggesting where R&D must be initiated to support ITER data needs. Therefore, the IMPH and Appendix A are useful to support the design and analysis of fusion test reactor components, and also as vehicles for identifying the type of data needed to qualify new or existing materials for use in an experimental fusion reactor.

In developing rules for high temperature design, the rules are only as good as the supporting data base. Fig. 1 shows that the structural design rules support both the component design and the experimental verification of component performance. The experimental verification of component performance is an iterative process with the ISDC. The test results of the various components are analyzed, and the results of the analysis are compared with the predictions from the ISDC. If the predictions match, the rules are verified. If they do not, then a more thorough analysis must be done to determine if the problem is with the rules or with the test procedure. Currently all of the irradiated material properties data is derived from fission reactors. While it is possible to build a DEMO-type fusion reactor with fission spectrum data on material properties, a materials test facility such as the International Fusion Materials Irradiation Facility (IFMIF) [10] is ultimately needed to observe the property changes that will occur in materials when exposed to the high energy neutron spectrum encountered in a fusion reactor. Without the IFMIF an accurate assessment of component lifetimes cannot be obtained. In addition to material properties information, the analysis community needs experimental data on the integrated performance of components exposed to the cyclic environment of a fusion test reactor. Currently the high heat flux information is being obtained by rastered electron beams or plasma guns which cyclically heat the surfaces of small components. The lifetimes are essentially the survival time of the thermal shock treatment without cracking or debonding. While this type of testing provides valuable information for analyzing thermal stresses, it does not provide the integrated testing achieved by components operating in a reactor environment. This type of data will require a dedicated material test facility such as a volumetric neutron source (VNS) [11]. Ultimately both the information obtained from IFMIF and VNS must be incorporated into a design criteria such as the ISDC and the IMPH to develop the design rules necessary to qualify new materials and also to gain confidence on prediction component performance and lifetimes. In the interim, near term machines such as ITER are providing valuable information on what type of data are needed for construction.

4. The role of near-term reactor designs in materials development

ITER also plays a role in identifying new materials and processes as well as testing new materials in its experimental test modules. The near-term nature of the ITER project means that the designers need to address fabrication issues, maintenance, and material selection. In some cases the fabrication approaches can drive material selection. For example, the ITER first wall (also called the primary wall) is to be fabricated by solid Hot Isostatic Pressing (HIP) copper to stainless steel and then stainless steel to stainless steel. The temperature to accomplish this is roughly 1000°C. The high temperature fabrication process restricts the copper selection to non-heat treatable coppers such as dispersion strengthened copper; whereas the divertor, which uses a different fabrication technique, can use a precipitation strengthened copper such as Cu–Cr–Zr. To reduce fabrication costs, new approaches to fabricating the stainless steel blanket and divertor are being examined such as HIPing of powders and casting complete shapes. Attachment of the plasma facing materials, such as beryllium, CFCs, and tungsten to the copper structure brazes are being evaluated. Since the blanket and divertor components must be replaced, techniques to weld irradiated materials must be developed. The ITER R&D activities not only focus on developing a data base on new materials such as copper alloys but also on developing an irradiated data base on fabricated forms such as bimetallic joints, cast structures, and HIPed powders. These issues are not unique to ITER but will need to be addressed in future fusion experiments that will work in the ignition regime of a D–T plasma.

Once ITER is constructed, it will play a key role as the first integrated fusion test facility capable of evaluating various blanket concepts.

5. ITER as an integrated test facility

ITER will provide four equatorial test ports exclusively for the purpose of testing developmental breeding blanket systems. These test blankets are to provide test data on complete first wall and blanket systems while in an operational fusion reactor. The test conditions may not be fully representative of a DEMO reactor, but they can reasonably simulate (in an integrated fashion) the key test conditions, such as first wall and plasma interaction; 14 MeV neutron heating, breeding, and shielding; high temperature operation; remote handling operations; and instrumentation/diagnostics. Long-duration ($\sim$1000 s) pulsed operation will be conducted, with several of these shots back-to-back to simulate continuous operations.

