CONF-851102--58

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ORNL FACILITIES FOR TESTING FIRST-WALL COMPONENTS[*]

CONF-851102--58

DE86 004793

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Abstract

Future long-pulse magnetic fusion devices will have operating characteristics similar to those described in the design studies of the Tokamak Fusion Core Experiment (TFCX), the Fusion Engineering Device (FED), and the International Tokamak Reactor (INTOR). Their first-wall components (pumped limiters, divertor plates, and RF waveguide launchers with Faraday shields) will be subjected to intense bombardment by energetic particles exhausted from the plasma, including fusion products. These particles are expected to have particle energies of ~100 eV, particle fluxes of $\sim 10^{18}$ $cm^{-2} \cdot s^{-1}$, and heat fluxes of ~1 kW/cm^2 CW to ~100 kW/cm^2 transient. No components are available to simultaneously handle these particle and heat fluxes, survive the resulting sputtering erosion, and remove exhaust gas without degrading plasma quality. Critical issues for research and development of first-wall components have been identified in the INTOR Activity. Test facilities are needed to qualify candidate materials and develop components. At Oak Ridge National Laboratory (ORNL), existing neutral beam and wave heating test facilities can be modified to simulate first-wall environments with heat fluxes up to 30 kW/cm^2, particle fluxes of $\sim 10^{18}$ $cm^{-2} \cdot s^{-1}$, and pulse lengths up to 30 s, within test volumes up to ~100 L. The characteristics of these test facilities are described, with particular attention to the areas of particle flux, heat flux, particle energy, pulse length, and duty cycle, and the potential applications of these facilities for first-wall component development are discussed.

Introduction

First wall components such as divertors, pumped limiters, and RF launchers including Faraday shields have been used for plasma heating and impurity control, thus improving plasma quality in a variety of magnetic confinement devices [1–6]. Located at the plasma periphery of a device, these components are subjected to intense bombardment by exhausted plasma particles and must handle high fluxes of energetic particles. As detailed in the INTOR design study [1], average continuous heat fluxes can be 1000 W/cm^2, and the average particle flux could be 10^{19} $particles/cm^2 \cdot s$. During plasma disruptions, transient (~20-ms) heat fluxes of 10 to 100 kW/cm^2 can occur. At the moment, no components are available to simultaneously handle these particle and fusion products (with the associated heat fluxes), survive the resultant sputtering erosion, and remove exhaust gas without degrading plasma quality. Design studies and recent technical assessments for present and future fusion devices [1–5] have identified many critical issues and problem areas for research and development. Some of the major ones for component technology development are component configurations, fabrication techniques, thermal hydraulics, thermal fatigue, material erosion, radiation damage, and tritium permeation.

In the ongoing fusion research effort, the development of first-wall components has been aggressively pursued with a goal of enhancing reliability and functionality for application to near-term experimental devices. In addition, a major concern is the lifetime limitation due to thermal fatigue and sputtering erosion. At the moment, favored candidate components are those with duplex structures, which are made of actively cooled substrates and protective shield materials. Protective materials are those that meet the criteria of minimal erosion, survival of high temperatures, and mitigation of deleterious effects on the plasma. Current candidates are Be, BeO, C, Mo, SiC, Ta, TiC, and W. Cooled substrates must be able to remove all heat from exhausted plasma particles. Candidates are copper alloys and vanadium alloys. To withstand the enormous electromagnetic forces during plasma disruptions, duplex structures can be further strengthened by materials such as stainless steel or Inconel.

To evaluate their structural integrity and the fabrication technology used, developed components must be tested in a facility that can simulate the anticipated harsh environment of high fluxes of energetic particles and the resulting heat. Information on the survival of protective materials under high heat fluxes, the net erosion of protective materials under high fluxes of energetic particles, and the fatigue under thousands of cycles of quasi-steady-state heat loads is needed for component development.

Some dedicated electron beam, ion beam, and plasma facilities [5] are being used to perform physics, materials, and engineering experiments, but none of these facilities can provide the desired steady-state high heat fluxes and energetic ion particle fluxes for testing moderate-size first-wall components. Thus, a steady-state (30-s) Plasma Materials Test Facility (PMTF) has been designed and is being constructed at Sandia National Laboratories (SNL), Albuquerque. As described in Table I, this facility is designed to provide 30-s ion beams and peak heat fluxes of 8 kW/cm^2. When it is commissioned, first-wall components for long-pulse operation can be conditioned and qualified for overall performance evaluation. However, existing ORNL facilities that can produce higher heat fluxes and particle fluxes [7] require only minor modification to be operated for first-wall component conditioning and qualifications. These ORNL facilities are listed in Table I and further described in what follows.

