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FIRST WALL AND BLANKET STRUCTURE PERFORMANCE

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Abstract

Because of its economic and environmental impact on a fusion power plant, the performance of the first wall and blanket structure has become a key question in fusion reactor development. This paper gives a brief summary of load and operation conditions to which the structure will be exposed in a Tokmakak reactor. Further load conditions prescribed by the blanket design and cooling concept are discussed for three different blanket concepts: the flowing liquid concept, the stagnant liquid concept, and the solid breeder concept. Finally, the necessary procedure for assessing the structural performance in terms of lifetime is outlined and some comments are made about the methods now in use. It is concluded that stronger interaction between the fields of structural mechanics and materials sciences is needed in order to proceed towards more reliable estimates.

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1. Introduction

Within the last decade, fusion reactor research and development has undergone an exploratory phase the main goal of which was to identify the problems ahead on the way from present-day plasma physics experiments to a full scale commercial fusion power plant. Among the many problems found those of the first wall and blanket structure performance have been recognized as one of the most serious obstacles to both technical and commercial feasibility.

The unique load and operating conditions with which the first wall and blanket structure will be confronted are unprecedented in the history of technology. To our knowledge there is no material which can withstand these conditions for the whole reactor life without failure. As a consequence, fusion reactor blankets have to be constructed in such a way as to allow easy replacement of defective parts. Since the first wall and blanket consitute the innermost part of the reactor structure this procedure will take an appreciable amount of time, thus affecting the availability and hence the economy of the power plant. Furthermore, frequent blanket renewal means a high rate of consumption of raw materials and a high rate of production of radioactive waste. Thus, in addition to the economic issue, environmental issues are also involved. This makes the first wall and blanket structure performance a key question in future fusion reactor development.

In this paper, it is attempted to summarize the present state of investigations of this problem area. Attention is confined to solutions proposed for Tokamak reactors. Among these only those devoted to pure electricity production are considered. In Sec. 2 the external load conditions for first wall and blanket are briefly reviewed. In Sec. 3 we discuss those load conditions imposed by the blanket concept itself. Sec. 4 comments on the state of art in the field of life prediction.

2. Typical external load conditions

In a Tokamak reactor, the first wall and blanket structures will be exposed to typical load conditions prescribed by the thermonuclear burn:

- The neutrons released by the fusion reactions in the plasma cause nuclear heating inside the material by neutron and gamma interaction with matter. The mean power densities in the first wall will be of the order of 10 W/cm^3 for a neutron wall loading of 1 MW/m^2. The power density decreases rapidly with increasing distance from the first wall.
- Plasma radiation and heat losses hit the surface of the structure in the form of an external heat flux density. Its intensity is about 20 % of the neutron wall loading for an unprotected wall. If divertors or other protection schemes are applied, the surface load will be correspondingly lower.
- Both the nuclear power density and external heat flux density are of a pulsed nature. Typical burn times range from about 100 to a few 1000 seconds, depending on whether pessimistic or optimistic assumptions are made concerning plasma performance.
- Neutron interactions with the structural material will cause radiation damage. The primary damaging processes are the production of atom displacements at a rate of ≈ 10 dpa/yr and the generation of helium and hydrogen at rates of ≈ 300 ppm/yr and ≈ 600 ppm/yr, respectively, these values being valid for a stainless steel first wall and a neutron wall loading of 1 MW/m^2. Swelling and irradiation creep will occur as secondary effects, these influencing the stress fields in the structure over the long

term. Additionally, a number of properties of materials will be affected mostly in a negative sense.

This list of conditions roughly defines the frame which blanket designs have to fit in order to guarantee reliable operation and an acceptable lifetime.

3. Load conditions imposed by the blanket concept

Load conditions imposed by the blanket itself result primarily from the design and cooling concept. They determine temperature and pressure loads on the structure.

A large number of blanket design concepts have been proposed during the past few years. Characteristic features and data of some of these are summarized in Tab. I. The table presents concepts which have been investigated to a sufficient depth as to allow some preliminary conclusion about their performance. As can be seen from Tab. I, a distinction is made between three general types of blankets which are briefly discussed below.

3.1 Flowing liquid type blanket

The characteristic feature of this type of blanket is that the breeding and moderating substance is simultaneously used as the heat transfer agent. Liquid lithium is the only fluid seriously considered at present. Molten salts, widely suggested in earlier concepts, have now been rejected mainly because of their marginal tritium breeding capability.

The six concepts listed in Tab. I were devised by the University of Wisconsin [1, 2], Culham Laboratory [3], Argonne National Laboratory [4], and W.M. Wells [5]. They differ in the choice of structure material and design concept.

