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FUSION ENERGY DIVISION ANNUAL PROGRESS REPORT

Period Ending December 31, 1987

O. B. Morgan, Jr.

L. A. Berry

J. Sheffield

Fusion Energy Division Staff

Date published - November 1988

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
Martin Marietta Energy Systems, Inc.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

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ORNL-6234	Period Ending December 31, 1985
ORNL-6332	Period Ending December 31, 1986

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SUMMARY

The Fusion Program of Oak Ridge National Laboratory (ORNL), a major part of the national fusion program, carries out research in nearly all areas of magnetic fusion. Collaboration among staff from ORNL, Martin Marietta Energy Systems, Inc., private industry, the academic community, and other fusion laboratories, in the United States and abroad, is directed toward the development of fusion as an energy source. This report documents the program's achievements during 1987. Issued as the annual progress report of the ORNL Fusion Energy Division, it also contains information from components of the Fusion Program that are external to the division (about 15% of the program effort).

The areas addressed by the Fusion Program include the following:

- experimental and theoretical research on magnetic confinement concepts,
- engineering and physics of existing and planned devices,
- development and testing of diagnostic tools and techniques in support of experiments,
- assembly and distribution to the fusion community of databases on atomic physics and radiation effects,
- development and testing of technologies for heating and fueling fusion plasmas,
- development and testing of superconducting magnets for containing fusion plasmas, and
- development and testing of materials for fusion devices.

Highlights from program activities follow.

Toroidal Confinement Experiments

The Advanced Toroidal Facility (ATF) is the principal focus of the division's toroidal confinement program. The ATF experimental program is designed to address a broad range of toroidal confinement physics issues, including high beta and magnetohydrodynamic (MHD) stability; low-collisionality transport and the role of electric fields; electron cyclotron heating (ECH), neutral beam injection (NBI), and heating in the ion cyclotron range of frequencies (ICRF); plasma-materials interactions, and particle control and energy removal. The construction project that provided the basic torsatron was completed on December 17, 1987. Progress was made on all other requirements for facility operation, and by the end of 1987 the operational phase had begun; a first plasma was created on January 13, 1988.

In the area of advanced projects, the low-aspect-ratio torsatron was investigated further and the Spherical Torus Experiment (STX) concept was updated. The minimum-size torsatron reactor studies continued, and the energetic orbit confinement properties of these configurations were examined; preliminary ideas for a successor to ATF were discussed. A project to build a prototypical ohmic heating solenoid for STX was nearing completion at year's end.

Work in the area of advanced studies continued to provide strong support to the U.S. efforts to define and design both the Compact Ignition Tokamak (CIT) and the International Thermonuclear Experimental Reactor (ITER).

As in the past, the toroidal confinement program was involved in extensive collaborative activities. In addition to many fruitful exchanges with U.S. and international institutions, formal collaborations with the Federal Republic of Germany and Japan on the TEXTOR tokamak and with France on the Tore Supra tokamak continued.

Atomic Physics and Plasma Diagnostics Development

Activities in the atomic physics and plasma diagnostics development program are divided among atomic collisions research, data compilation and evaluation, and plasma diagnostics development.

The atomic collisions research activity focuses on inelastic processes that are important for determining the energy balance and impurity transport in high-temperature fusion plasmas and for diagnostic measurements. The addition of three new beam lines to the electron cyclotron resonance (ECR) multicharged ion source this year extended the experimental efforts in the study of atomic collision processes involving highly ionized plasma impurity ions.

Data compilation and evaluation are carried out by the Controlled Fusion Atomic Data Center (CFADC). During the year, the bibliographic database on atomic collisions was moved to an advanced database management system and made available for online searching. Volume 5 of the "Redbook" series of recommended data for fusion research, *Collisions of Carbon and Oxygen Ions with Electrons, H, H₂ and He*, was published. The CFADC hosted a meeting of the International Atomic Energy Agency (IAEA) Atomic and Molecular Data Center Network in November; representatives from six countries made plans to collaborate in establishing a computerized numerical database for atomic data relevant to fusion research.

The plasma diagnostics program concentrates on the development of advanced diagnostics for magnetic fusion experiments. Work continued on the use of small-angle Thomson scattering of a pulsed CO₂ laser beam to measure the density and velocity distribution of fusion-produced alpha particles. A long-pulse CO₂ laser and heterodyne infrared receiver were constructed and tested, and a simulated scattering experiment was conducted; this diagnostic will be tested on ATF. An advanced multichannel far-infrared (FIR) laser interferometer system is also being prepared for installation on ATF; at year's end, the support frame and the laser and optical systems were ready for transportation to the ATF experiment enclosure.

Plasma Theory and Computing

The plasma theory and computing program of the Fusion Energy Division is characterized by close interactions with the division's experimental program and with the national and international fusion programs.

During 1987, theoretical calculations were performed to predict the performance of ATF and to determine optimum operational scenarios. The bootstrap current was studied to determine ways of reducing or increasing it for easy measurement and study. ECH breakdown of the ATF plasma was modeled to quantify the range of parameters for effective plasma initiation. The neutral beam deposition and heating codes were benchmarked against those used at Kyoto University to study Heliotron-E. Ion cyclotron resonance heating (ICRH) codes were improved to allow modeling of realistic antenna geometries, wave propagation, and energy absorption and coupling. A detailed study of pressure-gradient-driven turbulence saturation phenomena showed that, for ATF parameters, anomalous losses may decrease as the second stability regime is reached.

New low-aspect-ratio torsatron configurations were created and studied with an improved version of the three-dimensional spectral equilibrium code, VMEC. The designs of the Large Helical System (LHS) device, under consideration by the Japan Atomic Energy Research Agency (JAERI), and of the H-1 heliac, to be built in Canberra, Australia, were evaluated. In support of the CIT and ITER studies, scenarios of operation and of alpha particle effects were modeled, and heating, fueling, and current drive were investigated.

Regimes of improved plasma performance following pellet injection into the Joint European Torus (JET) were analyzed. The ORNL rf heating code was modified to allow calculation of cyclotron emission from energetic ions in tokamaks; these calculations can be applied to fusion alpha particles in devices such as JET and the Tokamak Fusion Test Reactor (TFTR). The method will also be useful for studying other kinds of plasma radiation, such as that produced by impurities.

A new effort this year is the use of particle simulation techniques to study the stability and turbulence of plasmas. These techniques are also being applied to the study of plasmas in the near field of ICRH antennas.

Details of single particle orbits in stellarator geometry were studied by using the toroidal adiabatic invariant. This technique is also being used to study the transport of particles out of the divertor stripes in ATF.

The computing support group developed programs to support ATF operations, data acquisition, and data analysis. Computer control systems were developed for the JET pellet injector, the ICRH antenna for TFTR, and several components for Tore Supra. Two VAX 8700 computers were added to handle the ATF data analysis needs, and networks were upgraded.

Plasma-Materials Interactions

The Plasma-Materials Interactions Program addresses issues related to the interactions of hot plasmas with surrounding material surfaces. This includes wall conditioning procedures, studies of plasma-surface interactions, and implementation of impurity and particle removal schemes. In 1987, activities were concentrated on preparation of wall conditioning techniques and plasma edge diagnostics for ATF, modeling and diagnostics preparation for the Tore Supra pump limiter, and H_α studies and preparation of a helium removal experiment for the Advanced Limiter Test-II (ALT-II) on TEXTOR.

Wall conditioning techniques in ATF include baking, glow discharge cleaning, ECR discharge cleaning, and gettering; during the initial operating period, glow discharge and ECR discharge cleaning were used successfully. Plasma edge diagnostics prepared for the first phase of ATF operations included two instrumented limiters, H_α monitors, charge-coupled device cameras, an infrared camera, an instrumented movable divertor plate, and fast pressure gauges.

In collaboration with Sandia National Laboratories of Albuquerque (SNLA), the performance of a system of modular limiters for Tore Supra was modeled. An ATJ graphite limiter without pumping capabilities was installed and will be used for the first six months of operation. A number of diagnostics were prepared for the pump limiter, and data acquisition equipment and software for acquisition and analysis were tested and shipped to Cadarache.

Six H_α detectors were installed on TEXTOR for studies of particle confinement with ALT-II. A plan for the helium removal experiment was developed in collaboration with the TEXTOR group. An optical mass analyzer for charge-exchange spectroscopy on helium was purchased, tested, and shipped to TEXTOR.

Plasma Technology

The Plasma Technology Section comprises the division's research and development of plasma fueling systems, rf technology, and negative ion sources. During 1987, increased emphasis was placed on applications, with several large projects completed and others in progress. Substantial progress was also made in technology development. The section's modeling group provided modeling and computational support to these efforts.

Much of the work in the plasma fueling program involved international collaborations. Accomplishments include the delivery and commissioning of a three-barrel repeating pneumatic pellet injector for JET and continuing work on a centrifugal injector for Tore Supra. In JET experiments with the pneumatic injector, peak densities of $1.2 \times 10^{20} \text{ m}^{-3}$ were achieved in ohmically heated discharges. In the area of plasma fueling development, the Tritium Proof-of-Principle pneumatic injector was completed and tested at ORNL and installed on the Tritium Systems Test Assembly at Los Alamos National Laboratory (LANL). Work on advanced pellet

acceleration methods continued with the construction of an electron-beam rocket pellet accelerator and the design and fabrication of a two-stage pneumatic gun.

In the rf technology program, a 4-MW compact loop antenna for ICRF heating of TFTR was constructed. This antenna incorporates several advanced features, including a resonant double loop design and a Faraday shield clad with graphite tiles. It was delivered to TFTR following tests in the ORNL RF Test Facility. Design work was completed and component fabrication began for an ICRF antenna to be used on Tore Supra. This compact loop antenna, designed for >30-s pulses, will have several actively cooled components. The ORNL prototype cavity antenna for the Doublet III-D tokamak at General Atomics in San Diego underwent modifications that were predicted to increase the plasma loading and power handling capabilities of the design. Development work in the rf group included the construction and successful low-power testing of a full-size folded waveguide ICRF antenna and the improvement of brazing techniques for graphite-clad Faraday shield tubes.

Negative ion source development for high-energy neutral particle beams continued during 1987. A new source that uses transverse extraction of negative ions, designated VITEX-II, and a Ringatron source, which uses longitudinal extraction, were in progress.

Magnetics and Superconductivity

The highlight of the year in the magnetics and superconductivity area was the successful completion of the international Large Coil Task (LCT). The LCT program to test six different superconducting toroidal field coils produced informative, gratifying results.

On September 3, all six coils simultaneously reached peak fields of 9.0 to 9.2 T, while carrying currents of 98 to 108% of their design values; these are the largest coils (in size, weight, or stored energy) ever to produce 9 T. The test results indicate that either a forced-flow or a pool-boiling design could be extrapolated to a reactor-size magnet.

Repatriation of the foreign coils began in October. Members of the ORNL scientific and technical staff continued their evaluation of results and preparation of a summary report in collaboration with representatives of the other participants. With the completion of the LCT, the focus of the ORNL magnetics group began to shift to long-range tasks in fusion magnet development.

Advanced Systems

The Advanced Systems Program was organized in 1987 as a focal point for design studies of future fusion experiments. The Fusion Engineering Design Center is the major engineering resource for this program. This group of 25 to 30 persons consists of roughly equal numbers of ORNL researchers and outside industrial participants.

The principal activity of the Advanced Systems Program during most of the year was the CIT project, with some effort applied to design studies for the Tokamak Ignition/Burn Experimental Reactor (TIBER II) and the International Tokamak Reactor (INTOR). Activities in preparation for the ITER project were initiated, with the Design Center taking a key role in the overall design team.

In 1987, ORNL had the lead responsibility for design integration and six major elements of the CIT design: ex-vessel remote maintenance, shielding, external structure, vacuum systems, ICRH, and fueling.

Support for the TIBER II design effort, led by Lawrence Livermore National Laboratory (LLNL), included work on configuration development, facilities, remote maintenance, cost estimating, first wall and divertor design, fueling system design, and toroidal field magnet design. In addition, a systems code called TETRA was developed, under the direction of the Design Center, for use in the TIBER II design point selection.

The Design Center continued to lead the engineering activities for the INTOR program. These efforts, along with the assignment of one staff member to work with the design team for the Fusion Engineering Reactor in Japan, reinforced the Design Center's position as the primary point of interaction between the major international design teams and the U.S. reactor studies program. The Design Center will play a major role in the ITER project.

Materials Research and Development

The focus of the Fusion Materials Program is the development of materials for use in components of a fusion reactor that will be exposed to high neutron fluences during their design life. Austenitic and martensitic steels are being developed for first wall and structural applications; copper alloys, graphite, and carbon-carbon composites for high-heat-flux components; and ceramics for electrical insulators, rf windows, and possible structural applications.

In a collaborative program with JAERI, now in its fourth year, ORNL is investigating the effects of fusion reactor radiation damage levels on the engineering properties of austenitic steels. Central to this effort is the irradiation of these alloys in mixed-spectrum reactors, such as the High-Flux Isotope Reactor (HFIR), with tailoring of the neutron spectrum to produce damage levels equivalent to those produced in a fusion reactor spectrum. Analysis of initial results shows that microstructural evolution, swelling, and irradiation creep are strong functions of the damage level.

To simplify the decommissioning of fusion machines, structural alloys that undergo rapid decay of induced radioactivity are being developed. An experimental survey of the Fe-Cr-Mn-C system led to the development of alloys with strength and ductility superior to AISI 316 stainless steel.

To develop low-activation martensitic steels, tungsten is proposed as a substitute for molybdenum, and niobium is replaced by tantalum and vanadium. An initial series of Cr-W steels, analogous to the Cr-Mo steels, was produced; microstructural

examination, tensile tests, tempering studies, and Charpy impact tests indicate that three of the Cr-W steels, with 9 to 12% chromium, are comparable to commercially available 9Cr-1MoVNb and 12Cr-1MoVW steels.

Vanadium and the elements normally used in vanadium alloys are acceptable components for low-activation alloys. Tests of such alloys in the Experimental Breeder Reactor-II and the Fast Flux Test Facility revealed that the effects of irradiation on the mechanical properties of such alloys are strongly dependent on alloy composition.

Welding properties are being studied in collaboration with the Materials Engineering Department of Auburn University. Initial results have confirmed that welding of AISI 316 stainless steel with helium levels [from (n, α) reactions] several orders of magnitude below those expected in a fusion reactor's first wall presents a difficult problem.

Experiments to establish compatible combinations of structural material, coolant, and tritium breeder and to understand the mechanisms of corrosion and mass transfer continued during the year, with emphasis on the corrosion of low-activation austenitic and martensitic steels in lithium and Pb-Li systems. A qualitative model was developed to explain the corrosion-induced surface morphological changes of austenitic steels and the contrasting uniform corrosion of Fe-Cr alloys exposed to the same liquid metal under similar conditions.

During the year, several batches of Al_2O_3 and MgAl_2O_4 spinel were fabricated into disk specimens for irradiation studies. These isotopically tailored ceramics will be irradiated in HFIR to damage levels characteristic of fusion reactor environments; post-irradiation testing will include strength, dimensional stability, fracture toughness, loss tangent, and dielectric constant.

Neutron Transport

The Neutron Transport Program, carried out within the Engineering Physics and Mathematics Division, includes three elements: analyses, cross-section evaluation and processing, and the work of the Radiation Shielding Information Center.

The analysis program is part of a joint U.S.-Japan neutronics program and is directed at validating computer codes and cross-section data by comparing calculated results with experimental data obtained from the Fusion Neutron Source facility at JAERI. Neutron distributions and induced activation were calculated; the agreement between measured and calculated responses is generally good for threshold-type reactions.

The data evaluation and processing program is directed at producing accurate cross-section data for materials that are of interest to fusion reactor designers. The year, calculations for all isotopes of chromium and nickel were completed, and assembly of complete isotopic evaluations for chromium and nickel was initiated.

The Radiation Shielding Information Center responds to inquiries about radiation transport problems from an international community. Staff members provide

guidance by drawing on a technical database that includes a computerized literature file, a collection of complex computer programs, and a substantial body of nuclear data libraries. Recent contributors to this information cycle include Kernforschungsanlage Jülich (Federal Republic of Germany), the University of Tokyo (Japan), JAERI, LLNL, Sandia National Laboratories, and LANL.

The range of activities, the scope of the collaborations, and the achievements described in this report clearly illustrate the diversity and the strengths of the ORNL Fusion Program.

O. B. Morgan, Jr.
Director, ORNL Fusion Energy Division

L. A. Berry
Associate Director for Development and Technology,
ORNL Fusion Energy Division

J. Sheffield
Associate Director for Confinement,
ORNL Fusion Energy Division

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Section 1

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TOROIDAL CONFINEMENT ACTIVITIES

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J. L. Dunlap, Toroidal Confinement Physics Section Head
M. J. Saltmarsh, Confinement Projects Section Head

D. L. Abers ¹	M. D. Galloway ²¹	R. R. Kindsfater	J. P. Rudd
A. M. Alban ²	R. F. Gandy ³	C. C. Klepper	C. R. Scheich
D. R. Alford ³	D. C. Giles ³	M. Kwon ²⁰	D. D. Schurecho ⁶
F. S. B. Anderson ⁵	J. C. Glowacki	R. A. Langley	J. Sheffield ²⁷
S. E. Attenberger ³	G. C. Goodman ¹⁰	V. D. Latham ¹²	W. D. Shipley ²
F. W. Bailey ³	P. L. Goranson ²	E. A. Lazarus	G. H. Simon ¹²
G. C. Barber ³	R. P. Gormley ²¹	D. K. Lee ³	J. E. Simpkins
D. D. Bates ⁷	R. H. Goulding ³	J. Lee ²¹	E. Slaughter ²⁰
L. R. Baylor ²	D. E. Greenwood ⁵	V. E. Lynch ³	B. A. Smith ¹⁰
G. L. Bell ³	A. D. Guttery ¹	J. F. Lyon	D. A. Spong ¹⁰
J. D. Bell ³	C. L. Hahn ³	C. H. Ma ¹⁰	R. A. Stevens ²⁰
R. D. Benson ²	J. W. Halliwell	J. B. Mac ³	K. A. Stewart ¹⁰
T. S. Bigelow ²	E. L. Halstead ²²	L. A. Mac ³	K. D. St. Onge ²
C. Bridgman ³	C. J. Hammonds ²	J. A. Mayhall ²	J. N. Summers ¹⁰
R. A. Brown ²	K. Hanatani ²³	T. J. McManamy ²	I. N. Sviatoslavsky ⁴
R. L. Brown ¹⁰	G. R. Hanson ²⁰	G. S. McNelly ³	D. W. Swain ³
L. L. Burnette ¹¹	J. H. Harris	M. M. Memon	D. J. Taylor ²
R. D. Burris ³	J. W. Hask ¹²	D. L. Milnes ³	C. E. Thomas ²⁴
C. E. Bush	G. R. Haste ³	P. K. Miodunewski	C. K. Thomas ³
J. V. Byrd ¹²	D. I. Hatch ¹²	J. F. Monday ²	J. H. Thompson ¹²
E. J. Byrne ¹³	P. S. Hays ²³	E. R. Monroe ⁴	M. S. Thompson ¹
J. W. Campbell ¹²	G. H. Henkel	R. N. Morris ³	P. B. Thompson ²
A. Carnevali ¹⁶	R. L. Hickok ¹⁰	O. Motojima ²³	J. S. Tolliver ³
B. A. Carreras ¹⁶	R. E. Hill ³	M. Murakami	E. L. Tolano ²⁰
W. H. Casson ¹⁰	D. L. Hillis	G. H. Neilson	N. A. Uchian
K. K. Chipley ³	S. Hiroe	B. E. Nelson ²	T. Uchian
T. L. Clark ¹⁷	S. P. Hirshman ¹³	R. S. Norris ¹³	K. Uo ²³
R. J. Colchin	J. T. Hogan ¹³	H. Okada ²³	L. M. Vinyard ³
M. J. Cole ³	P. A. Holliday ¹	D. R. Overbey ¹³	M. R. Wade ²⁴
C. A. Collins ¹⁰	L. D. Horton	L. W. Owen ³	E. R. Wells ³
K. A. Connor ¹⁴	W. A. Houlberg ¹³	S. L. Painter ²¹	J. M. Whatley ¹²
D. L. Coppenger ¹³	H. C. Howe ¹³	V. K. Pare ⁷	J. A. White ²
E. C. Cruise, Jr.	D. P. Hutchinson ¹⁰	T. C. Patrick	T. L. White ³
W. R. DeVan ¹⁴	R. C. Isler	E. N. Patterson ¹	J. C. Whitson ⁴
R. A. Dory ¹³	E. O. Jenkins ¹³	H. R. Payne ³	J. B. Wilgen
G. R. Dyer	W. C. Jennings ¹⁶	N. S. Ponte ²⁰	D. E. Williamson ²
C. C. Eberle ²	H. W. Jernigan ³	D. A. Rasmussen	C. T. Wilson ²
P. H. Edmonds ¹⁰	T. C. Jernigan	T. F. Rayburn	W. R. Wing
J. F. Ellis ²⁰	L. M. Johnson ³	W. J. Redmond	R. J. Wood ²
A. C. England	R. L. Johnson ²	R. K. Richards	R. E. Wright ⁶
J. W. Forseman ²	G. H. Jones ²	J. R. Rider ¹²	R. B. Wyser ³
R. H. Fowler ³	L. M. Jordan ¹³	J. A. Rome ¹³	J. L. Yarber
W. A. Gabbard	K. L. Kannan ³	J. L. Rowe ¹²	K. G. Young ¹³

1. Section secretary
2. Engineering Division, Martin Marietta Energy Systems, Inc
3. Management Services Section
4. University of Wisconsin, Madison
5. Computing and Telecommunications Division, Martin Marietta Energy Systems, Inc
6. Plasma Technology Section
7. Instrumentation and Controls Division
8. Auburn University, Auburn, Ala
9. Grumman Aerospace Corporation, Bethpage, N Y
10. Magnetics and Superconductivity Section
11. Product Certification Division, Y 12 Plant
12. Maintenance Division, Y 12 Plant
13. Quality Department
14. Researcher Polytechnic Institute, Troy, N Y
15. Plasma Theory Section
16. Physics Division
17. Tennessee Technological University, Cookeville
18. Midwest Technical, Inc., Oak Ridge, Tenn
19. University of Texas, Austin
20. Large Coil Program
21. The University of Tennessee, Knoxville
22. Purchasing Division, Martin Marietta Energy Systems, Inc
23. Kyoto University, Kyoto, Japan
24. Georgia Institute of Technology, Atlanta
25. Virginia Polytechnic Institute and State University, Blacksburg
26. Consultant
27. Associate Division Director, Fusion Energy Division
28. Energy Division
29. Princeton Plasma Physics Laboratory, Princeton, N J

1. TOROIDAL CONFINEMENT EXPERIMENTS

SUMMARY OF ACTIVITIES

Most of the activities described here relate directly to the Advanced Toroidal Facility (ATF) program. The construction project that provided the basic torsatron was completed on December 17, 1987. Progress was made on all other requirements for facility operation, with the result that first plasmas should be achieved within a short time.

Advanced projects are represented by further investigations of the low-aspect-ratio torsatron, as a next-generation experiment and as a reactor, and by an update on the Spherical Torus Experiment. Our advanced studies continue to provide strong support for the U.S. effort to define and design both the Compact Ignition Tokamak and the International Thermonuclear Experimental Reactor.

Brief reviews of our participation in the U.S.-Federal Republic of Germany-Japan collaboration on ALT-II and in the U.S.-France collaboration on Tore Supra are presented.

1.1 THE ATF PROGRAM

1.1.1 Construction Project

T. C. Jernigan, project manager
P. B. Thompson, engineering manager

R. D. Benson, L. L. Burnette, J. V. Byrd, J. W. Campbell, K. K. Chipley, M. J. Cole, D. L. Coppenger, W. R. DeVan, G. R. Dyer, P. H. Edmonds, J. F. Ellis, J. W. Forseman, R. D. Foskett, W. A. Gabbard, J. C. Glowienka, E. L. Halstead, C. J. Hammonds, J. H. Harris, J. W. Hash, D. I. Hatch, G. H. Henkel, E. O. Jenkins, R. L. Johnson, G. H. Jones, L. M. Jordan, V. D. Latham, L. A. Massengill, P. K. Mioduszewski, J. F. Monday, R. N. Morris, G. H. Neilson, B. E. Nelson, R. S. Norris, T. F. Rayburn, J. R. Rider, J. A. Rome, J. L. Rowe, J. P. Rudd, M. J. Saltmarsh, G. H. Simon, J. E. Simpkins, D. J. Taylor, C. K. Thomas, L. M. Vinyard, J. M. Whatley, J. A. White, J. C. Whitson, and J. L. Yarber

The major device fabrication (MDF) construction project for the Advanced Toroidal Facility (ATF) was successfully completed in December 1987 within the

total estimated cost of \$19.9 million. The project was behind schedule by approximately one year, largely because extended reworking of the vacuum vessel was required to correct for weld shrinkage that occurred during manufacturing. The delay was exacerbated by a three-month strike of the craft unions at ORNL during the final assembly phase.

The first half of 1987 was devoted to completion of the vacuum vessel repairs at the manufacturer's plant. The manufacturer received extensive help from Fusion Energy Division personnel and from the Engineering Division of Martin Marietta Energy Systems, Inc., particularly in developing fixtures and methods for measuring the vessel contours. The vessel was finally delivered to the ATF site with a few known leaks in June, and it was temporarily installed to check for interferences.

The trial fit revealed some interferences with the helical field (HF) coil cooling tubes, and some recontouring of the vessel was required. This work was completed, the remaining vessel leaks were repaired, and the inside of the vessel was cleaned by the beginning of August. The final total leak rate of the vessel and flanges was approximately 1.5×10^{-5} torr-L/s of air equivalent.

Once the vessel was installed in August (see Fig. 1.1), the final assembly stage began. This phase went smoothly, although it was somewhat slowed by the craft strike (which lasted until the beginning of October).

ORNL-PHOTO 8377-87

Fig. 1.1. The completed vacuum vessel being lowered into place on the lower half of the ATF device.

The HF coil joints were thermally cycled to accommodate the initial relaxation of joint bolt tension that was observed during the joint development program. Final acceptance tests—which included low-power tests of the HF and vertical field (VF) coil circuits, operation of the water cooling system, and satisfactory performance of the vacuum system—were completed in mid-December. At this point, the device was handed over to the operations group for integrated testing and commissioning. Figure 1.2 shows the completed device with some of the many people who contributed to its construction.

ORNL-PHOTO 11007-87

Fig. 1.2. The completed ATF device with some of the many personnel who were associated with the construction phase.

1.1.2 Facility Modifications

G. H. Neilson, P. H. Edmonds, R. D. Foskett, J. C. Glowienka, G. R. Dyer, J. W. Halliwell, W. A. Gabhard, J. N. Sumner, R. D. Benson, W. R. DeVan, C. T. Wilson, J. A. White, R. L. Johnson, and M. J. Saltmarsh

The facility modification effort for ATF began in late 1984 with the disassembly and removal of the Impurity Study Experiment (ISX-B) tokamak. In the three succeeding years, the plasma heating systems required for the initial phases of the ATF

experimental program were prepared; these tasks included construction of a new electron cyclotron heating (ECH) facility, adaptation of the ISX-B neutral beams systems, and commissioning of transmitters for ion cyclotron range of frequencies (ICRF) heating. In addition, major upgrades of the magnetic field power supplies were undertaken, a new control system based on programmable logic controllers (PLCs) was installed, and a new control room was erected. Two discharge cleaning systems, glow and electron cyclotron, were installed, as was an induction heating system for vacuum vessel baking. By the end of 1987, much of the installation work had been completed as the MDF construction project ended and the operational phase began.

Throughout 1987, the efforts concentrated on preparations for commissioning, first plasma, and initial neutral beam heating studies in ATF. Unforeseen problems with the ECH system, encountered in late 1986, were resolved in 1987 after substantial modification of the power supply. Many tasks had to be suspended for several months while we awaited delivery of the vacuum vessel. To recover some of the schedule slippage, precommissioning tests were conducted on as many systems as possible in an attempt to uncover and correct latent problems prior to operation. For example, all major power supplies and the ECH gyrotron were dummy-load tested, and the vacuum pumping system was fully operated in a blanked-off header before it was installed on the ATF vacuum vessel. This approach proved to be successful, because very few difficulties were encountered once ATF commissioning began in December. As a result, a rapid beginning to the ATF experimental program was made.

Future facility modification work will concentrate on two broad objectives. The first is the development of a total of 4.5 MW of ECH, neutral beam, and ICRF plasma heating capability, required for studies of beta limits and transport in ATF. The second is the development of experimental capabilities needed to prepare for long-pulse and, ultimately, steady-state operation. Many of these tasks were already well under way by the end of 1987. As an example of a task that addresses both objectives, the design of a prototype ICRF antenna was completed in 1987, and fabrication was started. Toward the second objective, divertor scoping studies beginning in 1988 will constitute a first step in the development of steady-state particle and energy handling capability. Graphite limiters fabricated and installed in 1987, combined with a graphite target plate and various diagnostics, will play major roles in these studies. Further details of this apparatus and the planned experimental program are given in Sect. 4.2 of this report.

1.1.2.1 Electron cyclotron heating

T. L. White, T. S. Bigelow, C. R. Schaich, J. N. Sumner, and J. W. Halliwell

Work on the gyrotron power supply for the ECH system was completed by mid-year; this allowed well-regulated gyrotron operation into a test load. A beam voltage series regulator was installed and tested, and many other improvements were made to increase the reliability of the power supply system. The 53-GHz gyrotron was

routinely operated at the full 200-kW output power for 100–200 ms. The completed waveguide system is shown schematically in Fig. 1.3. It consists of an optical arc detector, three bellows, a waveguide mode analyzer, two TiO_2 mode absorbers, two 90° miter bends, two waveguide pumpouts, an insulating break, a gate valve, and miscellaneous straight waveguide sections ranging in length from 1.7 to 18 m. The inside diameter of the entire system is 6.35 cm. To preclude boiling water in the test load, a preload was built consisting of a thick coating of TiO_2 on the inside of the 6.35-cm waveguide. Mode purity measurements on the two-bend transmission system showed that about 75% of the power was transmitted in the TE_{02} mode. A feedback control circuit was built to level the gyrotron output power for operation into ATF. The circuit uses the output signal from the waveguide mode analyzer, which is set to monitor the TE_{02} mode power produced by the gyrotron. The signal is compared to an ideal square pulse, and the error signal is fed back into the gun modulator circuit to level the output power.

Development of the waveguide mode analyzer device (Fig. 1.4) was completed, and the device was installed above the gyrotron to measure gyrotron mode purity

Fig. 1.3. The ECH waveguide system for ATF, including the locations of the test load.

Fig. 1.4. Waveguide mode analyzer for ECH system.

and output power. It uses a series of holes in the waveguide that radiate a small amount of power. Hole spacing and size are designed to produce focused spots that fall at different points for each mode, because of differences in the phase velocities of the modes. Waveguide vacuum is maintained by a mica sheet and special vacuum tape to cover the holes.

With the addition of feedback, routine operation of the ATF ECH system at 200 kW for pulse lengths up to 200 ms was achieved. A microwave protection system was installed to limit exposure of personnel to power that might radiate outside the enclosure wall; however, initial measurements indicated that these levels are well below the maximum allowed.

Planned improvements in the launch configuration should increase the efficiency of ECH power absorption by the plasma. A prototype Vlasov mode-converting launcher that converts the unpolarized TE_{02} mode into a linearly polarized beam was built and tested with a polarization rotating focusing reflector. The polarization rotating reflector consists of a low-loss Teflon substrate with a printed circuit

copper grating mounted on a spherical copper backing. The measured -20 -dB beam width is 14 cm, and the polarization rotation efficiency is 95% or greater. In addition, a TE_{02} to TE_{01} ripple-wall mode converter was designed; it should allow the waveguide system mode purity to increase to 90%.

1.1.2.2 Neutral beam injection

M. M. Menon, G. C. Barber, W. R. DeVan, D. C. Giles, C. L. Hahs, L. A. Massengill, N. S. Ponte, R. J. Wood, and R. E. Wright

The principal means of heating the ATF plasma is neutral beam injection (NBI). Three injectors are planned; each will be able to deliver about 1 MW of neutral power to the plasma. The first of these has been installed, and all of its subsystems have been checked out. This injector will be used for the initial experiments scheduled during the first phase of ATF operation. Installation of the second injector is nearly complete as well. This injector is scheduled to operate during the second phase of ATF operation. All of the mechanical components for the third injector have been fabricated, but plans for its installation and operation will not be finalized until experimental results from the first two injectors are available.

The nominal beam energy from these injectors is 40 keV, with a pulse length of 300 ms. However, it may be possible to increase the beam energy to a maximum of 50 keV and, at somewhat lower power levels (<750 kW), to extend the pulse length to about 500 ms.

The ATF NBI systems are modified versions of the injectors used on ISX-B; the primary modification is in the front section of the beam line that adapts to ATF. This section has been optimized for near-tangential injection, which provides minimal beam interception on the vacuum vessel (HF coil troughs) while maximizing the power reaching the plasma. This optimization has resulted in a final aperture area 50% smaller than that on ISX-B. As a result of this change in geometry, there is substantial uncertainty about the amount of power reaching the plasma. Reionization losses in the drift section of the beam line will further obscure the results. An in-vessel calorimeter is being designed to measure the power reaching the plasma.¹ The beam-intercepting surface of this calorimeter will be an array of water-cooled graphite tiles for compatibility with the plasma and to sustain the high power density (6 kW/cm^2) of the beam.

Reliable operation of the NBI system requires judicious adjustments of different ion source parameters. Automation of beam line operation is being pursued to achieve high reliability for the multiple beam line systems with a minimum number of operating personnel. We plan to adhere closely to the automation system that was successfully implemented on the Poloidal Divertor Experiment (PDX)/Princeton Beta Experiment (PBX) injection system at Princeton Plasma Physics Laboratory (PPPL), since the ion sources for ATF are identical to those used in PBX.

1.1.2.3 ICRF heating

F. W. Baity, R. H. Goulding, and L. M. Vinyard

Fabrication of a prototype fast-wave ICRF antenna for ATF was begun, with completion expected in March 1988. The antenna is configured as a resonant double loop (RDL), a design developed by ORNL, and is installed in one of the "Tennessee" ports. It provides tuning and impedance matching to the rf transmission line by means of two vacuum variable capacitors. The ATF antenna incorporates several of the features used in the compact loop antennas built for Doublet III-D, the Tokamak Fusion Test Reactor (TFTR), and Tore Supra by the RF Development Group of the Plasma Technology Section,² including a graphite-coated tubular Faraday shield and shaped graphite bumpers. The structure is designed to be radially movable over 15 cm, allowing maintenance of the antenna-plasma separation under a variety of magnetic field configurations and retraction of the antenna to a relatively remote position when not in operation. The orientation was selected to maximize antenna loading on the basis of two-dimensional (2-D) antenna modeling in the stellarator geometry. The antenna is designed to cover a frequency range of 10 to 30 MHz, which will allow exploration of most of the usual ICRF heating schemes, including mode conversion and higher harmonic heating. The antenna assembly is shown in Fig. 1.5.

This prototype antenna is not water-cooled and thus will be limited to pulse lengths of less than 1 s. Its primary purpose is to map the plasma loading under a wide variety of operating conditions and to obtain preliminary ion heating results with moderate power (≤ 300 kW) and short pulse lengths. The addition of water

ORNL-PHOTO 8313-87

Fig. 1.5. Fast-wave ICRF antenna assembly.

cooling to the Faraday shield and current strap would extend the pulse length to 30 s.

A modification of the present antenna design has been completed to convert the structure to an ion Bernstein wave (IBW) launcher by reconfiguring the Faraday shield and current strap. With a different capacitor, the frequency range would extend to more than 50 MHz in the IBW configuration.

