TRANSACTIONS
of the
8th International Conference on

STRUCTURAL MECHANICS IN REACTOR TECHNOLOGY

Centre de Conférences Albert Borschette
Brussels, Belgium ■ August 19-23, 1985

Vol. N. Mechanical and Thermal Problems of Fusion Reactors

Conference organization by:

CEC The Commission of the European Communities

International Association for Structural Mechanics in Reactor Technology

NORTH-HOLLAND
for
THE COMMISSION OF THE EUROPEAN COMMUNITIES

Technology Issues and Testing Requirements in the Development of High Heat Flux Components

K.W. Kleefeldt
Kernforschungszentrum Karlsruhe GmbH, Institut für Reaktorentwicklung, Postfach 3640, D-7500 Karlsruhe 1, Germany

M.A. Abdou
University of California, School of Engineering and Applied Science, 6288 Boelter Hall, Los Angeles, California 90024, U.S.A.

Abstract

In a current study aimed at developing a strategy for fusion nuclear technology experiments, FINESSE / 1 /, the issues and testing needs have been assessed comprehensively. In this paper the issues and testing requirements of high heat flux components are summarized in six groups: (1) material data base development, (2) surface damage mechanisms, (3) thermomechanical performance, (4) system integration, (5) plasma edge conditions and exhaust, and (6) radio frequency heating components. These groups reflect the pertaining testing needs in an order of increasing complexity, i.e., from specimen and element tests to module, component and system tests. The adequate test facilities in the near and long term perspective are discussed.

1. Introduction

The primary high heat flux component (HHFC) in tokamak reactors is the limiter or divertor, whichever is chosen. This relatively large component is simultaneously exposed to a strong particle flux, high heat flux including transients and a high neutron flux. There are other HHFCs, such as crucial portions of the first wall and parts of the heating system or, generic to mirror devices, plasma end dumps, direct convertor units, and beam dumps. These might reveal even more severe operating conditions in some respects. However, looking at the combined effects, the limiter/divertor encompasses most of the HHFC issues.

In a current study aimed at developing a strategy for fusion nuclear technology experiments, FINESSE / 1 /, the issues and testing needs have been assessed comprehensively with respect to the level of concern, operating parameters, importance of neutrons, and potential test facilities. The assessment focusses on the design of a demonstration reactor for commercial fusion power production. A total of 120 issues have been identified, the majority of which being devoted to the blanket/first wall system, and about one quarter addresses HHFCs.

After an overview of the typical operating conditions for HHFCs in section 2, we summarize the 27 key issues related to HHFCs and outline the necessary experimental effort to resolve the issues (section 3). It is concluded in section 4, that new and sophisticated experimental facilities are needed to provide the unique and complex fusion environment in the long-term perspective.

2. Operating Conditions and Environment

The design of components to be used in high heat and particle flux regions of fusion devices depends critically upon the operating conditions. They include most importantly the heat and particle fluxes, which govern the material selection, as for instance, with respect to allowable thermal stresses, erosion rates, and plasma impurities (choice of high vs. low Z surface materials). Also the neutron environment with its damaging effects, the number of burn cycles, and the operating temperature further narrow the design options. Finally the chemical environment (corrosion) as well as the magnetic conditions have to be considered.

In order to characterize the operating conditions of HHFCs three components have been selected, for which typical operating parameter ranges are listed in Table I. These are limiters/divertors, beam dumps, and the first wall, representing components with the highest particle flux, the highest heat flux and the most severe neutron fluence, respectively. There are large band widths in the operating parameters, mainly due to uncertainties in the plasma edge conditions and due to the yet undefined optimum target plant design. The upper bounds refer in most cases to the long term commercial type reactor like the DEMO / 2 /. Note that there is a decrease in the number of cycles, as steady state operation in tokamaks may be achieved.

3. Issues and Testing Requirements

The key issues generic to HHFCs but of particular relevance for limiters/divertors, can be grouped into five categories (Table II): (1) material data base development, (2) surface damage mechanisms, (3) thermomechanical performance, (4) systems integration, and (5) plasma edge conditions and exhaust. A sixth group is added in Table II covering special features of the radio frequency (RF) heating components. Within each group the issues are ranked according to their level of concern, where "critical" means a feasibility issue. A "high" level of concern issue poses a serious question on plant availability or safety. Most of the issues shown here are judged to be of high or critical importance. These issue groups reflect the pertaining testing needs in an order of increasing complexity, i.e., from specimen and element tests (categories 1 and 2) to module, component, and system tests (categories 3, 4, and 5, respectively). The test categories and their required environment are summarized in Table III. In the following subsections the issue groups and their main line testing needs will be described.