With respect to the performance characteristics the fundamental advantage of this blanket type is that a high percentage of the total heat is directly produced inside the working fluid of the primary heat transfer loop. Only a small fraction has to be transmitted from the structure to the coolant by heat transfer. The maximum operating temperature of the structure may therefore be close to the maximum coolant temperature. The latter is primarily limited by the compatibility between the coolant and structure materials. According to an overview recently presented by J.H. DeVan [6], the temperature limits are about 600° C for stainless steels, 500° C for nickel-base alloys, and 700° C for titanium alloys. With refractory alloys on a vanadium, niobium, or molybdenum base higher temperatures may be reached if the entire primary system is fabricated from the same material.

It is well known that for this type of blanket the coolant pressure is determined by the MHD pressure drops. As can be seen from Tab. I, they range from about 3 to 10 MPa in present designs. In fact, the different design approaches to not have an overwhelming influence on these figures. This is supported by a study recently completed by M. Korzen et al. [7], who found that the pressure drops occuring in the inlet and outlet pipes generally exceed those occurring in the blanket itself. Nevertheless, the design is important for two reasons. Firstly,it has to prescribe the flow path of the coolant, avoiding stagnation and hot spots at critical locations [8]. Secondly, the design determines the stresses resulting from the pressure load. Most existing designs prefer the pressure vessel type solution. Since the wall thickness of such a vessel may not be excessively large, significant pressure stresses will add to the cyclic thermal stresses resulting from the heat load. Viewed from this perspective, there is a certain attractiveness in the concept of W.M. Wells [5], in which the lithium flows through a bundle of small diameter tubes. This pressure tube approach permits either higher pressures or thinner walls as compared with the pressure vessel approach.

3.2 Stagnant liquid type blanket

As compared with the flowing liquid concept, the stagnant liquid type blanket needs a separate coolant. This may be a gas, primarily helium, or a molten salt. Five concepts of this type are listed in Tab. I, all employing liquid lithium as the breeding and moderating substance and stainless steel as the structure material. The two Oak Ridge designs [9] use the molten salt HITEC as coolant, whereas the FINTOR 1 [10] and the FINTOR-D [11] as well as the Argonne blanket [4] designs rely on helium.

Regardless of the choice of coolant, the stagnant liquid type blanket has the disadvantage as compared to the flowing liquid type blanket that all the heat produced inside the blanket including the structure has to be transferred to the coolant. This necessitates the existence of temperature gradients. Since the compatibility problems are still governed by the interaction between the lithium and the structure, this means an appreciably lower maximum temperature within the primary heat transfer loop. This feature is emphasized by the numbers contained in Tab. 1.

With respect to the coolant pressures, however, significant differences between the coolants are obvious. According to the Oak Ridge studies [9] a molten salt coolant should be operable at very low pressures. In this case, the first wall and blanket structures have essentially to withstand the cyclic thermal stresses. In the case of helium cooling, pressure levels of 3 to 7 MPa are discussed. These values are, in fact, comparable with those for the flowing liquid type concept. The difference has, however, to be seen in the fact that the stagnant liquid concept calls for a pressure tube solution (pressurized coolant tubes submerged in the breeding and moderating fluid), whereas it is optional for the flowing liquid concept. Hence, in a stagnant liquid type blanket the outer walls of a module are, in principle, kept free from pressure stresses. In some cases there may still exist the problem of separate first wall cooling, which may again diminish the advantage just stated. On the other hand, in this respect as well the pressure tube solution is mandatory.

3.3 Stagnant solid type blanket

Solid breeding and moderating substances usually necessitate a separate coolant, the prime candidate being helium gas. (One exception where no additional coolant is needed is briefly mentioned in the next section.) Blankets of this type have been proposed for UWMAK-II [12] and for the designs of General Atomic Co. [13], JAERI [14], and Brookhaven National Laboratory [15]. Each concept makes use of a different structure material and follows a different design approach.

Because of the similarity of problems associated with the necessary heat transfer to the coolant the same conclusions with regard to temperatures apply, in principle, to this blanket type as to the stagnant liquid type. If one anticipates that solid breeders do not interact with the structure, the question of compatibility is shifted to the coolant - structure interaction. In this case the coolant temperature could be raised to a higher level. According to the summary of J.H. DeVan [6] the materials least sensitive to helium corrosion are stainless steels and nickel-base alloys, which set temperature limits at about 750 and 800^{0} C, respectively. The use of refractory alloys excludes temperatures in excess of 450 to 550^{0} C.