Fully autonomous blanket modules are installed into the test ports from the beginning of ITER operation to accumulate as much neutron fluence as possible. One or more separate test blanket modules may occupy each test port. The test blanket concepts will be from all the participating ITER parties and will represent diverse design and material choices. At present, the generic blanket types are:

- low-temperature, water-cooled, solid breeder with austenitic steel structure;
- high-temperature, water-cooled, solid breeder with ferritic steel structure;
- high-temperature, helium-cooled, solid breeder with ferritic steel structure;
- high-temperature, water-cooled, lithium-lead breeder with ferritic steel structure;
- high-temperature, lithium-cooled breeder with vanadium structure;

This list illustrates the diverse set of structural materials, but there are many other material choices for the test blankets (breeder, coatings, insulators, etc.). Since these test blankets are to be installed in the ITER reactor, they must meet the same design code criteria as the primary ITER materials. The quality of the test articles cannot be less than the basic device or the entire ITER program will degrade. This infers that a similar material data base must be developed for these test blanket materials before they can be installed in ITER.

6. Introduction of new materials into fusion power plants

While conceptual reactor designs will identify new materials which could provide advances for operational power plants, it is unlikely that the next generation reactors will be constructed from these advanced materials unless there is a substantial increase in funding in the development of these materials and their associated material property data base. This means that the next generation D–T fusion reactors will likely be constructed with materials which have a large data base, low fabrication risk, and favorable experience in past fusion/fission experiments. Materials in this category are the stainless steels, including ferritic steels, and nickel-based alloys. This is not unique to fusion, but occurs in almost every program involving new designs. For example, in the early 1970s conceptual designs of new aircraft, such as the F-15, used almost all titanium, which was a 'new' material at that time. When the first test and production F-15 fighter aircraft were built, they were almost all aluminum, which was the past material of choice. The thinking then, as it is today, in large systems is that the initial performance of the system is critical and once that is accomplished new materials can be introduced and the performance be enhanced. Today almost all of these aircraft are constructed from titanium and composite structures.

To gain insight on how new materials will likely be introduced into a fusion reactor, one can look at how new materials are introduced into existing products. This is accomplished by taking an existing system component and substituting an improved component which, if it failed, would still allow the system to function. As confidence in performance of the new material increases, the new material receives wider usage until it eventually replaces the older material. In fusion the same logic could also be applied. New materials such as vanadium or silicon carbide would be used in a component which is easily replaceable and would not cause damage to the reactor if it failed. It is possible that the component material could be in a test module, similar to those proposed for ITER. As experience is gained in the performance of these materials, more aggressive usage would likely follow, with large components such as blankets or divertors being fabricated from the new materials. Once this step has been successfully accomplished, then the designer/analyst would have confidence in the use of this material and would baseline this new material in the next generation reactor or upgrade of the reactor system.

7. Summary and conclusions

If new materials are to be successfully used in fusion power plants, the materials community must be more proactive in working with the design community and vice versa. This can only be accomplished by increased communication between the design community and materials community. Better communication will lead to an understanding of the issues and properties that drive material selection. This understanding will help to develop materials because it will identify which properties are critical for reliable and predictable performance. In addition, the materials community needs to be more responsive to the designers' requests for information and provide information in an understandable form and in a timely manner. A vehicle to provide data in a format that is understandable to the design community is a material properties handbook, similar to the one developed by the ITER Program.

The design community, in turn, needs to provide a better definition of the criteria used to determine the end-of-life of the component. This is essentially the type of failure mode or the determination of when a component must be replaced. This information will help to guide the materials experts on the properties which need to be improved to extend component lifetimes.

Finally, there are currently no design rules that provide guidance on designing with ceramic materials such as SiC. This is a potential area of collaboration between the materials and design community. Until this information is developed, the use of ceramic materials in a complex structure such as a fusion reactor will be difficult or impossible.

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