For long-pulse heating, we have obtained the two 1-MW transmitters originally procured for the Mirror Fusion Test Facility upgrade (MFTF-B) at Lawrence Livermore National Laboratory (LLNL). These transmitters will be installed at ATF in time for operation in 1990. The units now operate over a frequency range of 6 to 20 MHz but can be modified to provide operation at up to 30 MHz, which will permit high-power, long-pulse minority hydrogen heating at 1.9 T.

1.1.2.4 Vacuum pumping and wall conditioning

R. A. Langley, T. S. Bigelow, P. H. Edmonds, J. C. Glowienka, T. F. Rayburn, J. E. Simpkins, J. N. Sumner, and J. A. White

Pumping system

The vacuum pumping system, which provides a pumping speed of about 3200 torr-L/s at the vessel, was installed. The system consists of a roughing line and three turbopump lines. The time to pump the vessel from atmosphere to about 5×10^{-6} torr is about 30 min. The control system was upgraded from the original design to improve the operator interface and is modified as diagnostics are installed to incorporate these additions.

Glow discharge cleaning

The dc glow discharge system, which can produce a maximum anode voltage of 1 kV and a current of 2 A, was installed. Gas pressures of about 10 mtorr are required to initiate a glow discharge, but once the discharge is initiated it can be maintained down to a pressure of about 1 mtorr, which allows continuous pumping during glow discharge operation. Unattended glow discharge cleaning at nights and over weekends was established to significantly increase the rate of accumulated wall conditioning time.

ECR discharge cleaning

A 6-kW, 2.45-GHz magnetron microwave source and rectangular waveguide connections to the ATF vacuum vessel were installed. Water cooling and interlocks were installed, and the system was checked out using a waveguide dummy load. The system delivers 50 to 6000 W to the vacuum vessel for extended periods of time and was successfully operated on ATF. With an 875-G magnetic field generated by a 330-kW dc supply, a steady-state discharge was produced. The vacuum vessel temperature was found to increase to 140°F with the launching of 4 kW of microwave

power. Plans are under way to automate the system for continuous unattended operation during nights and weekends.

Vessel baking

Induction heating of the vacuum vessel was implemented by applying a 480-V, 60-Hz feed to the HF windings. Experiments to measure the efficiency and uniformity of heating were conducted. It was observed that about 100 kW could be coupled to the vessel but the heating nonuniformity was much greater than expected. A new scheme using the VF coils is being investigated so that better uniformity may be achieved.

1.1.2.5 Timing and shot control

G. R. Dyer

The experiment timing system for ATF was designed to satisfy several criteria that were established from experience with previous experiments:

1. Accurate timing based on a central frequency standard.
2. Synchronization with the power grid.
3. Simultaneous availability of the centrally generated pulse sequence at many remote locations.
4. Optical isolation of remote stations, with a minimum of connecting wiring between stations.
5. Autonomous operation of each remote station, allowing local generation of the startup pulse sequence for testing purposes without help from the control room.

The timing cycle consists of a master timing generator (MTG) in the ATF control room and a number of "repeaters" at various locations around the machine area that provide local access to the startup pulse sequence. Each repeater receives CLOCK and ENABLE signals through optical isolators from a bus driven by the MTG. The timing bus is simply a pair of coaxial cables.

Timing pulses can be produced at any time during an experiment cycle by triggering a delayed pulse generator from one of the repeater outputs, after setting the delay for the desired time. For applications that require a timed logic level or switch closure (instead of a pulse sequence), a level generator/gate module was developed. This module provides eight channels, each with an isolated reed-relay switch that will close or open, as determined by input signals. Complementary output connectors in each channel provide TTL signals for applications that require a logic level instead of a switch closure.

The system successfully met the requirements of first plasma and initial operation. Expansions to accommodate phase II diagnostics are now in progress.

1.1.2.6 The ATF data system

W. R. Wing, L. R. Baylor, R. D. Burris, W. R. DeVan, D. C. Giles, D. E. Greenwood, K. L. Kannan, J. B. Mankin, K. A. Stewart, J. N. Sumner, and K. G. Young

Highlights of data system activity during 1987 included improvements to the available cpu capacity, development of software to support new data system functionality, and logistical work in preparation for the first plasma in ATF.

The complex topology of the ATF plasma will require much more elaborate data analysis than was needed on ISX-B to reach equivalent levels of understanding. This translates directly into requirements for more available cpu power. As a step toward providing this power, a second VAX 8700 was procured and added to the division's VAXcluster. This system has roughly six times the cpu throughput of a VAX 780 and will significantly improve our ability to analyze data between ATF discharges.

Development of new software for ATF has concentrated in three areas: implementation of a new data management system for storing and providing access to ATF data; the integration of a PLC-based status and control system with the data system; and implementation of a cluster-based timing and synchronizing system to replace the shared-memory system used on ISX-B. In midsummer, the data system passed a major milestone when it demonstrated successful basic data system operation using the new hardware and software. It created a control waveform in response to a trigger signal from the master timing and shot control system and then acquired, stored, and retrieved this signal for analysis.

The ISX-B data system formally supported only one model for data, a 512-element array that was assumed to be time-series data sampled at 1-ms intervals. Any data that did not fit this model were either coerced into it or became an unsupported exception. This meant that the standard analysis utilities were usable only on data that fit the standard model. For ISX-B, this situation was (marginally) acceptable, since the vast majority of data fit the standard model. For ATF, the complex shape will require more array diagnostics, the wider variety of time scales will be reflected in sampling times, and the larger number of "smart" diagnostics such as optical multichannel analyzers (OMAs) will generate data with independent variables other than time. To accommodate these circumstances, a new data management system has been developed. The new system supports data as simple as single elements or as complex as arrays of arbitrary length and dimension, and it allows the independent variable to be any desired quantity. In addition, the system identifies data by name (rather than by numbers) and retrieves at three levels of conversion: raw binary data, data converted to module units, or data converted to physical units. Finally, it provides for proper handling of calibration (and calibration changes) during the life of a diagnostic.

The data system for ATF is being closely coupled to a PLC-based engineering status and control system. The two systems have complementary features. The PLC system's rigid programming structure and direct support for ladder-logic-style

programs make it well suited to monitoring interlocks and safety. Thus, it is responsible for all vacuum, electrical, cooling, and safety interlocks and state controls. Its limited computational ability and its restricted analog input/output limit its usefulness for dynamic control. Thus, it controls power supply permissives but does not generate the signals that drive them in real time. The PLC system has no provision for long-term data recording or storage. Finally, it has only limited facilities for presenting data to operators. For these reasons, the ATF system uses PLCs for state control and for monitoring all critical pre- and post-operational set points. These data are presented to the ATF operators via mimic panel screens displayed on IBM personal computers using a commercial software package. During 1987 the commercial package was extended to allow the internal database to be either read from or written to by VAX-resident programs other than the PLC support code. This has (for example) allowed the canned trending display software to provide trend lines of X-ray exposure in the control room based on data from the personnel monitor.

The third area of new development for ATF is in the Synchronizing and Monitoring System (SAMS). The ISX-B data system was based on distributing data, timing signals, and logical names through a bank of shared memory that was common to the two VAX 780 computers that formed the data system. For ATF, with a data system consisting of at least two VAX 8700 computers and an unknown number of microVAX front-end systems, this shared memory approach is not available. In its place, SAMS has been rewritten to function on a cluster-wide basis and to be independent of the number of mainframe computers available for operation.

The final highlight of the year has been the refurbishing of software and hardware from ISX-B that will be applied to ATF with only slight extensions or modifications. Examples of software refurbishing include extending PLOTCH to support the new data management software, similarly extending the SENSION physics display, and converting the ECH software from the ELMO Bumpy Torus to function in the ATF system. A considerable amount of logistical preparation centered on reinstalling the CAMAC hardware necessary to support the diagnostic set for first plasma operation.

1.1.2.7 Hard X-ray suppression

D. A. Rasmussen, A. C. England, C. C. Eberle, W. R. DeVan, J. H. Harris, T. C. Jernigan, R. R. Kindsfather, R. N. Morris, M. Murakami, G. H. Neilson, J. A. Rome, M. J. Saltmarsh, R. B. Wysor, O. Motojima, H. Okada, and K. Uo

Pulsed-field torsatrons (such as ATF) are susceptible to hard X-rays generated by runaway electrons that hit solid material (e.g., vacuum vessel, limiter, or antenna structures). The runaways result from the combined effect of loop voltages (up to 20 V in ATF) induced during the ramp-up and rampdown of the helical field and good electron confinement on closed magnetic surfaces. An initial assessment of this problem, which incorporated data from Heliotron-E, indicated that hard X rays posed a potential hazard to personnel and internal ATF components and that some

measures to suppress them would be required. Measurements made during the initial operating period of ATF and detailed in Sect. 1.1.6 have indicated relatively low X-ray levels, which are further reduced by the technique described below. This fortunate situation will be continuously monitored to ensure that changes in operating parameters do not result in increased X-ray production.

The technique uses a movable paddle probe that can be rotated so as to intersect all magnetic flux surfaces. Standard procedure is to insert the paddle during the ramp-up and rampdown of the helical field. It limits the number of transits around the torus that electrons can complete and, by thus limiting their final energy, prevents dangerous X-ray emissions.

The apparatus is shown in Fig. 1.6. The paddle itself is a quarter-loop of stainless steel rod that passes through a vacuum feedthrough on one of the top ports. The drive is pneumatic, since ATF stray fields prevent the use of electric motors close to the device. The scheme provides direct control of the acceleration and deceleration, an important consideration. Rotation is easily accomplished in 500 ms or less. The paddle remains in its deployed position (across the flux surfaces) during intervals between ATF discharges. After the helical field has reached its desired "flat-top" value, the paddle is withdrawn. After the plasma discharge has ended and the density has decayed, the paddle is reinserted. Less than 1 s of the HF flat-top is dedicated to the combined withdrawal and insertion operation. The sequence of events is illustrated in Fig. 1.7.

As this figure indicates, vertical field programming during helical field ramps is also part of the suppression technique. At "spoiled" values of the vertical field, the flux surfaces are shifted outward, thus reducing the area of flux surfaces on which runaway electrons can be confined. The shifts available on ATF (5 to 10 cm) are not as large as on Heliotron-E, but do complement and enhance the effectiveness of the paddle.

The design incorporates interlocks and position indicators that are monitored by the ATF PLC system. The interlock logic prevents ramp-up of the helical field unless the paddle is in the deployed position. Proper operation of the paddle is verified before the start of daily ATF operations.

1.1.3 Operational Readiness Activities

J. C. Glowienka, G. H. Neilson, M. J. Saltmarsh, M. M. Menon, D. R. Alford, and H. W. Jernigan

Before any new, complex device funded by the U.S. Department of Energy (DOE) can operate, the device operators must demonstrate that the facility and its personnel are ready for safe, reliable operation. The assessment of readiness is obtained by subjecting all aspects of the project—the facility, its personnel, and its documentation—to an operational readiness review (ORR).

Preparation for the ORR of the ATF facility involved the compilation of several documents that describe the facility and its operation. In the area of device safety, the two primary documents are the Final Safety Analysis Report (FSAR) and the

Fig. 1.6. Rotating intercept probe.

Fig. 1.7. Sequence of events for a normal discharge.

Operating Safety Requirements (OSR). The FSAR identifies the hazards associated with the operation of the facility; describes the steps taken to eliminate, control, or mitigate these hazards; and analyzes and evaluates potential accidents and associated risks. The OSR defines the required equipment, the necessary procedures, and the operating limits for safe, reliable operation. In the area of facility operation, the primary documentation is the set of operating procedures manuals. One manual was prepared for each system, including the machine and physics diagnostics systems. Each manual describes the system, identifies the materials needed for its operation, and outlines the procedures and training requirements for operation. Personnel training requirements are clearly delineated in the FSAR and the OSR. An Operations Quality Assurance Assessment/Plan documents the logic used in obtaining and maintaining operational readiness.

In late August, the documentation was complete and the facility was nearing completion. The ORR committee—an independent panel of experts from ORNL, the Y-12 Plant, and DOE's Oak Ridge Operations Office (ORO)—examined the facility and its documentation to check for compliance with national standards in health physics, electrical safety, industrial safety, industrial hygiene, fire prevention, and quality assurance. In parallel with this effort, ORO determined that ATF was a low-risk facility and that its FSAR and OSR did not require ORO approval. A positive assessment from the ORR committee was the only requirement for approval to begin operations.

By early November 1987, over 250 persons associated with ATF had received general ATF safety training, which consists of viewing the 20-min ATF safety video, reading a condensed version of the FSAR and the OSR, and passing a written test. Approval to begin operation was received November 12, 1987, from the Y-12 ORR coordinator; the first step, device commissioning, is described in Sect. 1.1.4.

1.1.4 Device Commissioning

G. H. Neilson, W. R. DeVan, G. R. Dyer, J. C. Glowienka, M. Murakami, M. J. Saltmarsh, J. N. Sumner, J. A. White, C. T. Wilson, and J. L. Yarber

The primary objective of the ATF device commissioning was to bring all systems into operation in a systematic manner so that a 0.95-T plasma suitable for NBI could be created by second harmonic ECH. The systematic approach allowed for an examination of several issues related to subsystem interaction, operating safety, and personnel training. Each system was operated alone, when possible, and then integrated with other systems required for plasma generation. A logical intermediate step was the generation of a demonstration plasma when all the basic hardware needed to create a plasma had been commissioned. This demonstration required operation of the safety interlock system, the status and control system, the data acquisition system, the hard X-ray suppression system, the water cooling system, the HF coil system and its power supply, the vacuum system, and the microwave heating system. Assessment of the plasma's suitability for NBI required the addition of the trim VF coil system, its power supply, and a basic set of physics diagnostics.

This set includes a bolometer; a H_{α} monitor; a 2-mm, single-channel interferometer; a charge-coupled device (CCD) camera; a pulse height analyzer (PHA); and a residual gas analyzer (RGA).

Once approval to operate was received (see Sect. 1.1.3), the last month of the year was devoted to commissioning. Considerable progress was made in the commissioning effort (first plasma was achieved in January 1988). The safety interlock system and the status and control system were tested and accepted for operation, as was the vacuum system. Acceptance testing of the magnetic field coils included checks of circuit resistance, bus-to-bus and bus-to-ground resistance, and current flow polarity. The hard X-ray suppression system was tested. The VF power supplies were commissioned at the 6-kA, 5-s level by operating them into a dummy resistive load. In addition to satisfying the requirements for generation of first plasma, these activities allowed for integrated commissioning of the safety interlock system, the status and control system, and the data acquisition system. The final major commissioning effort in December was to energize the HF coils with a 20-kA, 160-ms pulse from the HF power supply. The goal of a 60-kA, 3-s pulse with a 2-s flattop was realized soon after that.

1.1.5 Diagnostics Preparation

Design and construction of ATF diagnostics proceeded steadily during the year. Mounting platforms and flange modifications for the PHA, the neutral particle analyzer, the 2-mm interferometer, and spectrometers are complete, and it is expected that all of these diagnostics, except for the neutral particle analyzer, will be ready for initial operation in January and February 1988. The spectrometer system is described in Sect. 1.1.5.1. Additional diagnostics that have been installed include Rogowski coils, diamagnetic loops, two H_{α} monitors, a bolometer module, CCD cameras, and hard X-ray monitors. Work is proceeding on schedule for the phase II diagnostics (listed in Table 1.1 of last year's annual report³). These diagnostics include a scannable Thomson scattering system, described in Sect. 1.1.5.2; an electron cyclotron emission (ECE) apparatus, described in Sect. 1.1.5.3; and a 15-channel far-infrared (FIR) interferometer, described in Sect. 2.4.2.

1.1.5.1 Spectrometer system

R. C. Isler, E. C. Crume, Jr., and L. D. Horton

Three spectrometers will be installed on ATF for the early operating phases of the machine. The physical arrangement is shown in Fig. 1.8; all three are positioned so that their fields of view include neutral beam line 1 in order to detect spectral lines formed by charge-exchange excitation. The grazing incidence spectrometer will be used primarily for impurity surveys between 100 and 1200 Å. The vacuum Czerny-Turner instrument is intended for measuring ion temperatures and plasma

Fig. 1.8. Physical arrangement of spectrometers on ATF.

rotation by using high orders of $2^3P \rightarrow 2^3S$ transitions from helium-like ions and from hydrogenic lines produced by charge-exchange excitation. It views the plasma radially via a mirror system. It is hoped that this instrument can eventually be equipped with a 2-D detector array, so that simultaneous spatial and spectral resolution can be realized. The visible Czerny-Turner instrument will be equipped with an OMA; it will be used for spectral surveys above 2000 Å and for measuring temperatures and rotations from long-wavelength lines. Initially, it will be installed with optics that provide a line of sight through a tangential viewing window.

1.1.5.2 Thomson scattering diagnostic

D. A. Rasmussen, R. R. Kindsfather, T. L. Clark, R. P. Gormley, P. S. Hays, W. D. Shipley, R. A. Stevens, K. D. St. Onge, and C. E. Thomas

The Thomson scattering diagnostic for ATF is described in detail in refs. 4-7. Substantial progress was made during 1987 in procuring and installing hardware for the Thomson scattering system. The multiple-element viewing lens, ~60 cm long and 30 cm in diameter, was assembled in conjunction with staff at PPPL and shipped to Oak Ridge. The large (30- by 50-cm), front-surface mirrors were received and installed on the rotating and translating stages, which are driven by stepper motors. An optical table, 1.3 m long $\times$ 3 m wide $\times$ 0.5 m thick, for mounting the viewing optics was installed in the ATF enclosure. A shielded room that is located on top of this table was also installed. Sixteen 1- by 6-mm optical fiber bundles, each 25 m long, that carry light from the lens to remote spectrometers were received and inspected. The calibration system was designed and fabricated. This system uses a high-intensity lamp and a broad-spectrum reflective "white" plate to provide a calibration light for all of the spectrometers. An upgrade of the data acquisition and analysis codes inherited from ISX-B was begun. The laser system (also from ISX-B) was reinstalled and optimized to provide the required 20 J per shot.

1.1.5.3 Electron cyclotron emission diagnostic

G. L. Bell, R. F. Gandy, D. A. Rasmussen, and J. B. Wilgen

Electron cyclotron emission from ATF will be measured to provide time-dependent electron temperature information.⁸ For low-field operation (at 0.95 T), access to second harmonic emission is severely restricted, by extraordinary wave cutoff, to central densities below $1.7 \times 10^{13} \text{ cm}^{-3}$. For this reason, optically thin third harmonic emission from 67 to 83 GHz, with a corresponding cutoff density of $5.2 \times 10^{13} \text{ cm}^{-3}$, will be used instead to provide central electron temperature information. For high-field operation (at 1.9 T), second harmonic emission is accessible for electron densities up to $7.0 \times 10^{13} \text{ cm}^{-3}$. In this case, much of the ECE spectrum, in the range from 83 to 114 GHz, is optically thick and can provide $T_e(r)$ profile information.

A vertical view of the ATF mod-*B* spatial contours, as shown in Fig. 1.9, provides a line of sight along which the mod-*B* contours are nearly symmetric with

Fig. 1.9. Orientation of ECE viewing system.

respect to flux surfaces. A single horn-lens viewing beam system with a vertical view is designed to cover the entire range from 67 to 114 GHz, providing a spot size on the order of 6 cm (ref. 9). Radiation will be delivered to one of three waveguide mixers by oversized C-band waveguide. Each of the three mixers, using fixed-frequency local oscillators, covers a 16-GHz segment of the emission spectrum, downconverting it to the 2- to 18-GHz intermediate-frequency (IF) band. After amplification, the IF power is equally divided into 16 channels for processing by an array of 16 bandpass filters and IF detectors (Fig. 1.10). The bandwidth of each filter is 1 GHz, with center frequencies at 2.5, 3.5, ..., 17.5 GHz. The signal from each detector is then amplified, digitized, and recorded, providing the time evolution of the ECE spectrum with a frequency resolution of 1 GHz and sampling rates up to 100 kHz.

1.1.6 X-Ray Surveys and Monitoring

A. C. England, D. A. Rasmussen, R. R. Kindsfater, M. Murakami, G. H. Neilson, and J. L. Dunlap

The levels of X-ray doses during ATF operation with and without runaway suppression (Sect. 1.1.2.7) were measured for normal and fault conditions. These characterizations were needed to establish safe operating procedures.

Fig. 1.10. Block diagram of ECE system.

Instrumentation was distributed over a sizable portion of Bldg. 9201-2, in which ATF is located. Integrating monitors included pocket dosimeters, thermoluminescent dosimeters, monitrons, and special computer-controlled monitors in the control room and an adjacent shop area to record doses per shot. Active monitors [NaI(Tl) scintillators and gamma ionization chambers] within the ATF enclosure gave approximate source location, time histories, and doses of the X-ray emission.

Studies were conducted with and without plasma produced by ECH, and parameters were varied to establish a worst-case situation: an ECH plasma occurring just before the helical field rampdown. Even in that case, however, the one-shot dose in the control room was less than 1 mR with the runaway suppression system disabled. The personnel dose limit is 20 mR/day, so a shot at a 1-mR level would prompt careful monitoring of the X-ray production but would not curtail operation. With conventional timing of the ECH pulse and helical field rampdown, and with the suppression paddle operating, dose reductions relative to the worst case were of order 10^{-3} inside the enclosure and 10^{-2} (down to background) in the control room. Thus, X radiation has not proved to be a serious operational safety hazard and, while monitoring will continue, some of the more restrictive procedures established for these survey activities have been relaxed.

Most of the X rays appear on the helical and vertical field rampdown and are generated at the paddle. The spectrum of the bremsstrahlung has not been measured, but the observation that no activity has been produced from photonuclear processes in the stainless steel establishes an upper limit of ~ 12 MeV on the energy of the runaway electrons.

1.1.7 Confinement Analysis for ATF

M. Murakami, H. C. Howe, S. E. Attenberger, R. H. Fowler, J. H. Harris, K. Hanatani, W. A. Houlberg, K. L. Kannan, D. K. Lee, R. N. Morris, and J. A. Rome

Progress in developing the confinement analysis for ATF was made in two areas: (1) determining finite-beta equilibria and (2) benchmarking neutral beam calculations with Monte Carlo codes. Data from Heliotron-E (courtesy of the Heliotron-E group) were used for these studies.¹⁰

The transport analysis code PROCTR-Mod (ref. 11) previously used three-dimensional (3-D) vacuum geometry based on a field-line-following code.¹² Finite-beta equilibrium is now included in the analysis through a 3-D free-boundary code, VMEC.¹³ Procedures were set up to run VMEC on a computer at the National Magnetic Fusion Energy Computing Center to obtain magnetohydrodynamic (MHD) equilibria consistent with observed pressure profiles. A test was performed with the Heliotron-E data.¹⁰ The magnetic axis shifts substantially with increasing beta, as shown in Fig. 1.11, so data input must be iteratively interpreted in arriving at a solution. As an example, Thomson scattering on Heliotron-E was taken along the vertical chord on the "vacuum" magnetic axis, but the magnetic axis shifts 3-5 cm from this chord at high beta. The iteration for equilibria consistent with

Fig. 1.11. Shift of the magnetic axis as a function of beta.

the interpreted pressure profile converged quickly, and only two VMEC runs were usually required. Parameterization of finite-beta equilibria (R_{mn} and Z_{mn}) will be used in the future so that the analysis can be done between shots. The test with the Heliotron-E data showed that the inclusion of finite-beta equilibria is important for estimating "central" parameters [such as $\beta(0)$], but "average" (or "global") parameters [such as $\langle\beta\rangle$ or $\tau_E(a)$] are relatively insensitive ($<5\%$).

Both the ORNL and the Heliotron (Hanatani) Monte Carlo codes were benchmarked, and this work is discussed in Sect. 3 of this report. Perpendicular injection data from Heliotron-E were analyzed with both Monte Carlo codes at Oak Ridge and at Kyoto. These calculations showed that the orbit loss in perpendicular injection is sensitive to details of treatments, in particular the location of the loss boundary. In order to better treat both the boundary problem and the reabsorption of charge-exchange fast neutrals, a real-space code, DESORBS, was developed at ORNL. When the loss boundary was placed at the last closed flux surface, the orbit loss was 40–50% of the absorbed power P_{abs} . When the loss boundary was an idealized description of the vessel walls, some particles that crossed the last flux surface returned to the plasma, and the orbit loss was $\leq 10\%$ of P_{abs} . The actual vessel has protrusions not represented in the ideal model, so the actual wall boundary would yield greater losses. As Fig. 1.12 shows, the estimate of orbit loss used in the original scaling studies^{10,14} turns out to be a good compromise between the results from the two Monte Carlo codes. That estimate was based on Hanatani's calculation,¹⁵ $P_{orbit}/P_{abs} = 0.23\bar{n}_e$ (10^{20} m^{-3}).

Fig. 1.12. Orbit losses given by three models.

In summary, finite-beta distortion of flux surfaces is important in profile analysis, but its effects on "global" quantities in Heliotron-E data analysis ($\langle \beta \rangle \leq 2\%$) are relatively small ($< 5\%$). Benchmarking of Monte Carlo codes for NBI has shown some complications in dealing with orbit loss that occurs with perpendicular injection. However, the original scaling of global confinement time in Heliotron-E appears to be valid.

1.2 ADVANCED PROJECTS

1.2.1 ATF-II and Stellarator Reactor Studies

B. A. Carreras, R. H. Fowler, V. E. Lynch, J. F. Lyon, and S. L. Painter

Torsatrons with plasma aspect ratio $A = R_0/\bar{a}$ from 3.5 to 5 up to ≈ 8 are being studied as minimum-size reactors and as the basis for a next-generation experiment (ATF-II). These devices have magnetic configurations similar to that of ATF, with $\epsilon(\bar{a}) \approx 1$ and a central magnetic well that allows access to a second

stability region where the beta is limited by equilibrium rather than by stability, as shown in Fig. 1.13. The equilibrium beta increases at lower aspect ratio [$\beta_{\text{crit}} \propto \epsilon^2(\bar{a})/A \propto 1/A$, because $\epsilon(\bar{a}) \simeq 1$], rather than decreasing as in conventional torsatrons with constant pitch [$\beta_{\text{crit}} \propto \epsilon^2(\bar{a})/A \propto A$, because $\epsilon(\bar{a}) \propto A$]. In addition to the potential for higher beta, these configurations lead to smaller devices: next-generation experiments ($\bar{a} \sim 0.5$ m) with major radius $R_0 \simeq 2$ m, deuterium-tritium (D-T) ignition experiments with $R_0 \sim 4$ m, and 1.9-GW(e) reactors with $R_0 = 8-11$ m. Conventional stellarator designs lead to larger devices: next-generation experiments with $R_0 = 4-5$ m, ignition experiments with $R_0 = 8-15$ m, and reactors with $R_0 = 20-25$ m. While the higher- A route may also lead to attractive reactors, the high cost of developing this route could be a serious disadvantage.

Previous reports¹⁶⁻¹⁸ have dealt with the physics properties of these low- A torsatrons and their minimum-size reactor embodiment.¹⁹ The three cases examined in most detail are those with $M = 6$ and $A = 3.9$, $M = 9$ and $A = 4.7$, and $M = 12$ and $A = 7.8$. During 1987, we updated the minimum-size reactor studies, examined their energetic orbit confinement properties, and studied preliminary ideas for an ATF-II successor to ATF.

Fig. 1.13. Beta limits vs M ($\propto A$) for low- A torsatrons.

1.2.1.1 Reactor studies

The minimum size for reactors with $M = 6, 9$, and 12 field periods is determined by constraints on plasma-wall separation, coil shielding requirements and materials, insulation and coil case thickness, and current density and elongation for the HF coils, as discussed in last year's report.¹⁶ The present studies have added self-consistent values for the HF winding-pack current density j and the maximum field on the superconductor $B_{\max}$ by using the j - $B_{\max}$ relation for Nb_3Sn and values for the elongation of the HF winding cross section K . The finite element magnetic field code MAGFOR was used to calculate $B_{\max}$. The resulting change in major radius for the minimum-size reactor is relatively small; a larger drop is seen in the fractional area available for tritium breeding, assuming breeding under the outboard 40% of the HF winding:

	Major radius R_0 (m)	Fractional area for tritium breeding (%)
$M = 6$		
Previous study	8.01	88
Present study	8.37	76
$M = 9$		
Previous study	10.25	87
Present study	10.54	72
$M = 12$		
Previous study	11.02	81
Present study	11.13	67

Corresponding increases occur in the required breeding ratio in the blanket and in the reactor weight, and the net electrical power output drops. The resulting mass utilization efficiency drops from 200-250 kW(e)/t to 170-230 kW(e)/t. The relative insensitivity of minimum reactor size to various assumptions on j , K , the distance Δ_0 from the plasma edge to the HF conductor, and the central magnetic field B_0 is discussed in detail in ref. 19.

Alpha particle losses in reactors are another area of concern. Low- A torsatrons have a relatively large fraction of helically trapped particles ($\sim 1/3$ for the cases studied here). Essentially all of the alpha particles that are helically trapped are lost in the $M = 6$ reactor case, and about half are lost in the $M = 12$ case. Circulating alpha particles are well confined, except for those within a poloidal gyroradius of the plasma edge. The direct alpha particle loss is $\sim 15\%$ at $A = 8$ ($M = 12$) and $\sim 35\%$ at $A = 4$ ($M = 6$), as shown in Fig. 1.14. Fortunately, the lost alpha particles exit in a very narrow helical strip, and the energy can be recovered externally. The perpendicular loss region also provides an ash removal mechanism. Confined alphas slow down to energies of $\sim 30T_e$ (~ 0.4 MeV) before scattering into the loss region. This represents an additional energy loss of $\sim 15\%$. Ions with energy

Fig. 1.14. Fraction of alpha particles confined vs r/a for $M = 6, 9$, and 12 compact torsatron reactors.

lower than two to three times the thermal energy are well confined because of the $\mathbf{E} \times \mathbf{B}$ orbit rotation induced by the ambipolar radial electric field. The main effect of the alpha particle loss is to reduce the heating power to the background plasma and hence increase, by ≈ 50 – 60% , the heating power required for ignition.

1.2.1.2 ATF-II studies

The issues of greatest concern for the low- A torsatron approach are fragility of magnetic surfaces and deterioration of confinement (including that of energetic ions). Although there are potential solutions to these problems (e.g., a flexible poloidal field system to restore broken flux surfaces¹⁸ and edge profile control to reduce anomalous and neoclassical losses¹⁹), an experiment with sufficient plasma radius, field, and heating power is needed to study this approach. ATF-II is envisioned as a hydrogen physics experiment that, in conjunction with other experiments, would provide the justification for going to D-T operation. It would have a major radius close to that of ATF ($R_0 \approx 2$ m) but a larger scope ($\bar{a} = 0.4$ – 0.5 m with $B_0 = 4$ T, superconducting coils, $P = 10$ – 15 MW, and active cooling of the first wall and in-vessel components). It should serve to make a definitive test of beta limits, low-collisionality transport, and long-term plasma evolution at reactor-relevant parameters ($n = 3 \times 10^{13}$ cm⁻³ to 3×10^{14} cm⁻³, $T \sim 5$ – 10 keV, $\langle \beta \rangle > 5\%$, and $\tau_E \approx 50$ – 100 ms).

Figure 1.15 shows $\bar{a}$ vs A for various existing and proposed stellarators. The Compact Helical System (CHS) in Nagoya, Japan, is at the upper end of the range of aspect ratios of interest, and tokamaks are at the lower end. There are three existing devices—ATF ($B_0 = 2$ T), Wendelstein VII-AS ($B_0 = 3$ T), and Heliotron-E ($B_0 = 2$ T)—with $R \approx 2$ m. Two devices now being proposed that would operate in the 1990s—Wendelstein VII-X (ref. 20) at Garching, Federal Republic of Germany, and the Large Helical System²¹ (LHS) of the Ministry of Education, Science, and Culture at Toki, Japan—would have $R_0 \approx 4$ m, $a = 0.4$ – 0.5 m, $B_0 = 4$ T, $P = 10$ – 20 MW, and $A \approx 8$ – 10 vs the goal of $A \approx 3.5$ – 5 for ATF-II.

Fig. 1.15. Size vs aspect ratio for various stellarator experiments.

Parameters for ATF-II reference cases are given in Table 1.1, with LHS and ATF parameters shown for comparison. The $M = 9$ configuration could evolve into an $M = 8$ or $M = 10$ configuration, because the separate HF windings of a device with even M would be easier to fabricate and would provide some additional flexibility (helical axis). The sizes are based on minimizing cost (which is proportional to R^2) and maximizing compatibility with the existing ATF facilities. The proposed 4-T field provides better confinement and allows high-density operation with ECH [110-GHz resonance at 4 T, ordinary mode (O-mode) cutoff density $\approx 1.5 \times 10^{14} \text{ cm}^{-3}$]. With superconducting coils, long-pulse to steady-state operation at maximum field is possible, and the ~ 340 -MW power consumption required with copper coils is avoided.

Table 1.1. Comparison of ATF-II options with other torsatrons

	ATF-II			
	Case A	Case B	LHS	ATF
Plasma				
Major radius, m	2.4	1.6	4.0	2.1
Average radius, m	0.52	0.41	0.5	0.27
Plasma volume, m ³	13	5.3	20	3
Field on axis, T	4	4	4	2
HF winding				
Number of periods	9	6	10	12
Radius, m	0.74	0.64	1.05	0.48
Current, MA-turns	5.33	5.33	8	1.75
HF current density, kA/cm ²	5	5	2.5	1.6
Maximum <i>B</i> on coil, T	6.8	7.6	7.6	
Vacuum vessel				
Outside diameter, m	6.8	4.9	12.4	5.4
Inside (hole) diameter, m	2.8	1.5	3.6	3
Height, m	3.3	2.3	5.0	1.2
Minimum and maximum first-wall ID, m	1.0, 2.0	0.9, 1.7	1.2, 2.8	0.65, 1.2
Outside port dimensions, m × m	1.45 × 1.0	1.7 × 0.8	1.0 × 1.0	0.9 × 0.6
Diagonal size of top and bottom ports, m	0.7	0.8	0.8	0.5
Inside port diameter, m	0.1	^a	0.6	0.2
Other				
Cold (coil) mass, kg	4.8 × 10 ⁴	4.0 × 10 ⁴	~2 × 10 ⁵	3.3 × 10 ⁴
Power for 4.2 K refrigerator, kW	1.4	1.3	5-7	^a

^aNot applicable.

For both cases, it is assumed that an insulating case surrounds the HF conductor, allowing a thin, replaceable, actively cooled first wall between the plasma and the HF and VF coil sets. All of the superconducting coil sets and the first wall are in a common toroidal vacuum vessel with vertical cylindrical side walls and curved top and bottom toroidal shells, similar to the vessel proposed for LHS. The HF windings are NbTi conductor wound on precision helical (segmented) forms, which serve as part of the HF winding structural case. Segmented windings have not been considered because of the difficulties involved in superconducting joints and the need for high current density. However, the detailed issues connected with actual HF windings and large VF coils have not been examined.

The ATF-II target range in Fig. 1.15 is for a cost of approximately \$50 million for a device with $A \geq 4.7$ and less for smaller values of A (because of the higher risk and lack of even a small experiment at the lowest values of A). This cost is for the device alone; on the same basis, the cost of ATF was \$20 million. Cost estimates were derived from estimates of the base device cost for a number of low- A torsatrons with different R_0 , B_0 , and M . The costs were calculated from the weight of each component, the cost per unit weight for machined material, a complexity factor (derived from benchmarking component costs against those for ATF), and the appropriate power supply or refrigeration costs. Costs for plasma heating systems, diagnostics, site preparation, and other areas that are less dependent on device scope were not included. For the assumptions used here, the database for the range from \$30 million to \$300 million gives a cost (in millions of dollars) of $20.2B_0^{0.84}R_0^{1.96}M^{-0.8}$ for copper-coil devices and $19.2B_0^{1.0}R_0^{2.11}M^{-1.06}$ for superconducting-coil devices (with B_0 in tesla and R_0 in meters).