As far as the pressure loads are concerned, the designs proposed so far combine the disadvantages of both blanket types discussed in the preceding sections. To achieve adequate heat transfer, the pressure levels have to be similar to those of the other concepts. Furthermore, the existing design solutions are exclusively of the pressure vessel type. High pressure stresses and cyclic thermal stresses therefore have to be accommodated in a material environment allowing high temperatures. This makes careful design necessary in order to arrive at satisfactory solutions. More relaxed conditions may be achieved by following the pressure tube approach although problems will then be shifted to heat transfer.

3.4 Other blanket types

In addition to the three blanket types discussed so far, a few other concepts are briefly examined with regard to their special performance characteristics.

Two concepts employ boiling liquids as the coolant. A.P. Fraas [16] proposed potassium for cooling a blanket in which lithium is circulated and niobium is used as the structure material. The achievement of high temperatures and low pressures is typical of this approach. It remains questionable, however, whether the introduction of a potassium topping cycle really pays in the overall economy of the power plant. The second concept, adopted for the NUMAK reactor design [17], utilizes boiling water guided in multilayer titanium alloy pressure tubes to cool a eutectic salt mixture. The originality of this concept is to operate the salt just at the melting point in order to attenuate the discontinuous heat input by utilizing the latent heat of fusion for the purpose of energy storage. This concept avoids, at least, cyclic thermal stresses in the presence of high pressure stresses at intermediate temperatures.

For completeness, the blanket proposed by D.K. Sze [18] should be mentioned. He suggests utilizing solid breeding materials directly for transporting the heat to a heat exchanger. The flow of solid pellets through the blanket is sustained by gravity. In this concept, pressure problems would be completely absent. Separate cooling of the structure may be avoided by using graphite which radiates the energy deposited in it to the solid "coolant". Clearly, the problems are here shifted to the heat exchanger.

4. Methods and problems of life prediction

In the preceding sections we have summarized the load conditions prescribed by the plasma burn characteristics and have pointed to some differences with respect to temperature and pressure loads typical of various blanket design concepts. We did not comment on the impact on structural performance which follows from the strong spatial variations of power densities and damage rates. We did not make any attempt either to present an overview about the available material data base. This would be far beyond the scope of this paper. Nevertheless, all these items are necessary prerequisites for judging structural performance.

With respect to problems of the overall system the question of structural performance reduces to that of structure lifetime. It is obvious that today an answer to this question can only be attempted by means of numerical studies. This calls for six steps of analysis if both the materials and the design are specified:

1) Nuclear analysis to obtain information about the distributions of power densities and damage rates.
2) Thermohydraulic analysis for calculating the temperature distribution and pressure loads.
3) Stress/strain analysis to obtain the mechanical response of the design to the initial load conditions.
4) Long-term mechanical analysis to include the inelastic response due to swelling and creep.
5) Long-term analysis of the properties of materials to take into account changes associated

with the irradiation dose.

6) Lifetime analysis by drawing conclusions from a comparison between loads, inelastic response, and properties of materials.

The methods of performing nuclear, thermohydraulic, and stress/strain analysis are well established today. There exist a number of one, two, and three-dimensional codes for performing the nuclear analysis. Much work has been done in past years to improve the data base for these calculations. To perform the thermohydraulic as well as the stress/strain analyses, a number of finite element codes which guarantee most reliable results are available.

Quite different is the situation concerning stages 4 to 6. Long-term inelastic analysis, for instance, requires a knowledge of the swelling and creep behaviour. Some information about these effects has emerged from fission reactor development. Reliable data are, however, only available for materials of interest in this field and for conditions typical of their application. Measurements under simulated fusion reactor conditions are just in their infancy but have already revealed large discrepancies due to the different ratio of helium atom and displacement production and due to the pulsed nature of irradiation. Thus, basing the inelastic analysis on present-day knowledge means introducing a large amount of uncertainty.

To an even larger extent this holds for the analysis of the properties of materials. Properties used in the course of life prediction are: yield strength, ultimate tensile strength, time rupture strength, time yield limit, uniform elongation, creep ductility, fatigue behaviour, and crack growth rates. If at all, these data for irradiated materials are only available from measurements under fission reactor conditions. Even in this case, significant discrepancies are observed, depending on whether they were made during or after irradiation. Some properties are only known for the unirradiated state. Therefore, another large element of uncertainty arises from this field.