ORNL Facilities

To develop and test neutral beam injection systems for heating plasmas in magnetic confinement devices such as tokamaks and mirrors, several large, high-power neutral beam test facilities were constructed at ORNL in the last decade. The High Heat Flux Facility (HHFF), the Medium-Energy Test Facility (METF), and the High-Power Test Facility (HPTF) were used to develop ion sources [8–14] that produce hydrogen ion beams with 10 to 100 A, 30 to 120 keV, and 0.05 ms to 30 s and neutral beam injectors that inject neutral beams with power ranging from 700 kW to multimegawatt levels. Recently, a Radio-Frequency Test Facility (RFTF) [15] has been constructed at ORNL for developing RF heating technology. As listed in Table I, these facilities can be operated to adequately cover the desired test conditions for development and qualification of first-wall components. For example, the METF is an extremely high heat flux test facility. Using developed 30-s, 80-keV ion sources and beam line components, it has already produced 100-MJ ion beams with about 15 kW/cm^2. The source can be tuned to produce beams with peak power density of 30 kW/cm^2. A beam stop (made of swirl tubes) at this facility has survived 25,000 full-power beam pulses and 70,000 cumulative beam seconds [16]. The swirl tube target has been demonstrated to be a favorable

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[*] Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

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Table I. Ion and plasma facilities

	ORNL test facilities				SNL-Albuquerque facility
	HHFF	HPTF (HPFF)	METF (EHHFF)	RFTF	PMTF
Particle	He^+, H^+	He^+, H^+, D^+, e	H^+	He^+, H^+, D^+, e	H^+
Energy, eV	30,000	100	80,000	10	40,000–80,000
Particle flux rate, ions/cm^2·s	10^{18}	10^{19}	10^{18}	10^{17}	
Power, MW	0.3	0.3	3	1	1.6
Peak heat flux, W/cm^2	8,000	1,000	30,000	400	8,000
Target area, cm^2	50	1,000	1,000	3,000	100–200
Pulse length, s	1.0	60	30	cw	30
Duty cycle, s	10	150	150		
Active on-time, s/year	1.4×10^5	2.3×10^6	1.2×10^6	5.8×10^6	
Fluence, cm^{-2}·year	5.6×10^{23}	2.3×10^{25}	1.2×10^{24}	6×10^{23}	
Erosion rate, cm/year					
He^+ + stainless steel	0.8	15.3		0.2	
D^+ + stainless steel		1.3		0.10	
H^+ + stainless steel	0.024	0.5	0.019	0.007	
Heat removal capacity, MW	0.15	10	10	10	10
Status	Operational	Operational	Operational	Operational	Construction

candidate substrate for first-wall components and has passed thermal fatigue tests without deleterious effects.

The capabilities of each facility for testing first-wall components are discussed in this section. Their application to investigations of active cooling techniques, heat flux handling capability, material survivability, net erosion, and fabrication techniques (such as cladding, bonding, and coating) is also described.

High Heat Flux Facility

The HHFF can produce hydrogen and helium ion beams with a peak power density approaching 10 kW/cm^2. Its peak power density is well above that of existing ion facilities in the U.S. High Heat Flux Component Development Program. The HHFF (Fig. 1) uses an ORMAK 10-cm source [8], which was developed to form 30-keV, 10-A, 50-ms ion beams and is now producing 3-s ion beams with energy up to 26 keV, current up to 7 A, and peak power density up to 7 kW/cm^2. The vacuum system can be evacuated to a base pressure below 10^{-6} torr and maintained at 5×10^{-4} torr during a beam pulse by six 25-cm-diam diffusion pumps with a pumping speed of 12,000 L/s. Many vacuum ports with diameters of 20 and 30 cm provide access for experimental instrumentation. The electronics in this facility offers the flexibility of changing the beam pulse length and the duty factor. In addition, the well-developed 10-cm ion sources can reliably produce long-pulse, high-heat-flux ion beams for more than 10,000 shots without maintenance. Moreover, the high duty factor (~10%), fast pumpdown time (~1 h), flexibility for changing the experimental setup, and low operating cost make this facility very attractive for concept evaluation and technology development.