1.2.2 Spherical Torus Experiment (STX)

T. J. McManamy, R. D. Benson, R. L. Brown, G. H. Henkel, E. A. Lazarus, and D. E. Williamson

At year's end, we had not received a definitive response from DOE to our proposal to construct the Spherical Torus Experiment (STX). Work on the prototypical ohmic heating (OH) solenoid, an activity funded from the ORNL Director's Exploratory Funds, continued during the year, and the winding of that solenoid is complete. It is a one-third length prototype that will produce 12.2 T at a coil current of 30 kA. The conductor is Glidcop grade AL-15 dispersion-strengthened copper.* Details of construction and fabrication are given in ref. 22. Tests of this coil will be carried out in early 1988 and will use the ATF HF power supply.

*SCM Metal Products, Bradford Woods, Pa.

1.3 ADVANCED STUDIES

N. A. Uckan, W. A. Houlberg, R. A. Dory, S. E. Attenberger, B. A. Carreras, J. T. Hogan, H. C. Howe, D. A. Spong, J. Sheffield, and J. S. Tolliver

1.3.1 Overview

In the past year, strong support was provided for the national effort to define and design both the Compact Ignition Tokamak (CIT) and the International Thermonuclear Experimental Reactor (ITER). These studies include confinement assessment; plasma modeling, burn analysis, particle transport, and pellet fueling; current drive; alpha particle physics; MHD stability and beta limits; and effects of rf fields.

There are several performance indicators for tokamaks; the level of plasma current I is one of the most important because of the favorable scaling of confinement time τ_E and limits on plasma beta β_{crit} and density $(n)_{max}$ with increasing I . One key quantity to be determined in the design of burning-plasma devices is the level of plasma current required to meet the desired plasma performance goals and machine objectives. A simple formulation was developed and shows that these goals and objectives can be expressed in terms of the "figure-of-merit" parameter IA^α/R^z , where α and z depend on the confinement assumptions and the operational limits or requirements ($(n)_{max}$, β_{crit} , safety factor q , wall loading L_w , current drive power P_{CD} , etc.). To reach ignition or high Q (with inductive or noninductive current drive), subject to the constraints imposed by operational limits, the main goal is to optimize IA^α/R^z .

For broad profiles, ignition requires $(T/10 \text{ keV})(n/10^{20} \text{ m}^{-3})\tau_E \sim 3(1 \pm 0.1)$ for $(T) \sim 7\text{--}25 \text{ keV}$. With a Murakami-Hugill limit for the density ($n < n_{mu} \sim B/Rq$, $\sim I/a^2$), the Troyon limit for the beta ($\beta < \beta_{crit} \sim 3I/aB$), and $q_\psi > 3\text{--}3.5$ for MHD stability, the optimum temperature for ignition is typically $\sim (10 \pm 2) \text{ keV}$ for many confinement scaling models. Table 1.2 lists (for a given plasma shape and q) the ignition/burn-related plasma performance goal $Tn\tau_E$ in terms of IA^α/R^z .

Table 1.2. Scaling of performance goals with current and aspect ratio

$Tn\tau_E$ ($n = n_{mu}$, for fixed q, κ, δ , and $\langle T \rangle$)		
Basic formula		$\sim (IA^\alpha)/R^z$
With confinement scaling		
NC	neoclassical	$[(IA^{3/8})/R^0]^2$
NA	neo-Alcator (OH)	$[(IA^{1.5})/R^{0.5}]^2$
G	Goldston	$[f_L(IA^{1.37})/R^{0.12}]^2$
KG	Kaye-Goldston	$[f_L^{0.8}(IA^{1.32})/R^{0.55}]^3$
K	Kaye	$[f_L(IA^{1.5})/R^{0.4}]^2$
AX	ASDEX H-mode	$[(IA^{1.0})/R^{0.5}]^2$
M	Mirnov	$[(IA^{0.5})/R^{0.5}]^2$
MM	Merezhkin-Mukhovatov	$[(IA^{1.87})/R^{0.5}]^2$
OS	Oda-jima-Shimomura	$[f_L(IA^0)/R^0]$
S	Shimomura (H-mode)	$[(IA^{1.5})/R^{0.5}]^2$
RL	Rebut-Lallia	$[f_L^{0.5}(IA^{0.5})/R^{0.25}]^2$
Other parameters (at $\beta = \beta_{crit}$, $n = n_{mu}$, for fixed q, κ, δ)		
Energy gain factor Q		$[(IA^{1.0})/R^0]$
Wall loading L_w		$[(IA^{1.25})/R^{0.75}]^4$
Fusion power P_{fus}		$[(IA^{1.0})/R^{0.25}]^4$
Current drive power P_{CD}		$[(IA^{1.0})/R^{1/3}]^3$

for a number of empirical confinement scalings. Also listed are the scalings of Q , P_{fus} , L_w , and P_{CD} . The lower bound on IA^α/R^x , in terms of confinement, is set by the containment of alpha particles ($\alpha = 0.5$, $x = 0$) and the irreducible neoclassical transport ($\alpha = 3/8$, $x = 0$). All of the scalings show a strong dependence on A ($\alpha \sim 1-1.5$), with the exception of the Mirnov, Odajima-Shimomura, and Rebut-Lallia scalings (where $\alpha \leq 0.5$), and a weaker dependence on size ($x \sim 0.1-0.5$). In general, leaving aside the differences in α and x , all of the confinement scalings favor small, high-current, large-aspect-ratio devices. Although small R , high I , and large A improve the confinement properties (and the wall loading, fusion power, and Q), they may make it difficult to meet the current drive power requirements. Systems analysis should be able to address this question.

Figure 1.16 shows the normalized current $[I(A/3)^\alpha]$ needed for ignition as a function of plasma size (R or a) for some of the confinement scalings given in Table 1.2. The plasma shape is fixed at $\kappa = 2$ and $\delta = 0.4$, the safety factor $q_\psi \approx 3.5$, $n \approx n_{mu}$, and $\langle T \rangle \approx 10$ keV. Because the neo-Alcator (NA) scaling represents an upper limit to confinement, in Fig. 1.16 we have used a combined (in a quadratic mean) form for the confinement time, $\tau_E = [(\tau_{NA})^2 + (\tau_{aux})^2]^{-1/2}$, where "aux" indicates the additional scaling used. Typically, the NA component does not significantly influence the L-mode scalings ($f_L = 1$). However, many H-mode scalings (with $f_L \geq 1.4-2$) are so favorable that they would allow ignition at very low plasma currents, and in such cases the NA limit becomes operative.

Fig. 1.16. Plasma current $I(A/3)^\alpha$ needed for ignition vs size (R , a) for various confinement scalings [combined with neo-Alcator (NA) scaling] with a fixed plasma shape ($\kappa = 2$, $\delta = 0.4$) and $q_\psi \approx 3.5$, evaluated at ($n \approx n_{mu}$, $T \approx 10$ keV). (See Table 1.2 for notation.)

For a device similar to CIT (with $R \sim 1.75\text{--}2\text{ m}$), the ignition requirement is $I(A/3)^{\alpha} \sim 9\text{--}15\text{ MA}$ for H-mode-like scalings. For a device similar to ITER ($R \sim 4\text{--}5\text{ m}$), $I(A/3)^{\alpha} \sim 15\text{--}22\text{ MA}$ is required for ignition. An ITER with noninductive current drive and $L_{\infty} \sim 1\text{ MW/m}^2$ would require $I(A/3)^{\alpha} \sim 12\text{--}14\text{ MW}$, in which case $Q \sim 10$ operation is possible for optimistic current drive schemes requiring $P_{CD} \sim 50\text{--}75\text{ MW}$, and $Q \sim 5$ operation is possible for nominal current drive schemes requiring $P_{CD} \sim 100\text{--}150\text{ MW}$.

1.3.2 Activities in Support of CIT

Work on CIT was carried out in collaboration with the national program being developed through PPPL. Primary areas of input to the CIT physics assessments were (1) confinement assessment; (2) plasma modeling, burn analysis, particle transport, and pellet fueling; and (3) alpha particle effects.

1.3.2.1 Confinement assessment

The confinement capability and operational (n - T or β - q) space of CIT-class plasmas have been examined using both global and WHIST transport calculations. Given the considerable uncertainty in the energy confinement of burning plasmas and the relationship between the confinement properties and operational limits (n , β , q , etc.), the main goals have been to provide useful choices and guidance as to which parameters the design should emphasize. This guided the effort to optimize the energy confinement/operating window so as to ensure that confinement capability was sufficient to reach ignition and compatible with detailed alpha particle physics studies. In this area, numerous inputs, detailed analysis, and comparative assessments were provided to the Ignition Technical Oversight Committee and the CIT design team.

Another aspect of the study was an assessment of the projected performance of the CIT design alternatives for a variety of specific confinement models. The evaluation was based mainly on various empirical scaling laws deduced from experiments, although theoretical models were also considered. The results show that ignition in the 1987 baseline CIT (10 T, 9 MA, 1.75 m) requires an energy confinement time $\tau_E \sim 400\text{--}600\text{ ms}$ (see Figs. 1.17 and 1.18), depending on the density and temperature (and, in turn, pressure) profiles that can be realized from various fueling and heating scenarios, subject to sawtooth and stability considerations. For the most part, attaining ignition (and significant margin for ignition) relies mostly on reaching the H-mode, with the assumption that $\tau_E(\text{H-mode}) = f_L \tau_E(\text{L-mode})$ and that the presently observed improvement in confinement ($f_L \sim 1.5\text{--}3$) holds for burning plasma conditions. Performance projections with saturated ohmic and L-mode confinement scalings vary widely (ranging from marginally ignited to driven operation). With marginal or poor confinement, access to high- Q operation depends sensitively on the available auxiliary heating power (P_{aux}).

Fig. 1.17. Maximum ignition margin and Q vs τ_E for three beta limits in CIT.

Fig. 1.18. Maximum ignition margin and Q vs τ_E for different profile assumptions in CIT.

1.3.2.2 Plasma modeling, burn analysis, and pellet fueling

The dynamics of startup, ignition, and rampdown in CIT were examined with the WHIST transport code. Emphasis was placed on determining the flexibility of the operating scenarios against uncertainties in confinement projections and on exploring the additional control over plasma behavior offered by pellet injection (through control over the density profile) and ICRH (through control of the resonance position).

The sensitivity of the CIT performance to the shape of the density profile was quantified; a more centrally peaked density profile leads to an enhanced fusion rate and therefore a greater margin against confinement losses. In evaluating the relative effects of pellet and neutral gas fueling on the density profile, it was found that large uncertainties exist in extrapolating empirical diffusive and particle pinch models to CIT parameters. Partial pellet penetration improves the density profile peaking over that obtained with neutral gas injection in all cases, but the time-averaged density profile still exhibits a strong sensitivity to the relative magnitudes of the diffusive and pinch terms.

Pellet penetration as a function of pellet size and velocity was studied for conditions from ohmic plasma through ignition and burn in CIT. Under startup and ohmic conditions, pellets containing as little as 10% of the plasma mass penetrate to near the magnetic axis with velocities characteristic of current technology (1.5 km/s). Under burn conditions, these pellets penetrate only about 25% of the plasma radius and show a very weak velocity dependence. Partial penetration of tritium pellets (through the scrape-off layer and poorly confined edge region) reduces the tritium injection requirements by a factor of 2-3 below those with neutral gas injection.

1.3.2.3 Alpha particle physics

Calculations of alpha population effects on ballooning modes continued to evolve toward more realistic models of fusion-generated alphas. The ballooning stability code has been coupled to a quasianalytic, noncircular equilibrium model and applied to a range of tokamak devices such as TFTR, CIT, and ITER. This has indicated that the kinetically modified ballooning stability boundaries are not as sensitive to shaping as in the ideal MHD case. The code has now been coupled to a fully numerical equilibrium calculation that should allow better accuracy for the more highly elongated cases. The sensitivity of kinetic ballooning stability to a number of additional physics parameters, such as $k_{\perp} \rho_i$, modifications to the alpha energy distribution, alpha pressure, electron temperature, and magnetic field strength, was examined. These studies are helpful for illuminating the physical mechanism of the precessional mode interaction, and they point the way for methods of improving stability.

1.3.3 Activities in Support of ITER

The ITER work was carried out in collaboration with the national program being developed through LLNL. Primary areas of input to the ITER physics assessments were (1) confinement assessment, (2) particle transport and pellet fueling, (3) current drive, (4) alpha particle physics, and (5) MHD stability and beta limits.

1.3.3.1 Confinement assessment

The confinement capability and operational (n - T or β - q) space of the ITER plasma for ignited and steady-state phases of operation were also examined using both global and WHIST transport calculations. Again, given the considerable uncertainty in the energy confinement of burning plasmas and the relationship between the confinement properties and operational limits (n , β , q , current drive efficiency, etc.), the main goals have been to provide initial choices and guidance as to which parameters the design should emphasize. In this area, preliminary results on the current needed for ignition, the ignition window in MHD operating space, and the confinement characteristics of an ITER-like device were provided to the U.S. delegation to the May, July, and September 1987 meetings of the Technical Working Group in Vienna. A close working relationship with the ITER physics assessment group has been established to help formulate the initial physics design guidelines.

The sensitivity of the projected performance of an evolving U.S. ITER design was assessed for a variety of confinement models and some specific current drive schemes. Operating regimes that simultaneously provide confinement capability sufficient to reach ignition and are compatible with current drive requirements in steady state appear to exist, though they are sensitive to the current drive efficiency.

An area of importance to ITER (especially during the steady-state, current-driven phase) is the role of synchrotron radiation in power balance, if wall reflectivity is very low. Global calculations have shown that synchrotron radiation can approach or exceed the current drive power requirements with a synchrotron-to-alpha power ratio approaching 30-60%, thus adversely affecting the performance characteristics.

1.3.3.2 Particle transport and pellet fueling

The sensitivity of ITER performance to the degree of central peaking in the density profile was quantified; a more centrally peaked density profile leads to an enhanced fusion rate and therefore a greater margin against confinement losses. However, the relative effects of pellet and neutral gas fueling on the density profile are difficult to evaluate because of the large uncertainties in extrapolating empirical diffusive and particle pinch models to ITER parameters. Partial pellet penetration improves the density profile peaking over that obtained with neutral gas injection

in all cases, but the time-averaged density profile still exhibits a strong sensitivity to the relative magnitudes of the diffusive and pinch terms.

Fueling issues in ITER were essentially the same as those for CIT. Under burn conditions, pellets penetrate only to the outer portions of the plasma, and penetration is not very sensitive to pellet velocity. The uncertainty in particle pinch and diffusive terms leads to a large uncertainty in the shape of the density profile. Even partial penetration of tritium pellets leads to a reduction in tritium processing requirements by at least a factor of 2 from those expected with neutral gas injection.

1.3.3.3 Current drive

Initial studies of current drive requirements have been carried out for ITER-like plasmas using the WHIST transport code and a generic current drive model typical of neutral beam or lower hybrid sources. Operating regimes that simultaneously satisfy current drive and auxiliary power requirements as well as the usual plasma beta and density limit constraints were identified; they compared well with global calculations. Although the region in density-temperature space where all constraints are met is generally small, it appears to exist over a reasonable range of confinement assumptions and current drive efficiencies.

Prospects for current drive with high-energy neutral beams were evaluated. Preliminary results suggested that neutral beam injection has the flexibility necessary to reproduce the current profiles required for stability at the beta levels predicted by the Troyon scaling.

1.3.3.4 Alpha particle physics

The effect of fast alpha diffusion and thermal alpha ash accumulation on the confinement capability of an ITER-like plasma in achieving ignition and steady-state driven operation was quantified using global and $1\frac{1}{2}$ -dimensional ($1\frac{1}{2}$ -D) WHIST transport models. The fast alpha contribution to pressure is substantial (10–30%) at ITER burn temperatures (8–20 keV). A relatively low level of fast alpha radial diffusion or a modest level of thermal alpha buildup can significantly influence the ignition and steady-state burn capability. The fast alpha population can also modify the background plasma ballooning mode stability boundaries, lowering the beta limit. In particular, operation at the high electron temperatures needed for efficient current drive is found to exacerbate this effect.

1.3.3.5 MHD stability and beta limits

A study of ideal MHD beta limits has been undertaken, through the Ignition Physics Study Group, to assess and extend the state of understanding of ideal MHD stability physics as it affects design considerations for ITER. Surveys have been conducted for the range of U.S. ITER designs, covering two aspect ratios

($A = 2.9$ and 3.6) for a wide range of elongations ($1.5 \leq \kappa \leq 3.2$) and triangularities ($0 \leq \delta \leq 0.6$). Both localized (ballooning and Mercier) and low- n ($n = 1, 2, 3$) modes have been examined with the PPPL PEST suite of codes. An extensive ITER equilibrium database for poloidal field design and axistability application has been generated. A collaboration with LLNL has been initiated to develop an advanced version of the EFIT code (originated by GA Technologies) that will be suitable for design applications. Close working relationships with U.S. MHD experts and the ITER physics assessment group have been established to help formulate the initial ITER physics design guidelines. A useful spinoff of the study has been the application of the LOCUS database from PPPL to catalog the MHD runs made and provide cross-correlation and plotting of the results, as well as retrospective analysis. The utility of this automated database approach has been advertised to the several laboratories that are studying stability in ITER.

1.3.4 Abstracts

1.3.4.1 "Relative Merits of Size, Field, and Current on Ignited Tokamak Performance"²³

N. A. Uckan

A simple global analysis is developed to examine the relative merits of size ($L = a$ or R_0), field (B_0), and current (I) on ignition regimes of tokamaks under various confinement scaling laws. Scalings of key parameters ($n\tau_E$, β , P_{aux} , P_{fus} , etc.) with L , B_0 , and I are presented at several operating points, including (1) optimal path to ignition (saddle point), (2) ignition at minimum beta, (3) ignition at 10 keV, and (4) maximum performance at the limits of density ($n_{max} \sim B_0/R_0$) and beta ($\beta_{crit} \sim I/aB_0$). Expressions for the saddle point and the minimum conditions needed for ohmic ignition are derived analytically for any confinement model of the form $\tau_E \sim n^x T^y$. For a wide range of confinement models, the "figure of merit" parameters aB_0^2/q , $\sim IB_0(R_0/a)$ and I are found to give a good indication of the relative performance of the devices, where q is the cylindrical safety factor. As an illustration, the results are applied to representative "CITs" (a class of compact, high-field ignition tokamaks) and "Super-JETs" [a class of large (few $\times$ JET), low-field, high-current (≥ 20 MA) devices].

1.3.4.2 "Influence of Fast Alpha Diffusion and Thermal Alpha Buildup on Tokamak Reactor Performance"²⁴

N. A. Uckan, J. S. Tolliver, W. A. Houlberg, and S. E. Attenberger

The effect of fast alpha diffusion and thermal alpha accumulation on the confinement capability of a candidate Engineering Test Reactor (ETR) plasma [Tokamak Ignition/Burn Experimental Reactor (TIBER-II)] in achieving ignition and steady-state driven operation has been assessed using both global and 1 1/2-D transport

models. Estimates are made of the threshold for radial diffusion of fast alphas and thermal alpha buildup. It is shown that a relatively low level of radial transport, when combined with large gradients in the fast alpha density, leads to a significant radial flow with a deleterious effect on plasma performance. Similarly, modest levels of thermal alpha concentration significantly influence the ignition and steady-state burn capability.

1.3.4.3 "Physics Analysis of the TIBER-II Engineering Test Reactor"²⁵

N. A. Uckan, W. A. Houlberg, S. E. Attenberger, R. A. Dory, D. A. Spong, J. S. Tolliver, and J. Sheffield

Confinement capability, burn characteristics, heating and fueling requirements, and fast alpha particle effects are assessed for the TIBER-II (ETR/ITER). Confinement predictions for a wide variety of empirical scaling laws show that ignition in TIBER-II (or any ETR-like device) is marginal at 10 MA, whereas the design goal to achieve noninductively driven, steady-state burn with $Q > 5$ could easily be attained. Operation at higher plasma currents or the possibility of attaining higher density limits and/or favorable H-mode scalings improves the ignition capability. Pellet penetration calculations indicate that density profile control with pellets may not be feasible for pellet velocities up to about 50 km/s; however, density peaking could result from an anomalous inward pinch. The fast alpha contribution to pressure is substantial (10–30%) at TIBER-II (or any ETR/ITER) burn temperatures (8–20 keV). A relatively low level of fast alpha radial diffusion or a modest level of thermal alpha concentration significantly influences the ignition and steady-state burn capability. The fast alpha population can also modify the background plasma ballooning mode stability boundaries, lowering the beta limit β_{crit} —in particular, operation at high electron temperatures needed for efficient current drive can exacerbate this effect. The use of high-energy neutral beams may offer promise of two important improvements in projected performance: an effective method for non-inductive current drive and a means for controlling current density profiles deep within the plasma required for stable operation at high beta levels.

1.3.4.4 "Synchrotron Radiation Losses in ETRs"²⁶

N. A. Uckan

In next-generation ETRs, one major objective is envisioned to be a long-pulse or steady-state burn using noninductive current drive. At the high temperatures needed for efficient current drive, synchrotron radiation could represent a large power loss, especially if wall reflectivity ($\mathcal{R}$) is very low. Many INTOR-class ETR designs (FER, NET, OTR, TIBER, etc.) call for carbon-covered surfaces for which wall reflectivity is uncertain. Global radiation losses are estimated for these devices using empirical expressions by Trubnikov (and others). Various operating scenarios

are evaluated under the assumption that the plasma performance is limited by either the density limit (typical of the ignition phase) or the beta limit (typical of the current drive phase). For a case with $\geq 90\%$ wall reflectivity, synchrotron radiation is not a significant contribution to the overall energy balance (the ratio of synchrotron to alpha power is less than 10–20%, even at $\langle T_e \rangle \sim 30$ keV) and thus should not adversely alter performance in these devices. In extreme cases with 0% wall reflectivity, the ratio of synchrotron radiation to alpha power may approach 30–60% (depending on the device and limiting operating scenario), adversely affecting the performance characteristics.

1.3.4.5 "Transport Simulations of Ohmic Ignition Experiment—IGNITEX"²⁷

N. A. Uckan and H. C. Howe

The IGNITEX device is a compact, super-high-field, high-current, copper-coil tokamak envisioned to reach ignition with ohmic heating alone. Several simulations of IGNITEX were made with a zero-dimensional (0-D) global model and with the one-dimensional (1-D) PROCTR transport code. It is shown that ohmic ignition is a sensitive function of the assumptions about density profile, wall reflectivity of synchrotron radiation, impurity radiation, plasma edge conditions, and additional anomalous losses. In IGNITEX, ohmic ignition is accessible with nearly all scalings based on favorable ohmic confinement (such as neo-Alcator, etc.). Also, ohmic ignition appears to be accessible for most (not all) L-mode scalings (such as Kaye-Goldston, etc.), provided that the density profile is not too broad (parabolic or more peaked profiles are needed), Z_{eff} is not too large (≤ 2), and anomalous radiation and alpha losses and/or other enhanced transport losses (η_i modes, edge convective energy losses, etc.) are not present. In IGNITEX, because the figure-of-merit parameters ($aB_0^2/q \sim IB_0$, etc.) are large, the ignition can be accessed (either with ohmic heating alone or with the aid of a small amount of auxiliary power) at relatively low beta, far from stability limits. Once ignited, thermal runaway is prevented naturally by a combination of the increased synchrotron radiation, the burnout of the fuel in the plasma core and replacement by thermal alphas, and the reduction in the thermal plasma confinement assumed in L-mode-like scalings.

1.3.4.6 "Tokamak Operational Boundaries—Implications for CIT and ITER Designs"²⁸

N. A. Uckan

Tokamak operation is limited in density (n), beta (β), and q (or current) space. The maximum density is given either by the Murakami limit ($n \sim B/Rq$) or by the Greenwald limit ($n \sim \kappa J \sim I/\pi a^2$). The maximum volume-averaged (total) beta is constrained by the Troyon limit ($\langle \beta \rangle \sim C_\beta I/aB$, the ballooning limit). In

addition, a current (q) limit is set by the kink modes. Results from many tokamak experiments suggest that the confinement degrades and disruptivity increases markedly as the operational limits are approached. We first consider the implications of these operational limits on projected CIT and ITER plasma performance for various confinement (L- and H-mode) scalings. Next, we show how the extent (in n - T and β - q spaces) of the ignition (CIT and ITER—pulsed physics phase) and driven (ITER—steady-state, noninductive current drive phase) regimes depends on these limits.

1.3.4.7 "Plasma Performance Analysis of Current-Driven Tokamak Reactors"²⁹

S. E. Attenberger, N. A. Uckan, W. A. Houlberg, and J. S. Tolliver

A simple current drive model has been added to the WHIST 1¹/₂-D transport code in order to study profile effects on the operating window of current-driven tokamak reactors. The current density is not allowed to diffuse; a fully self-consistent treatment of the current profile is beyond the scope of this preliminary investigation. The operating window in density-temperature space is bounded by the density and beta limits and the requirements for current drive and minimum acceptable Q (≥ 5). Sensitivity of the operating window to changes in plasma current and current drive efficiency is analyzed. The results are compared to a 0-D treatment. Possible improvements to the model are discussed.

1.3.4.8 "Physics Considerations for the Compact Ignition Tokamak"³⁰

R. Parker,* D. Post,[†] G. Bateman,[†] M. Bell,[†] P. Colestock,[†] J. Helton,[†]
W. Houlberg, M. Hughes,[†] D. Ignat,[†] S. Jardin,[†] J. Johnson,[†] S. Kaye,[†]
C. Kieras-Phillips,[†] L.-P. Ku,[†] G. Kuo-Petravic,[†] B. Lipschultz,* J. Manickam,[†]
M. Peng, M. Petravic,[†] M. Phillips,[†] M. Porkolab,* N. Pomphrey,[†] J. Ramos,*
J. Schmidt,[†] D. Sigmar,* R. Stambaugh,** D. Stotler,^{††} D. Strickler,^{††}
A. Todd,[†] N. Uckan, J. Wesley,** and K. Young[†]

The CIT is a compact ($R \sim 1.5$ m), high-field ($B_T \sim 10$ T), high-current ($I_p \sim 10$ MA) tokamak whose objective is to reach ignition, thereby permitting study of ignited plasma regimes. Owing to the high field and concomitant magnet heating rate, the duration of the ignited phase is about $10\tau_E$, where τ_E is the energy confinement time. Thus, it is expected that processes characterized by the τ_E time scale can be comprehensively studied, while phenomena associated with current relaxation as well as long-pulse plasma-wall issues can only be partially addressed. Notable among those physics issues which will be studied is confinement and its optimization under conditions where the alpha power dominates.

The baseline design features a diverted, highly elongated ($\kappa \geq 2$) plasma cross section. The divertor option has been selected on the basis of relevancy to future devices of the ETR class, as well as confinement optimization (i.e., H-mode). Indeed, it is found that CIT-class devices can be ignited in the L-mode regime only by peaking the density profile (using pellet injection) with simultaneous operation at the extremes of well-accepted tokamak operational limits [q_ψ , nR/B , and $\beta/(I/aB)$]. The poloidal field (PF) shaping system in the baseline design is located external to the toroidal field (TF) system. Optimizing coil positions results in an economical design from the viewpoint of PF energy, especially at high elongation ($\kappa > 2$) and moderate triangularity ($\delta > 0.3$) where a separatrix naturally forms. However, some internal control coils appear to be necessary for control of the X-point and intense divertor heat loads, as well as providing for additional vertical stability.

The calculated beta limit for ignited CIT discharges depends strongly on the assumed pressure and current profiles. Optimized profiles yield stable values of beta well above that required for ignition. More realistic current profiles would have broad, nearly shearless regions in which high- n ballooning and low- n internal modes limit the pressure gradient and which would therefore not be conducive to ignition. Determination and optimization of beta limits in ignited plasma regimes is identified as a major motivation for the experimental program.

While the intense ohmic heating associated with high-field, compact tokamaks is expected to produce multi-keV temperatures, transport simulations show that 5-10 MW of auxiliary heating power is generally required. ICRH at the second harmonic of tritium (~ 100 MHz) has been chosen as the baseline heating method. ECH has been chosen as a backup, assuming that power at the cyclotron frequency and its harmonic will be available. Heating at $\omega = 2\omega_{ce}$ is preferred owing to the higher density limit and absence of tight specifications on polarization; this mode will potentially be available using free-electron laser (FEL) technology. Fundamental-frequency heating could also be used, depending on the operating density, in which case more conventional technology (gyrotrons) might be appropriate.

*Massachusetts Institute of Technology, Cambridge.

†Princeton Plasma Physics Laboratory, Princeton, N.J.

‡Grumman Corporation, Princeton, N.J.

**General Atomics, San Diego, Calif.

††Institute for Fusion Studies, University of Texas, Austin.

‡‡Computing and Telecommunications Division, Martin Marietta Energy Systems, Inc.

1.4 THE U.S.-FRG-JAPAN COLLABORATION ON ALT-II

D. L. Hillis, J. T. Hogan, P. K. Mioduszewski, L. W. Owen, and T. Uckan

The Advanced Limiter Test-II (ALT-II) is a collaborative effort of the United States, the Federal Republic of Germany, and Japan. The effort is focused on studies of a toroidal belt pump limiter for the TEXTOR tokamak and is designed to extend the database for single pump limiter modules to a full-size energy removal and particle control system for future steady-state fusion devices. Staff members from ORNL participate in the experimental program and in computer modeling of experimental results. In particular, ORNL staff are responsible for making H_α measurements as part of particle confinement studies and for the helium removal experiment.

An experimental plan for the helium removal experiment and the corresponding diagnostics have been developed in collaboration with the TEXTOR group. The TEXTOR 30-keV lithium beam will be used for charge-exchange (CX) spectroscopy of helium in the plasma edge; initial measurements have been performed. The neutral beam injector will be available in fall 1988 for CX spectroscopy of the central helium. Additional details of the ALT-II collaboration can be found in Sect. 4 of this report.

1.5 THE U.S.-FRANCE COLLABORATION ON TORE SUPRA

C. C. Klepper, P. K. Mioduszewski, and T. Uckan

The Tore Supra pump limiter program is a collaborative U.S.-France project to be carried out on the Tore Supra device in Cadarache, France. In Tore Supra, density control with strong pellet fueling is foreseen for long pulses of 30 s. The corresponding particle exhaust will be provided by pump limiters. In contrast to the ALT-II on TEXTOR, the Tore Supra pump limiter system will consist of up to seven single pump limiter modules. Participation of ORNL staff involves the development of an experimental plan, conceptual design of the limiter system, testing and implementation of suitable pump limiter diagnostics, operation of the pump limiters, and coordination of the overall task. Engineering and fabrication of the pump limiter modules are the responsibility of the Sandia National Laboratories, Albuquerque, N.M. Additional details of the Tore Supra pump limiter experiments are given in Sect. 4 of this report.

REFERENCES

1. M. M. Menon, P. H. Edmonds, and C. L. Haas, "A Calorimeter for Measuring the Neutral Beam Power Reaching the Plasma," pp. 1119-21 in *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, California, October 1987*, Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1987.
2. F. W. Baity et al., "Progress in ICRF Heating Technology and Designs for Future Large Tokamak Heating Systems," p. 743 in *Proceedings of the 14th Symposium on Fusion Technology (Avignon, France, September 1986)*, Vol. 1, Pergamon Press, Oxford, 1987.
3. *Fusion Energy Division Annual Progress Report for Period Ending December 31, 1986*, ORNL-6332, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., October 1987, p. 25.
4. R. R. Kindsfather et al., "Two-Dimensional Thomson Scattering System," *Rev. Sci. Instrum.* **57**, 1816 (1986).
5. S. L. Painter, "Optimizing Performance of the Advanced Toroidal Facility's Thomson Scattering System Spectrometer Array," master's thesis, The University of Tennessee, Knoxville, 1987.
6. W. D. Shipley, R. R. Kindsfather, and D. A. Rasmussen, "Mechanical Design Aspects of the Advanced Toroidal Facility Thomson Scattering Diagnostics," p. 1297 in *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, California, October 1987*, Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1987.
7. R. P. Gormley, "Spectral Calibration of a Thomson Scattering System," master's thesis, The University of Tennessee, Knoxville, 1988.
8. G. L. Bell et al., "ECE Diagnostic for ATF," *Rev. Sci. Instrum.* **59** 1614 (1988).
9. G. L. Bell et al., *ECE Radiation Path Design for ATF*, MMESI-19X-5596V-2, Auburn University, Auburn, Ala., October 1987.
10. K. Uo et al., "Studies on Currentless Heliotron E Plasma," p. 355 in *Plasma Physics and Controlled Nuclear Fusion Research (Proceedings of the 11th International Conference, Kyoto, Japan, 1986)*, Vol. 2, International Atomic Energy Agency, Vienna, 1987.
11. H. C. Howe, *Physics Models in the Tokamak Transport Code PROCTR*, ORNL/TM-9537, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., 1985.
12. D. K. Lee, J. H. Harris, and S. P. Hirshman, "Numerical Computations of Fourier Representations for 3-Dimensional Toroidal Flux Surfaces," *Bull. Am. Phys. Soc.* **31**, 1493 (1986).
13. S. P. Hirshman, W. I. van Rij, and P. Merkel, "Three-Dimensional Free-Boundary Calculations Using a Spectral Green's Function Method," *Comput. Phys. Commun.* **43**, 143-55 (1986).
14. M. Murakami et al., "Energy Transport in Currentless, Beam-Heated Plasmas in Heliotron-E," p. 149 in *Proceedings of the International Stellarator/Heliotron Workshop*, Vol. 1, PPLK-5, Kyoto University, Gokasho, Japan, 1986.

15. K. Hanatani et al., "Confinement of Helically Trapped Fast-Ion Orbits in a Neutral-Beam-Sustained Heliotron E Plasma," *Nucl. Fusion* **25**, 259 (1985).
16. B. A. Carreras et al., "ATF-II and Stellarator Reactor Studies," p. 29 in *Fusion Energy Division Annual Progress Report for Period Ending December 31, 1986*, ORNL-6332, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., 1987.
17. B. A. Carreras et al., "ATF-II and Stellarator Reactor Studies," p. 1-28 in *Fusion Energy Division Annual Progress Report for Period Ending December 31, 1985*, ORNL-6234, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., 1986.
18. B. A. Carreras et al., *Compact Torsatron Configurations*, ORNL/TM-10030, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., September 1987.
19. J. F. Lyon et al., *Compact Torsatron Reactors*, ORNL/TM-10572, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., April 1988.
20. *Proceedings of the Workshop on Wendelstein VII-X, Schloss Ringberg, 18-20 March, 1987*, EUR-11058, Commission of the European Communities, Brussels, 1987.
21. *Next Generation Large Helical Device Design Group* (in Japanese), unpublished, 1987.
22. T. J. McManamy et al., "Design and Fabrication of a Prototype Solenoid for the Spherical Torus Experiment," pp. 350-52 in *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, California, October 1987*, Vol. 1, Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1987.
23. N. A. Uckan, "Relative Merits of Size, Field, and Current on Ignited Tokamak Performance," *Fusion Technol.* **14**, 299-319 (1988); also published as ORNL/TM-10365, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., August 1987.
24. N. A. Uckan et al., "Influence of Fast Alpha Diffusion and Thermal Alpha Buildup on Tokamak Reactor Performance," *Fusion Technol.* **13**, 411 (1988); also published as ORNL/TM-10612, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., November 1987.
25. N. A. Uckan et al., "Physics Analysis of the TIBER-II Engineering Test Reactor," pp. 1428-33 in *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, California, October 1987*, Vol. 2, Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1987; also published as ORNL/TM-10611, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., November 1987.
26. N. A. Uckan, "Synchrotron Radiation Losses in ETRs," pp. 1394-97 in *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, California, October 1987*, Vol. 2, Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1987; also published as ORNL/TM-10584, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., November 1987.
27. N. A. Uckan and H. C. Howe, "Transport Simulations of Ohmic Ignition Experiment—IGNITEX," pp. 1398-1401 in *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, California, October 1987*, Vol. 2, Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1987.