Because of these uncertainties regarding both data on inelastic processes and properties of materials it is not difficult to assess the accuracy of life prediction. In awareness of this situation, nevertheless life prediction was attempted to make for some of the designs listed in Tab. I. G.M. Fuller [19] edited a study on the UWMAK-I blanket design [1], J.R. Stanbridge et al. [20] investigated the Culham concept [3], R.F. Mattas and D.L. Smith [21] prepared a methodology to treat the ANL design concepts [4], and also the GA design [13] has been investigated. In doing so, additional sources of uncertainty have been introduced: pulsed operation has been treated only very crudely and the inelastic response has been completely neglected. Nevertheless, the outcome of these studies has at least stimulated the initiation of a broad fusion reactor materials research and development program in the U.S. and is starting to exert appreciable pressure on the development of refined life analysis methods.

In fact, developments of this kind are already underway in the U.S. [22, 23] and Germany [24]. They aim at covering stages 4 to 6 mentioned above and follow slightly different approaches. As a commom feature, they do not make use of the time consuming finite element methods• for thermal and structural analysis but rely on analytical solutions for model geometries. This is a hint that present efforts are devoted to the development of a consistent methodology and understanding as the prime interest. It should be made a characteristic feature of these models to be constructed in such a way that the results expected from the experimental programs can be rapidly included.

5. Conclusions

First wall and blanket structure performance represent a field of investigation involving the expertise of a number of disciplines.Contributions from nuclear physics, thermohydraulics, material sciences, mechanical engineering, and structural mechanics are necessary to cope with the various problem areas and to arrive at a reasonable synthesis. At present the fields of materials sciences and structural mechanics are not sufficiently advanced to permit reliable information on performance which can lead to a quantitative prediction of lifetime.

The most urgent prerequisite for performing lifetime analyses is the establishment of an appropriate material data base. This is, however, so large a task that it seems necessary to set priorities. Decisions of this kind may well be prepared within the field of present structural mechanics by utilizing the long-term models now under development for sensitivity studies. The feedback from the materials programs should then enable the same models to be improved step by step to provide answers to the question of lifetime with increasing accuracy.

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References

[1] B.Badger et al.: "UWMAK-I, a Wisconsin toroidal fusion reactor design", Univ. of Wisconsin, Rep. UWFDM-68 (1974, 1975)

[2] B.Badger et al.: "UWMAK-III, a noncircular Tokamak power reactor design", Univ. of Wisconsin, Rep. UWFDM-150 (1976)

[3] J.T.D. Mitchell, R.Hancox: "A lithium cooled toroidal fusion reactor", Culham Lab., Rep. CLM-P 319 (1972)

[4] B.Misra, V.A. Maroni: "Thermal hydraulic analysis of two fusion reactor first wall blanket concepts", Argonne Nat. Lab., Rep. ANL/FPP/TM-94 (1977)

[5] W.M. Wells: "ORNL Fusion power demonstration study: Lithium as a blanket coolant", Oak Ridge Nat. Lab., Rep. ORNL/TM-6214 (1978)

[6] J.H. DeVan: "Compatibility of structural materials with coolant and breeder fluids", 1st Top. Meet. on Fus. React. Mat., Miami, Florida (U.S.A.), Jan.1979 (to be published)

[7] M.Korzen, W.Daenner: "MHD-Druckverluste in Rohrleitungssystemen für Fusionsreaktoren", MPI für Plasmaphysik Report (to be published)

[8] J.C.R. Hunt, R.J. Holroyd: "Applications of laboratory and theoretical MHD duct flow studies in fusion reactor technology", Culham Lab., Rep. CLM-R 169 (1977)

[9] D.Steiner et al.: "ORNL fusion power demonstration study: Interim report", Oak Ridge Nat. Lab., Report ORNL/TM-5813 (1977)

[10] F.Farfaletti-Casali (ed.): "FINTOR 1, a minimum size Tokamak DT experimental reactor", Joint Res. Centre Ispra, Draft Rep. (1976)

[11] F. Farfaletti-Casali et al.: "Design of a modular blanket with gas cooled liquid lithium", 3rd Top. Meet. on the Technol. of Contr. Nucl., Fus.", Santa Fé, New Mexico (U.S.A.), May 1978 (to be published)

[12] B.Badger et al.: "UWMAK-II, a conceptual Tokamak power reactor design", Univ. of Wisconsin, Rep. UWFDM-112 (1975)

[13] D.W. Kearney et al.: "Mechanical and thermal design of a gas-cooled fusion blanket module", General Atomic Co.,Rep. GA-A14671 (1977)

[14] K. Sako et al.: "Conceptual design of the JAERI demonstration fusion reactor", 2nd Top. Meet. on the Technol. of Contr. Nucl., Fus., Richland, Washington (U.S.A.), Sept. 1976

[15] J.R. Powell (ed.): "Preliminary reference design of a fusion reactor blanket exhibiting very low residual readioactivity", Brookhaven Nat. Lab., Rep. BNL 19565 (1974)