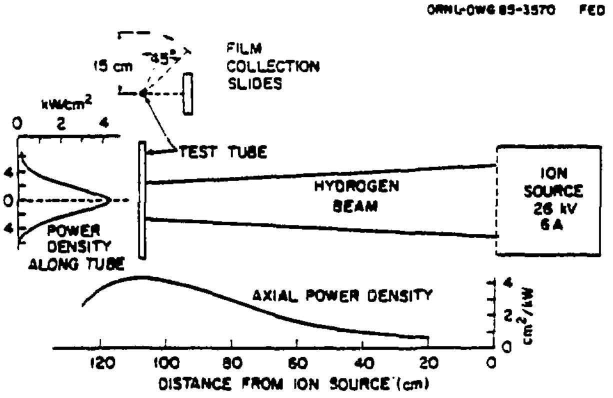

Figure 1. Test arrangement in the High Heat Flux Facility (HHFF).

In 1982, the ORNL neutral beam program began to develop a 30-s, 80-keV ion source for the Tandem Mirror Fusion Test Facility (MFTF-B). The requirement of good beam optics (divergence below 0.3° HWHM) created a great demand for a beam stop that could handle peak power fluxes of 30 kW/cm^2 for 30 s. Swirl tube cooling technology developed at ORNL in the 1960s [17] was chosen for this application after test of candidate samples of a plain copper tube, a tube with inner fins, and a swirl tube (made of a plain copper tube threaded with a twisted Inconel ribbon). As described in Ref. 16, the swirl tube is best for heat removal and handling peak power density with minimal water flow. Swirl tube heat transfer has been further analyzed for a swirl tube limiter [18]. The analysis indicates that such a limiter can be developed to handle steady-state heat fluxes of ~1 kW/cm^2 and transient heat fluxes of several tens of kilowatts per square centimeter.

To develop a reliable Faraday shield for ion cyclotron resonance heating (ICRH) [19], a series of sputtering tests of swirl tubes with different candidate plasma-side (protective) materials was conducted in the HHFF during the last two years [20]. The ion source was used to produce beams with a peak power density of 4 kW/cm^2 and an average power density of 1.7 kW/cm^2 over a 13-cm width for the erosion test. Without active cooling, a 0.6-cm-thick stainless steel plate was melted through by a 2-s ion beam pulse at 26 kV and 6 A. However, with active swirl cooling, the candidate materials graphite, TiC, Cr, Ni, Cu, Ag, Au, and Al survived the test. As discussed in Ref. 20, the net erosion was measured by weight loss after sputtering by 2000 shots of 1-s beams. The measured erosion rate of all the materials except TiC is at least three times above the reference value estimated from published data [21]. The best

Table II. Erosion results of tested samples

	Material and coating type[a]							
	Graphite	TiC	Cr		Ni	Cu	Ag	[illegible]
		PS	EP	PS	EP		EP	EP
Hydrogen Beam								
Mass loss, mg	18	17	38		62	132	256	228
Number of sputtered particles N_{SP}, $\times 10^{20}$ atoms	9.0	1.7	4.4		6.4	12.5	14.3	7.0
Number of beam particles N_B, $\times 10^{22}$ particles	2.1	1.6	1.6		1.6	1.6	1.6	1.6
N_{SP}/N_B, atoms/particle	0.04	0.01	0.03		0.04	0.08	0.09	0.04
Sputter coefficient S_R, atoms/ion		0.006			0.006	0.01	0.03	0.01

[a]PS = Plasma-sprayed coating, EP = electroplating.

material is TiC, for which the measured erosion rate is only 1.6 time the reference value. The results of our tests are given in Table II.

Medium Energy Test Facility

The METF, shown in Fig. 2, was designed and constructed to develop neutral beam injectors for the Princeton Large Torus (PLT) tokamak in 1976 [10]. The injectors were used to inject multimegawatt neutral beams that allowed PLT plasmas to achieve record temperatures [22].

The METF consists of two PLT beam line chambers at the two ends and a target chamber in the middle, with absolute valves to isolate them from each other. In each beam line chamber, a water-cooled target stops the injected beams and a cryopump provides the primary vacuum pumping. This is the first cryopumped beam line developed for plasma heating. The base pressure is in the 10^{-8}-torr range. Under neutral beam development and qualification, the hydrogen vapor pressure is in the middle of the 10^{-6}-torr range. During beam or arc pulses, the chamber pressure can be raised to 10^{-4} torr.