28. N. A. Uckan, "Tokamak Operation Boundaries—Implications for CIT and ITER Designs," *Bull. Am. Phys. Soc.* **32**, 1923 (1987).
29. S. E. Attenberger et al., "Plasma Performance Analysis of Current-Driven Tokamak Reactors," *Bull. Am. Phys. Soc.* **32**, 1760 (1987).
30. R. Parker et al., "Physics Considerations for the Compact Ignition Tokamak," in *Proceedings of the 14th European Conference on Controlled Fusion and Plasma Heating, Madrid, June 1987: Europhys. Conf. Abstr.*, 11D, Pt. I, 301 (1987).

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Section 2

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**ATOMIC PHYSICS AND
PLASMA DIAGNOSTICS DEVELOPMENT**

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R. A. Phaneuf,¹ Program Manager

C. F. Barnett²	M. S. Huq⁴	F. M. Ownby¹⁴
C. A. Bennett³	D. P. Hutchinson¹	M. S. Pindzola¹⁵
C. Bottcher¹	R. K. Janev⁸	R. K. Richards
W. H. Casson⁴	M. I. Kirkpatrick¹	K. Rinn¹⁶
H. B. Gilbody⁵	J. Lee⁹	K. J. Snowdon⁷
D. C. Gregory¹	C. H. Ma¹	N. Stolterfoht¹⁷
D. C. Griffin⁶	E. W. McDaniel¹⁰	J. K. Swenson⁴
J. W. Hale¹	F. W. Meyer¹	E. W. Thomas¹⁰
C. C. Havener¹	T. J. Morgan¹¹	K. L. Vander Sluis¹
W. Heiland⁷	A. Müller¹²	L. J. Wang¹⁸
H. T. Hunter¹	S. H. Overbury¹³	D. M. Zehner¹⁹

-
1. Physics Division.
 2. Consultant.
 3. Oak Ridge Associated Universities faculty research participant, University of North Carolina, Asheville.
 4. Oak Ridge Associated Universities postdoctoral research associate.
 5. Consultant, Queen's University, Belfast, Northern Ireland.
 6. Research subcontractor, Rollins College, Winter Park, Fla.
 7. University of Osnabrück, Osnabrück, Federal Republic of Germany.
 8. Consultant, Institute of Physics, Belgrade, Yugoslavia.
 9. Graduate student, the University of Tennessee, Knoxville.
 10. Consultant, Georgia Institute of Technology, Atlanta.
 11. Consultant, Wesleyan University, Middletown, Conn.
 12. Justus Liebig Universität, Giessen, Federal Republic of Germany.
 13. Chemistry Division.
 14. Program secretary.
 15. Auburn University, Auburn, Ala.
 16. Postdoctoral research associate, Physics Division, ORNL, and Joint Institute for Laboratory Astrophysics, Boulder, Colo.
 17. Hahn-Meitner Institut, Berlin, Federal Republic of Germany.
 18. Postdoctoral research associate, on assignment from Wesleyan University, Middletown, Conn.
 19. Solid State Division.

2. ATOMIC PHYSICS AND PLASMA DIAGNOSTICS DEVELOPMENT

SUMMARY OF ACTIVITIES

The activities within this program are divided among atomic collisions research, data compilation and evaluation, and plasma diagnostics development. The majority of this research is supported through the ORNL Fusion Program and is carried out within the Physics Division.

The atomic collisions research focuses on inelastic processes that are important for determining the energy balance and impurity transport in high-temperature plasmas and for diagnostic measurements. This activity is not directed toward a particular fusion device but concentrates rather on developing a better basic understanding of collision processes involving highly ionized atoms at kinetic energies that are characteristic of magnetic fusion plasmas. Close coordination of experimental and theoretical programs guides the selection of key experiments and provides both benchmarks and challenges for theory. A state-of-the-art electron cyclotron resonance (ECR) multicharged ion source is central to this program, facilitating the study of atomic collision processes involving highly ionized plasma impurity ions. Recent crossed-beams experiments and theoretical efforts have concentrated on electron-impact ionization of multicharged nickel ions in charge states ranging from 5 to 14. Indirect excitation-ionization and metastable states were found to play a major role in this isonuclear sequence. Parallel development of theoretical methods for treating ions with complex electronic structures has been crucial to this systematic effort, as well as to calculations of the dielectronic recombination process. Experimental and theoretical studies of the possible role of resonances in ionization were also completed. In the merged-beams experiments that provide charge-exchange cross-section measurements down to electron-volt relative energies, measurements have been completed for $O^{5+} + H$ and $N^{5+} + H$ collisions, which play important roles at the plasma edge. In a related experiment, high-resolution electron spectroscopic measurements were made of electrons ejected from autoionizing states produced in double-electron-capture collisions of multiply charged ions with helium and H_2 . Studies of electron ejection during the neutralization of multicharged ions at metal surfaces have also been performed; these have applications in divertors and impurity control.

The atomic physics group also operates the Controlled Fusion Atomic Data Center, which, with the assistance of a network of consultants, searches and categorizes publications on atomic collisions and prepares and distributes indexed bibliographies and compilations of recommended data to the fusion research community. The major effort during the last several years has been the preparation of a revised and expanded "Redbook" series of recommended data for fusion research. Volume

5, entitled *Collisions of Carbon and Oxygen Ions with Electrons, H, H₂ and He*, was published and distributed during the period. In coordination with the International Atomic Energy Agency (IAEA) Data Center Network, database assessments and data parameterizations were also published for charge-exchange and electron-impact ionization of iron ions. The bibliographic database was moved to a newly implemented advanced database management system on a personal computer and is available for on-line searching.

The plasma diagnostics program concentrates on the development of advanced diagnostics for existing and future magnetic fusion experiments and relies primarily on optical and laser technology. The current emphasis is on the application of infrared lasers to the diagnostics of ignited multicomponent plasmas. A technique under development uses small-angle Thomson scattering of a pulsed CO₂ laser beam to measure the density and velocity distribution of fusion-product alpha particles. Detailed modeling calculations have been made of the scattered power spectrum expected from the proposed Compact Ignition Tokamak (CIT). A long-pulse CO₂ laser and heterodyne infrared receiver have been constructed and tested, and a simulated scattering experiment has been conducted in our laboratory in preparation for a proof-of-principle test of the diagnostic method on the Advanced Toroidal Facility (ATF). An advanced multichannel far-infrared (FIR) laser interferometer system is being prepared for installation on ATF. A single channel will be available during early ATF operations, and expansion to 10-15 channels will take place during the ensuing three months. Also in progress is a feasibility study of a proposed two-color interferometer/polarimeter system for CIT. A polarization modulator has been developed and tested, and graphite reflectivity measurements have been completed. Emphasis in the ORNL diagnostics program continues to be placed on the development of computer-based remote handling systems for all the laser diagnostic systems, which will become more important with each succeeding generation of fusion experiments.

2.1 EXPERIMENTAL ATOMIC COLLISIONS

2.1.1 Electron-Impact Ionization of Multiply Charged Nickel Ions

L. J. Wang, K. Rinn, and D. C. Gregory

Nickel is an important impurity element in modern fusion devices, especially in those with vessel walls made of high-nickel-content alloys [e.g., the Joint European Torus (JET)]. A good knowledge of atomic processes involving nickel ions is essential in order to understand and accurately model these plasmas, but detailed calculations and measurements are available for ionization of only the first three charge states of nickel. The present work involves the measurement of cross sections for electron-impact ionization of Ni⁵⁺, Ni⁶⁺, Ni⁷⁺, Ni⁸⁺, Ni¹²⁺, and Ni¹⁴⁺.

The absolute cross-section measurements reported here used the ORNL electron cyclotron resonance (ECR) ion source¹ and the electron-ion crossed-beams apparatus.² The results and interpretation of the data can most easily be considered by dividing the measurements into two parts, with Ni^{5+} through Ni^{8+} forming one group, and Ni^{12+} and Ni^{14+} the other. One example from each group is discussed, and general trends are noted.

The cross-section data for Ni^{6+} are plotted in Fig. 2.1 along with a calculation for direct ionization based on the semiempirical Lotz formula.³ The measured cross sections are up to 40% larger than theory. The difference is attributed to excitation-autoionization (excitation of an inner electron followed by autoionization of the resulting highly excited ion). The influence of this process is observed over the entire energy range studied here, with no sharp onsets that would indicate a single transition dominating the indirect contribution. Excitation-autoionization from hundreds of transitions adds together to produce the smooth enhancement observed in this case.

The electronic configurations of the four ions in the first group are similar ($3p^6 3d^n$, where $n = 5, 4, 3$, and 2 for Ni^{5+} , Ni^{6+} , Ni^{7+} , and Ni^{8+} , respectively), and this accounts for the similarities in cross section observed in these measurements. In each case, indirect ionization contributes a featureless enhancement to the cross section over the entire energy range. Since the direct ionization cross section decreases fairly rapidly with increasing charge and the contribution of excitation-autoionization remains more or less constant, indirect ionization becomes relatively

Fig. 2.1. Electron-impact ionization measurements for Ni^{6+} , with calculated direct ionization.

more important as the charge state increases along this sequence. This trend is predicted to end abruptly as the ion reaches an inert-like electron configuration, where indirect contributions must come from excitation of more tightly bound inner electrons.

Figure 2.2 shows the cross-section measurements for ionization of Ni^{12+} along with Lotz calculations representing direct ionization of outer-shell $3s^23p^4$ electrons. In contrast to the Ni^{6+} data discussed above, direct ionization accounts for about 75% of the measured cross section up to about 850 eV, where an abrupt change in slope is observed. This feature is the signature for excitation of inner-shell $2p$ electrons to autoionizing excited configurations. These $\Delta n = 1$ (or more) transitions contribute up to 40% of the total at the peak cross section, in contrast to recent predictions⁴ that excitation-autoionization due to $\Delta n = 1$ transitions would be insignificant for higher charge states of nickel. An additional feature of this curve is the onset of ionization below the threshold for direct ionization of ground-configuration $3p^4$ electrons. This indicates the presence of metastable ions in the beam at the collision volume. On the basis of the observed low-energy behavior of the cross section (and making certain assumptions about the energy dependence of the cross section for ionization of the metastable ions), we estimate that 20% of the ion beam was in $3p^33d$ metastable levels.

As predicted above, the direct ionization cross section for Ni^{12+} is considerably smaller than that for Ni^{6+} . Indirect ionization is no larger proportionally for Ni^{12+}

Fig. 2.2. Electron-impact ionization measurements for Ni^{12+} , with calculated direct ionization.

than for Ni^{6+} , which again is expected since more tightly bound inner-shell electrons must be excited to autoionizing configurations for the higher-charged ions. As the sequence continues up in charge, Ni^{14+} (with a $3s^2 3p^2$ electron configuration) has relatively more indirect contribution to its total cross section than is observed for Ni^{12+} .

These measurements provide an extended database for ionization of nickel ions, as well as a basis for comparison of accurate experimental data with planned detailed calculations for this sequence. This work may also be combined with similar measurements and calculations for the iron isonuclear sequence to study the scaling of cross sections along isoelectronic sequences.

2.1.2 Search for Recombination Resonances in Electron-Impact Ionization of O^{5+}

K. Rinn, D. C. Gregory, L. J. Wang, R. A. Phaneuf, and A. Müller

Lithium-like ions, with a $1s^2 2s$ electron configuration, are prime candidates for detailed experimental and theoretical studies of electron-impact ionization. A number of experiments and theoretical studies in the last ten years have focused on O^{5+} as an example of the lithium isoelectronic sequence. Recent major improvements in the ORNL crossed-beams apparatus and improved stability and intensities of beams from the ORNL ECR ion source made further study⁵ of this ion worthwhile. The two primary aims of this work were to measure the excitation-autoionization contribution to the total cross section with improved accuracy and to search for isolated recombination resonances that were beyond the resolution of previous studies. This summary concentrates on the latter effort.

In addition to direct ionization (the "knockout" of an outer electron in an electron-ion collision) and excitation-autoionization (the excitation of an inner-subshell electron, leaving the ion in a highly excited configuration that autoionizes), an ionization event may be produced by more exotic processes. One of these, termed resonant excitation double Auger (REDA) ionization by its originators,⁶ was predicted to make a significant contribution to the total cross section for ionization of sodium-like Fe^{15+} . The variation of this process sought in this study is illustrated by the sequence

In this example, the incoming projectile electron excites a $1s$ target electron to the $2p$ subshell and is captured in the process to the $2p$ subshell. This is a resonant process (since the energy levels must match exactly) and may decay through a number of channels, one of which is illustrated in Eq. (2.1). This is the only exit channel that produces a net ionization event, and it requires the simultaneous ejection of two electrons from the target ion (i.e., a correlated event). The other resonance considered here involves the $\text{O}^{4+}(1s^2 2s^2 2p)$ intermediate state, which also requires

a correlated double autoionization to produce a net ionization. These two intermediate states produce isolated ionization resonances that would be observed as sharp enhancements in the ionization cross section at 436.3 and 449.0 eV.

To increase the sensitivity of the experiment to the presence of resonance structures, a special computer program was written to control the experiment and data collection. Measurements were made at each of up to 30 closely spaced electron energies for approximately 4 s each, and this scan was repeated for hours to obtain data with good statistics and a common background at all energies. Any features in the data produced by drifting experimental parameters will cancel in such a scan, producing a solid baseline that will reveal any resonance structures.

The data are shown in Fig. 2.3, with the energies where resonances are expected marked by arrows and identified by the O^{4+} intermediate state. Although the features observed at these energies cannot be clearly resolved from the background cross section, there are suggestions of structures at the predicted energies. We place an upper limit of 10^{-20} cm^2 on the cross sections for the resonant processes, with an experimental energy spread of 2.4 eV. This result is in good agreement with more recent detailed calculations for this process.⁷

Fig. 2.3. Electron-impact ionization of O^{5+} , with predicted resonance features indicated by the arrow.

2.1.3 ECR Ion Source Upgrade: Addition of New User Beam Lines

J. K. Swenson, F. W. Meyer, and J. W. Hale

A new beam line has been installed recently at the ORNL ECR ion source facility. This upgrade increases to four the number of user ports available for experiments. Figure 2.4 shows the new beam line configuration and the location of the user ports.

The new user beam line starts with a half-scale version of the main 90° double-focusing charge-analyzing magnet, followed by an x - y micrometer slit assembly and a biased Faraday cup. The magnet is designed to transport the entire beam envelope into the new beam line. A large-bore electrostatic einzel lens images the magnet exit slit onto the entrance aperture of a 90° spherical deflector, shown positioned at the end of the beam line. This deflector allows switching the beam to either of the two 90° ports, port 3 or port 4, as indicated in Fig. 2.4. It can also be positioned out of the beam path via the ultrahigh-vacuum rotation feedthrough so that the beam travels undeflected into port 2. An experiment may be positioned at each of these three beam ports. The beam line pressure is typically a few $\times 10^{-8}$ torr and the deflector chamber pressure is a few $\times 10^{-9}$ torr. The deflector chamber is pumped by a 2000-L/s cryopump and acts as a differential pumping section between experiments and the rest of the beam line. A beam profile monitor at the entrance of

Fig. 2.4. Schematic representation of ECR ion source and beam transport, showing location of main experimental port 1 and new user beam line ports 2, 3, and 4.

the spherical deflector chamber facilitates positioning and shaping of the ion beam before it is directed into one of the on-line experiments.

The new beam line has already been used to perform a second series of Auger electron spectroscopy measurements in which electrons emitted at 0° to the beam axis were energy analyzed in high resolution, following collisions of helium-like second-row ions (O^{8+} , F^{7+} , Ne^{8+}) with He, H_2 , and Ne. The only location at which the beam was available for the first series of these measurements was downstream of the merged-beams and crossed-beams experiments, semi-permanently in place at port 1. This location suffered from poor upstream beam transport. Increases in usable beam currents by factors of 10 to 20 were obtained at the new port. Thus, the addition of the new beam lines has already demonstrated enhanced flexibility and overall accessibility of the ECR ion source facility.

2.1.4 Electron Capture Cross Sections for $O^{5+} + H$ and $N^{5+} + H$ at Electron-Volt Energies Using Merged Beams

C. C. Havener, M. S. Huq, and R. A. Phaneuf

Electron capture collisions of multiply charged ions with hydrogen atoms in the 1- to 500-eV/amu energy range play an important role in astrophysics and in the edge plasma of magnetic fusion devices. At such low energies, theoretical models of many inelastic processes remain essentially untested. Our objective is to perform benchmark measurements of independently absolute total cross sections for electron capture that result from collisions of various multicharged ions with hydrogen atoms in the relative energy range extending from tenths of an electron volt to several hundred electron volts. During the past year absolute cross-section measurements were completed for the $O^{5+} + H$ (D) systems, and preliminary measurements were made for the $N^{5+} + H$ (D) systems at relative energies ranging from 0.8 to 800 eV/amu. This extends the previous measurements⁸ for these systems to lower energies by two orders of magnitude, allowing comparison with theory for the first time in this energy range.

Experimentally, a pure ground-state beam of hydrogen or deuterium atoms is produced by passing a 6- to 9-keV beam of H^- or D^- ions through the optical cavity of a 1.06- μm Nd:YAG laser, where up to 1 kW of power circulates. Typically, 0.5 to 1% of the negative ions in the beam are neutralized by photodetachment. A 50- to 90-keV, 2- to 4- μA beam of O^{5+} ions produced by the ORNL ECR ion source is merged electrostatically with this neutral beam. The 80-cm-long interaction path of the beams is maintained at an average pressure of 2×10^{-10} torr. The product H^+ (D^+) ions are magnetically separated from the primary beams and are deflected and focused onto a channel electron multiplier, where they are counted. Typical neutral beams of 15 nA (equivalent) produce $60 s^{-1}$ of beam-beam signal and $12,000 s^{-1}$ of background due to stripping on residual gas. A fast, two-beam chopping scheme is used to separate the signal from the background. To quantify the spatial overlap

of the beams, two-dimensional intensity profiles of each beam are measured at four different positions along the merged path.

Several improvements to the original apparatus were made during the last year. These include modifications of two beam scanners used to measure the beam-beam spatial overlap and introduction of a 1-in.-diam channel electron multiplier. The new electron multiplier increased the angular acceptance of the reaction products by 50%, ensuring complete collection of products at the lowest center-of-mass energies. Furthermore, the larger detector essentially eliminated the sensitivity of the method to spurious signals produced by space-charge modulation, allowing measurements to be performed below 1 eV/amu. Modifications of the beam scanners helped improve the accuracy of the cross-section measurements.

Results for absolute total cross sections for electron capture for collisions of $O^{5+} + H(D)$ are shown in Fig. 2.5 as a function of relative collision energy. Data shown correspond to several different laboratory-frame conditions, which provide important diagnostic tests of the method: the hydrogen beam was interchanged with a heavier deuterium beam, the neutral beam was prepared at a higher or lower velocity than the multicharged ion beam, and the laboratory-frame energies of all beams were significantly changed. Figure 2.5 also shows the previous ion-beam gas target measurements⁸ for the same system, the recent unpublished theoretical calculations by Bottcher and Heil,⁹ and the results of Gargaud and McCarroll.¹⁰ The cross sections rise with decreasing energy in the 20- to 200-eV/amu range, consistent with previous measurements down to 80 eV/amu and with the calculations. However, below 20 eV/amu, the experimental cross section turns over and decreases with decreasing energy. Below 3 eV/amu, the measured cross section rises again with

Fig. 2.5. Cross sections for total electron capture of O^{5+} from H and D.

decreasing energy, consistent with the $1/v$ dependence and cross-section magnitude predicted by the classical orbiting model.¹¹

Preliminary measurements for $N^{5+} + H$ and $N^{5+} + D$ collisions are shown in Fig. 2.6. The energy dependence of N^{5+} collisions is significantly different from that for the O^{5+} case. Evidence suggestive of the role of the orbiting mechanism is also apparent in the lowest energy data for this system.

2.1.5 High-Resolution Auger Electron Spectroscopy of Low-Energy Double-Electron Capture Collisions of Multiply Charged Ions with Neutral Atoms and Molecules

F. W. Meyer, C. C. Havener, J. K. Swenson, D. C. Griffin, M. S. Huq, R. A. Phaneuf, and N. Stolterfoht

Our investigation of double-electron capture by multicharged ions into autoionizing final states has continued. The experimental apparatus was moved to a newly completed beam line of the ORNL ECR source facility that delivered factors of 10 to 20 times more beam current to the experiment than was available during previous runs. This enhanced capability made possible an extension of earlier measurements to helium-like fluorine and neon incident ions, as well as improved measurements of spectra for helium-like oxygen incident ions. The focus of study during this reporting period was a series of systematic, high-resolution measurements of

Fig. 2.6. Cross sections for total electron capture of N^{5+} from H and D.

the production of L and M Coster-Kronig, as well as L and M Auger, electrons in double-electron capture collisions involving helium-like multicharged ions as a function of projectile charge and target species. The Coster-Kronig electrons result from the decay of nonequivalent electron configurations, whose production has been shown to involve electron-electron correlation effects.¹² Comparison of Coster-Kronig electron production to total Auger electron production provides a relative measure of the importance of correlation effects in double-electron capture collisions of multicharged ions.

Figure 2.7 shows a sample L Coster-Kronig electron spectrum for 60-keV O^{6+} colliding with helium. A well-defined Rydberg series starts at principal quantum number $n = 6$, at which the $1s^2 2pn\ell$ configurations become autoionizing, and terminates at a series limit of 12 eV. Figure 2.8 shows high-resolution scans of the first two members of the $1s^2 2pn\ell$ Coster-Kronig series measured for 30-keV projectile energy; partially resolved structures are seen within the $n = 6$ and $n = 7$ transition manifolds. Also shown in Fig. 2.8 are calculated Hartree-Fock transition energies for those levels belonging to the $2p6\ell$ and $2p7\ell$ electron configurations that have significant singlet content. The calculations are being used¹³ together with the high-resolution experimental spectra to obtain information about the ℓ distributions characterizing double-electron capture into nonequivalent electron configurations.

Figure 2.9 shows electron spectra in the range from 0 to 20 eV for Ne^{8+} incident on He and H_2 . The figure illustrates the increasing complexity of the spectra as the projectile charge is increased, which results from the increased number of final channels populated. The magnitude of the electron emission cross sections is enhanced in the case of the H_2 target, since the positions of the relevant curve crossings are shifted to larger internuclear separations because of the reduced total initial binding energy of the two target electrons.¹⁴ The doubling of the L Coster-Kronig peaks is due to the fine structure splitting of the $Ne^{8+} 2p$ core level.

Fig. 2.7. High-resolution spectrum of L Coster-Kronig electrons produced in 60-keV $O^{6+} + He$ collisions, after low-energy background subtraction. The energy scales of all spectra shown refer to the projectile frame.

Fig. 2.8. High-resolution spectrum of the first two members of the $1s^2 2pnl$ Coster-Kronig series produced in 30-keV $O^{6+} + He$ collisions. The vertical lines are calculated transition energies of the levels belonging to the $6l$ and $7l$ configurations; heights of the lines are proportional to singlet purity.

Fig. 2.9. Low-energy electron spectra for 80-keV Ne^{8+} ions incident on (a) He and (b) H_2 .

2.1.6 Studies of Low-Energy Multicharged Ion-Surface Interactions by Ejected-Electron Spectroscopy

F. W. Meyer, C. C. Havener, D. M. Zehner, S. H. Overbury, K. J. Snowdon, and W. Heiland

Observation of the ejected-electron energy spectra from ion-surface collisions provides information on the dynamics of the neutralization of the ion as it interacts with the solid. This year's activity in this area consisted of analyzing measurements made during the last fiscal year for multiply charged N, O, F, Ne, and Ar ions with energies of a few kilo electron volts per atomic mass unit incident at grazing angles on gold and copper surfaces. The detailed analysis has led to new proposals for understanding the interaction of multicharged ions with surfaces.

The multicharged ion beams from the ECR ion source were incident at 5° on the (110) surfaces of gold and copper single crystals (see Fig. 2.10) mounted in an ultrahigh-vacuum chamber (1×10^{-10} torr). The surfaces were sputter cleaned with 1-keV Ne^+ at 10° incident to the surface and annealed, and their cleanliness was monitored using electron-induced Auger electron spectroscopy. The energy distributions of emitted electrons arising from the multicharged ion surface interaction were measured using a cylindrical mirror analyzer (CMA). The CMA pass energy and data collection were controlled by a minicomputer-based multichannel scaler.

Figure 2.11 shows the electron emission spectra for hydrogen-like, helium-like, and lithium-like oxygen ions on gold. As is typical in all the spectra, most of the

Fig. 2.10. Schematic illustration of the experimental and detection geometries. The CMA axis is located at 90° to the incident ion beam direction.

Fig. 2.11. Electron kinetic energy distributions for collisions of O^{7+} , O^{6+} , and O^{5+} projectiles with gold metal target, for the geometry of Fig. 2.10.

electrons are ejected at low energies (<10 eV) by the mechanism of kinetic electron emission, which is quite sensitive to surface effects. Above about 50 eV, the emission has been proposed¹⁵ to result from quasielastic scattering processes, which involve promotion of bound electrons in the target and projectile to the continuum.

Superimposed on the low-energy emission and giving information about the dynamics of the neutralization of the projectile are one-center Auger decay features of both projectile and target vacancies. One way that neutralization can proceed is by capture of valence-band electrons to the projectile excited states, followed by one-center Auger decay.¹⁶ Figure 2.11 shows broad peaks at 500 eV; these are identified as Doppler-broadened KLL-Auger peaks resulting from filling the projectile $1s$ vacancy by the above process. This structure is absent in the lithium-like O^{5+} spectra, since these projectiles contain no initial inner-shell vacancies and apparently produce none during the interaction with the surface. For the helium-like O^{6+} spectra, the high-energy structure is still present, pointing to the existence of $1s2s^3S$ metastables in the beam. The correlation between the Auger peaks and the initial vacancies in the incident ion beam allowed the metastable fraction to be determined for the beams listed in Table 2.1. This technique is the basis for a proposed simple metastable detector¹⁷ suitable for use with low-energy ion beams.

In Fig. 2.11, the additional structures at 69 and 239 eV are due to the transfer of the projectile inner-shell vacancy to the target gold $N_{IV,V}$ level and subsequent

decay by Auger emission. The presence of these target vacancies suggests an additional mode for neutralization of the incident ion. Long-lived projectile inner-shell vacancies survive until close encounters with the atoms in the solid. At these binary collisions, pseudocrossings of molecular orbitals can transfer the vacancy from the projectile to the target.

Further evidence of the survival of the vacancies until close encounters with the atoms in the solid is in the electron emission for various F^{q+} ions on copper (not shown). The Doppler-broadened KLL-Auger peak resulting from the filling of the $1s$ vacancy is observed not only in the F^{8+} spectra, but also, with diminishing intensity, for charge states F^{6+} down to F^{2+} , for which no initial K-shell vacancies exist. By constructing the correlation diagram for the fluorine-copper system, one finds that initial $2p$ -subshell vacancies, which are always present even for the lower-charge-state fluorine ions, can be transferred to the K-shell of the projectile by means of rotational coupling between the $3d\pi$ and $3d\sigma$ molecular orbitals of the fluorine-copper system. These molecular orbitals correlate with the $2p$ and $1s$ levels of fluorine, respectively.

Table 2.1. Metastable fractions of several beams from the ORNL ECR multicharged ion source

Ion	Metastable fraction (%)
N^{5+}	6.2 ± 0.6
O^{6+}	2.6 ± 0.5
Ar^{8+}	15.5 ± 0.7
Ar^{7+}	10 ± 1

2.2 ATOMIC COLLISION THEORY

2.2.1 Abstract of "Distorted-Wave Calculations of the Electron-Impact Ionization of Highly Ionized Na-Like Ions"¹⁸

D. C. Griffin, M. S. Pindzola, and C. Bottcher

We report on distorted-wave calculations of the electron-impact ionization cross sections and rate coefficients for the sodium-like ions Ti^{11+} , Cr^{13+} , Fe^{15+} , and Ni^{17+} . The cross sections for direct ionization out of the $3s$, $2p$, and $2s$ subshells were

determined using the configuration-average, distorted-wave approximation. In addition, excitation-autoionization contributions originating from inner-shell excitations of the type $2s^2 2p^6 3s \rightarrow 2s^2 2p^5 3s n l$ ($n = 3, 4, 5$) and $2s^2 2p^6 3s \rightarrow 2s 2p^6 3s n l$ ($n = 3, 4$) were calculated by employing the distorted-wave approximation and configuration-interaction, bound-state wave functions.

Near threshold, the total ionization cross sections in all four ions are enhanced by approximately a factor of five through excitation-autoionization. These excitation-autoionization contributions are large, even though they have been substantially reduced by radiative decay to the bound states of the initial ion. Furthermore, although electron correlation has a minimal effect on the excitation cross sections, the magnitude of the branching ratios for autoionization is quite sensitive to configuration interaction in the autoionizing levels. This is especially true for the $2p \rightarrow 3d$ excitations, where configuration interaction between $2p^5 3s 3d$ and $2p^5 3p^2$ can increase the magnitude of the autoionizing rates for levels within the $2p^5 3s 3d$ configuration by as much as three orders of magnitude. Thus, for example, in the case of the $2p \rightarrow 3d$ excitation in Ni^{17+} , correlation increases the overall branching ratio for autoionization from 0.27 to 0.53.

2.2.2 Abstract of "Electron-Ion Collisions in the Average-Configuration Distorted-Wave Approximation"¹⁹

M. S. Pindzola, D. C. Griffin, and C. Bottcher

Explicit expressions for the electron-impact excitation, ionization, and resonant-recombination cross sections are derived in the average-configuration distorted-wave approximation. Calculations using these expressions are applied to several types of phenomena in electron-ion scattering where comparison with other theoretical methods and experimental measurements can be made.

2.2.3 Abstract of "Ionization in Collisions Between Electrons and Complex Ions"²⁰

C. Bottcher, D. C. Griffin, and M. S. Pindzola

Most models of hot plasmas containing complex ions still rely on simple, semi-empirical formulas for electron-impact ionization rates. These formulas often fail when applied to complex ions, through neglect of two factors: (1) indirect ionization mechanisms involving autoionizing states and (2) long-lived metastable states of the target ion. Extensive calculations and measurements on the iron isonuclear sequence, carried out by groups at Oak Ridge,²¹ provide an instructive case study. While the distorted-wave approximation is often adequate, some progress has been made toward more precise calculations. Even approximate calculations on complex systems require extensive computer resources.

2.2.4 Abstract of "Double-Auger Processes in the Electron-Impact Ionization of Lithium-Like Ions"²²

M. S. Pindzola and D. C. Griffin

Contributions to the electron-impact ionization of lithium-like ions due to resonant recombination followed by double Auger emission are calculated using first- and second-order perturbation theory. The double Auger rate is found to be quite sensitive to the choice of both continuum phase and excited orbital basis sets. In particular, we find that resonant recombination to the $1s2s^22p^3P$ term of O^{4+} , followed by double Auger emission to the $1s^2\ ^1S$ term of O^{5+} , has a cross section ranging from 6.4×10^{-22} cm² to 4.9×10^{-21} cm², depending on how the double Auger rate is calculated. The maximum represents 0.65% of the total ionization cross section for O^{5+} at the resonance energy of 436.3 eV. Thus, a noise level of 1.0%, which is probably a lower limit of current crossed-beams experiments, will mask the contribution in O^{5+} . Similar results are found for other lithium-like ions in the first-row periodic table elements.

2.2.5 Abstract of "Theoretical Calculations of Indirect Processes in Electron-Impact Ionization of Atomic Ions"²³

M. S. Pindzola, D. C. Griffin, and C. Bottcher

The application of continuum Hartree-Fock theory to the calculation of indirect processes in the electron-impact ionization of atomic ions is reviewed. Comparison between theory and recent crossed-beams experiments is made for several multiply charged atomic ions.

2.3 CONTROLLED FUSION ATOMIC DATA CENTER

C. F. Barnett, H. B. Gilbody, D. C. Gregory, C. C. Havener, H. T. Hunter, M. S. Huq, R. K. Janev, M. I. Kirkpatrick, E. W. McDaniel, F. W. Meyer, T. J. Morgan, R. A. Phaneuf, M. S. Pindzola, J. K. Swenson, and E. W. Thomas

The primary task of the Controlled Fusion Atomic Data Center (CFADC) is to collect, review, evaluate, and recommend numerical atomic collision data of interest in controlled thermonuclear fusion research. The CFADC operates with an equivalent of 1.5 full-time staff members, as well as a number of expert consultants from the research community, upon which it depends heavily.

Participants in the ORNL program in experimental atomic physics for fusion also contribute a small fraction of their time to literature searches and categorization of relevant publications. The major activities of the data center are threefold:

- the maintenance of up-to-date bibliographies of fusion-related publications on atomic collision processes in computer files for on-line searching and publication,

- the preparation and publication of compilations of recommended atomic collision data for fusion research, and
- the handling of user requests for specific data or information about relevant atomic processes.

The data center actively participates in cooperative agreements with the Atomic Data Center for Fusion at the Institute for Plasma Physics of Nagoya University, Japan, the Atomic and Nuclear Data Center of the Japan Atomic Energy Research Institute, and the Atomic and Molecular Data Unit of the International Atomic Energy Agency (IAEA) in Vienna. Our staff continues to participate in the IAEA International Atomic and Molecular Data Center Network and to advise the IAEA data center on its activities. Our bibliographic updates are sent to these centers every six months and form the basis for the semiannual IAEA *International Bulletin on Atomic and Molecular Data for Fusion*.

Our data center also maintains a close cooperation with the Atomic and Molecular Processes Information Center at the Joint Institute for Laboratory Astrophysics in Boulder, Colorado, and with the National Bureau of Standards Data Center on Atomic Spectral Lines and Transition Probabilities in Gaithersburg, Maryland.

During this reporting period, a major effort continued to be directed toward the preparation of an updated and expanded version of the 1977 two-volume compilation of recommended tabular and graphical data, entitled *Atomic Data for Controlled Fusion Research* and published as ORNL-5206 and ORNL-5207 (commonly referred to as the "Redbooks"). The new multiple-volume series is entitled *Atomic Data for Fusion* and consists of five volumes (ORNL-6086 through ORNL-6090). These volumes, with their (expected) publication dates, are as follows:

- Vol. 1: Collisions of H, H₂, He, and Li Atoms and Ions with Atoms and Molecules (publication expected in 1988),
- Vol. 2: Collisions of Electrons with Atoms and Molecules (publication expected in 1989),
- Vol. 3: Particle Interactions with Surfaces (published 2/85),
- Vol. 4: Spectroscopic Data for Iron (published 2/85),
- Vol. 5: Collisions of Carbon and Oxygen Ions with Electrons, H, H₂, and He (published 2/87).

All of the tabular and graphical data for the new "Redbook" series are computer-generated in publication-ready format. A computer code calculates Maxwellian rate coefficients from the cross sections and produces Chebyshev polynomial fits to both the cross sections and the rate coefficients. This facilitates our plans to place these recommended collision data in internationally accessible files on the National Magnetic Fusion Energy Computer Network.

A subset of Vol. 5 of the "Redbook" series, entitled "Recommended Cross Sections for Electron Capture and Ionization in Collisions of C^{q+} and O^{q+} with H, He, and H₂," has been accepted for publication in *Atomic Data and Nuclear Data Tables*.

In addition, two database assessments have been prepared for collision processes involving iron ions, in coordination with the IAEA Atomic and Molecular Data Unit.

These form part of a recently published supplementary issue of *Nuclear Fusion*. These articles, "Electron-Impact Ionization Data for the Fe Isonuclear Sequence," by M. S. Pindzola, D. C. Griffin, C. Bottcher, and H. T. Hunter, and "Charge Exchange Processes Involving Iron Ions," by R. A. Phaneuf, R. K. Janev, and H. T. Hunter, contain recommended and parameterized data. A similar database assessment for heavy-particle processes specific to the edge plasma of magnetic confinement devices is in preparation.