[16] A.P. Fraas: "Conceptual design of the blanket and shield region and related systems for a full scale toroidal fusion reactor", Oak Ridge Nat. Lab., Rep. ORNL-TM-3096(1973)

[17] R.W. Conn et al.: "NUMAK: An attractive medium field, medium size, conceptual Tokamak reactor", Univ. of Wisconsin, Rep. UWFDM-249 (1978)

[18] D.K. Sze et al.: "Thermal, mechanical, and neutronic design considerations for a graphite structure Li_2O cooled blanket", Univ. of Wisconsin, Rep. UWFDM-223 (1977)

[19] G.M. Fuller et al.: "Fusion reactor first wall/blanket systems analysis; Tokamak concepts", Electric Power Res. Inst.,Rep. EPRI ER-582 (1977)

[20] J.R. Stanbridge et al.: "Design of stainless steel blanket cells for a fusion reactor", Culham Lab., Rep. CLM-R 127 (1974)

[21] R.F. Mattas, D.L. Smith: "Modeling of life-limiting properties of fusion reactor structural materials", Argonne Nat. Lab.,Rep. ANL/FPP/TM-84 (1977)

[22] W.G. Wolfer, R.D. Watson: "Structural performance of a graphite blanket in fusion reactors", Univ. of Wisconsin, Rep. UWFDM-258 (1978)

[23] S. Mukherjee et al.: "Mechanical analysis of a first wall model by using a state variable approach", 1st Top. Meet. on Fus. React. Mat., Miami, Florida (U.S.A.), Jan. 1979 (to be published)

[24] W. Daenner, J. Raeder: "FWLTB - A computer program for predicting the lifetime of a fusion reactor first wall", 5th Int. Conf. on Struct. Mech. in React. Technol., Berlin/Germany), Aug. 1979 (to be published)

Table I : Some characteristic features of various blanket concepts

Concept	BM	C	SM	P_w	τ_B	P	ϑ_{cm}	SA	LA	Design Features	Ref.
Flowing Liquid Type Blankets											
UWMAK-I	Li	Li	SS	1.25	5400	2.8	489	yes	yes	U-bend modular cells	[1]
UWMAK-III	Li	Li	TZM	1.90	1800	6.9	870	yes	no	U-bend modular cells	[2]
Culham-I	Li	Li	SS	3.90		3.5	650	yes	yes	rad.oriented circular or hexagonal cells	[3]
ANL-I	Li	Li	SS	a)	a)	a)	a)	partly	yes	rad. oriented circular modules	[4]
ANL-II	Li	Li	V	a)	a)	a)	a)	partly	yes	rad. oriented circular modules	[4]
Wells	Li	Li	SS	3.14	1200	10.0	500	yes	no	poloidal tube bundles	[5]
Stagnant Liquid Type Blankets											
ORNL-I	Li	HITEC	SS	2÷4	1200	low	} 450÷	prelim.	no	modules following plasma shape	[9]
ORNL-II	Li	HITEC	SS	2÷4	1200	low	} 500	prelim.	no	specially shaped "cassettes"	[9]
FINTOR 1	Li	He	SS	0.08	260	3.0	375	yes	no	poloid. oriented cells	[10]
FINTOR-D	Li	He	SS	1.3		5.0	350	no	no	toroid. oriented circular modules	[11]
ANL-III	Li	He	SS	a)	a)	7.0	a)	partly	yes	modules following plasma shape	[4]
Stagnant Solid Type Blankets											
UWMAK-II	$LiAlO_2$	He	SS	1.16	5400	5.2	650	yes	partly	U-bend modular cells	[12]
GA-DEMO	Li_7Pb_2	He	Ni	1.85	308	5.0	585	yes	yes	rad.oriented circular modules	[13]
JAERI	Li_2O	He	Mo	1.42	5880	2.0	700	?	?	rad. oriented circular modules	[14]
BNL	$LiAlO_2$	He	Al	1.25	5400	2.0	760	yes	no	rad. oriented circular modules	[15]
Other Blanket Types											
Fraas	Li	K	Nb	0.69		low	1052	no	no	toroid. oriented big cells	[16]
NUMAK	Salt	H_2O	Ti	4.00	245	8.6	300	no	no	none	[17]
Sze	Li_2O	Li_2O	C	2.00	?	0	600	yes	yes	modular poloidal cells	[18]

Explanations:
BM = breeding material
C = coolant
SM = structure material
P_W = wall loading (MW/m^2)
τ_B = burn time (sec)
p = coolant pressure (MPa)

ϑ_{cm} = max. coolant temperature (°C)
SA = stress analysis performed
LA = life analysis performed

a) Trade studies performed