With the ion sources developed for PLT and the Impurity Study Experiment (ISX), the 40-keV, 60-A, 0.3-s ion beams have a peak power density exceeding 15 kW/cm^2 at 2 m downstream [23]. The METF has been modified to permit 100-A source and 30 s source development. With Poloidal Divertor Experiment (PDX)/ISX sources, the peak power density for 50-keV, 100-A, 0.5-s ion beams approaches 30 kW/cm^2 at 2.5 m downstream. With the 30-s Advanced Positive Ion Source (APIS) [14], the peak power density for 80-keV, 50-A ion beams is as high as 30 kW/cm^2 at 6 m downstream. In addition to the current facility capability of long (~30-s) pulses and extremely high power density (~30 kW/cm^2), the large volume, large vacuum ports (45 by 70 cm), and ~1000-cm^2 beam area are all attractive features for testing high-heat-flux first-wall components. Hence, the METF can function as an Extra High Heat Flux Facility (EHHFF). This facility could be used for conditioning and qualifying full-scale, actively cooled pumped limiters or divertor plates. Overall cooling techniques can be tested, and the net sputtering erosion of plasma-side materials can be evaluated. Techniques of fabrication of duplex structures, including bonding, coating, brazing and cladding, can also be tested.

High Power Test Facility

The HPTF is a cryopumped clean vacuum facility similar to the METF, as shown in Fig. 3. The facility can use a well-developed ion source or plasma generator to furnish high heat fluxes or high particle fluxes for first-wall component development applications.

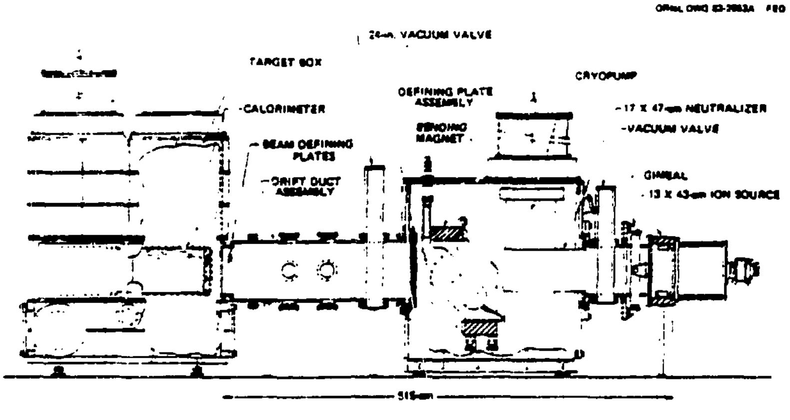

Figure 2. Medium Energy Test Facility can be used as an Extra High Heat Flux Facility (EHHFF).

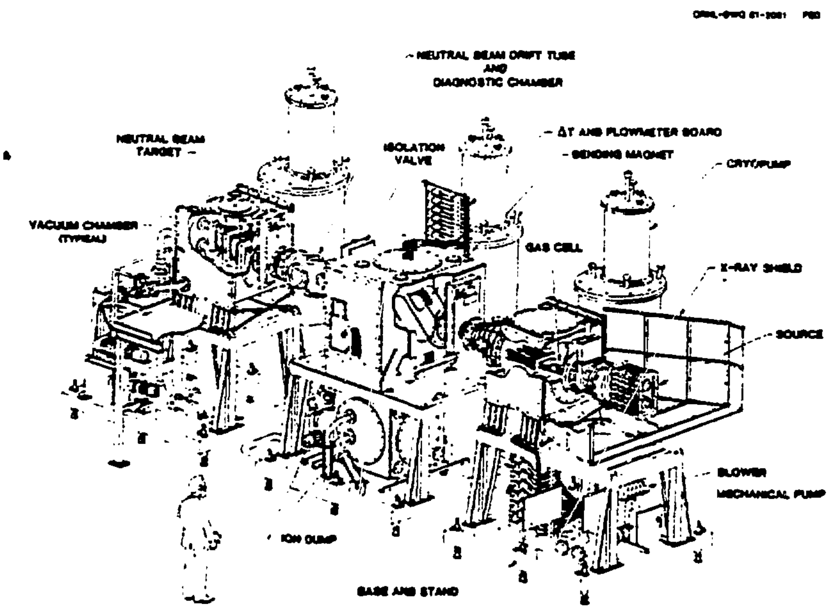

Figure 3. High Power Test Facility can be used as a High Particle Flux Facility (HPFF).