Another major accomplishment of this reporting period has been the development of a new database management system for the CFADC's bibliographic files and the transfer of approximately 20,000 existing records to this advanced system, which is based on a personal computer. These current files are now available for instant on-line retrieval and can be accessed according to collision process, reactants, or authors.

2.4 ADVANCED PLASMA DIAGNOSTICS DEVELOPMENT

2.4.1 Development of a Diagnostic for Fusion-Product Alpha Particles Based on Pulsed CO₂-Laser Thomson Scattering

R. K. Richards, D. P. Hutchinson, H. T. Hunter, K. L. Vander Sluis, and C. A. Bennett

In a deuterium-tritium (D-T) fusion reactor, the kinetic energy of the 3.5-MeV fusion-product alpha particles will be required to heat cold D-T fuel in order to sustain the fusion reaction. The study of the physics of this alpha particle heating is a primary goal of the next generation of fusion experiments, and the development of diagnostic techniques to measure alpha particle behavior is an important part of the fusion program. To produce such a diagnostic system, we have been investigating a CO₂ laser Thomson scattering technique for the measurement of the alpha particle density and velocity distribution in a D-T burning plasma.²⁴ During the past year we have made progress in three areas of investigation: a high-power, long-pulse CO₂ laser; an absorption cell; and a full system test.

A necessary component of this diagnostic is a long-pulse, high-power CO₂ laser. The long pulses are achieved by adding a low-pressure cell within the cavity of a commercial transferred-electron amplifier (TEA) CO₂ laser. By firing the low-pressure cell slightly before the main discharge, the laser pulse is lengthened from 0.1 to 1 or 2 μ s, with the pulse length controlled by varying the low-pressure cell conditions.

It is important to minimize the laser beam divergence because the Thomson scattered radiation related to the alpha particles has only a small angular displacement from the laser beam direction. We have used unstable resonator optics to minimize the divergence of the laser beam. Laser beam profiles were measured at

30 and 50 m from the laser to estimate the divergence; these were in good agreement with the theory for unstable resonator cavities.²⁵

To reduce unscattered laser radiation, which could be collected by the detector optics and may interfere with measurement of scattered radiation, an absorption cell was constructed and tested. The absorption cell consists of a tube of heated CO_2 gas that resonantly absorbs unscattered CO_2 laser radiation but not the Thomson scattered radiation, which is shifted in wavelength. Tests with the cell placed in front of the heterodyne detector demonstrated this reduction of laser radiation without reducing blackbody continuum radiation between the CO_2 lines. These tests were part of a full system test for this diagnostic and included subsystems of the heterodyne receiver, absorption cell, optics, and high-power pulsed CO_2 laser. The full system test demonstrated the compatibility of the subsystems and established a threshold for signal detection.

In further investigations we plan to measure the free-electron velocity distribution in the Advanced Toroidal Facility (ATF). A schematic of the proposed scattering arrangement for this proof-of-principle test is shown in Fig. 2.12. Since the free-electron scattering in ATF is expected to be smaller than the alpha particle scattering in a burning plasma device, this test will establish the feasibility of detecting alpha particles and will also establish the level of background signal from the free electrons.

Fig. 2.12. Scattering system for proof-of-principle test of pulsed CO_2 laser Thomson scattering diagnostic on ATF.

2.4.2 Multichannel Interferometer System Development for ATF

C. H. Ma, D. P. Hutchinson, W. H. Casson, K. L. Vander Sluis, and J. Lee

The first phase of the interferometer system being developed for the ATF at ORNL is ready for installation. The interferometer system, shown in Fig. 2.13, consists of two laser systems, each with a $119\text{-}\mu\text{m}$ wavelength CH_3OH optically pumped laser and a $9.6\text{-}\mu\text{m}$ CO_2 laser. The CO_2 laser developed for the ATF interferometer produces more than 150 W in a single mode on the $9.6\text{-}\mu\text{m}$ pump line required by the CH_3OH far-infrared (FIR) laser. This pump power level has allowed us to operate the FIR lasers at a power level of more than 1.1 W. A feedback control system to lock the frequency of the pump lasers to the absorption peak of the CH_3OH molecule has been developed to enhance the frequency and amplitude stability of the FIR lasers. The control system uses a resonant opto-acoustic cell containing 0.5 to 2 torr of CH_3OH vapor. By comparing the output of the acoustic cell microphone with the voltage produced by a pyroelectric detector, which is

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Fig. 2.13. Schematic of 15-channel FIR interferometer developed for ATF.

proportional to the output of the CO₂ laser, a feedback signal may be derived to lock the pump laser on the absorption peak of the FIR lasing molecule.

The support column for the ATF interferometer optical system has been fabricated and will be placed on the ATF device during the first quarter of 1988. The support structure consists of three legs and cross members made of 12- by 12-in. fiberglass H-beam. The FIR laser beams will be enclosed in fiberglass tubing filled with dry air to minimize transmission losses due to atmospheric water vapor. The structure was assembled from fiberglass to eliminate the possibility of vibration produced by eddy currents during ATF operation. Such vibration could result in substantial errors in the density measurements because of the short wavelength of the interferometer.

During the initial experimental phase of ATF, the interferometer will be operated on a single channel. A 15-channel segmented detector array is under development, along with a beam expansion optical system that will provide density measurements over the entire plasma cross section.

2.4.3 Feasibility Study of an Infrared Interferometer/ Polarimeter System for the Compact Ignition Tokamak

C. H. Ma, D. P. Hutchinson, and K. L. Vander Sluis

During the past year, the feasibility of a two-dimensional infrared interferometer/polarimeter system for measurements of electron density and plasma current profiles in the Compact Ignition Tokamak (CIT) has been investigated both theoretically and experimentally. The system uses continuous-wave CO₂ lasers at a wavelength of 10.6 μm . This wavelength represents a trade-off; it is short enough to limit both the angle of beam refraction by plasma density gradients and the ellipticity of the polarized wave to an acceptable value, yet long enough to obtain adequate sensitivity for the measurements. A schematic diagram of the proposed system is shown in Fig. 2.14. A Bragg cell diffracts approximately 50% of the laser power into a reference beam. The acousto-optic cell also introduces a frequency shift Δf of 40 MHz in the diffracted beam. The probing beam is passed through a polarization modulator and a plasma simulator and is mixed with the reference beam. The detector is a liquid-nitrogen-cooled HgCdTe photovoltaic diode. The output of the detector, V_s , can be expressed by

$$\begin{aligned} V_s = & \{ \sqrt{RP_p} \cos[\theta_p + \theta_m \sin(\omega_m t)] \sin(\omega t + \phi) \\ & + \sqrt{RP_r} \sin[(\omega + \Delta\omega)t] \}^2 \\ = & R \sqrt{P_p P_r} \cos[\theta_p + \theta_m \sin(\omega_m t)] \cos(\Delta\omega t + \phi) \\ & + \text{terms of dc and other frequencies} \end{aligned}$$

Fig. 2.14. Schematic of the proposed infrared interferometer/polarimeter system for CIT.

where R is the responsivity of the detector, θ_m is the amplitude of the modulation angle, ω_m is the modulation frequency, ϕ is the phase shift due to plasma density, θ_p is the poloidal-field-induced Faraday rotation in plasma, and P_p and P_r are the powers of the probing and the reference beams at the detector, respectively. The signal is synchronously detected by two lock-in amplifiers at 40 MHz and ω_m , yielding an output voltage

$$V = V_0 \sin(\theta_p) , \quad (2.2)$$

where $V_0 = 2RA\sqrt{P_p P_r} J_1(\theta_m)$, A is the total voltage gain of the amplifiers, and $J_1(\theta_m)$ is the Bessel function of the first kind with order one. For CIT plasma parameters, the maximum value of θ_p is approximately 1.5° (ref. 26). Therefore, V can be considered a direct measure of θ_p , and Eq. (2.2) becomes

$$\theta_p = V/V_0 . \quad (2.3)$$

The calibration constant V_0 is obtained by setting the rotation angle of the plasma simulator at a few degrees ($\leq 4^\circ$) and measuring the value of V .

Both magneto-optic and electro-optic polarization-modulation techniques have been investigated to determine the sensitivity and time response of the polarimetry. Cadmium telluride (CdTe) crystal polarization rotators are used as the modulators and the plasma simulator. The magneto-optic modulator consists of a 210:1 rf current transformer, a 4:1 bifilar-wound matching transformer, and a CdTe crystal. The primary of the current transformer is connected in series with a 0.01- μ F capacitor to achieve a resonant frequency of approximately 80 kHz. The secondary is a three-turn copper coil that acts as the load of the transformer. The CdTe crystal, which is $12.5 \times 12.5 \times 50.8$ mm, is mounted in the center of the secondary coil. The electro-optic modulator consists of a ZnSe Fresnel $\lambda/4$ rhomb and a CdTe crystal, $4 \times 4 \times 50$ mm, with a half-wave voltage of 4.24 kV. An indium-doped CdTe crystal, $12.5 \times 12.5 \times 50.8$ mm, is used in the plasma simulator. A 65-mm-long, 7.6-mm-ID, 94-mm-OD solenoid produces a magnetic flux density of approximately 2.7 kG at a dc current of 3.5 A. A test stand for the system has been designed and constructed, and experiments are under way.

REFERENCES

1. F. W. Meyer, "The ORNL ECR Multicharged Ion Source," *Nucl. Instrum. Methods Phys. Res. B* **9**, 532 (1985).
2. D. C. Gregory et al., "Experimental Cross Sections for Electron-Impact Ionization of Iron Ions: Fe^{5+} , Fe^{6+} , and Fe^{9+} ," *Phys. Rev. A* **34**, 3657 (1986).
3. W. Lotz, *Z. Phys.* **220**, 466 (1969).
4. P. G. Burke, W. C. Fon, and A. E. Kingston, *J. Phys. B* **20**, 2579 (1987).
5. K. Rinn et al., "Electron-Impact Ionization of O^{5+} : Improved Measurements," *Phys. Rev. A* **36**, 595 (1987).
6. K. J. LaGattula and Y. Bahn, "Electron-Impact Ionization of Fe^{15+} by Resonant Excitation Double Auger Ionization," *Phys. Rev. A* **24**, 2273 (1981).
7. D. C. Griffin and M. S. Pindzola, "Double Auger Processes in Electron-Ion Scattering," *Bull. Am. Phys. Soc.* **32**, 1274 (1987).
8. R. A. Phaneuf et al., "Electron Capture in Low-Energy Collisions of C^{7+} and O^{6+} with H and H_2 ," *Phys. Rev. A* **26**, 1892 (1982).
9. C. Bottcher and T. G. Heil, unpublished data, March 30, 1988.
10. M. Gargaud and R. McCarroll, *J. Phys. B* **8**, 463 (1985).
11. G. Gioumousis and D. P. Stevenson, *J. Chem. Phys.* **29**, 294 (1958).
12. N. Stolterfoht et al., *Phys. Rev. Lett.* **57**, 74 (1986).
13. F. W. Meyer et al., "Population of High-Angular-Momentum States in Low-Energy Double-Electron-Capture Collisions of O^{6+} with He," *Phys. Rev. Lett.* **60**, 1821 (1988).
14. F. W. Meyer et al., "Correlation Effects on Double Electron Capture in Highly-Charged, Low-Energy Ion-Atom Collisions," invited paper presented at the XV International Conference on the Physics of Electronic and Atomic Collisions, Brighton, U.K., July 22-28, 1987; to be published in the collection of invited papers.
15. K. J. Snowdon et al., *Phys. Rev. A*, accepted for publication (1988).
16. F. W. Meyer et al., "Observation of the Neutralization of Highly Charged Ions Interacting with a Metal Surface," *Phys. Rev. A* **35**, 3176-79 (1987).
17. K. J. Snowdon et al., *Rev. Sci. Instrum.* **59**, 902 (1988).
18. D. C. Griffin, M. S. Pindzola, and C. Bottcher, "Distorted-Wave Calculations of the Electron-Impact Ionization of Highly Ionized Na-Like Ions," *Phys. Rev. A* **36**, 3642 (1988).
19. M. S. Pindzola, D. C. Griffin, and C. Bottcher, "Electron-Ion Collisions in the Average-Configuration Distorted-Wave Approximation," pp. 75-91 in *Atomic Processes in Electron-Ion and Ion-Ion Collisions*, F. Brouillard, ed., NATO Advanced Study Institute Ser. B145, Plenum, New York, 1986.
20. C. Bottcher, D. C. Griffin, and M. S. Pindzola, "Ionization in Collisions Between Electrons and Complex Ions," *Bull. Am. Phys. Soc.* **33**, 144 (1988).
21. M. S. Pindzola, D. C. Griffin, and C. Bottcher, "Electron-Impact Ionization in the Iron Isonuclear Sequence," *Phys. Rev. A* **34**, 3668-75 (1986).
22. M. S. Pindzola and D. C. Griffin, "Double-Auger Processes in the Electron-Impact Ionization of Lithium-Like Ions," *Phys. Rev. A* **36**, 2628-32 (1987).

23. M. S. Pindzola, D. C. Griffin, and C. Bottcher, "Theoretical Calculations of Indirect Processes in Electron-Impact Ionization of Atomic Ions," *Comments At. Mol. Phys.*, submitted for publication (1988).

24. D. P. Hutchinson et al., "Feasibility of Alpha Particle Measurement by CO₂ Laser Thomson Scattering," *Rev. Sci. Instrum.* **56**, 1075 (1985).

25. W. F. Krupke and W. R. Sooy, *IEEE J. Quantum Electron.* QE-5, 575 (1969).

26. C. H. Ma and D. P. Hutchinson, "Feasibility Study of Infrared System for Plasma Diagnostics on CIT," *Bull. Am. Phys. Soc.* **31**, 1541 (1986).

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Section 3

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5

PLASMA THEORY AND COMPUTING

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R. A. Dory

C. L. Alejandre ¹	C. E. Gibson	J. F. Lyon ²
S. A. Artman ²	R. C. Goldfinger ³	P. M. Lyster ⁹
S. E. Attenberger ³	D. E. Greenwood ³	J. B. Mankin ³
D. B. Batchelor	J. H. Han ⁹	A. C. Matas ²
C. O. Beasley, Jr.	J. D. Hanson ¹¹	D. L. Million ³
C. D. Beidler ⁴	C. L. Hedrick	R. N. Morris ³
E. T. Blair ³	T. C. Hender ¹²	D. R. Overbey
R. D. Burris ³	H. R. Hicks ³	L. W. Owen ³
H. J. Burum	S. P. Hirshman	J. J. Ramos ¹³
J. D. Callen ⁵	W. N. G. Hitchon ⁵	J. A. Rome
B. A. Carreras	J. T. Hogan	K. C. Shaing
M. D. Carter	J. A. Holmes ³	D. J. Sigmar ¹³
J. R. Cary ⁶	W. A. Houlberg	D. A. Spong
L. A. Charlton ³	H. C. Howe, Jr.	K. A. Stewart ³
P. F. Cole	J. V. Hughes	D. J. Tate
P. L. Colestock ⁷	M. M. Hutchinson	P. W. Terry ⁹
E. C. Crume, Jr. ⁸	E. F. Jaeger	J. S. Tolliver ³
P. F. Diamond ⁹	D. M. Jollay ²	N. A. Uckan ¹⁴
N. Doninguez	K. L. Kannan ³	W. I. van Rij ³
R. H. Fowles ³	J-N. Leboeuf	H. Weitzner ¹⁵
J. M. Friend ³	D. K. Lee ³	M. B. Wright ³
L. Garcia ¹⁰	G. S. Lee	K. G. Young
	V. E. Lynch ³	

-
1. Centro de Investigaciones Energéticas, Medioambientales, y Tecnológicas, Madrid, Spain.
 2. Co-op student, The University of Tennessee, Knoxville.
 3. Computing and Telecommunications Division, Martin Marietta Energy Systems, Inc.
 4. Summer student, University of Wisconsin, Madison.
 5. Consultant, University of Wisconsin, Madison.
 6. Consultant, University of Colorado, Boulder.
 7. Princeton Plasma Physics Laboratory, Princeton, N.J.
 8. Toroidal Confinement Physics Section.
 9. Institute for Fusion Studies, University of Texas, Austin.
 10. Facultad Ciencias Físicas, Universidad Complutense, Madrid, Spain.
 11. Consultant, Auburn University, Auburn, Ala.
 12. Culham Laboratory, Abingdon, England.
 13. Massachusetts Institute of Technology, Cambridge.
 14. Confinement Projects Section.
 15. Consultant, Courant Institute for Mathematical Sciences, New York University, New York.

3. PLASMA THEORY AND COMPUTING

SUMMARY OF ACTIVITIES

The theory and computation program of the Fusion Energy Division is characterized by a close interaction with the experimental program and by a sustained relevance to the national and international fusion programs.

During the past year, while the Advanced Toroidal Facility (ATF) was under construction, numerous theoretical calculations were performed to predict the performance of ATF, to determine optimum operational scenarios, to prepare new data analysis codes, and to benchmark existing codes for stellarator geometry. In particular, the unique flexibility of the ATF configuration was exploited to find ways of modifying the bootstrap current to reduce it to negligible levels or to increase it for easy measurement and study. Careful tuning of the shaping and vertical field coil system can also be used to restore broken flux surfaces that may occur as beta is increased. Electron cyclotron heating (ECH) breakdown of the ATF plasma was modeled to quantify the range of parameters that can be used for effective plasma initiation in ATF. The neutral beam deposition and heating codes were benchmarked against the codes used at Kyoto University for Heliotron-E. Ion cyclotron resonance heating (ICRH) codes have been improved to allow modeling of realistic antenna geometries, propagation of the wave from the antenna, and absorption and coupling of the energy into the plasma.

New low-aspect-ratio compact torsatron configurations were created and studied using an improved version of the three-dimensional spectral equilibrium code, VMEC, as a basis for stellarator reactor evaluations. The designs of the Large Helical System (LHS) device (Toki, Japan) and H-1 heliac (Canberra, Australia) were evaluated.

In the past year, important support was provided for the Compact Ignition Tokamak (CIT) and International Thermonuclear Experimental Reactor (ITER) ignition tokamak studies. These studies include modeling of scenarios of operation and of alpha particle effects and investigations of heating, fueling, and current drive.

A new effort is using particle simulation methods to study the stability and turbulence of plasmas. These techniques are also being applied to study plasmas in the near field of ICRH antennas.

A detailed study of resistive pressure-gradient-driven turbulence saturation phenomena showed that, for ATF parameters, anomalous losses may decrease as the second stability regime is entered.

The adiabatic invariant J^* has been exploited to study the details of single particle orbits in stellarator geometry, especially near the trapping-detraping boundary. Using J^* in the kinetic calculations of transport in the $1/\nu$ regime has extended the regime of validity of these calculations to include finite aspect ratio and helical field

amplitude corrections. The technique is also being used to study the transport of particles out of the divertor stripes in ATF.

Theoretical support for the Joint European Torus (JET) pellet injector team included analysis of the resulting regimes of improved plasma performance.

The computing support group added two VAX 8700 computers to handle the ATF data analysis needs. Networks in the division have been upgraded and expanded. Computer programs were developed to support ATF operations, data acquisition, and data analysis. Computer control systems were developed for the JET pellet injector, the ICRH antenna for the Tokamak Fusion Test Reactor, and several systems for Tore Supra.

In the following sections, technical summaries are provided for the main areas of effort, followed by more detailed discussion in the form of abstracts.

3.1 EQUILIBRIUM, STABILITY, AND TURBULENCE

The long-standing efforts in magnetohydrodynamic (MHD) equilibrium, stability, and turbulence are characterized by the parallel use of analytic and numerical fluid models to study the behavior of magnetically confined plasmas. Equilibria are determined, and their linear and nonlinear stability properties are analyzed. Calculations are also made of nonlinearly evolved fluctuation levels and their consequences for particle and heat transport. Research is carried out on two strongly interconnected levels. First, fundamental physics research is performed, generally in a simplified geometry, to unveil the basic mechanisms that underlie plasma behavior. This work establishes a sound basis for further theoretical development. Theoretical results are then applied to specific devices, providing basic physics understanding and tools for configuration optimization and for plasma modeling.

In the area of MHD equilibrium theory, improvements in calculation techniques continued to provide efficient computations and a better physics understanding. The ORNL three-dimensional (3-D) spectral code VMEC, with the incorporation of the 3-D Mercier and resistive instability criteria, continues to be one of the most efficient tools for equilibrium studies in 3-D configurations. Applications were mainly oriented toward confinement optimization. The development of compact torsatrons, with an aspect ratio about half that of the Advanced Toroidal Facility (ATF), continued; these configurations are used as the basis for stellarator reactor evaluations (Fig. 3.1). The basic configurations considered in the design studies for the Large Helical System (LHS), proposed for construction at Toki, Japan, were evaluated at ORNL, as were those for the H-1 heliac to be built at Canberra, Australia. These collaborative efforts complemented the scoping studies done at ORNL for potential next-generation stellarator experiments.

In the area of linear stability theory, work continued in extending the resistive MHD theory to the long mean-free-path regime. The fully toroidal implicit code

Fig. 3.1. Magnetic flux surfaces at the beginning of and halfway through a field period for a sequence of compact torsatron configurations.

that incorporates the neoclassical MHD equations derived by Shaing and Callen was used to study the transition from the resistive MHD regime to the long mean-free-path regime (Fig. 3.2).

In the area of nonlinear stability theory and turbulence, continued study of resistive pressure-gradient-driven turbulence saturation phenomena supported last year's work, which showed that fluctuation levels obtained in the numerical calculations could be explained by an enhancement factor. The numerical calculations were carried out to a high degree of resolution, which permitted the separation of an inertial range from the dissipative range. In this way, it was possible to compare the numerical results with analytic results for the spectra from two-point theory. The agreement, as shown in Fig. 3.3, is excellent. The resistive pressure-gradient-driven diffusivity was calculated for ATF-like parameters; the characteristic self-stabilization effect appears as a reduction of the anomalous losses with increasing beta (Fig. 3.4). Access to the second stability regime in ATF will manifest itself as a regime of improved transport. Nonlinear stability studies of the $m = 1$ instability continued. As found last year, the resistive instability is considerably reduced with decreasing aspect ratio and can be totally stabilized for some q profiles, even with $q(0) < 1$. The nonlinear evolution of the $m = 1$ instability for these q profiles has been studied in detail (Fig. 3.5) for a variety of aspect ratios and plasma cross sections.

A new effort this year is extension of the basic MHD fluid model using fluid equations for the ions and treating the electrons as particles. This approach offers

ORNL-DWG 88C-3032 FED

Fig. 3.2. Linear growth of an $n = 6$ pressure-driven instability vs electron viscosity with and without compressibility.

ORNL-DWG 88-2613RFED

Fig. 3.3. Wave number spectrum $\langle \tilde{p}^2 \rangle_m$ as a function of the poloidal mode number m . The solid line is the theoretical prediction.

Fig. 3.4. Anomalous diffusivity D , influenced by the pressure-gradient-driven turbulence in ATF. The level is reduced with increasing beta and becomes zero when the second stability regime is accessed.

Fig. 3.5. Magnetic field line plots of nonlinear evolution of an internal kink at four different times for a case with a hollow q profile.

a simpler alternative to gyrokinetics. Both analytic and numerical particle models have been developed; the judicious combination of the fluid and kinetic approaches will make tractable problems that were previously inaccessible with either method alone.

The development of particle methods and their application to magnetically confined plasmas are being pursued on several fronts. The goals are to compare the computer calculations with existing theories—linear and nonlinear, fluid and kinetic—and to gain insight from these kinetic calculations, particularly in the nonlinear stage, that will advance the theory.

Conventional particle codes, in which both species are treated kinetically and which respond self-consistently to the field that they induce and to externally imposed fields, continue to be applied to linear and nonlinear studies of low-frequency plasma instabilities. A guiding center description is used for the electrons; this means that their parallel dynamics are followed exactly but their perpendicular motion is governed by the $\mathbf{E} \times \mathbf{B}$ drift to lowest order. The ion dynamics are solved for exactly, in order to retain all finite Larmor radius (FLR) effects. This is done for both zero-beta and finite-beta plasmas. In the finite-beta case, the displacement current is neglected and the electromagnetic fields are solved for in the Darwin or magnetoinductive approximation.

We are applying these techniques to such phenomena as density- and/or temperature-gradient-driven drift waves and resistive interchange modes. An interesting result from nonlinear calculations for the slab branch of the ion temperature-gradient-driven drift waves is that fluctuations with high radial mode number are more unstable than those with low radial mode number. Such fluctuations persist in the saturated state. A nonlinear, fast-interchange mode instability calculation is shown in Fig. 3.6.

3.1.1 MHD Equilibrium and Stability—Abstracts

3.1.1.1 "Three-Dimensional MHD Calculations"¹

B. A. Carreras

The study of MHD equilibria in stellarator configurations is greatly complicated by the fully 3-D nature of the configurations. In general, the existence or uniqueness of solutions cannot be proved and numerical methods have to be used to find solutions to these types of problems. Most of the numerical approaches use a variational technique to solve for the equilibria. One approach is to solve the so-called inverse equilibrium problem [H. R. Hicks, R. A. Dory, and J. A. Holmes, *Comput. Phys. Rep.* 1, 373 (1984)], in which the problem is reformulated into that of solving for the flux coordinates, instead of solving directly for the magnetic fields and pressure. An alternative approach [T. C. Hender et al., *J. Comput. Phys.* 60, 76 (1985)] is to solve the equilibrium equation by minimizing the energy on a Eulerian grid. The first approach has the advantages of conserving flux exactly and being capable of high accuracy in calculating zero-current equilibria. It is a suitable

Fig. 3.6. Example of fast interchange instability. (a) Potential eigenmode structure. (b) The electron $\vec{E} \times \vec{B}$ response to the eigenmode.

approach to be extended to stability calculations. The second approach permits the consideration of magnetic topology changes and magnetic island formation. Both ways of calculating the 3-D equilibria offer complementary views of the plasma beta limit.

For some configurations, the finite-beta effects are dominantly two-dimensional (2-D). In this case, semi-analytic approaches can also be used to solve the equilibrium problem, and they give a more intuitive physics picture [J. M. Greene and J. L. Johnson, *Phys. Fluids* 4, 875 (1961)]. That is the situation for planar-axis toratrons, like the ATF device [J. F. Lyon et al., *Fusion Technol.* 10, 179 (1986)] under construction at ORNL. However, configurations like the H-1 heliac (S. Hamberger et

al., in *Proceedings of the 6th International Stellarator/Heliotron Workshop*, PPLK-005, Kyoto University, Kyoto, Japan, 1986) being built at the Australian National University in Canberra are intrinsically 3-D. In this case the plasma beta limit is probably caused by magnetic surface breaking. This type of experiment, apart from testing a new interesting configuration, can provide important information on the basic 3-D MHD equilibrium problem.

3.1.1.2 "MHD Stability of Tokamaks with Low Shear at the $q = 1$ Surface"²

B. A. Carreras, J. A. Holmes, L. A. Charlton, and V. E. Lynch

In toroidal geometry, and for single-valued q profiles with the $q = 1$ surface in the plasma, the tokamak $m = 1$ resistive kink mode can be stabilized when the shear at the $q = 1$ surface is reduced, if the aspect ratio of the plasma is low enough. Before reaching marginal stability, the $m = 1$ instability can change character, and it becomes a tearing mode. This fact can be clearly established by the change of the eigenfunction and the scaling of the growth rate with S . The changes of the stability properties are not limited to the linear stability. Nonlinearly, the instability evolves in different ways depending on the aspect ratio and shear at the $q = 1$ surface. The final state of the nonlinear evolution can be either axisymmetric, through a Kadomtsev reconnection, or helical, with a $1/1$ saturated magnetic island.

3.1.1.3 "The Effects of Compressibility on Full Nonlinear Resistive MHD Tokamak Calculations in Toroidal Geometry"³

L. A. Charlton, B. A. Carreras, J. A. Holmes, and V. E. Lynch

A study is under way to test the effects of compressibility since many recent nonlinear MHD calculations have used incompressible equations ($\nabla \cdot \mathbf{v} = 0$) in order to simplify the complex nature of the numerical problem. As previously reported, for all cases investigated (which were predominantly $m/n = 1/1$ modes) compressibility effects were small at low beta for linear calculations. In the present study we consider the effects of compressibility for the full nonlinear case and also for modes which are not predominantly $m/n = 1/1$. Results will be reported.

3.1.1.4 "Fully Toroidal MHD Nonlinear Studies of the $m = 1$ Fast Sawtooth Crash"⁴

L. A. Charlton, B. A. Carreras, J. A. Holmes, V. E. Lynch, R. J. Hastie,* and T. C. Hender

Recent experimental results on both the Tokamak Fusion Test Reactor (TFTR) (H. Yamada et al., PPPL-2213, Princeton Plasma Physics Laboratory, Princeton, N.J., 1985) and the Joint European Torus (JET) [A. W. Edwards et al.,

Phys. Rev. Lett. 57, 210 (1986)] at low beta have shown sawtooth drops which take place on a very rapid time scale. These sawtooth drops occur in two steps. The first step is a shift of the hot central region of the plasma helically outward, and the second is a thermal decay of this hot region to form a relatively flat temperature profile at the end of the sawtooth drop. The rapid time scale is inconsistent with the Kadomtsev reconnection model, which involves a resistive MHD mode, and the low beta precludes an ideal MHD mode generated with conventional monotonic profiles being responsible, since these modes are stable at low beta. Wesson, however, has pointed out [J. A. Wesson, *Plasma Phys. Controlled Fusion* 28, 243 (1986)] that certain types of nonconventional safety factor (q) profiles can destabilize ideal $m = 1$ modes at low beta and can cause the initial shift of the plasma interior. In addition, these profiles give a very sharp stability boundary which is necessary to explain the required fast-time-scale "trigger" needed to excite these precursorless modes. Fully toroidal resistive MHD nonlinear calculations have been done using two of these nonconventional profiles: (1) a flat profile where q is very close to unity across the entire central region of the plasma and (2) a hollow profile with the safety factor value at the magnetic axis being greater than that just outside the plasma interior. Both types of profiles evolve nonlinearly on about the right time scales to be responsible for the initial shift seen during the sawtooth drops. The hollow profiles give a range of time scales close to the experimental values. The flat profiles, on the other hand, give scales at the upper end of those observed experimentally. Results of these studies will be presented.

*Culham Laboratory, Abingdon, Oxfordshire, U.K.

3.1.1.5 "3-D Stability of Low- n MHD Modes"⁵

N. Dominguez, B. A. Carreras, and V. E. Lynch

Full 3-D stability calculations have been carried out for several 3-D configurations (e.g., ATF) using a minimization of the potential energy and different codes [F. Bauer, O. Betancourt, and P. Garabedian, *Magnetohydrodynamic Equilibrium and Stability of Stellarators*, Springer-Verlag, New York, 1984; R. Chodura and A. Schluter, *J. Comput. Phys.* 41, 68 (1981); U. Schwenn, *Europhys. Conf. Abstr.* 10D, 149 (1986)]. Here the stability of low- n MHD perturbations is studied numerically for 3-D configurations using the equilibrium code VMEC [S. P. Hirshman, W. I. van Rij, and P. Merkel, *Comput. Phys. Commun.* 43, 143 (1986)]. A direct second minimization scheme as was used by Schwenn is followed. We include low- n modes in the calculation which do not have the equilibrium symmetry and are resonant at certain rational surfaces. The final configurations are unstable if they have a potential energy less than that of the equilibrium. Stability analysis will be presented for fixed boundary equilibria of several configurations.

3.1.1.6 "Ideal Mercier Stability in 3-Dimensions"⁶

N. Dominguez, B. A. Carreras, V. E. Lynch, and S. P. Hirshman

A 3-D evaluation of the Mercier criterion has been added to the equilibrium code VMEC developed at ORNL. The Mercier criterion for stability for a full 3-D geometry can be written as:

$$D_S + D_W + D_I + D_{P-S} > 0 .$$

Here the four terms are the shear, magnetic well, net current, and Pfirsch-Schlüter current contributions, respectively. To evaluate the Mercier criterion, we have used as input the VMEC equilibrium results, and detailed convergence studies have been performed. The 3-D equilibrium and Mercier criterion will be presented for Heliotron-E, ATF, and the $M = 3$ configurations being studied as reference designs for the Australian heliac H-1. The dominant contributions in the Mercier criterion arise from different terms for the different configurations. For Heliotron-E, the dominant stabilizing contribution comes from the shear, while for the ATF, the combination of the well and the shear is stabilizing. For heliac configurations, only the well and the Pfirsch-Schlüter terms are important. For the heliac configurations studied, the last term was the dominant one, and large destabilizing contributions arise near the low-order resonant surfaces.

3.1.1.7 "Free-Boundary Helias Stellarator Equilibria"⁷

S. P. Hirshman and P. Merkel*

The NEMEC 3-D free-boundary MHD equilibrium code is applied to the Helias stellarator configuration. The earlier parameter studies of the Helias class of stellarators, based on the computation of 3-D fixed-boundary equilibria which are stable according to the resistive interchange criterion, yielded $\langle \beta \rangle$ values of up to 0.09.

A method has been developed to construct external currents producing the Helias vacuum field so that the NEMEC free-boundary code can be applied to the Helias configuration.

Preliminary results show a beta-dependent outward shift of $\Delta R/R \approx 0.13\langle \beta \rangle$. The outward shift can be compensated with a vertical magnetic field $B_z/B_0 \approx 0.2\langle \beta \rangle$ (B_0 is the toroidal field).

*Max-Planck-Institut für Plasmaphysik, Garching, Federal Republic of Germany.

3.1.1.8 "MHD Stability and Evolution for Very Low Shear and Hollow Safety Factor Profiles in Toroidal Geometry"⁸

J. A. Holmes, B. A. Carreras, L. A. Charlton, and V. E. Lynch

The MHD stability and evolution of the ideal internal kink are studied in toroidal geometry for safety factor profiles which are slightly hollow with $q_{\min} \gtrsim 1$ and which have very low shear. For such profiles very slight changes in q or beta or moderate changes in plasma cross-section shape can have significant impact. Previous calculations show that the internal kink is unstable for hollow safety factor profiles, even at $\beta = 0$, and for low shear profiles with $q \approx 1$ and $\beta > 0$. The nonlinear evolution involves substantial helical shifting and crescent shaping of the plasma center on the ideal time scale resulting in a saturated state of 1/1 dominated helicity. The saturation mechanism is an increase in the field line bending. By combining the features of low shear and hollow q profiles, present calculations lead to evolution times of $10^3 \tau_{HP}$, and axis shifts of 20% minor radius can be obtained for changes in q of 3×10^{-3} from marginal stability. These results suggest an excellent candidate for the fast sawtooth observed in large tokamaks.

3.1.1.9 "Nonlinear Evolution of the Internal Kink Mode in Toroidal Geometry for Shaped Tokamak Plasmas"⁹

J. A. Holmes, B. A. Carreras, L. A. Charlton, V. E. Lynch, R. J. Hastie,* and T. C. Hender

The nonlinear evolution of the internal kink mode is studied in toroidal geometry for noncircular cross-section tokamak plasmas. The study is focused on very low shear and hollow q profiles with $q(\rho) \geq 1$ for which the internal kink is unstable, in the latter case even at $\beta = 0$. The nonlinear evolution is dominated by ideal MHD, and the instability saturates, giving a quasi-helical shift to the magnetic axis. The nonlinear saturation is caused by increased field line bending. Time scales of $10^3 \tau_{HP}$ and axis shifts of 20% are reached when changes in q on the order of 3×10^{-3} from the marginal profile are produced.

*Culham Laboratory, Abingdon, Oxfordshire, U.K.