3.1 Material Data Base Development

The variety of candidate materials, material combinations, and special treatments is large, and the property data base is scarce or nonexistent. The major need for first wall materials (e.g., PCA, HT-9, V-15Cr-5Ti) are mechanical property data at very high fluence levels (100 - 200 dpa), including swelling and irradiation creep behavior as well as fatigue and fracture mechanics data. The knowledge gained from fission reactors (FR) and point neutron source (PNS) experiments has to be extended, and it is an open question, whether the fusion spectrum could reveal new radiation effects not observed in fission testing. The major issues associated with other HHFC materials is the lack of bulk property data for copper alloys at elevated temperature and of candidate refractory materials (W, Ta, Mo) up to medium fluence levels. Tests are typically performed with small specimens ($1 \times 1 \times 5$ cm^3) out-of pile and in-pile, where the great number of variations (several thousands) and the time of irradiation and endurance tests are major factors. Fission reactors and point neutron sources are the most suitable facilities. Fabrication, bonding, and welding techniques for large and complex components have to be developed in a complementary program.

3.2 Surface Damage Mechanisms

Plasma Material Interaction (PMI) processes govern the material selection for plasma side materials. Of most concern is the surface erosion by physical sputtering. This crucially depends on the plasma edge temperature. At very low plasma edge temperature (50 eV) erosion is attractively low. At medium edge temperature typical particle flux of several 10^{23} $m^{-2}s^{-1}$ at the limiter/divertor liberates in the order of 10^{20} $m^{-2}s^{-1}$ wall atoms, corresponding to about 10 atom layers per second or about 10 cm per full power year (FPY). A high degree of redeposition is predicted from theoretical modeling. Thus, the life time is very sensitive to the difference between these two large numbers for erosion and redeposition rates. At the first wall the incident charged particle flux is typically smaller by three orders of magnitude, but the charge exchange neutral flux, redeposition rate, and the particle path length are less predictable. Other surface damage mechanisms of high to medium concern are arcing, chemical erosion, helium implantation (blistering), and vaporization and melting by plasma disruption. All of these phenomena, reviewed by Conn et al./ 3 /, are very condition-specific and their level of understanding is limited. The tests should focus on candidate plasma side materials of both low-Z (Be, C, SiC, and BeO) and high-Z (W, Ta, V, Nb, Mo) type probes or elements, typically 10 x 10 cm^2 large, to broaden the data base. A well defined plasma stream with high density and variable particle energy and species is needed for sputtering/redeposition and arcing tests. The other phenomena essentially require a neutral particle or an ion stream. For special purposes a high magnetic field (e.g., in redeposition studies) or tritium bombardment (see tritium issues in 3.4) are required. Plasma test stands (PMI-TS) are the appropriate tools for these element tests.

3.3 Thermomechanical Performance

Stable heat removal and structural integrity are critical issues, involving high heat fluxes in parallel coolant channel arrays with large length-to-diameter ratios and high thermal stresses in composite thick walls at alternating temperatures. Heat fluxes of up to 10 MW/m^2 for limiters/divertors or 30 MW/m^2 for beam dumps are at the limit of present technology and can best be removed by water cooling, since the viability of helium gas or liquid metal cooling is questionable (Abdou et. al. / 4 /). Thermal stress is another limiting factor: The maximum allowable heat flux, max q, with respect to producing a maximum allowable thermal stress, S, in a flat plate of thickness, d, is, for instance, for copper alloy 10 MW/m^2 (with d = 0.5 cm, S = 200 MPa) and for first wall candidate materials PCA, HT-9, and V-15Cr-5Ti max q = 0.3, 0.6, and 0.8 MW/m^2, respectively (with d = 1 cm, S = 300 MPa). Thus, design limits are reached, disregarding other stress components. These and the other issues listed in group 3 of Table II are very design specific and require both non-nuclear multiple interaction tests with smaller elements and module tests of the third category with increasing complexity beginning in test stands (TS) and ending in fusion engineering research facilities (FERF), as indicated in Table III.