The facility was constructed to develop high-power ion sources that can produce ion beams with energies up to 150 keV. The generic study of tetrode ion accelerators [24] revealed that the peak power density of ion beams can be increased by raising the ratio of the electric field in the second gap to that in the first gap of the accelerator. As shown in Fig. 4, the peak power density can be varied five times. Given the current understanding of accelerator physics, the range of power density variations should be easily extended to 100 times. In fact, the field ratio can be changed simply by varying the potential to the second (or gradient) grid in the accelerator, using a gradient grid modulator in the high-voltage power supply. For instance, to study the effects of transient heat fluxes (during plasma disruptions) on the protective surface materials of first-wall components, the ion source can be operated to produce 30-s ion beams with a 1-kW/cm^2 heat flux with a superimposed 20-ms, 100-kW/cm^2 transient heat flux. Under such extremely harsh conditions, the survivability of the protective materials and the integrity of fabrication techniques for duplex-structure components can be evaluated.

The sputtering erosion of protective materials is a factor of major concern for the lifetime of components. A facility that can provide high fluxes of energetic particles (10^{18} to 10^{19} particles/cm^2·s) and 10 to 1000 eV is needed. The HPTF can function as a high particle flux facility (HPFF) using a well-developed plasma generator [25] as a particle source. As noted in Table I, this facility can provide different charged particles (He^+, H^+, D^+, and e) at energies from tens to hundreds of electron volts and particle fluxes up to 10^{19} particles/cm^2·s. During one year's operation, if the active on-time is 2.3×10^6 s, the fluence will be up to 2.3×10^{25} particles/cm^2. For stainless steel, the sputtering erosion rate is 15.3 cm/year for 100-eV He^+ ions, 13 cm/year for 100-eV D^+ ions, and 0.5 cm/year for 100-eV H^+ ions. The high fluence features of this facility offer the opportunity to study the erosion of different protective materials with different charged particles at different energies. This summer, an experimental study of sputtering rates in graphite-covered Faraday shields revealed a 4× increase with RF power on an ICRH loop antenna [26]. The details of the physics are being investigated.

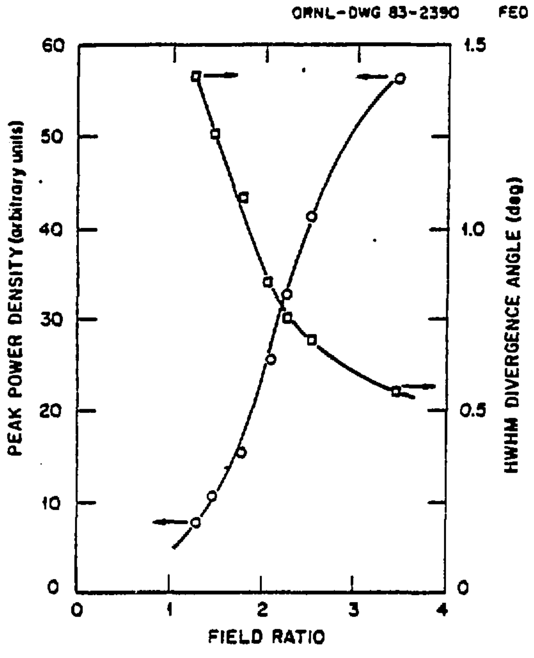

Figure 4. Peak power density and divergence angle varied with the field ratio for 90-keV, 9-A beams.

RF Test Facility

The RFTF as constructed is designed to provide a national test facility for evaluating steady-state, high-power (~1.0-MW) ICRH systems and components [15]. As shown in Fig. 5, the facility consists of a vacuum vessel and two fully tested superconducting