3.1.1.10 *Nonlinear Dynamics of Tearing Modes in the Reversed Field Pinch*¹⁰

J. A. Holmes, B. A. Carreras, P. H. Diamond, and V. E. Lynch

The results of investigations of nonlinear tearing-mode dynamics in reversed-field pinch (RFP) plasmas are described. The linear instabilities have poloidal mode number $m = 1$ and toroidal mode numbers $10 \lesssim n \lesssim 20$, and the resonant surfaces are therefore in the plasma core. The nonlinear dynamics result in dual cascade processes. The first process is a rapid $m = 1$ spectral broadening toward high

n , with a simultaneous spreading of magnetic turbulence radially outward toward the field-reversal surface. Global $m = 0$ perturbations, which are driven to large amplitudes by the $m = 1$ instabilities, in turn trigger the $m = 1$ spectral broadening by back-coupling to the higher n . The second process is a cascade toward large m and is mediated by $m = 2$ modes. The $m = 2$ perturbations have the structure of localized driven current sheets and nonlinearly stabilize the $m = 1$ modes by transferring $m = 1$ energy to small-scale dissipation. The calculated spectrum has many of the qualitative features observed in experiments.

3.1.1.11 "Correlation of MHD Stability With Mean-Field Safety Factor"¹¹

Y.-K. M. Peng,* D. J. Strickler,[†] and J. T. Hogan

The influence of plasma shaping and safety factor on MHD β_{crit} is one of the design issues for the International Thermonuclear Experimental Reactor (ITER). Assessment of this question is complicated by separatrix-induced singularity in elongated plasmas. We propose a mean-field safety factor, based on the flux-surface averaged poloidal magnetic field, $\bar{q} = RB_T/2\pi\bar{B}_p \int dl/R^2$, where $\bar{B}_p = \int dl B_p / \int dl$. Equilibrium calculations exhibit the expected reduction in $\bar{q}$ near the edge for separatrix-bounded cases, and we examined the functional dependence $I_p(\kappa, \delta, \bar{q})$. We found that $\bar{q}$ is useful for characterizing ideal MHD stability, since the definition emphasizes total plasma current. We studied ballooning and PEST ($n = 1, 2, 3$) stability for Engineering Test Reactor (ETR) cases to establish the dependence $C_{\text{Troyon}}(\kappa, \delta, \bar{q})$.

*Fusion Engineering Design Center.

[†]Computing and Telecommunications Division, Martin Marietta Energy Systems, Inc.

3.1.1.12 "Numerical Studies of Neoclassical MHD Pressure Gradient Driven Instabilities"¹²

D. A. Spong, K. C. Shaing, and J. D. Callen

Neoclassical MHD models of tokamak behavior are of importance in understanding the experimentally relevant banana-plateau regime in which the Coulomb collision mean free path λ exceeds the magnetic connection length $R_0 q$. In this regime a new type of pressure-gradient-driven mode is possible which scales in a similar way as resistive- g and ballooning modes but is driven by expansion free energy from the viscous damping terms. A numerical code (NEOMHD) has been developed (based on the FAR code) which calculates the linear time evolution of the four-field coupled equations for flux, vorticity, density, and parallel velocity in toroidal geometry with large-aspect-ratio tokamak ordering. The new dissipative terms of neoclassical MHD involving rotation damping, bootstrap currents, and the

Ware pinch are included, as well as diamagnetic drift and compressibility corrections. The mode structure of this instability and scaling of its growth rate and real frequency will be presented over a range of parameters and compared with analytic calculations.

3.1.2 MHD Turbulence—Abstracts

3.1.2.1 "On Mixing Length Theory and Saturated Turbulence"¹³

P. H. Diamond and B. A. Carreras

Conventional methods for estimating turbulent transport are discussed in the light of recent investigations. Some of the pitfalls inherent in such methods are identified, and possible means for improvement are suggested.

3.1.2.2 "Ion Pressure Gradient Driven Turbulence"¹⁴

J. N. Leboeuf, B. A. Carreras, P. H. Diamond, and G. S. Lee

The ion-pressure-gradient-driven turbulence evolved from linear η_i modes is thought to be responsible for the observed anomalous ion heat loss in tokamaks. A "five-field" fluid model including parallel ion velocity evolution is derived to describe the linear and nonlinear development of η_i modes. The 3-D nonlinear initial value code KITE has been modified to include ion diamagnetic, ion polarization, FLR, and parallel ion viscosity and conductivity effects appropriate for the η_i modes. Comparison between linear kinetic theory, linear fluid theory, and linear initial value calculations with the new code KITI is made. Nonlinear calculations which serve to determine the saturation mechanism, the nonlinear mode widths, and saturation spectra will be reported.

3.1.2.3 "Frequency Spectrum of Resistivity-Gradient-Driven Turbulence Due to Sheared Radial Electric Field"¹⁵

G. S. Lee, B. A. Carreras, and P. H. Diamond

In order to explain the origin of experimentally observed frequency and wave number spectra of turbulent fluctuations in the tokamak edge, the previously studied resistivity-gradient-driven turbulence model is extended to include the frequency Doppler shift effect on the basic mode due to a sheared radial electric field. The computational studies have been carried out with the 3-D nonlinear resistive MHD code KITE. The results indicate that the frequency and wave number spectra of turbulent fluctuations are in fair agreement with experimentally deduced spectra. We will discuss the shear flow driven effects (Kelvin-Helmholtz) on resistivity-gradient-driven turbulence for experimentally relevant regimes.

3.1.2.4 "Study of Resistive Pressure-Gradient-Driven Turbulence with Temperature Evolution"¹⁶

G. S. Lee, B. A. Carreras, and P. H. Diamond

The simplest model of resistive pressure-gradient-driven turbulence involves only pressure and electric field (flow) fluctuations. Analytical and numerical studies of steady-state turbulence for this model have been reported [B. A. Carreras, L. Garcia, and P. H. Diamond, *Phys. Fluids* 30, 1388 (1987)]. The main result of the previous studies is that an enhancement factor exists over the mixing length result, which weakly depends on the dissipation.

In going beyond the electrostatic model and incorporating the effect of magnetic fluctuations on electron thermal transport, it is necessary to consider an electromagnetic model with independent evolution of the density and electron temperature fluctuations. Analytical theory of this model electromagnetic turbulence is proposed and a numerical calculation is performed using the 3-D nonlinear initial value code KITE. The analytical predictions and numerically calculated results will be presented. Comparison with previous studies will also be discussed.

3.1.2.5 "Inter-Relations Between Scale Invariance and Mixing Length Theory Based on g and Rippling Mode Turbulent Transports"¹⁷

M. Yagi,* M. Wakatani,[†] and K. C. Shaing

When the transport coefficient based on the mixing length theory, D^M , does not include a poloidal mode number, m , it is exactly the same as the scale invariance result, D^S . For the g -mode turbulence in stellarators, D^M and D^S corresponding to the convective and the collisionless stochastic transport coincide with each other. For the rippling mode turbulence in tokamaks, D^M includes m and disagrees with D^S as well as the collisional stochastic transport in the g -mode case. However, by taking account of the scale transformation for the poloidal mode number into the expression of D^M , the coincidence is recovered. It is examined how the bootstrap current produced by the electrostatic turbulence changes the transport in the g -mode case. A possibility is pointed out that the Kolmogorov spectrum appears in the g -mode and the rippling mode turbulence.

*Nuclear Engineering Department, Faculty of Engineering, Kyoto University, Kyoto, Japan.

[†]Plasma Physics Laboratory, Kyoto University, Gokasho, Uji, Japan.

3.1.3 Particle Simulation Methods—Abstracts

3.1.3.1 "A Hybrid Vlasov-Fluid Model of Kinetic Ions and Massless Fluid Electrons"¹⁸

F. Kazeminejad,* R. Sydora,* J. M. Dawson,* J.-N. Leboeuf, and F. Brunel†

We have developed 2-D and 3-D computer models with kinetic ions and massless fluid electrons. We have also developed the analytic aspect of the linear theory of the model; we are able to eliminate the electric field from the analysis and obtain a Vlasov model involving only the ions and the perturbed B field. From this we obtain the linear dispersion relation for arbitrary angles of propagation. The model exhibits such important effects, such as ion Bernstein waves (IBW's), ion cyclotron waves, low-frequency whistler waves, Alfvén waves, and magnetosonic waves. The model shows excellent agreement with the analytic dispersion relation. The model has thus far been used to study the microinstabilities analogous to the ones which can arise in neutral beam heating of a plasma, i.e., the ion ring in velocity-space instabilities. The growth rates of the various modes propagating at right angles to the external magnetic field have been measured and thus the most unstable modes have been found; nonlinear saturation effects are investigated.

*University of California, Los Angeles.

†National Research Council Division of Physics, Ottawa, Canada.

3.1.3.2 "Ion Temperature Gradient Driven Drift Waves: Particle Simulation and Theory"¹⁹

J.-N. Leboeuf, G. S. Lee, D. R. Thayer,* and P. H. Diamond

The ion temperature gradient driven drift wave in a sheared magnetic field is analyzed using particle simulation of full dynamic ions and adiabatic electrons in slab geometry with a temperature and density gradient [J. N. Leboeuf et al., *Bull. Am. Phys. Soc.* **31**, 1403 (1986)]. Simulation results for the linear frequencies and growth rates are compared with a shooting code result. The higher radial mode harmonics are fundamental to our theoretical description of the ion temperature gradient driven drift waves (P. W. Terry et al., presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, April 6–8, 1987). Scalings of the nonlinear saturation of electrostatic fluctuations with η and L_S/L_T are presented. It is found that large modifications of the temperature profiles are prevalent for most of our simulations. Therefore, we compare the saturation

levels from our particle simulation with a quasilinear plateau theory calculation [J. N. Leboeuf et al., *Phys. Fluids* **29**, 4147 (1986)].

*Institute for Fusion Studies, University of Texas, Austin

3.1.3.3 "Particle-Fluid Model of Low Frequency Plasma Instabilities"²⁰

P. M. Lyster, P. H. Diamond, J-N. Leboeuf, G. S. Lee, and B. A. Carreras

A hybrid-model computer code for the study of plasma instabilities is being developed. The ion component is treated as a fluid in the low-frequency regime where $\mathbf{E} \times \mathbf{B}$ and polarization drifts are important. Also, the parallel ion momentum and the ion temperature equations are retained. The electrons are treated as macroparticles; the perpendicular velocity is given by the $\mathbf{E} \times \mathbf{B}$ drift while the parallel motion is followed exactly. The electrostatic potential is obtained by imposing quasineutrality. Electron kinetic effects on fluidlike modes such as the ion temperature-gradient-driven instability or the resistive interchange instability can thus be studied.

3.1.3.4 "A Fluid-Particle Simulation Model for Plasma Instabilities"²¹

P. M. Lyster and J-N. Leboeuf

Fluid-particle simulation models, often referred to as "hybrid codes," have been used for a number of years to study low-frequency plasma phenomena. In a typical model, the ions are represented by macroparticles, while the electrons are described by fluid equations. This approach uses the low noise associated with a fluid simulation while retaining the kinetic contributions of the ions. When quasineutrality is imposed and the transverse displacement current is neglected, the simulation timestep and the spatial scales are not limited by the usual inverse plasma frequency and the Debye length, respectively.

We are developing a new hybrid model for simulating plasma instabilities of characteristic frequency less than the ion cyclotron frequency. The main motivation is to study fluidlike modes such as ion temperature-gradient-driven turbulence; this may be an important mode in high-temperature fusion devices. The ions are modeled in the fluid drift approximation; the perpendicular ion velocity is given by

$$\mathbf{v}_{\perp i} = \mathbf{v}_{Di} + \mathbf{v}_p ,$$

where

$$\mathbf{v}_{Di} = \left(\frac{c}{B} \hat{\mathbf{b}} \times \nabla \phi \right) + \left(\frac{c}{eBn_i} \hat{\mathbf{b}} \times \nabla P_i \right) ,$$

with the terms on the right-hand side corresponding to the $\mathbf{E} \times \mathbf{B}$ and magnetization drifts, respectively, and

$$\mathbf{v}_p = -\frac{c}{B\Omega} (\partial_t + \mathbf{v}_{Di} \cdot \nabla) \nabla_{\perp} \phi$$

is the polarization drift. Here ϕ is the electrostatic potential, B is the magnetic field strength, n_i and P_i are the ion density and pressure, $\Omega = eB/m_i c$ with m_i the ion mass, and

$$\hat{\mathbf{b}} = \mathbf{B}/B.$$

An equation for the electrostatic potential can be found by imposing quasineutrality. This gives

$$\rho_S^2 (\partial_t + \mathbf{v}_{Di} \cdot \nabla) \nabla_{\perp}^2 \left(\frac{e\phi}{T_e} \right) = \nabla_{\parallel} (v_{\parallel i} - v_{\parallel e}), \quad (3.1)$$

where $\rho_S = c_S/\Omega$, $c_S = \sqrt{T_e/m_i}$, T_e is the electron temperature, and the terms on the right-hand side are the parallel ion and electron velocities, respectively. The ion description is completed by using simplified versions of the fluid equations for the parallel ion velocity and temperature,

$$m_i n_i (\partial_t + \mathbf{v}_E \cdot \nabla) v_{\parallel i} = -en_i \nabla_{\parallel} \phi - \nabla_{\parallel} P_i, \quad (3.2)$$

$$n_i (\partial_t + \mathbf{v}_E \cdot \nabla) T_i + \frac{2}{3} n_i T_i \nabla \cdot \mathbf{v}_i = 0, \quad (3.3)$$

where

$$\mathbf{v}_E = \frac{c}{B} \hat{\mathbf{b}} \times \nabla \phi.$$

The electrons are treated as macroparticles. The parallel dynamics are followed exactly while the motion perpendicular to the magnetic field is given by the $\mathbf{E} \times \mathbf{B}$ drift velocity,

$$\begin{aligned} \mathbf{v}_{\perp k} &= \frac{c}{B} \hat{\mathbf{b}} \times \nabla \phi(\mathbf{x}_k), \\ m_{ek} \frac{d}{dt} \mathbf{v}_{\parallel k} &= e \nabla_{\parallel} \phi, \\ \frac{d}{dt} \mathbf{x}_k &= \mathbf{v}_{\perp k} + \mathbf{v}_{\parallel k}, \end{aligned} \quad (3.4)$$

where the subscript k refers to individual particles. The electron parallel velocity that is needed in Eq. (3.1) and the density in Eqs. (3.2) and (3.3) are evaluated using standard particle-grid interpolation schemes. Equations (3.1)–(3.4) constitute the basis for the hybrid scheme.

At present a linear one-dimensional (1-D) code has been implemented. A uniform constant magnetic field is imposed nearly perpendicular to the direction of spatial variation. With a time step equal to 20 times the inverse plasma frequency and with no sources or sinks of energy, the algorithm conserves energy up to 8000 time steps. The ion sound wave dispersion relation has also been verified. We are now working on a 2-D version of the code. This will include the advection

terms in Eqs. (3.1)–(3.4) and the driving terms that are responsible for drift wave instabilities.

3.1.3.5 "Simulation of the Kelvin-Helmholtz Instability with Electrostatic Implicit Particle Code"²²

J. Schutkeker,* T. Tajima,* W. Horton,* T. Kamimura,[†] D. Barnes,[‡] and J. Leboeuf

A fully implicit, 2-D, Cartesian, electrostatic particle simulation with conducting boundaries in the x -direction and periodic boundaries in the y -direction has been employed to study the low-frequency Kelvin-Helmholtz (KH) instability in a magnetized plasma. An overview of the algorithm and capabilities of the simulation code are given along with a discussion of the numerical damping effects inherent in the implicit algorithm. An electric field that drives a sheared $\mathbf{E} \times \mathbf{B}$ flow of particles has been imposed on the simulation, and the evolution of the KH instability is observed in the MHD time scale regime where the ion polarization drift is important and the growth rates are much slower than the ion cyclotron frequency ($\gamma \ll \omega_{ci}$). Realistic mass ratios (M_i/m_e) are used, and the duration of a typical simulation is about 2500 ion cyclotron periods.

The KH instability progresses from the formation of vortices at the fluid shear layer through the coalescence of those vortices until finally a single large vortex is observed that fills the space of the system and oscillates in time with a very low frequency. A simple theoretical treatment of the instability is presented in which a linearized Orr-Sommerfeld equation with conducting boundaries at infinity is solved analytically in the inviscid limit. The equation's eigenvalues identify frequencies that show a positive growth rate, and its eigenfunctions describe the structure of the electrostatic potential in space. A more exact, but numerical, solution of the Orr-Sommerfeld equation, for the more accurate case of a system with a finite length, is performed by discretizing the Orr-Sommerfeld equation and numerically solving the resulting eigenvalue problem, which has the matrix form, $\mathbf{A}\mathbf{X} = \lambda\mathbf{B}\mathbf{X}$.

The final analytical aspect of the treatment is to describe the structure of the small-scale KH vortices by assuming a polar structure of the electrostatic potential within the shear layer and matching the potential values at the shear layer to the Cartesian structure of the sheared potential that exists outside the polar core. The structure of the vortices predicted by theory agrees well with the simulation results. However, the analytical theory predicts a critical value of $k_y a$ (a product of y -direction wave number and width of shear layer) above which no instability should grow, but the simulation shows growth for all wave numbers. A possible explanation for the discrepancy is considered, specifically, that the KH instability does not undergo a linear stage, but is a strictly nonlinear instability, including ballistic modes and negative energy modes. Finally, an assumption pivotal to the development of the analytic theory of the vortex structure, that the vorticity scales

linearly with the potential, is shown to hold true by measuring the appropriate values generated by the simulation code.

*Institute for Fusion Studies, University of Texas, Austin.

†Institute of Plasma Physics, Nagoya University, Nagoya, Japan.

‡Science Applications International Corporation, Austin.

3.2 TRANSPORT AND KINETIC THEORY

During 1987, various new initiatives in the area of transport theory for toroidal devices were pursued. Some of these, as in past years, deal primarily with transport in nonsymmetric devices (typified by applications to ATF). In addition, previously developed techniques for treating complex 3-D geometries were successfully applied to tokamak quasilinear transport problems, yielding a more complete theory of fluctuation-driven transport. A direct application of this effort was found in the study of the transition from L-mode to H-mode operation in tokamaks; the observed improvement in confinement is attributed to the multiplicity of stable roots for the radial electric field. The analogy with the role of the electric field in stellarator transport proved useful for studying this current topic of interest for tokamaks.

The theoretical and numerical evaluation of the bootstrap current for stellarator devices continued to receive attention. This work culminated in an analytic formula for the bootstrap current in the low-collision-frequency regime for stellarators; results from the formula compared favorably with numerical calculations.

The DKES code, developed over the last few years for studying transport in general, magnetically complex toroidal devices, was applied to a device with ATF-like parameters and yielded a new and encouraging scaling law for transport in the low-collision-frequency regime. The dependence of the thermal conductivity on the helical field amplitude was computed to be weaker than that estimated earlier. This bodes well for device designs for which MHD equilibrium considerations require finite helical effects. However, extensions of this scaling law into reactor-relevant regimes of lower aspect ratios and smaller toroidal mode numbers remain to be made.

In the course of applying DKES to these and other problems (such as transport-optimized helias configurations, a study undertaken jointly with our colleagues at the Max-Planck-Institut für Plasmaphysik, Garching, Federal Republic of Germany), it became apparent that the minimax nature of DKES did not lend itself to the detailed convergence studies that were necessary to obtain accurate transport coefficients in complex geometries. "Intuitive" insight, as well as straightforward mathematical reasoning, was required to obtain adequate convergence sequences in many cases of interest. To alleviate this situation, a new form of DKES is under development; it yields monotonically convergent bounds on each of the transport

coefficients. These upper and lower bounds are guaranteed to improve as the number of trial functions is increased. This property can be exploited to find a path through the complicated space of Fourier-Legendre mode numbers along which the bounds' convergence is optimized.

The theory of single particle orbits in complex magnetic fields has been advanced by a detailed study of the trapping-detrapping boundaries implied by the constancy of the adiabatic invariant J^* . In addition to orbit effects, the introduction of J^* in the theory of multiple-harmonic transport in the collisional ($1/\nu$) regime has been extended to include finite aspect ratio and helical field amplitude corrections. Because of the strong dependence on the major radius and helical field amplitude appearing in the particle drifts, even moderate values for the aspect ratio can yield sizable effects on the resulting transport coefficients. This theory has been benchmarked against numerical DKES results and eliminates discrepancies that were thought to exist between the theory for large-aspect-ratio configurations and DKES.

3.2.1 Abstract of "Comparison of Analytic and Numerical Transport Coefficients in the $1/\nu$ Regime for Stellarators and Torsatrons"²³

C. O. Beasley and C. L. Hedrick

Neoclassical transport in the $1/\nu$ regime is of considerable interest for advanced stellarators and torsatrons. Analytic expressions for the transport coefficients have been developed for magnetic fields with multiple helicities [K. C. Shaing and S. A. Hokin, *Phys. Fluids* **28**, 2136 (1983)]. Using the spectral structure of the magnetic field, these expressions can be used to optimize the transport properties of various stellarator designs. Here we benchmark these analytic expressions with numerical results from the DKES code developed at ORNL [S. P. Hirshman et al., *Phys. Fluids* **28**, 2951 (1986)]. Numerical comparison over a broad range of parameters will be given.

3.2.2 Abstract of "Ion Heat Conductivity and Bootstrap Current in Low-Aspect-Ratio Tokamaks"²⁴

C. O. Beasley, Jr., J. T. Hogan, W. I. van Rij, and S. P. Hirshman

Using DKES, the numerical method for solving a drift kinetic equation for tori with arbitrary geometry, we have examined neoclassical transport and bootstrap current in a variety of low-aspect-ratio tokamaks. Using these results, we are able to obtain an empirical expression for both which depends on collisionality, beta, aspect ratio, and a geometry factor (which depends on exact shaping, but otherwise varies only slightly from bean to crescent to D-shaped plasma). In addition, bootstrap current is compared with a recently derived expression derived by Hirshman.

Results are consistent with earlier work, and are applicable to the Spherical Torus Experiment (STX), JET, and the Compact Ignition Tokamak (CIT).

3.2.3 Abstract of "Unified Theory of Ripple Transport in Stellarators"²⁵

C. D. Beidler, W. N. G. Hitchon, W. I. van Rij, S. P. Hirshman, and J. L. Shohet*

The distribution function for ripple-trapped particles has been found in a series form valid for all low collision frequencies, for standard and transport-optimized stellarators. The diffusion coefficient obtained with this distribution function shows excellent agreement with the results of Monte Carlo and Fokker-Planck computer codes, in the cases studied.

*University of Wisconsin, Madison.

3.2.4 Abstract of "Transport Scaling in the Collisionless-Detrapping Regime in Stellarators"²⁶

E. C. Crume, Jr., K. C. Shaing, S. P. Hirshman, and W. I. van Rij

Stellarator transport scalings with electric field, geometry, and collision frequency in the reactor-relevant collisionless-detrapping regime are determined from numerical solutions of the drift kinetic equation. A new geometrical scaling, proportional to $\epsilon_i^{3/2}$ rather than $\epsilon_i \epsilon_h^{1/2}$, is found, where ϵ_i is the inverse aspect ratio and ϵ_h is the helical ripple. With the new scaling, no reduction in energy confinement time is associated with large helical ripple, which provides design flexibility. Integral expressions for the particle and heat fluxes that are useful for transport simulations are given.

3.2.5 Abstract of "Bootstrap Current in Nonaxisymmetric Toroidal Plasmas"²⁷

E. C. Crume, Jr., K. C. Shaing, J. S. Tolliver, S. P. Hirshman, and W. I. van Rij

An analytic expression for the bootstrap current in nonaxisymmetric toroidal plasmas has been given by Shaing and Callen [*Phys. Fluids* **26**, 3315 (1983)]. This expression contains a number of line integrals that are difficult to evaluate numerically; consequently, it is desirable to devise a formula that is easier to use. Such a formula was recently presented [K. C. Shaing, S. P. Hirshman, and J. S. Tolliver, *Phys. Fluids* **29**, 2548 (1986)] but requires a correction that is presented here. We

evaluate the corrected formula for ATF-like stellarator/torsatron configurations and compare the results with those obtained using a numerical solution of the Fokker-Planck equation [S. P. Hirshman et al., *Phys. Fluids* 29, 2951 (1986)] and those obtained in a recent numerical evaluation [T. Ohkawa and M. S. Chu, GA-A18688 (1986)] of the original analytic expression. Very good agreement among the results is obtained, demonstrating that the corrected formula is equivalent to the original analytic expression. We also compare results from the corrected formula and the numerical solution for a systematic variation of the helical and toroidal geometrical parameters and find agreement to within the accuracy of the numerical method.

3.2.6 Abstract of "Comparison of Analytic and Full Guiding Center Behavior at a Trapped-Passing Interface in Stellarators"²⁸

C. L. Hedrick, J. S. Tolliver, and J. R. Cary

The toroidal adiabatic invariant, J^* , provides a good approximation to particle orbits in stellarators except near a boundary between locally passing and ripple-trapped particles. At this boundary incident, locally passing particles can be "transmitted" to become ripple-trapped particles or "reflected" to become passing particles with the opposite sign of the parallel velocity. Here we compare solutions of the full guiding center equations of motion to previously derived analytic expressions for the "transmission" and "reflection" coefficients, and an alternate derivation is given which facilitates extending the analytic formulas. Such extension is desirable when the boundary surface is nearly tangent to a flux surface, and either different orbit topology occurs (high energy), or higher-order corrections become important (modest energy). Numerical comparison of the full guiding center and approximate expressions will be given for ATF.

3.2.7 Abstract of "Transitions from Passing to Trapped in Stellarators and Rippled Tokamaks"²⁹

C. L. Hedrick, J. S. Tolliver, and J. R. Cary

Here we compare numerical and analytic approximations for phenomena which occur at a boundary layer between trapped and passing particles in stellarators and tokamaks with ripple. Previously, the toroidal adiabatic invariant has been shown to give orbits which agree well with solutions to the full guiding center equations of motion for both passing and trapped particles [J. S. Tolliver, C. L. Hedrick, and L. W. Owen, *Bull. Am. Phys. Soc.* 31, 1389 (1986)]. For transitional particles, which sometimes transit a field period and sometimes are trapped in the ripple of a boundary field period, the agreement is also good except at a boundary layer. Here we focus on phenomena in which some incident passing particles are reflected at the boundary layer to become passing particles with the opposite sign of the

parallel velocity, and some particles cross the boundary layer to become trapped. In particular, we compare numerical calculations of the fraction trapped to analytic expressions for the fraction given previously [J. R. Cary, *Bull. Am. Phys. Soc.* **31**, 1388 (1986)].

3.2.8 Abstract of "Bootstrap Current in Toroidal Plasmas"³⁰

K. C. Shaing

Understanding the bootstrap current (I_{BS}) in toroidal systems with low collisionality is important for design of a long-pulse or steady-state device at the ETR stage of the fusion program. The ATF torsatron experiment can determine characteristics of I_{BS} in a toroidal system where it is not masked by ohmic heating currents. This provides a unique opportunity to test the neoclassical physics which is the basis for bootstrap currents in tokamaks and stellarators. Values of I_{BS} are generally lower in stellarators (by as much as a factor of 10), but can be raised to make detection and study more practical. Detailed calculations for ATF have given the dependence of I_{BS} on magnetic field shape parameters and shown that changing vertical field coil currents can change I_{BS} by a factor of about five. The dependence of I_{BS} on plasma density can permit discrimination between bootstrap and neutral beam driven currents. Extensive comparisons have been carried out to validate the analytical theory of bootstrap currents in 3-D configurations and results of numerical treatment of the drift kinetic equation.

3.2.9 Abstract of "The Effects of Electric Field Fluctuations on Bootstrap Current and Resistivity in Toroidal Plasmas"³¹

K. C. Shaing

The effects of electric field fluctuations on bootstrap current and resistivity in toroidal plasmas are studied in the plateau regime. A tokamak is discussed as an example. The bootstrap current density is more sensitive to the fluctuations than the plasma resistivity because the bootstrap current density depends on the poloidal mode number of the fluctuations, while plasma resistivity depends on the parallel wave vector.

3.2.10 Abstract of "Transport Theory for Fluctuating Electric Fields in Toroidal Plasmas"³²

K. C. Shaing

Fluctuating electric fields are ubiquitous in toroidal confinement devices such as tokamaks, stellarators, and RFPs. The inherent helical structures of the fluctuations break the toroidal symmetry of tokamaks and RFPs. From this point of view, the transport properties of toroidal symmetric systems with fluctuating electric fields are similar to those of stellarators. A transport theory for fluctuating electric fields in toroidal plasmas is constructed by using the methods developed for neoclassical stellarator transport theory. Flux-force relationships are derived from the momentum and heat flux balance equations with the emphasis of the symmetry-breaking effect introduced by the helical structures of the fluctuating electric fields. The term that is responsible for the transport is $\tilde{N}\tilde{E}$, where $\tilde{N}$ and $\tilde{E}$ are fluctuating density and electric fields. As an example, transport fluxes that include particle and heat fluxes, parallel current, modification of plasma resistivity, and toroidal momentum confinement time are calculated for the low-frequency fluctuations in the plateau regime. The results show that in tokamaks with modest fluctuating level ($e\tilde{\Phi}/T_e \gtrsim 1\%$) and mode number ($m \sim 10$) electron particle and heat fluxes can be larger than those obtained from neoclassical theory. There are particle and heat pinch fluxes associated with the off-diagonal terms. The bootstrap current induced by the fluctuating electric fields flows in the opposite direction on different sides of the mode rational surface. The toroidal momentum confinement time is reduced from its neoclassical value. The modification on the neoclassical resistivity becomes important if $e\tilde{\Phi}/T_e \gtrsim \epsilon$, the inverse aspect ratio. The qualitative features of the theory are consistent with experimental observations. The results obtained by removing the low-frequency assumption will also be presented.

3.2.11 Abstract of "Energy Transport Equations for Toroidal Plasmas"³³

K. C. Shaing, Y. Nakamura,* and M. Wakatani*

The differences in energy transport equations for tokamaks and stellarators associated with $\Gamma_r E_r$ are discussed, where Γ_r is the radial particle flux and E_r is the radial electric field. The energy exchange quantities are evaluated in terms of poloidal plasma flow, pressure gradient, and E_r . It is found that the radial flux Γ_r in $\Gamma_r E_r$ should be $\Gamma_r = \Gamma_{na}$, the nonaxisymmetric flux, instead of the total particle flux.

*Plasma Physics Laboratory, Kyoto University, Gokasho, Uji, Kyoto, Japan.

3.3 RF HEATING AND CURRENT DRIVE

The work over the last year in rf heating theory has emphasized four main areas: (1) full-wave numerical calculations of ion cyclotron resonance heating (ICRH) and ion cyclotron emission, (2) Fokker-Planck modeling of the plasma response in rf-heated plasmas, (3) ray tracing calculations of electron cyclotron resonance heating (ECRH) and ICRH in stellarators and tokamaks, and (4) the effect of ICRH power on the low-density edge plasma in tokamaks.

Full-wave ICRH calculations in two and three dimensions using the ORION code were extended to treat tokamaks with noncircular flux surfaces and conductive boundaries. Antennas were generalized to arbitrary shapes with divergence-free currents (see Fig. 3.7). A simplified treatment of the IBW as a driven response to the fast wave was incorporated to eliminate arbitrariness in the ad hoc collision model previously used to estimate absorption. A new and improved version of the Harwell matrix inversion package has been obtained and implemented in both the full-wave (ORION) and Fokker-Planck codes for the Cray-2 computer. This package, combined with dynamic memory allocation techniques, has improved computational efficiency by over a factor of two and will permit the solution of much larger problems than were previously convenient. With this improved code,

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Fig. 3.7. Typical calculation of E_y for JET with a recessed antenna. The rectangle outlined in (a) is enlarged in (b) and (c) to show calculations at very high resolution for an antenna (b) without and (c) with a Faraday shield consisting of discrete conducting bars.

modeling calculations were carried out for TFTR; these included modeling of the double current strap antenna with arbitrary phasing between the straps. Similar calculations allowed comparison with loading measurements on Alcator-C.

The 2-D, full-wave, finite-difference code was also modified to allow calculation of cyclotron emission from energetic ions in tokamaks with immediate application to fusion alpha particles in JET and TFTR. Ion cyclotron emission spectra were calculated and found to depend on details of the shape of the fusion product density profile. In addition, a new 2-D full-wave code that is based on an existing MHD stability code and uses a poloidal and toroidal mode expansion has been developed. This code is written in flux coordinates and retains $E_{\parallel}$. Final testing is under way, and comparisons are being made with the 2-D finite difference code.

Modeling of the plasma response to various heating and transport processes has evolved along three separate paths, including a bounce-averaged version with point modeling for transport; a multiregion version that is coupled to the 1-D, real-space, full-wave code with point modeling for transport; and a fully 3-D version with two velocity dimensions and one real-space dimension in slab geometry to provide diffusive as well as direct loss modeling for transport. New sources have been included in all versions to model neutral beams and alpha particles as well as Maxwellian sources. Nonlinear Coulomb collisions have been added to the homogeneous versions for the study of neutral beam and rf current drive.

The multiregion code that is coupled to the full-wave code has been used to model both fast wave and IBW launch in tokamak geometry. The fast wave modeling has been quite successful; however, problems were encountered with high-power IBW launch because of spatially localized absorption. This led to the development of the 3-D code with both real-space diffusion and direct loss transport models. In the bounce-averaged code with a point model for transport, a new rf operator has been included to account for finite gyroradius effects in resonant wave-particle interactions using the complete Bessel function expansion so that short-wavelength absorption and rf coupling to alpha particles can be studied. The code has also been extended so that currents carried by passing particles can be calculated, and diagnostics to show these currents have been added.

A model of second harmonic ECH breakdown in a stellarator is in reasonable agreement with the performance observed in ATF. Simple modeling has been done for first harmonic ECH breakdown in ATF, with preliminary indications that reasonable performance can be expected. Progress on modeling low-frequency plasma production includes an exchange with the U.S.S.R. in which experimental data were taken. Modeling of this process is complicated by poor confinement in the edge region of the Uragan-3 stellarator, but many of the salient features of the process can be understood in terms of electron excitation by evanescent electric fields.

In the area of ray tracing, continuing development of the RAYS geometrical optics code has added to its power and flexibility. RAYS has been modified to permit ray tracing in vacuum and to include the effect of multiple ion species. A finite-temperature dispersion package is under development for IBW studies. A power balance model has been developed to treat the effects of wall-reflected power. This code has been used to compare the efficiency of various antenna designs

and launching scenarios for second harmonic ECH in ATF. Third harmonic ECH calculations for ATF were also done. Collaboration with outside workers continued, and the RAYS code was installed at the Centro de Investigaciones Energéticas, Medioambientales, y Tecnológicas (CIEMAT), Madrid, Spain, and at the Georgia Institute of Technology, Atlanta.

Work has also begun to understand the effects of ICRH on the edge plasma and the causes of increased impurity production during high-power ICRH in tokamaks. Various mechanisms of particle acceleration in antennas near fields have been investigated with Monte Carlo simulations. The effects of modified scrape-off plasma characteristics on impurity shielding are being studied.

3.3.1 Abstract of "A Coupled Model of Wave Damping, Quasilinear Heating and Radial Transport Applied to Bumpy Tori"³⁴

D. B. Batchelor, M. D. Carter, and C. L. Hedrick

A simple Fokker-Planck model of rf heating is presented which includes quasilinear velocity diffusion, collisions, and particle transport by radial collisional diffusion and direct-drift losses. In addition, the influence of the incident-wave electric field spatial profile on the velocity-space structure of the quasilinear operator and, in turn, the effect of the nonlinear distribution function on the wave field are included. Application is made to electron cyclotron heating in the ELMO Bumpy Torus.