3.4 Systems Integration

A number of different issues have been compiled in this group, dealing with tritium, maintenance, activation products, disruption forces, etc. (Table II). These issues are very device and design dependent and, therefore, require mainly component tests in a fusion environment. In the near term this can be plasma burning experiments (PBS) with low flux and fluence goals, as for instance, for tritium permeation, choice of limiter vs. divertor, maintenance procedures, disruption mechanical consequences, and component alignment accuracy (issues 4a, b, d, e, g and h in Table II). The investigation of the activated product transport in the vacuum chamber and exhaust will ultimately require prototypical fluence goals with substantial gross material transport (predictions for DEMO / 2 / estimate several m^3/yr). These can only be achieved in an engineering test facility (ETF). Some of the issues require preceding non-nuclear experiments on a small scale as indicated by the test categories in Table II. The coolant compatibility (e.g. liquid metal cooled and water cooled components in the same device) and heat recovery issue is merely a philosophical question, which cannot be solved by experiments but which impacts the thermomechanical design.

3.5 Plasma Edge Conditions and Exhaust

In a tokamak, the plasma edge temperature and density control establish the link between the physics performance of the device and the limiter/divertor design with respect to sputtering and heat flux control. The edge conditions also influence the helium removal as well as other impurity introduction into and removal from the plasma, where the surface conditioning comes into play. These fundamental physics and design issues can only be resolved in a steady state DT burning tokamak plasma, involving the entire exhaust system, which means system tests of the fifth category. From the viewpoint of the limiter or divertor design, one can distinguish between short-term performance tests (showing the adequacy of the overall design with respect to heat removal, pumping capability, plasma burn characteristics, operating transients) and lifetime performance tests (which add erosion/redeposition effects, material degradation, and structure mechanics aspects). The short-term tests can be performed in PBX devices with sufficiently long burn times, whereas the lifetime performance tests require an engineering test facility (ETF) with substantial neutron fluence. The latter would be at the same time proof tests for most of the other plasma interactive components issues.

3.6 RF Components

The RF launcher system has to couple wave energy efficiently to the plasma. The plasma-interactive nature of the launching structure implies a dependence on the plasma parameters, structural behavior, and electrical properties. Ceramic windows are required for transmission lines to separate a gas-filled region from a vacuum, all in a high neutron/gamma flux-level. The transmission line itself may experience structural and electrical property changes, that can lead to voltage breakdown. Besides early material data base development (category 1) the main testing effort circles around component and system tests in a fusion environment, where the energy coupling and its consequence, on cooling and power stability can be demonstrated. In the near term this can be done in PBX type facilities but eventually high fluence levels are very important demanding tests in an ETF.

4. Conclusions

The long term fusion development strategy has to consider the following HHFC testing needs: (1) The material data base development is a near term issue, that must be pursued in non-neutron test stands, fission reactors (FR), and point neutron sources (PNS) on a broad basis. (2) Surface damage mechanism studies are well under way in existing plasma material interaction test stands (PMI-ST) but must be extended to include redeposition phenomena. (3) Thermomechanical issues require non-nuclear element tests in test stands with and without plasma. Later on module tests become necessary requiring new and larger test stands. (4) The issues in groups 4, 5, and 6 call for new and sophisticated facilities, in the near term with low fluence goals like in plasma burning experiments (PBX) or in a fusion engineering research facility (FERF), and in the long term with high fluence goals in an engineering test facility (ETF).

5. References

/ 1 / M. Abdou et. al.: "FINESSE - A Study of the Issues, Experiments and Facilities for Fusion Nuclear Technology Research & Development", UCLA-ENG-84-30, PPG-821, 1984

/ 2 / M. Abdou et. al.: "A Demonstration Tokamak Power Plant Study (DEMO)", ANL/FPP/82-1, Argonne National Laboratory, 1982

/ 3 / R. W. Conn, W. B. Gauster, D. Heifetz et. al.: "Technical Assessment of the Critical Issues and Problem Areas in the Plasma Materials Interaction Field", PPG-765, 1984

/ 4 / M. Abdou, R. D. Boyd, J. R. Easoz et. al.: "Technical Assessment of the Critical Issues and Problem Areas in High Heat Flux Materials & Component Development", PPG-815, 1984