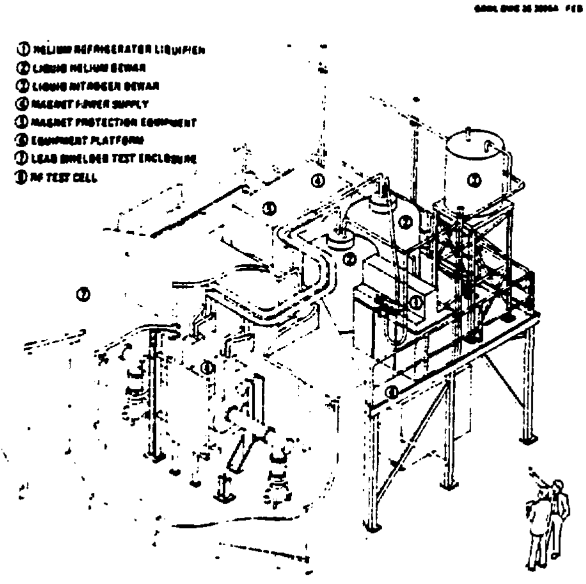

Figure 5. RF Test Facility.

development magnets from the ELMO Bumpy Torus Proof-of-Principle (EBT-P) program. The vacuum vessel has a large port (74 by 163 cm) and a test volume (~ 1.5 m^3) adequate for evaluating RF launchers for Doublet III-D, Tore Supra, and the Tokamak Fusion Test Reactor (TFTR). The magnets are arranged to form a mirror ratio of 4.8 and are capable of generating a steady-state field of ~ 3 T on the axis in the magnet throats. The 2000-L/s turbopumps evacuate the vacuum vessel down to 10^{-7} torr. Steady-state plasmas with a density of up to 5×10^{12} cm^{-3} and electron temperatures of ~ 10 eV will be created by a dedicated 28-GHz, 200-kW gyrotron. RF power sources with frequencies from 2 to 200 MHz and power from 1.5 to >1000 kW will be used for ICRH component evaluations. If the ICRH power is successfully coupled into the plasma, ion temperatures are calculated to exceed 50 eV [27]. This facility can provide a plasma environment (with various RF heating sources) for simulating plasma edge conditions and evaluating first-wall components.

Conclusions

It is clear that ORNL ion and plasma facilities can be employed for first-wall component development and qualification. In particular, the HPTF is the only controllable facility that can provide a heat load consisting of a long-pulse ($\sim$30-s) constant heat flux of 1 kW/cm^2 with a superimposed transient ($\sim$20-ms) peak heat flux of $\sim$100 kW/cm^2. Thus, this facility is extremely valuable for studying the thermal-mechanical properties of first-wall components and evaluating the erosion of protective materials due to sputtering, melting, and evaporating caused by the transient heat loads. The following tasks could be efficiently carried out using these ORNL facilities and other existing technology:

- applying the existing fabrication technology developed for quasi-steady-state neutral beam injectors and ion sources to the development of steady-state, actively cooled first-wall components;
- conditioning first-wall components as they are developed;
- evaluating the heat flux handling capability of first-wall components as they are developed;
- testing the sputtering erosion of plasma-side (or protective) materials of first-wall components; and
- evaluating the feasibility of bonding, coating, or cladding techniques used to apply protective materials to first-wall components.

Acknowledgments

The authors would like to thank their colleagues for contributions to the technology research and development program in the areas of neutral beam and wave heating. G. C. Barber, N. S. Ponte, D. O. Sparks, and R. E. Wright are acknowledged for their electrical and electronics support; C. W. Blue, R. C. Davis, S. C. Forrester, J. A. Moeller, and F. Sluss for their support in test facility maintenance; S. K. Combs, W. K. Dagenhart, P. M. Ryan, and D. E. Schechter for their participation in experiment preparation, operation, and evaluation; and C. A. Foster, S. L. Milora, and J. H. Whealton for constructive discussions. The authors also wish to extend their thanks to L. A. Berry, D. S. Beard, J. F. Clarke, F. E. Coffman, R. J. Dowling, G. M. Haas, O. B. Morgan, and H. S. Staten for their encouragement and endorsement of ORNL plasma heating technology research and development in the past decade.

References

[1] W. M. Stacey et al., eds., *The U.S. FED/INTOR Activity*, USA/FED-INTOR/82-1, 1982.

[2] Proceedings of various International Conferences on Plasma-Surface Interactions, published in the *Journal of Nuclear Materials*.

[3] P. K. Mioduszewski, *J. Nucl. Mater.*, Vols. 111 & 112, p. 253, 1982.

[4] M. M. Cohen and J. B. Roberto, presented at the Workshop on High Heat Flux Materials for TFCX, Germantown, Maryland, April 17–18, 1984.