3.3.2 Abstract of "Ion Cyclotron Emission Calculations Using a 2D Full Wave Numerical Code"³⁵

D. B. Batchelor, E. F. Jaeger, and P. L. Colestock

Measurement of radiation in the high-frequency band due to cyclotron emission by energetic ions produced by fusion reactions or neutral beam injection promises to be a useful diagnostic on large devices which are entering the reactor regime of operation. A number of complications make the modeling and interpretation of such measurements difficult using conventional geometrical optics methods. In particular, the long wavelength and lack of high directivity of antennas in this frequency regime make observation of a single path across the plasma into a viewing dump impractical. Pickup antennas effectively see the whole plasma and wall reflection effects are important. We have modified our 2-D full-wave ICRH code to calculate wave fields due to a distribution of energetic ions in tokamak geometry. The radiation is modeled as due to an ensemble of localized source currents distributed in space. The spatial structure of the coherent wave field is then calculated including cyclotron harmonic damping as compared to the usual procedure of incoherently summing powers of individual radiators. This method has the advantage that phase information from localized radiating currents is globally retained so the directivity

of the pickup antennas is correctly represented. Also, standing waves and wall reflections are automatically included.

3.3.3 Abstract of "Effects of Fast Ion Sources on Lower Hybrid Current Drive"³⁶

M. D. Carter and D. B. Batchelor

For lower hybrid current drive, the wave spectrum must be broad in order to achieve high current drive efficiency and also couple to a significant portion of a Maxwellian distribution. A distortion of the electron distribution function away from a Maxwellian is produced when fast ions from a neutral beam source or fusion reactions slow down by collisions with electrons. This distortion can provide more electrons that interact with waves that have a lower parallel refractive index, and enhance the lower hybrid coupling to electrons. Enhancement of the current drive efficiency ($n_e RI/P$) has been observed experimentally in the JT-60 device.

The effects of the electron distribution distortion caused by fast ions and current drive will be explored using a Fokker-Planck code for homogeneous magnetic fields. The ion distribution is determined using high-energy sources and various simple transport models of the form νf , which give reasonable confinement times and ion source powers. The collision operator for determining the electron distribution is then calculated from the fixed background ion distribution using the Rosenbluth potentials.

3.3.4 Abstract of "Fokker-Planck Calculations of Ion Bernstein Wave Absorption"³⁷

M. D. Carter, D. B. Batchelor, and E. F. Jaeger

A two velocity-space dimension Fokker-Planck code is coupled with a one real-space dimension full-wave ion cyclotron range of frequencies (ICRF) code (sixth-order code) in order to study the absorption of ion Bernstein modes. Plasma parameters are assumed for the full-wave calculation, and the Fokker-Planck code is used to determine the distribution function. Real space is approximated by a discrete uncoupled homogeneous magnetic field model in the Fokker-Planck calculation. The resulting distribution function is then approximated by hot and bulk Maxwellian distributions which are fed back into the full-wave ICRF code.

3.3.5 Abstract of "Current Drive by Opposing Energetic Neutral Beams"³⁸

R. A. Dory, H. C. Howe, Jr., J. A. Rome, K. C. Shaing, and N. A. Uckan

An early discussion [T. Ohkawa, *Nucl. Fusion* 10, 185 (1970)] of noninductive current drive using energetic neutral beams recognized the importance of avoiding

introduction of excessive momentum into the plasma. Use of mega-electron-volt beams with moderately high Z to obtain good penetration of reactor densities and minimize current cancellation by electron return currents has also been suggested [e.g., D. R. Mikkelsen and C. E. Singer, *Nucl. Technol./Fusion* 4, 237 (1983)]. It may not have been appreciated, however, that use of two opposing beams could provide a further benefit if one is of low Z and the other of moderate Z (C or O). Net momentum input can be zero—or nonzero to promote radial impurity outflow—while the return current electron response to the opposed beams would be additive when account is taken of the $(1 - Z_b/Z_{eff})$ factor. In the usual estimate, including an electron trapping correction $G(\epsilon, Z_{eff})$ on assuming the bulk of the beam to be at $r = \epsilon \cdot R$, $I_{total} = I_{b1}[1 - (Z_{b1}/Z_{eff})(1 - G)] + I_{b2}[1 - (Z_{b2}/Z_{eff})(1 - G)]$. To give an example, if $Z_{eff} = 1.5$, $Z_{b1} = 1$, $Z_{b2} = 8$, $\epsilon = 0.085$, $G \approx 0.49$, and $I_{b1} = -I_{b2} = I_b/2$, then I_{total}/I_b is 1.2. This value is almost twice that for a single deuterium beam, while allowing zero net momentum input.

3.3.6 Abstract of "Modeling of Ion Bernstein Wave Propagation in ATF"³⁹

R. C. Goldfinger and D. B. Batchelor

Ion Bernstein wave heating is being considered for use on the ATF torsatron at ORNL. Experience with tokamaks has shown that IBWs do better bulk heating with reduced formation of energetic perpendicular tails. This is particularly important for ATF due to the poor confinement of energetic ripple-trapped particles. Also, on the Uragan-3 stellarator at Kharkov it has been possible to break down and produce a high-density plasma using ICRF antennas oriented to have the current parallel to the magnetic field, as is the case with IBW antennas. Thus IBW power, with tunable rf transmitters, may be useful to produce a wider operating range of magnetic fields than is obtainable using ECH from fixed-frequency gyrotrons. The RAYS geometrical optics code is being generalized to treat IBW propagation and absorption. A spline fit of the fully 3-D vacuum magnetic and toroidal flux function is used in the ray tracing. This is important since the presence of gradients along $\vec{B}$ produces variation in $k_{||}$ and may strongly affect wave damping. We have developed a module of subroutines to calculate the derivatives of the full-finite-temperature dispersion relation. The plasma dispersion functions and modified Bessel functions can be included for an arbitrary number of cyclotron harmonics (no assumption is made of small $k_{\perp}\rho_i$). Results using this code will be presented.

3.3.7 Abstract of "Ray Tracing in ATF Using 3-D Splines"⁴⁰

R. C. Goldfinger and D. B. Batchelor

The ray tracing code, RAYS, requires a subroutine module which supplies magnetic field and density as well as their gradients ($\vec{B}$, ∇B , n_e , and ∇n_e) to propagate

rays using the cold plasma approximation. In order for the ray trajectory to remain a solution of the dispersion relation, $D(\omega, \vec{k}, \vec{r}) = 0$, the spatial derivatives of $\vec{B}$ and n_e numerically defined by the module must be a good approximation to the analytic derivatives of the field quantities themselves. This consistency, coupled with initializing the ray on a root of the dispersion relation, $D(\omega, \vec{k}_0, \vec{r}_0) = 0$, is sufficient for the ray to satisfy the dispersion relation along the ray. An additional requirement is that n_e be constant on a magnetic field line. Although this is not a necessary condition for the ray to satisfy the dispersion relation, the physics of the problem may dictate that this constraint be satisfied. The example of lower hybrid heating is described where this requirement should be satisfied in order to get meaningful results. A computationally efficient and robust way to solve these problems is to use 3-D cubic spline interpolation of a data set with the desired model for $\vec{B}$ and the accurate calculation of toroidal flux, Ψ . The advantages and use of splines are the subject of this paper.

3.3.8 Abstract of "Second Harmonic Electron Cyclotron Heating Calculations for the ATF Torsatron"⁴¹

R. C. Goldfinger and D. B. Batchelor

The heating of the ATF now under construction at ORNL has been investigated using ray tracing techniques. The effect of electron cyclotron waves at the second harmonic resonance is studied using the RAYS geometrical optics code assuming anticipated steady-state parameters. A comparison is made of the heating efficiency using two launching schemes: a linearly polarized antenna providing a narrow beam and a TE₀₂ waveguide. The first-pass ray tracing calculations are incorporated in a wall reflection/power balance model which includes the effects of wall-reflected rays and wall losses. It is shown that the power absorbed in the plasma after multiple reflections is preferentially absorbed near the center of the plasma. A significant fraction of the incident power is predicted to ultimately be deposited in the plasma, rather than lost to walls and ports.

3.3.9 Abstract of "ICRH in Large Tokamaks"⁴²

K. Imre,* D. C. Stevens,[†] H. Weitzner, and D. B. Batchelor

We apply a boundary layer analysis across the ion cyclotron resonance layers in a large toroidal device. We assume that the geometrical optics assumption holds in general, but the method fails within the boundary layer. When B_p/B is nonzero but still very small, the local theory based on the perpendicular stratification also breaks down. We obtain an integrodifferential equation for the field variables by deriving a nonlocal perturbed current density from the Vlasov equation and substituting it into Maxwell's equations. We study two separate problems: (1) the minority fundamental resonance and (2) the majority second harmonic resonance.

The field equations derived for these cases reduce to those obtained by the local theory when the poloidal field is sufficiently small. We present many analytical results for these two problems. We show that reciprocity relations hold for the nonlocal system also, but now we must compare the properties of the two adjoint problems, which are identical except for the direction of the poloidal field, which is reversed. We prove that in the first problem fast waves incident from the high-field side suffer no reflection, and the transmission coefficient is the same as that given in geometrical optics. The solutions of the nonlocal integrodifferential equations are numerically obtained. By taking suitable linear combinations of these solutions we obtain the solutions of the basic scattering problems, by which the wave propagation characteristics across the resonance layers can be investigated.

*College of Staten Island, City University of New York, New York.

†New York University, New York.

3.3.10 Abstract of "Cyclotron Emission from Energetic Ions in Tokamaks"⁴³

E. F. Jaeger, D. B. Batchelor, and P. L. Colestock

The ORNL 2-D full-wave rf heating code has been modified to allow calculation of cyclotron emission from energetic ions in tokamaks. The immediate application will be to fusion alpha particles in near-ignition devices such as TFTR and JET. This will permit detailed evaluation of proposed alpha particle diagnostics. The full-wave approach used automatically takes into account wall reflections, standing waves, and plasma absorption and overcomes the difficulties inherent in attempting to apply conventional geometrical optics to long wavelengths. By calculating the coherent radiation field due to an ensemble of localized current sources (and retaining the phase information) the directivity of pickup antennas is correctly represented. This method also promises to be useful for studying other kinds of plasma radiation such as that produced by instabilities.

3.3.11 Abstract of "Exact and Approximate Solutions to the Finite Temperature Wave Equation in a One-Dimensional Perpendicularly Stratified Plasma"⁴⁴

E. F. Jaeger, D. B. Batchelor, and H. Weitzner

The sixth-order wave equation which results from a finite temperature expansion of the Vlasov equation is solved globally in a perpendicularly stratified, 1-D slab plasma. The diamagnetic drift and associated anisotropy are included in the unperturbed distribution function to ensure a self-adjoint system. All x dependence in the plasma pressure and magnetic field is retained along with the electric field parallel to $\vec{B}$. Thus, Landau damping of the IBW is included as well. Because

the wave equation is solved implicitly as a two-point boundary value problem, the evanescent short-wavelength Bernstein waves do not grow exponentially as in shooting methods. Solutions to the complete sixth-order partial differential equation are compared to those from an approximate second-order equation based on local dispersion theory. Strong variations occur in the absorption and in the structure of the wave fields as resonance topology is varied.

3.3.12 Abstract of "Global ICRH Modeling in Large Noncircular Tokamak Plasmas with Finite Temperature"⁴⁵

E. F. Jaeger, D. B. Batchelor, H. Weitzner, and P. L. Colestock

Full-wave ICRF coupling calculations [E. F. Jaeger et al., *Comput. Phys. Commun.* **40**, 33 (1986)] in two and three dimensions have been extended to treat tokamaks with noncircular flux surfaces and conducting boundaries. The magnetic field configuration is derived from a Solov'ev equilibrium [L. S. Solov'ev, *Sov. Phys.-JETP* **26**, 400 (1968)] with finite radial and poloidal magnetic fields. The conducting boundary may be of arbitrary shape. The mode conversion model is that of Colestock et al. in which the fourth-order finite-temperature wave equation is reduced to a second-order equation that describes the effects of mode conversion on the fast wave but neglects the detailed structure of the IBW. Results show the effect of noncircular cross section on excitation, wave propagation, and absorption in Doublet III-D and JET. Also, in the limit of circular cross section, toroidal phasing of the resonant double loop antenna design for TFTR is studied.

3.3.13 Abstract of *ICRF Heating in a Straight, Helically Symmetric Stellarator*⁴⁶

E. F. Jaeger, H. Weitzner, and D. B. Batchelor

Experimental observations of direct ICRF heating at fundamental ion cyclotron resonance on the L-2 stellarator have stimulated interest in the theoretical basis for such heating. In this paper, global solutions for the ICRF wave fields in a helically symmetric, straight stellarator are calculated in the cold plasma limit. The component of the wave electric field parallel to $\vec{B}$ is assumed zero. Helical symmetry allows Fourier decomposition in the longitudinal (z) direction. The two remaining partial differential equations in r and $\phi \equiv \theta - hz$ (h is the helical pitch) are solved by finite differencing. Energy absorption and antenna impedance are calculated from an ad hoc collision model. Results for parameters typical of the L-2 and ATF stellarators show that direct resonant absorption of the fundamental ion cyclotron resonance occurs mainly near the plasma edge. The magnitude of the absorption is about half that for minority heating at the two-ion hybrid resonance.

3.3.14 Abstract of "ICRF Modeling Studies for TFTR"⁴⁷

C. K. Phillips,* P. L. Colestock, G. W. Hammett,* D. G. Swanson,[†]
D. B. Batchelor, E. F. Jaeger, D. N. Smithe,[‡] and P. Bonoli**

A computational package has been constructed to model forthcoming ICRF plus neutral beam heating experiments on TFTR. The package is composed of interlocking or stand-alone codes which treat the coupled problems of rf power deposition, fast-ion resonant acceleration and slowing down and radial transport. Several forms of the package may be used, which permit various approximations of the wave propagation and damping analysis suitable for large devices and which greatly facilitate on-line analysis of experimental data. In addition, an optimized Fokker-Planck solver allows modeling in two velocity dimensions of the beam slowing down in conjunction with rf resonant diffusion at either the fundamental or second harmonic frequencies. Relevant fast-ion transport and loss mechanisms are included in this model. Resulting power deposition profiles to the background electrons and ions are used in conjunction with existing transport codes to complete the modeling package. Considerable effort has been expended to formulate contracted, numerically tractable forms of the mode conversion and damping equations appropriate for tokamak geometry with 2-D equilibrium gradients and realistic antenna configuration. Preliminary benchmark studies and plans for future model development will be discussed.

*Princeton Plasma Physics Laboratory, Princeton, New Jersey.

[†]Auburn University, Auburn, Alabama.

[‡]University of Michigan, Ann Arbor.

**Massachusetts Institute of Technology, Cambridge.

3.3.15 Abstract of "Physical Mechanism of Plasma Currents Induced by Waves"⁴⁸

K. C. Shaing

The physical mechanism of plasma currents induced by waves is discussed using plasma momentum and heat flux balance equations. Through the coupling of momentum and heat friction forces, both momentum and heat flux sources associated with waves can drive currents along the magnetic field. It is shown that the parallel current induced by the electron cyclotron waves is due to the absorption of the heat flux from the waves.

3.3.16 Abstract of "Wave Propagation at Ion Cyclotron Resonance in Large Toroids"¹⁹

H. Weitzner, K. Imre,* and D. B. Batchelor

The range of validity of the perpendicularly stratified approximation near cyclotron harmonic resonance layers is examined for large toroids. Where the usual approximation fails integrodifferential equations apply. Some exact results are given.

*Courant Institute of Mathematical Sciences, New York University, New York.

3.4 CONFINEMENT OPTIMIZATION AND IMPROVEMENT

The confinement optimization and improvement effort integrates physics results from MHD equilibrium and stability, transport, and heating analyses to devise new ways of improving confinement in existing devices and optimizing designs for new devices.

Work on the "flexible heliac" configuration continued. In a collaboration with the Australian National University, the magnetic design of the H-1 device at Canberra was optimized for plasma volume, magnetic well depth, and resistance to low-order resonances. Detailed studies of flexible heliacs, including a review of engineering considerations, and of transport in the TJ-II device were carried out in collaboration with CIEMAT, Madrid. Work with research staff at the University of Washington, Seattle, led to a sample point design for a heliac reactor.

The low-aspect-ratio torsatron concept continued to be a focus of attention. Studies show that plasma aspect ratios of 3.5 to 5 should be achievable in compact torsatrons, and these devices should operate stably at high beta if the vertical field coil system can prevent breaking of the magnetic surfaces. An experiment is needed to further investigate this concept.

Studies of moderate-aspect-ratio torsatrons included a proposal to use the flexible magnetic field system in ATF to control the magnitude and direction of the bootstrap current, as shown schematically in Fig. 3.8. The demonstration of such configurational control would have significant consequences for future high-beta stellarator reactors. Bootstrap currents were calculated for several stellarator configurations and compared with those of tokamaks for a fixed value of beta; in general, bootstrap current is lower in stellarators than in tokamaks. Work on optimizing both bootstrap current and particle flux was begun.

The magnetic field model used in the generic reactor studies and the field scaling laws for ATF were used in the development of a design for a stellarator reactor. The resulting "moderate-size" reactor meets the conventional threshold for commercial attractiveness.

Fig. 3.8. Unbalancing the currents in the ATF helical coils. The effects of the helical axis induced in the configuration are (a) a change in the geometrical coefficient of the bootstrap current G_b and (b) a decrease in the bootstrap current level I to zero or even a negative value.

The study of low-aspect-ratio tokamak physics continued. Further studies of shape optimization focused on estimating the increase in the critical beta β_{crit} predicted by the ideal MHD model for various plasma shapes at low aspect ratio A . The results show that pressure-driven modes are suppressed for moderately D-shaped plasmas and that β_{crit} may increase by a factor of two to three for $A = 1.67$. A limited study of pressure profile optimization suggests that similar increases in β_{crit} at reduced aspect ratio can be obtained for $q(0) \sim 1$.

Shape optimization was also applied to stellarator design. Specifying the shape of the outermost closed flux surface specifies the relevant MHD parameters; the surface shape can then be modified to optimize these parameters and the transport, and the coil system can be designed to produce the desired field.

3.4.1 Abstract of "The Helic Configuration: Magnetic Design and Experiment"⁵⁰

B. D. Blackwell,* B. A. Carreras, L. E. Sharp,* X-H. Shi,* and N. Takeuchi†

H-1 is a low-aspect-ratio heliac ($R_0 = 1$ m, $B_0 = 1$ T, $I_{ring} = 0.5$ MA) under construction in Canberra. Using magnetic field line tracing codes, the magnetic design has been optimized for plasma volume, magnetic well depth, and freedom from low-order resonances. Further work is in progress to reduce the magnetic ripple and toroidal effects associated with the low aspect ratio. By modulation of the toroidal field coil spacing and choice of vertical field index, significant reduction in $|B|$ ripple can be obtained, at the expense of magnetic well depth. The $(0,1)$ toroidal component has so far remained relatively unaffected by these refinements, consistent with estimates of the toroidal shift from 3-D MHD codes, which show reasonable equilibria with central beta up to $\sim 10\%$. Some of the predictions of the vacuum field code have been tested experimentally on the prototype flexible heliac SHEILA. Results will be presented, including observations of the formation of islands and of the effects of error fields.

*Australian National University, Canberra, Australia.

†Sendai University.

3.4.2 Abstract of "Low-Aspect-Ratio Torsatrons"⁵¹

B. A. Carreras

Low-aspect-ratio torsatrons can make the stellarator reactor concept more attractive. Several physics issues related to these configurations have been studied and analyzed in recent years. An experiment in the very low aspect ratio range ($A_p \sim 3$ to 4) is needed to resolve some of the critical physics issues and provide the database for aspect ratio optimization.

3.4.3 Abstract of "Compact Torsatron Configurations"⁵²

B. A. Carreras, N. Dominguez, L. Garcia, V. E. Lynch, J. F. Lyon, J. R. Cary, J. D. Hanson, and A. P. Navarro*

Low-aspect-ratio stellarator configurations can be realized with torsatron windings. Plasmas with aspect ratios in the range 3.5 to 5 can be confined by these

compact torsatron configurations. Stable operation at high beta should be possible in these devices, if a vertical field coil system is adequately designed to avoid breaking of the magnetic surfaces at finite beta.

*Centro de Investigaciones Energéticas, Medioambientales, y Tecnológicas, Madrid, Spain.

3.4.4 Abstract of "Bootstrap Current in ATF"⁵³

B. A. Carreras, N. Dominguez, K. C. Shaing, V. E. Lynch, and J. S. Tolliver

Understanding the bootstrap current in toroidal systems with low collisionality is important for design of a long-pulse or steady-state device at the ETR stage of the fusion program. The ATF torsatron experiment can determine characteristics of the bootstrap current in a toroidal system in which it is not masked by ohmic heating currents. This provides an opportunity to test the neoclassical theory, which is the basis for bootstrap current in toroidally confined plasmas. The bootstrap current is usually smaller in stellarators than in tokamaks, but the flexibility of the magnetic system in ATF permits the enhancement of the current to a tokamak level. The possibility of external control of the bootstrap current in ATF also permits a more careful test of its predicted properties.

3.4.5 Abstract of "Systematics of Stellarator Reactor Designs Based on the Torsatron Coils"⁵⁴

R. A. Dory, B. A. Carreras, V. E. Lynch, J. F. Lyon, and J. Sheffield*

The magnetic field model used in previous studies with the generic fusion reactor model [*Fusion Technol.* 9, 199-249 (1985)] has been tailored to torsatron devices. Field scaling laws based on the ATF device have been added. Application, for an assumed 1200-MW(e) power level, yields a "moderate-sized" reactor, with fusion core weight W_c under 12 kt. This meets the conventional threshold for "commercial attractiveness" of a reactor concept, 100 kW(e)/t. There is a broad maximum in the dependence of P_{el}/W_c on field period number M , in the range 6 to 12 (major radius 8-13 m). The requisite power density, with beta values of 4-8%, can satisfy MHD equilibrium and ideal stability limits with a central field of 5-6 T. This is consistent with reasonable projections for superconducting coils: current densities of 2000 A/cm² and maximum fields of 9-10 T.

*Associate division director.

3.4.6 Abstract of "Studies of a Flexible Helic Configuration"⁵⁵

T. C. Hender, J. L. Cantrell,^{*} J. H. Harris,[†] B. A. Carreras, V. E. Lynch, J. F. Lyon, J. A. Fabregas,[‡] J. Guasp,[‡] A. Lopez-Fraguas,[‡] and A. P. Navarro[‡]

This paper documents a detailed study of the flexible heliac configuration. The remarkable flexibility of this device—which allows variation of the rotational transform, shear, and magnetic well depth over a relatively wide range—is described. Engineering considerations of error fields, finite cross-section conductors, and plasma coil clearances are also discussed.

^{*}Computing and Telecommunications Division, Martin Marietta Energy Systems, Inc.

[†]Toroidal Confinement Physics Section.

[‡]Centro de Investigaciones Energéticas, Medioambientales, y Tecnológicas, Madrid, Spain.

3.4.7 Abstract of "Shape Optimisation of Low-Aspect Ratio Tokamaks"⁵⁶

J. T. Hogan, J. A. Holmes, and E. A. Lazarus^{*}

Low-aspect-ratio improvements in stability are predicted by the ideal MHD model for pressure limits in tokamaks. We have conducted a series of calculations to estimate the increase in β_{crit} predicted by this model for various shaped configurations at aspect ratios below that of currently operating tokamaks.

The optimization of D configurations at $A = 1.67$ has been studied with the RSTEQ/Balloon system and with the PEST codes. We find that pressure-driven modes are suppressed, as expected, for a moderately D-shaped plasma. (Shaping at low aspect ratio is affected by the tendency toward some elongation without explicit external coils.) In comparison with reported optimizations at $A = 2.5$, we find a factor 2-3 increase in the expected β_{crit} for $A = 1.67$.

The infinite- n ballooning stability limits of D, bean, and crescent configurations have been compared for $1.67 \leq A \leq 2.5$ with the MOMCON fixed boundary moments equilibrium and the Balloon code. We find that, for the parameterization adopted, the ∞ - n stability improvements reported for strongly shaped configurations at higher aspect ratio persist in the low-aspect-ratio regime.

In addition to using the kink-optimized profiles suggested by the Lausanne group, which have relatively high central q (~ 1.6), we made a limited study of pressure profile optimization. The results suggest that similar aspect-ratio-related increases in β_{crit} can be obtained for $q(0) \sim 1$.

^{*}Toroidal Confinement Physics Section.

3.4.8 Abstract of "Optimization of the Bootstrap Current in Stellarators"⁵⁷

V. E. Lynch, J. S. Tolliver, K. C. Shaing, and B. A. Carreras

The magnitude of the bootstrap current is important for studying equilibrium and stability properties of stellarators. We calculate the bootstrap currents for several stellarator configurations such as ATF, Heliotron-E, and W7AS. We also compare the magnitude of the bootstrap current of stellarators with that of tokamaks for a fixed value of plasma beta but with appropriate safety factor q and aspect ratio A . We find that stellarators usually have a smaller value of bootstrap current than tokamaks.

For a given constraint on the relative magnitudes of the Fourier amplitudes of magnetic field strength B , we can find a configuration which has the smallest value of the bootstrap current. Several constraints will be considered. Since the bootstrap current is not directly related to the particle flux, the configuration that has optimized value of bootstrap current may not have optimized value of particle flux. The compatibility of optimizing these two transport properties will be discussed.

3.4.9 Abstract of "Stellarator Design by Surface Shape Optimization"⁵⁸

J. A. Rome, A. J. Spejewski,* and S. P. Hirshman

More freedom in stellarator design can be achieved by specifying the shape of the outermost closed flux surface (ofs) without reference to the coils which produce it. For the vacuum configuration, this specifies the relevant MHD parameters: the ϵ profile, the magnetic well, and the variation of $d\ell/B$ on a flux surface. The code VMEC was used to rapidly calculate the properties of such equilibria. The sensitivity of the parameters of interest to the various harmonics of the ofs were determined. The surface shape was then modified to optimize the MHD parameters and transport. Once the final shape is achieved, a coil set to produce the desired field can be synthesized using the techniques of P. Merkel.

*Cornell University, Ithaca, N.Y.

3.4.10 Abstract of "Study of Transport in the Flexible Helic TJ-II"⁵⁹

E. R. Solano,* J. A. Rome, and S. P. Hirshman

A numerical analysis of the classical loss mechanisms in the heliac TJ-II is presented. Using a guiding center orbit code in flux coordinates, it is found that for potentials on the order of the ion temperature, collisionless direct losses can be

eliminated by electric drift effects. Neoclassical losses resulting from the interaction of collisions and complex orbits are calculated by solving the drift kinetic equation. When electric drifts are included, the resulting transport coefficients are comparable to those of a tokamak with the same aspect ratio and a rotational transform equal to the transform per field period in TJ-II. In the absence of auxiliary heating, the expected energy confinement time in TJ-II is 2.5 ms, and it is found to decrease with increasing ion temperature.

*Institute for Fusion Studies, University of Texas, Austin.

3.4.11 Abstract of "Considerations in the Design of Helic Reactors"⁶⁰

R. M. Zubrin,* F. L. Ribe,* S. P. Hirshman, and D. K. Lee

A heliac is an $\ell = 1$ stellarator formed by orbiting a set of toroidal field coils about a single poloidal field coil or hardcore. In this paper we report on an ongoing study of the potential of the heliac as a commercial fusion reactor. A Biot-Savart code was used to create vacuum heliac magnetic field configurations. The ability of such configurations to contain plasma was then investigated using the 3-D MHD spectral moment equilibrium code VMEC. Stability of the equilibrium is assumed if a magnetic well is present. Toroidal heliac equilibria with average beta greater than 11% and peak beta greater than 20% have been found. Such configurations can produce 1000-MW(e) reactors with recirculating power fractions less than 0.15, provided that a resistive hardcore coil can be designed capable of withstanding neutron degradation with only weak shielding. The use of a vertical field is found to be necessary. A sample point design for a 1000-MW(e) heliac reactor is presented.

*University of Washington, Seattle.

3.5 ALPHA PARTICLE PHYSICS

The successful ignition of a thermonuclear plasma depends sensitively on confining a significant fraction of the energetic alpha component through the slowing-down time scale. This is much longer than the time scales associated with direct orbit loss or with turbulent losses driven by instabilities. As a result, alpha physics is becoming an increasingly important area in the design of tokamaks such as CIT and the international collaborative effort on ITER. It will also be important in work on future large stellarators. Alpha effects enter into nearly all areas of plasma theory, including instabilities (both kinetic MHD and purely kinetic modes), alpha transport modeling (2-D, i.e., in energy and radius), thermal instability (including use of pellet injection), helium ash buildup and removal, ripple transport, and interaction between alpha populations and rf waves (as used for both heating and current drive).

During the past year, interest continued to be focused on the effects of alpha populations on ballooning stability. Work is under way to examine a range of tokamak devices such as TFTR, CIT, and ITER using realistic, numerically generated noncircular equilibria. In most cases, at least a modest degree of destabilization is seen for alpha concentrations typical of breakeven and ignited plasma conditions. Also, the sensitivity of the stability boundaries to the additional physics parameters introduced by the alphas is being examined. This includes such quantities as $k_{\perp}\rho_s$, alpha pressure, electron temperature, and modifications to the alpha energy distribution. These studies are helpful for illuminating the physical mechanism of the precessional mode interaction and may point the way toward methods of improving stability.

3.5.1 Abstract of "Alpha Particle Ballooning Mode Studies"⁶¹

J. J. Ramos, D. A. Spong, and D. J. Sigmar

Destabilization of ballooning modes due to medium-energy alpha precession resonance effects has been known for some time. Recently, the formalism has been extended to noncircular plasma cross sections showing a strong sensitivity to elongation κ and more severe changes of stability than expected from previous results in circular plasmas. Besides ensuring convergence of the D-shaped equilibria and of the shooting code using the Floquet method for the boundary conditions at infinity, the kinetically modified integrodifferential ballooning equation is analyzed with respect to the existence of multiple eigenvalues and different branches of solutions which are introduced through the alpha resonance term. The Nyquist diagram and Cauchy's root-finding method are applied numerically.

3.5.2 Abstract of "Modification of Tokamak Ballooning Stability Boundaries by Alpha Populations"⁶²

D. A. Spong, D. J. Sigmar, and J. J. Ramos

For $T_\alpha/T_i < 150$ (where T_α is the alpha mean energy and T_i the ion temperature) the trapped alpha precession resonance destabilizes the kinetic ballooning mode of the bulk plasma. Using a slowing-down distribution and both circular and noncircular equilibrium models, the eigenfrequencies of the resonant ballooning integral equation are computed. One finds lower critical betas and a widening of the unstable region, particularly at higher electron temperature and for flat- q , steep pressure profiles typical of ignited sawtoothed plasmas.

3.5.3 Abstract of "Stability Properties of Shaped Tokamaks with Energetic Alpha Populations"⁶³

D. A. Spong, D. J. Sigmar, and J. J. Ramos

Energetic alpha populations can influence the stability of ballooning modes through coupling between the trapped alpha precessional drift and ballooning mode frequency. This mechanism has been examined in some detail for circular cross-section tokamaks where it was found to lower the first stability beta limit and, in some cases, close off access between first and second stable regimes. Such effects are of particular interest for noncircular ignition tokamaks such as the CIT which will operate near the ballooning stability limit and where the fusion-produced alpha pressure gradient can be a substantial fraction of the background gradient. We have extended this analysis by including a general equilibrium solution with elongated and triangular flux surfaces in the kinetic ballooning analysis. An isotropic model for the alpha pitch angle distribution has been used and the energy and pitch angle dependence of the precessional drift frequency is retained. The complete coupled integrodifferential mode equations have been solved using an iterative procedure; based on this solution it has been possible to also develop an approximate method which should be reasonably accurate but computationally more efficient for carrying out parameter studies. Results of these studies over a range of alpha and background plasma parameter regimes relevant to CIT will be discussed.

3.6 PLASMA MODELING AND EXPERIMENT INTERPRETATION

Fluid transport modeling represents the widest area of contact between plasma theory and experimentally measured quantities. Transport codes are used both to interpret experimental results in terms of theoretical models and to provide guidance for new experiments. The plasma transport modeling effort is therefore aimed at developing a comprehensive set of simulation models for application to both existing and planned toroidal devices. Heavy emphasis is placed on the development of generalized models that can be applied to either axisymmetric or nonaxisymmetric plasmas. The range of applications covers small experiments proposed to explore innovations in plasma physics, existing devices, and more advanced ignition devices. Continuity in the models and analysis codes, extending across the traditional boundaries of specific confinement concepts and plasma parameter regimes, is a very high priority so that useful comparisons can be made.

Coupling 3-D MHD equilibrium solutions for nonaxisymmetric plasmas with 1-D equations for particle, momentum, and energy transport poses many computational challenges. A set of efficient routines was developed to use the solutions of 2-D

and 3-D MHD equilibria in a broad class of transport-related physics problems. These include routines for inversion of chordal data in interpretive transport codes (e.g., PROCTR) and for calculating chordal signals in predictive transport codes (e.g., WHIST). An alternating-dimension algorithm was extended from two to three dimensions to study coupled transport and MHD evolution. Applications were made to high-beta tokamaks with large toroidal field ripple and to the ATF torsatron with a current source to demonstrate the computational method.

The 3-D geometry of stellarators complicates the calculation of neutral beam deposition and thermalization, particularly for neutral beam injection (NBI) nearly normal to the magnetic field, as in Heliotron-E. Extensive comparisons of Monte Carlo beam deposition codes developed at ORNL and at Kyoto were made, illuminating the sensitivities to approximations to the magnetic geometry and numerical algorithms. The ORNL code was applied to the problem of beam alignment and aperturing in ATF to minimize losses to the vacuum vessel from shinethrough (alignment) and scrape-off at the entrance port (aperturing). The heating profiles were then used to substantiate faster beam deposition routines for use in the PROCTR confinement analysis code.

The neutral shielding model for pellet ablation was upgraded to include an ionized shield extended along the magnetic field and contributions to the ablation process from fast alpha particles and beam ions. The model was verified against data from both single- and multiple-pellet injection on JET and data from the Impurity Study Experiment (ISX-B), Doublet III, the Poloidal Divertor Experiment, the Tokamak Fontenay-aux-Roses, the Texas Experimental Tokamak, and TFTR. The model predicts that fast alphas should not contribute significantly to ablation in fusion plasmas under conditions of classical, local thermalization.

Density profile control and particle recycle were studied in pellet-fueled JET plasmas. The combined effects of plasma and wall properties were used to explain an order of magnitude difference in particle pumpout rates after pellet injection. Excitation of $m = 2$ instabilities in the outer plasma temporarily raises the plasma edge temperature and the energy of charge-exchange neutrals, which are buried deeper in the wall and therefore have a reduced probability of reflection. Control of the plasma edge is therefore a critical part of controlling the total density profile through the particle source profile.

In collaboration with researchers at Princeton Plasma Physics Laboratory, ICRF studies of CIT and TFTR were carried out. It was found that minority-species heating in TFTR could be used to produce very high energy ^3He tails for simulating alpha particles in CIT and their susceptibility to ripple losses.

Sawtooth activity was shown to play an important role in assessing the volt-second consumption in low- q , low-collisionality plasmas such as that of CIT. Although the net effect on flux consumption was found to be small for the short-pulse CIT design, the differentiation of resistive, inductive, and MHD-induced contributions to the flux consumption can be very important in assessing long-pulse inductive or current-driven plasmas.

3.6.1 Transport Codes—Abstracts

3.6.1.1 "Classical Transport in Nonaxisymmetric Toroidal Magnetic Confinement Geometries"⁶⁴

A. Bayliss,* L. F. Ibáñez,* and J. T. Hogan

A numerical implementation of the alternating-dimension algorithm for tokamaks with ripple is presented. An explicit (Euler) method is used for the convective-diffusive system. The 1-D calculation is periodically interrupted for a new (3-D) equilibrium calculation. The transport system requires a small number of "quasi-geometrical" coefficients obtained through the Bauer-Betancourt-Garabedian code. Results are presented for the Braginskii classical transport model for the evolution of a high-beta elongated tokamak with high field ripple over the resistive skin time. The model is extended by adding the ripple-plateau coefficient for thermal diffusivity which couples the field ripple with enhanced loss at high temperature. Preliminary results are presented for the ATF torsatron searching for the pressure and rotational transform evolution to an external current source.

*New York University, New York.