TABLE I - TYPICAL OPERATING PARAMETERS OF HHFC

Parameter		Limiters, Divertors	Beam Dumps	First Wall Tokamak (TMR)
Heat Flux,	MW/m^2	~5 - 10	10 - 30	0.5 - 1 (0.1)
Ion Flux,	$10^{20} m^{-2} s^{-1}$	300 - 2000	1 - 10	1 - 5
Particle Energy,	eV, keV	10 - 1,000 eV	20 - 100 keV	~10 eV
Neutron Flux,	MW/m^2	1 - 5	< 1	1 - 5
Neutron Fluence,	dpa	~12 - 60	< 10	60 - 600
Target Life Time,	FPY	> 1	> 1	5 - 10
Burn Time,	s	~100 - CW	~100 - CW	~100 - CW (CW)
Number of Cycles		$10^5 - 10^3$	$10^5 - 10^3$	$10^6 - 10^4$ (10^3)
Surface Temperature,	°C	< 1000	< 500	400 - 600
Heat Sink Temperature,	°C	< 400 - 750	< 400	400 - 600
Magnetic Field,	T	~ 5 - 7	< 1 - 5;	5 - 12 (5-25)
Structural Materials		Copper Alloys, Refract. Metals	Copper Alloys,	PCA, HT-9, V-Alloys
Surface Materials		Be, SiC, BeO, C, W, Ta, V	Mo, W	-
Coolant		Water, LM	Water	Water, LM, Gas

TABLE II – HIGH HEAT FLUX COMPONENTS TECHNOLOGY ISSUES AND TESTING NEEDS

Issue/Technical Area	Level of Concern	Test Category 1	2	3	4	5
1. <u>Materials Data Base Development</u>						
a. First Wall Materials	high	X				
b. HHFC Materials and Composites	high	X				
2. <u>HHFC Surface Damage Mechanics</u>						
a. Physical Sputtering and Redeposition	critical		X			
b. Arcing and Related Erosion	high		X			
c. Chemical Erosion	medium		X			
d. Surface Damage due to Helium Implantation	medium		X			
e. Disruption-Induced Surface Melting and Erosion	medium		X			
3. <u>HHFC Thermomechanical Performance</u>						
a. HHFC Structural Integrity and Life Time Assessment	critical		X	X		
b. Heat Sink Bond Fabrication and Failure	high		X	X		
c. Thermal Hydraulic Techniques	high		X	X		
d. Hot Spot and Hot Channel Assessment	high			X		
e. Limiter Leading Edge	high			X		
4. <u>HHFC Systems Integration</u>						
a. Tritium Permeation and Inventory	critical		X		X	
b. Choice of Limiter vs. Divertor	high					
c. Coolant Compatibility and Heat Recovery	high					
d. Maintenance and Replacement	high			X	X	
e. Tritium Inventory Behavior during Maintenance	high		X		X	
f. Eroded Activation Product Transport	medium				X	X
g. Disruption Electromagnetic Loading	high				X	X
h. Alignment Accuracy and Stability	medium				X	
5. <u>Plasma Edge Conditions and Exhaust</u>						
a. Plasma Edge Temperature and Density Control	critical					X
b. Helium and Impurity Exhaust	high					X
c. Plasma Exhaust Stream Pressure and Composition	medium					X
d. Surface Conditioning Effectiveness	medium					X
6. <u>RF Components (Heating Systems)</u>						
a. RF Launcher Performance	critical	X			X	X
b. Window and Feedthrough Performance	critical	X			X	
c. RF Transmission System Performance	medium	X			X	X

TABLE III – HHFC TEST CATEGORIES AND REQUIREMENTS

Test Category	Test Article	Importance of Neutrons	Other Required Conditions	Adequate (Desirable) Test Facilities Near Term	—	Long Term
1. Materials Data Base Development	Specimen	critical	t	FR, PNS		
2. PMI Surface Damage Mechanisms	Elements	low	PMI, (B,T)	PMI-TS		
3. Thermomechanical Module Tests	Modules	high	PMI,Q,(B)	TS, PMI-TS, FERF (ETF)		
4. Integrated Component Tests	Components	medium	PMI,T,(RF)	TS	PBX or FERF	
5. Systems Performance Tests	Systems	low-high (Q,t)	PMI,B,T,RF		PBX	ETF