[5] R. W. Conn et al., eds., *Technical Assessment of the Critical Issues and Problem Areas in the Plasma-Materials Interaction Field*, PPG-765, Center for Plasma Physics and Fusion Engineering, University of California at Los Angeles, 1984.

[6] W. R. Becraft and H. H. Haselton, *The National RF Technology Research and Development Program Plan*, CONF-820758, 1982.

[7] C. C. Tsai et al., "Testing capability at ORNL for the simulation of fusion plasma-wall interactions," presented at NATO International Advanced Course on Physics of Plasma-Wall Interactions in Controlled Fusion, Val-Morin, Quebec, Canada, July 30–August 10, 1984.

[8] O. B. Morgan, "High intensity ion source for thermonuclear research and development," in *Proc. 2nd Symp. on Ion Sources and Formation of Ion Beams*, 1974, paper VII-1.

[9] T. C. Jernigan et al., "The DuoPIGatron ion sources and neutral injection heating in ORMAK," in *Proc. 2nd Symp. on Ion Sources and Formation of Ion Beams*, 1974, paper VI-9.

[10] H. H. Haselton et al., "PLT and Doublet III neutral beam injection systems," in *Proc. 6th Symp. on Engineering Problems of Fusion Research*, 1975, p. 865.

[11] C. C. Tsai et al., "DuoPIGatron ion sources for PLT injectors," in *Proc. 7th Symp. on Engineering Problems of Fusion Research*, 1977, p. 278.

[12] W. L. Stirling et al., "The new ORNL neutral beam transport system," in *Proc. 7th Symp. on Engineering Problems of Fusion Research*, 1977, p. 539.

[13] W. L. Gardner et al., "The ORNL prototype PDX neutral beam injection system," in *Proc. 8th Symp. on Engineering Problems of Fusion Research*, 1979, p. 972.

[14] M. M. Menon et al., "Quasi-steady-state multimegawatt ion source for neutral beam injection," *Rev. Sci. Instrum.*, Vol. 56, p. 242, 1985.

[15] W. L. Gardner et al., "The Oak Ridge RF test facility," paper presented at this symposium.

[16] S. K. Combs et al., "Compact, inexpensive target design for steady-state heat removal in high-heat-flux fusion applications," *Rev. Sci. Instrum.*, Vol. 56, p. 1526, 1985.

[17] W. R. Gambill et al., *Chem. Eng. Prog.*, Vol. 57, p. 127, 1961.

[18] S. L. Milora et al., *A Numerical Model for Swirl Flow Cooling in High-Heat-Flux Particle Beam Target and the*

Design of a Swirl-Tube Based Plasma Limiter, ORNL/TM-9183, Oak Ridge National Laboratory, 1984.

[19] D. J. Hoffman et al., "Materials and electromagnetic properties of Faraday shields for ion cyclotron antennas," in *Proc. 6th Topical Meeting on Technology of Fusion Energy*: *Nucl. Technol./Fusion*, Vol. 8, p. 392, 1985.

[20] D. E. Schechter et al., "Erosion tests of materials by energetic particle beams," *Proc. 6th Topical Meeting on Technology of Fusion Energy*: *Nucl. Technol./Fusion*, Vol. 8, p. 559, 1985.

[21] E. W. Thomas, "Particle interactions with surfaces," in *Atomic Data for Controlled Fusion Research*, Vol. III, ORNL-6088/V3, Oak Ridge National Laboratory, 1985.

[22] H. Eubank et al., "Neutral-beam-heating results from the Princeton Large Torus," *Phys. Rev. Lett.*, Vol. 43, p. 270, 1979.

[23] J. Kim and J. H. Whealton, "Beam intensity distribution in neutral beam injection systems," unpublished, 1976.

[24] C. C. Tsai et al., "Development of long-pulse (30-s), high energy (120-keV) ion source for neutral beam application," *Nucl. Technol./Fusion*, Vol. 4, p. 1424, 1983.

[25] C. C. Tsai et al., "Characteristics of a high particle flux plasma source for rf technology development," *Bull. Am. Phys. Soc.*, Vol. 29, p. 1221, 1984.

[26] J. B. O. Caughman et al., "The effect of rf on the sputtering rate of ICRH antenna components," *Bull. Am. Phys. Soc.*, Vol. 30, p. 1590, 1984.

[27] D. W. Swain, Oak Ridge National Laboratory, private communication, October 1985.