3.6.1.2 *Evaluation of Magnetic Coordinates in Finite-Beta, Asymmetric Plasmas*⁶⁵

C. O. Beasley, J. A. Rome, S. E. Attenberger, and S. P. Hirshman

Analytical and numerical stability or transport calculations for toroidal plasmas are facilitated by using flux coordinates in which the magnetic field lines are straight. A published method for obtaining these magnetic coordinates, or more specifically the Fourier components of the magnetic field in this coordinate system, has existed for a vacuum magnetic field. A procedure for calculating these components for a finite-beta plasma equilibrium, however, has not previously been available. (Here beta is the ratio of plasma pressure to magnetic pressure.) In this report, we describe such a procedure, in which we start with an arbitrary-beta magnetic equilibrium for which nested toroidal flux surfaces exist and obtain the Fourier components of the magnetic field in straight-line magnetic coordinates. We describe the various numerical procedures, referring to published documentation where needed. We then document the codes involved and apply them to a specific toroidally nonsymmetric, finite-beta plasma.

3.6.2 Neutral Beam Injection—Abstracts

3.6.2.1 "Benchmarks of Neutral Beam Injection Codes for Stellarators"⁶⁶

R. H. Fowler, J. A. Rome, R. N. Morris, and K. Hanatani*

The 3-D geometry of stellarators/heliotrons makes it more difficult to calculate beam deposition and thermalization. Extensive comparisons between the Oak Ridge and Kyoto codes were undertaken, using a simplified model for the Heliotron-E plasma and magnetic field. The perpendicular injection geometry causes most of the energetic fast ions to be helically trapped. The high transform and shear of the heliotron configuration helps to confine these orbits, but energy losses in the model cases ranged from 20% to 50%. Although the codes use different coordinate systems and collision operators, when they solve the same problem, the answers are equivalent. For perpendicular injection, very little, if any, acceleration of the slowing process can be tolerated.

*Plasma Physics Laboratory, Kyoto University, Gokasho, Uji, Kyoto, Japan.

3.6.2.2 "Advanced Toroidal Facility Neutral Beam Injection: Optimization of Beam Alignment and Aperturing"⁶⁷

R. N. Morris, R. H. Fowler, J. A. Rome, and T. J. Schlagel*

The application of the existing ISX-B neutral beam injectors for the ATF is studied. New techniques are required to handle the complicated stellarator geometry of both the vacuum vessel and the plasma. The power delivered to the plasma is found to be a strong function of the beam divergence but only a weak function of the beam focal length. Monte Carlo methods were used to follow the injected particles from the injector until they thermalized in the plasma. An aperture in the beam line is required to prevent excessive heating of the vacuum vessel by the injected beam. Shinethrough can be a serious problem if very low density startups are necessary. Reasonable assumptions on beam divergence yield an estimate of over 1 MW of power absorbed by the plasma. Preliminary calculations indicate that there will be no excessive fast-ion losses.

*Present address: University of Illinois, Urbana.

3.6.3 Pellet Fueling—Abstracts

3.6.3.1 "Edge Dynamics in Pellet-Fuelled Inner-Wall JET Discharges"⁶⁸

S. A. Cohen,* J. Ehrenberg,[†] D. V. Bartlett,[‡] D. J. Campbell,[‡] A. D. Cheetham,[‡] L. de Kock,[‡] A. Gondhalekar,[‡] N. Gottardi,[‡] R. Gräsetz,[‡] W. Houlberg, H. Jaeckel,[‡] E. Lazzaro,[‡] P. Morgan,[‡] J. O'Rourke,[‡] M. Pick,[‡] M. F. Stamp,[‡] D. D. R. Summers,[‡] E. van der Goot,[‡] M. Watkins,[‡] and A. Weller[‡]

Pellet fueling has shown itself to be an effective means for obtaining low- Z_{eff} , peaked density profiles in ohmic plasmas. Further uses of pellet fueling may develop when tokamaks enter their deuterium-tritium (D-T) burning phases. Then the above factors and the correct species mix become crucial for achieving the largest Q value. A necessary corollary for the success of sustained pellet fueling is good hydrogen removal from the plasma edge. Methods to control the edge exhaust have included various wall conditioning techniques and special limiter or divertor configurations. For any of these approaches to be optimized, an understanding of the basic processes of hydrogen transport in the plasma and in the walls must be developed.

In this paper we report on the density behavior in JET during pellet-fueled inner-wall discharges without auxiliary heating. Certain discharges, characterized by minor disruptions at the $q = 2$ surface, show a ten times more rapid decay of the plasma density than previously observed. We show that this is related to the combined effects of plasma and wall properties.

The time evolution of the plasma density is simulated by a 1-D plasma transport code which includes the effects of minor disruptions on both particle transport in the plasma and recycling behavior at the wall. As a starting point for the analysis we use transport coefficients from previous studies of the density profile evolution of neutral beam and ICRF-heated JET outer-limiter discharges. Several-fold changes in the particle transport and reflection coefficients during the minor disruptions are required to fit the present experiment. The detailed description of hydrogen transport in JET walls and limiters is in a companion paper.

* Princeton Plasma Physics Laboratory, Princeton, New Jersey.

[†] Max-Planck-Institut für Plasmaphysik, Garching, Federal Republic of Germany.

[‡] JET Joint Undertaking, Abingdon, Oxfordshire, U.K.

3.6.3.2 "Control of Density Profile and Particle Exhaust in JET"⁶⁹

A. Gondhalekar,* A. Cheetham,* S. A. Cohen,[†] W. Houlberg, T. T. C. Jones,*
P. D. Morgan,* J. O'Rourke,* K. Sonnenberg,* and M. Watkins*

Many optimizing options for plasma and heating performance and for achieving maximum Q_{DT} in JET rely on control of plasma density and its spatial profile. Such control might be exerted by adjusting the relative strengths of core and edge fueling and by controlling edge particle exhaust. Model calculations will be presented which define the requirements for control of recycling at the plasma edge to augment pellet and NBI fueling capabilities of JET. The calculations make use of measurements and analysis of (1) the behavior of particle fluxes at the plasma edge during ohmic and NBI heating and the contribution of these to plasma density, (2) particle transport in the bulk plasma, (3) characteristics of core fueling using NBI and single-shot pellet injection (PI), and (4) observations of improved pumping behavior of helium discharge conditioned walls. The density peaking factor $n(0)/\langle n \rangle$ is expressed in terms of the required core-to-edge fueling ratio. This leads to specific pumping requirements. $n(0)/\langle n \rangle \lesssim 4$ appears feasible with the planned enhancements of JET NBI and PI systems for core fueling and pump limiters for exhaust control.

*JET Joint Undertaking, Abingdon, Oxfordshire, U.K.

[†]Princeton Plasma Physics Laboratory, Princeton, New Jersey.

3.6.3.3 "Pellet Ablation by Fast Hydrogen Ions and Alphas"⁷⁰

W. A. Houlberg, S. E. Attenberger, and S. L. Milora*

Many instances of enhanced pellet ablation have been noted under conditions of intense auxiliary heating, current drive, etc., where non-Maxwellian distributions prevail. Threshold criteria for enhanced ablation by energetic ions are derived here and applied to pellet injection during neutral beam heating in TFTR (strongly enhanced ablation with a few megawatts of NBI heating) and JET (no significant enhancement up to 8 MW of NBI heating), yielding both qualitative and quantitative agreement. Extension of the analysis to fusion alphas shows that they may never be a factor in pellet ablation: when $T_e \geq 4.7$ keV the neutral shield required to stop Maxwellian electrons is thick enough to stop 3.5-MeV alphas; when $T_i = T_e \leq 4.7$ keV there are insufficient alphas to influence ablation under conditions of thermal fusion with local, classical thermalization.

*Plasma Technology Section.

3.6.3.4 "Neutral and Plasma Shielding Model for Pellet Ablation"⁷¹

W. A. Houlberg, S. L. Milora,* and S. E. Attenberger

The neutral gas shielding model for ablation of frozen hydrogenic pellets is extended to include the effects of (1) an initial Maxwellian distribution of incident electron energies; (2) a cold plasma shield outside the neutral shield and extended along the magnetic field; (3) energetic neutral beam ions and alpha particles; and (4) self-limiting electron ablation in the collisionless plasma limit. Including the full electron distribution increases ablation, but adding the cold ionized shield reduces ablation; the net effect is a modest reduction in pellet penetration compared with the monoenergetic electron neutral shielding model with no plasma shield. Unlike electrons, fast ions can enter the neutral shield directly without passing through the cold ionized shield because their gyro-orbits are typically larger than the diameter of the cold plasma tube. Fast alpha particles should not enhance the ablation rate unless their population exceeds that expected from local classical thermalization. Fast beam ions, however, may enhance ablation in the plasma periphery if their population is high enough. Self-limiting ablation in the collisionless limit leads to a temporary distortion of the original plasma electron Maxwellian distribution function through preferential depopulation of the higher-energy electrons.

*Plasma Technology Section.

3.6.3.5 "Plasma Performance and Density Profiles in 1 1/2 D ETR Transport Simulations with Pellet Injection and Pinch Terms"⁷²

J. S. Tolliver, W. A. Houlberg, and S. E. Attenberger

The WHIST 1 1/2-dimensional (1 1/2-D) transport code is used to study pellet injection combined with particle-flux pinch terms in an ETR/Tokamak Ignition/Burn Experimental Reactor (TIBER-II) plasma with a pellet ablation model that has been extensively benchmarked against single-pellet injection experiments on JET. The relationships between pellet size, pellet velocity, plasma temperature and density profiles, and plasma performance are examined using various models for the pinch term.

3.6.3.6 "A Model for Pellet Ablation in JET"⁷³

M. L. Watkins,* W. A. Houlberg, A. D. Cheetham,* A. Gondhalekar,*
R. Granetz,* F. Hendriks,* J. O'Rourke,* and P. M. Stubberfield*

Solid deuterium pellets have been injected into JET discharges for a wide variety of plasma conditions (including limiter, inner wall, and X-point discharges) with

ohmic heating alone and in combination with ICRF (up to 6 MW) and NBI (up to 8 MW of 75-kV deuterium injection). The pellets are injected in the midplane along a major axis of the plasma. The penetration of these pellets is compared with that determined by the neutral gas shielding model and the neutral gas and plasma shielding (NGPS) model. A suitable model is proposed for the effective ionization radius in the NGPS model which determines the ionized shield parameters. For present JET experiments penetration is found to be consistent with electron ablation alone. The lack of fast ion effects is interpreted in terms of expected energy and power thresholds.

*JET Joint Undertaking, Abingdon, Oxfordshire, U.K.

3.6.4 RF Heating—Abstract of "ICRF Modelling for CIT and TFTR"⁷⁴

G. W. Hammett,* P. L. Colestock, W. Houlberg, and C. K. Phillips*

Two integrated packages are used to model ICRF heating in CIT and TFTR. One uses ray tracing and an isotropic quasilinear damping model and has been interfaced with the WHIST and BALDUR transport codes. The other package is interfaced to the TRANSP transport analysis code and employs a 3-D calculation of the wave fields using a truncated warm-plasma dielectric operator as well as a bounce-averaged quasilinear Fokker-Planck code which solves for f as a function of energy, pitch angle, radius, and time. The Fokker-Planck code has recently been upgraded to include ripple transport which may become important for very energetic tails. Initial calculations predict good focusing of the wave energy to the center of the plasma and the ability to predominantly heat ions or electrons by adjusting the minority concentration. At low densities and low ^3He concentrations in TFTR, it is possible to produce extremely energetic ^3He tails which may be useful as a simulation of alpha particle heating and ripple transport.

*Princeton Plasma Physics Laboratory, Princeton, New Jersey.

3.6.5 Flux Consumption—Abstract of "Volt-Second Consumption in Tokamaks with Sawtooth Activity"⁷⁵

W. A. Houlberg

The effects of sawtooth activity on the poloidal magnetic flux and energy balances in tokamak plasmas on a diffusive time scale are evaluated through the application of conservation principles to Maxwell's equations. Poloidal magnetic flux (volt-second) consumption can be partitioned into internal and dissipative components by two methods: the "axial method" based on a magnetic flux balance and

the "Poynting method" based on a magnetic energy balance. Both methods require additional terms that specifically account for the poloidal flux and magnetic energy changes during magnetic reconnection derived from analysis on a magnetohydrodynamic time scale. In experimental analyses these terms are absorbed in the inferred resistive dissipation, while in predictive analyses they must be evaluated directly. The dissipation of poloidal flux by sawtooth activity can exceed the normal resistive dissipation when the axial method of accounting is used.

3.6.6 Power Loss—Abstract of "Synchrotron Radiation Losses in CIT"⁷⁶

W. A. Houlberg

Synchrotron radiation represents a potentially large power loss in fusion plasmas that have high magnetic fields and low wall reflectivity. Many reactor designs including the CIT design call for carbon-covered surfaces for which wall reflectivity is particularly uncertain; a smooth carbon surface may have reflective properties approaching those of a metal surface (i.e., $\approx 90\text{--}95\%$) but corrosion and redeposition of carbon could lead to very low reflectivity. This observation has raised the issue of whether operation of a CIT with carbon walls and with a toroidal field in the range of $B_T = 10\text{--}13$ T will have significant synchrotron radiation losses.

Synchrotron radiation losses are examined here by two methods. First, estimates are made of the global losses using empirical fits to slab calculations. Then a cylindrical model that includes nonlocal reabsorption is coupled to WHIST and POPCON plots are generated. Two sets of CIT parameters are examined—the baseline design of 1986 with $B_T = 10.27$ T and a somewhat larger device with 13-T capabilities. Comparisons are made between nominal cases with 90% wall reflectivity and extreme cases with 0% reflectivity. These results show that synchrotron radiation should not adversely affect ignition in CIT and could provide a positive benefit in passive thermal control. Caution should be exercised, however, in relying on these calculations since none of these models have been tested against more rigorous calculations above 5 T for machines as small as CIT.

3.7 COMPUTING

The Computing Support Group has two major missions: it provides effective computing support for Fusion Energy Division staff and associates, and it develops computer programs for division experiments and development projects.

3.7.1 Computing Support

Effective computing support involves both considerable day-to-day activity and the development of improved ways of doing business. The operation of the VAX

cluster computers, system management of those computers, and maintenance of the networks, computers, and terminal equipment are all activities vital to customers, though seldom noticed by them. Computing Support Group personnel continued to provide excellent service in each area. Improvements during the year included new hardware, extended networks, and increases in personal computer support.

At the beginning of the period, our central computing hardware included a VAX 8200, three VAX 11/780s, and a VAX 8600. At the end of the period, this had changed to one 11/780, the 8600, and two VAX 8700s—a net increase of more than 100% in computing power. Predictions of the need for that power have proved accurate; recent performance data show 90% utilization of all three major processors during the day shift for an entire week.

Our network involvement continued to change and to expand. Our terminal connections, at one time chiefly hardwired or linked through Digital Communications Associates (DCA) terminal multiplexors, are now nearly all ETHERnet based (with the remaining DCA lines retained for compatibility with and connection to other Energy Systems nodes). Our connections to external networks expanded through additional paths to Europe, and we increased the number of accounts whose only use of our resources is to access the Magnetic Fusion Energy Network (MFEnet). Along with other Energy Systems nodes, we changed our DECnet area number so that connections to the High Energy Physics Network (HEPNET) are possible. Finally, our internal ETHERnet continued to expand.

The use of personal computers in the division continued to grow considerably. The division now has more than 100 personal computers (nearly 80 of which are Macintosh systems). As an adjunct, use of desktop laser printers increased; there are now 30 such devices in the division. Users provide much of the support for personal computers (helping one another as necessary), but the Computing Support Group has provided considerable hardware and systems software support.

3.7.2 Programming

In a collaboration described in Sect. 5 of this report, a pneumatic pellet injector system was built and installed on JET. The computing system for this device was derived from the systems used to support the pellet injectors on TFTR and from the Radio-Frequency Test Facility (RFTF) support tasks.

In another collaboration, work began on several diagnostic systems that will be installed on the Tore Supra tokamak in Cadarache, France. The computing support for these devices is being performed by group personnel.

A computer system to operate the ICRH antenna for TFTR was completed and used to test the antenna on the RFTF. The code has been sent to Princeton for use in operating the antenna there.

The major project for the year, by far, was the development of a suite of programs to support ATF. Support codes included backbone systems (synchronization and monitoring, data management, and several data analysis codes), codes to control gas puff fueling and coil current, and a myriad of codes for data acquisition.

The software was operational before it was needed, so it received extensive use during the commissioning phases of operation as well as during normal operation. The tasks involved 11 people, most of whom also worked on other projects, and totaled 4 work-years of effort.

We are beginning to investigate the use of optical storage devices for ATF data. A single-platter 2.2-Gbyte optical disk device has been received and installed; a "jukebox" arrangement of several disks is being ordered. Both are being purchased with ATF funds.

3.7.3 Abstracts

3.7.3.1 "Spreadsheets for Physics"⁷⁷

R. A. Dory

Modern spreadsheet programs can provide a remarkable capability for quick and easy solutions to a broad range of small—and possibly large—physics, engineering, and astronomy problems. This usage can go far beyond the original applications of spreadsheets as accounting aids. However, sharp instruments can cut both ways, and these problems can be dangerous to the unwary user in providing quick and pretty collections of incorrect answers. Several spreadsheet techniques are shown by example; advantages and drawbacks are discussed.

3.7.3.2 "SAMS—The Synchronization and Monitoring System for ATF Data Acquisition"⁷⁸

D. E. Greenwood

SAMS performs much of the synchronization of the distributed data acquisition system for ATF. SAMS is responsible for propagating shot information and managing the data system directories and logical names. This paper describes how SAMS communicates with other processes, both within the VAX cluster that supports most of the ATF data acquisition and on VAXes that are connected to the cluster via DECnet.

3.7.3.3 "The ATF Data Management System"⁷⁹

K. L. Kannan and L. R. Baylor*

The ATF data management system (DMG) is a VAX-based software system that provides unified data access for ATF data acquisition and analysis. The system was designed with user accessibility, software maintainability, and extensibility as primary goals. This paper describes the layered architecture of the system design, the system implementation, use, and the data file structure.

*Engineering Division, Martin Marietta Energy Systems, Inc.

3.7.3.4 "The Data Acquisition and Control Systems for ATF: An Overview"⁸⁰

**K. A. Stewart, L. R. Baylor,* D. E. Greenwood, K. L. Kannan, D. R. Overbey,
W. R. Wing,[†] J. N. Sumner,[‡] and W. R. DeVan[‡]**

A data acquisition and control system is being developed to support ATF. This system has two separate elements: a VAX-based data acquisition and management system and a status and control system that uses programmable logic controllers. Although these systems can operate independently, they are intended to cooperate fully and complement one another. This paper presents an overview of the hardware components, software architecture, and operations of these systems.

***Engineering Division, Martin Marietta Energy Systems, Inc.**

[†]Toroidal Confinement Physics Section.

[‡]Midwest Technical, Inc., Oak Ridge, Tenn.

REFERENCES

1. B. A. Carreras, "Three-Dimensional MHD Calculations," paper presented at the Biannual Plasma Physics Meeting of the Australian Institute of Nuclear Sciences and Engineering, Canberra, February 8-11, 1987.
2. B. A. Carreras et al., "MHD Stability of Tokamaks with Low Shear at the $q = 1$ Surface," presented at the U.S.-Japan Workshop on Stability and Current Drive, Kyoto, Japan, November 16-19, 1987.
3. L. A. Charlton et al., "The Effects of Compressibility on Full Nonlinear Resistive MHD Tokamak Calculations in Toroidal Geometry," *Bull. Am. Phys. Soc.* **32**, 1774 (1987).
4. L. A. Charlton et al., "Fully Toroidal MHD Nonlinear Studies of the $m = 1$ Fast Sawtooth Crash," paper 1B1 presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, Calif., April 6-8, 1987.
5. N. Dominguez, B. A. Carreras, and V. E. Lynch, "3-D Stability of Low- n MHD Modes," *Bull. Am. Phys. Soc.* **32**, 1915 (1987).
6. N. Dominguez et al., "Ideal Mercier Stability in 3-Dimensions," paper 2C7 presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, Calif., April 6-8, 1987.
7. S. P. Hirshman and P. Merkel, "Free-Boundary Helias Stellarator Equilibria," paper 2B4 presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, Calif., April 6-8, 1987.
8. J. A. Holmes et al., "MHD Stability and Evolution for Very Low Shear and Hollow Safety Factor Profiles in Toroidal Geometry," *Bull. Am. Phys. Soc.* **32**, 1772 (1987).
9. J. A. Holmes et al., "Nonlinear Evolution of the Internal Kink Mode in Toroidal Geometry for Shaped Tokamak Plasmas," *Phys. Fluids* **31**, 1206-16 (1988); also published as ORNL/TM-10585, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., September 1987.
10. J. A. Holmes et al., *Nonlinear Dynamics of Tearing Modes in the Reversed Field Pinch*, IFSR 276, Institute for Fusion Studies, University of Texas, Austin, May 1987.
11. Y-K. M. Peng, D. J. Strickler, and J. T. Hogan, "Correlation of MHD Stability with Mean-Field Safety Factor," *Bull. Am. Phys. Soc.* **32**, 1763 (1987).
12. D. A. Spong, K. C. Shaing, and J. D. Callen, "Numerical Studies of Neo-classical MHD Pressure Gradient Driven Instabilities," *Bull. Am. Phys. Soc.* **32**, 1920 (1987).
13. P. H. Diamond and B. A. Carreras, "On Mixing Length Theory and Saturated Turbulence," *Comments Plasma Phys. Controlled Fusion* **10**, 271-8 (1987).
14. J. N. Leboeuf et al., "Ion Pressure Gradient Driven Turbulence," *Bull. Am. Phys. Soc.* **32**, 1891 (1987).
15. G. S. Lee, B. A. Carreras, and P. H. Diamond, "Frequency Spectrum of Resistivity-Gradient-Driven Turbulence Due to Sheared Radial Electric Field," paper 3A5 presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, Calif., April 6-8, 1987.

16. G. S. Lee, B. A. Carreras, and P. H. Diamond, "Study of Resistivity-Gradient-Driven Turbulence with Temperature Evolution," *Bull. Am. Phys. Soc.* **32**, 1921 (1987).

17. M. Yagi, M. Wakatani, and K. C. Shaing, "Inter-Relations Between Scale Invariance and Mixing Length Theory Based on g and Rippling Mode Turbulent Transports," *J. Phys. Soc. Jpn.* **57**, 117 (1988).

18. F. Kazeminejad et al., "A Hybrid Vlasov-Fluid Model of Kinetic Ions and Massless Fluid Electrons," paper 1D32 presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, Calif., April 6-8, 1987.

19. J. N. Leboeuf et al., "Ion Temperature Gradient Driven Drift Waves: Particle Simulation and Theory," paper 3B18 presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, Calif., April 6-8, 1987.

20. P. M. Lyster et al., "Particle-Fluid Model of Low Frequency Plasma Instabilities," *Bull. Am. Phys. Soc.* **32**, 1892 (1987).

21. P. M. Lyster and J. N. Leboeuf, "A Fluid-Particle Simulation Model for Plasma Instabilities," paper presented at the 12th Conference on Numerical Simulation of Plasmas, San Francisco, September 20-24, 1987; also presented at the U.S.-Japan Workshop on Plasma Modeling with MHD and Particle Simulation, Napa, California, September 25-26, 1987.

22. J. Schutkeker et al., "Simulation of the Kelvin-Helmholtz Instability with Electrostatic Implicit Particle Code," paper presented at the 12th Conference on Numerical Simulation of Plasmas, San Francisco, September 20-24, 1987.

23. C. O. Beasley and C. L. Hedrick, "Comparison of Analytic and Numerical Transport Coefficients in the $1/\nu$ Regime for Stellarators and Torsatrons," *Bull. Am. Phys. Soc.* **32**, 1836 (1988).

24. C. O. Beasley, Jr., et al., "Ion Heat Conductivity and Bootstrap Current in Low-Aspect-Ratio Tokamaks," paper 3B14 presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, Calif., April 6-8, 1987.

25. C. D. Beidler et al., "Unified Theory of Ripple Transport in Stellarators," *Phys. Rev. Lett.* **58**, 1745-7 (1987).

26. E. C. Crume, Jr., et al., "Transport Scaling in the Collisionless-Detrapping Regime in Stellarators," *Phys. Fluids* **31**, 11-14 (1988).

27. E. C. Crume, Jr., et al., "Bootstrap Current in Nonaxisymmetric Toroidal Plasmas," paper 2C1 presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, Calif., April 6-8, 1987.

28. C. L. Hedrick, J. S. Tolliver, and J. R. Cary, "Comparison of Analytic and Full Guiding Center Behavior at a Trapped-Passing Interface in Stellarators," *Bull. Am. Phys. Soc.* **32**, 1836 (1988).

29. C. L. Hedrick, J. S. Tolliver, and J. R. Cary, "Transitions from Passing to Trapped in Stellarators and Rippled Tokamaks," paper 2C24 presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, Calif., April 6-8, 1987.

30. K. C. Shaing, "Bootstrap Current in Toroidal Plasmas," *Bull. Am. Phys. Soc.* **32**, 1738 (1988).
31. K. C. Shaing, "The Effects of Electric Field Fluctuations on Bootstrap Current and Resistivity in Toroidal Plasmas," *Phys. Fluids* **31**, 8-11 (1988).
32. K. C. Shaing, "Transport Theory for Fluctuating Electric Fields in Toroidal Plasmas," paper 2D3 presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, Calif., April 6-8, 1987.
33. K. C. Shaing, Y. Nakamura, and M. Wakatani, "Energy Transport Equations for Toroidal Plasmas," *Phys. Fluids* **31**, 1288-90 (1988).
34. D. B. Batchelor, M. D. Carter, and C. L. Hedrick, "A Coupled Model of Wave Damping, Quasilinear Heating, and Radial Transport Applied to Bumpy Tori," *Phys. Rev. Lett.* **25**, 2664-7 (1987).
35. D. B. Batchelor, E. F. Jaeger, and P. L. Colestock, "Ion Cyclotron Emission Calculations Using a 2D Full Wave Numerical Code," paper 2D19 presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, April 6-8, 1987.
36. M. D. Carter and D. B. Batchelor, "Effects of Fast Ion Sources on Lower Hybrid Current Drive," paper 3B7 presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, April 6-8, 1987.
37. M. D. Carter, D. B. Batchelor, and E. F. Jaeger, "Fokker-Planck Calculations of Ion Bernstein Wave Absorption," *Bull. Am. Phys. Soc.* **32**, 1949 (1988).
38. R. A. Dory et al., "Current Drive by Opposing Energetic Neutral Beams," *Bull. Am. Phys. Soc.* **32**, 1956 (1988).
39. R. C. Goldfinger and D. B. Batchelor, "Modeling of Ion Bernstein Wave Propagation in ATF," *Bull. Am. Phys. Soc.* **32**, 1914 (1988).
40. R. C. Goldfinger and D. B. Batchelor, "Ray Tracing in ATF Using 3-D Splines," presented at the 12th Conference on the Numerical Simulation of Plasmas, San Francisco, September 20-24, 1987.
41. R. C. Goldfinger and D. B. Batchelor, "Second Harmonic Electron Cyclotron Heating Calculations for the ATF Torsatron," *Applications of Radio-Frequency Power to Plasmas*, S. Bernabei and R. W. Motley, eds., *AIP Conf. Proc.* **159**, 65 (1987).
42. K. Imre et al., "ICRH in Large Tokamaks," *Bull. Am. Phys. Soc.* **32**, 1949 (1988).
43. E. F. Jaeger, D. B. Batchelor, and P. L. Colestock, "Cyclotron Emission from Energetic Ions in Tokamaks," *Bull. Am. Phys. Soc.* **32**, 1778 (1988).
44. E. F. Jaeger, D. B. Batchelor, and H. Weitzner, "Exact and Approximate Solutions to the Finite Temperature Wave Equation in a One-Dimensional Perpendicularly Stratified Plasma," *Nucl. Fusion* **28**, 53-72 (1988).
45. E. F. Jaeger et al., "Global ICRH Modeling in Large Noncircular Tokamak Plasmas with Finite Temperature," *Applications of Radio-Frequency Power to Plasmas*, S. Bernabei and R. W. Motley, eds., *AIP Conf. Proc.* **159**, 394 (1987). A summary of this material was presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, Calif., April 6-8, 1987.

46. E. F. Jaeger, H. Weitzner, and D. B. Batchelor, *ICRF Heating in a Straight, Helically Symmetric Stellarator*, ORNL/TM-10223, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., July 1987.

47. C. K. Phillips et al., "ICRF Modeling Studies for TFTR," paper 2D4 presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, April 6-8, 1987.

48. K. C. Shaing, "Physical Mechanism of Plasma Currents Induced by Waves," *Plasma Phys. Controlled Fusion* **29**, 1637-41 (1987).

49. H. Weitzner, K. Imre, and D. B. Batchelor, "Wave Propagation at Ion Cyclotron Resonance in Large Toroids," *Applications of Radio-Frequency Power to Plasmas*, S. Bernabei and R. W. Motley, eds., *AIP Conf. Proc.* **150**, 358 (1987).

50. B. D. Blackwell et al., "The Helic Configuration: Magnetic Design and Experiment," *Bull. Am. Phys. Soc.* **32**, 1835 (1987).

51. B. A. Carreras, "Low-Aspect-Ratio Torsatrons," *Comments Plasma Phys. Controlled Fusion* **11**, 139-46 (1987).

52. B. A. Carreras et al., *Compact Torsatron Configurations*, ORNL/TM-10030, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., September 1987.

53. B. A. Carreras et al., "Bootstrap Current in ATF," presented at the U.S. Japan Workshop on Stability and Current Drive, Kyoto, Japan, November 16-19, 1987.

54. R. A. Dory et al., "Systematics of Stellarator Reactor Designs Based on the Torsatron Coils," *Bull. Am. Phys. Soc.* **32**, 1916 (1987).

55. T. C. Hender et al., "Studies of a Flexible Helic Configuration," *Fusion Technol.* **13**, 521 (1988); also published as ORNL/TM-10374, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., July 1987.

56. J. T. Hogan, J. A. Holmes, and E. A. Lazarus, "Shape Optimisation of Low-Aspect Ratio Tokamaks," paper 3B9 presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, April 6-8, 1987.

57. V. E. Lynch et al., "Optimization of the Bootstrap Current in Stellarators," paper 2D18 presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, April 6-8, 1987.

58. J. A. Rome, A. J. Spejewski, and S. P. Hirshman, "Stellarator Design by Surface Shape Optimization," *Bull. Am. Phys. Soc.* **32**, 1836 (1987).

59. E. R. Solano, J. A. Rome, and S. P. Hirshman, "Study of Transport in the Flexible Helic TJ-II," *Nucl. Fusion* **28**, 157-68 (1988).

60. R. M. Zubrin et al., "Considerations in the Design of Helic Reactors," *Bull. Am. Phys. Soc.* **32**, 1762 (1987).

61. J. J. Ramos, D. A. Spong, and D. J. Sigmar, "Alpha Particle Ballooning Mode Studies," *Bull. Am. Phys. Soc.* **31**, 1771 (1987).

62. D. A. Spong, D. J. Sigmar, and J. J. Ramos, "Modification of Tokamak Ballooning Stability Boundaries by Alpha Populations," *Fusion Technol.* **13**, 428 (1988).

63. D. A. Spong, D. J. Sigmar, and J. J. Ramos, "Stability Properties of Shaped Tokamaks with Energetic Alpha Populations," paper 2C23 presented at the 1987 Sherwood Theory Conference: Annual Controlled Fusion Theory Meeting, San Diego, Calif., April 6-8, 1987.

64. A. Bayliss, L. F. Ibáñez, and J. T. Hogan, "Classical Transport in Nonaxisymmetric Toroidal Magnetic Confinement Geometries," *Plasma Phys. Controlled Fusion* **29**, 957 (1987).

65. C. O. Beasley, Jr., et al., *Evaluation of Magnetic Coordinates in Finite-Beta, Asymmetric Plasmas*, ORNL/TM-10222, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., November 1987.

66. R. H. Fowler et al., "Benchmarks of Neutral Beam Injection Codes for Stellarators," presented at the U.S.-Japan Heliotron-Stellarator Workshop, Oak Ridge, Tennessee, November 9-13, 1987.

67. R. N. Morris et al., "Advanced Toroidal Facility Neutral Beam Injection: Optimization of Beam Alignment and Aperturing," *Fusion Technol.* **12**, 281 (1987).

68. S. A. Cohen et al., "Edge Dynamics in Pellet-Fuelled Inner-Wall JET Discharges," p. 694 in *Proceedings of the 14th European Conference on Controlled Fusion and Plasma Heating, Madrid, 1987*, Vol. II, 1987.

69. A. Gondhalekar et al., "Control of Density Profile and Particle Exhaust in JET," *Bull. Am. Phys. Soc.* **32**, 1838 (1988).

70. W. A. Houlberg, S. E. Attenberger, and S. L. Milora, "Pellet Ablation by Fast Hydrogen Ions and Alphas," *Bull. Am. Phys. Soc.* **32**, 1760 (1988).

71. W. A. Houlberg, S. L. Milora, and S. E. Attenberger, "Neutral and Plasma Shielding Model for Pellet Ablation," *Nucl. Fusion* **28**, 595-610 (1988); also published as ORNL/TM-10556, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., October 1987.

72. J. S. Tolliver, W. A. Houlberg, and S. E. Attenberger, "Plasma Performance and Density Profiles in 1-1/2-D ETR Transport Simulations with Pellet Injection and Pinch Terms," *Bull. Am. Phys. Soc.* **32**, 1370 (1988).

73. M. L. Watkins et al., "A Model for Pellet Ablation in JET," p. 201 in *Proceedings of the 14th European Conference on Controlled Fusion and Plasma Heating, Madrid, 1987*, Vol. I, 1987.

74. G. W. Hammett et al., "ICRF Modelling for CIT and TFTR," *Bull. Am. Phys. Soc.* **32**, 1922 (1988).

75. W. A. Houlberg, "Volt-Second Consumption in Tokamaks with Sawtooth Activity," *Nucl. Fusion* **27**, 1009 (1987); also published as ORNL/TM-10382, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., July 1987.

76. W. A. Houlberg, "Synchrotron Radiation Losses in CIT," CIT-P-870615-PPL-01, Princeton Plasma Physics Laboratory, Princeton, N.J., March 1987.

77. R. A. Dory, "Spreadsheets in Physics," *Computers in Physics* **2**, 70-74 (1987).

78. D. E. Greenwood, "SAMS—The Synchronization and Monitoring System for ATF Data Acquisition," *IEEE Trans. Nucl. Sci.* **NS-34**, 912 (1987).

79. K. L. Kannan and L. R. Baylor, "The ATF Data Management System," *IEEE Trans. Nucl. Sci.* **NS-34**, 921 (1987).

80. K. A. Stewart et al., "The Data Acquisition and Control Systems for ATF: An Overview," *IEEE Trans. Nucl. Sci.* **NS-34**, 739 (1987).

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Section 4

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PLASMA-MATERIALS INTERACTIONS

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P. K. Mioduszewski, Program Manager

T. S. Bigelow¹	D. L. Million⁴
R. E. Clausing²	R. N. Morris³
R. H. Fowler³	L. W. Owen³
J. C. Glowienka	T. F. Rayburn
L. Heatherly²	J. A. Rome⁴
D. L. Hillis	J. E. Simpkins
J. T. Hogan⁴	R. A. Strehlow²
C. C. Klepper	T. Uckan
R. A. Langley	K. G. Young⁴
R. T. McGrath⁵	

-
1. Plasma Technology Section.
 2. Metals and Ceramics Division.
 3. Computing and Telecommunications Division, Martin Marietta Energy Systems, Inc.
 4. Plasma Theory Section.
 5. Sandia National Laboratories, Albuquerque, N.M.

4. PLASMA-MATERIALS INTERACTIONS

SUMMARY OF ACTIVITIES

The Plasma-Materials Interactions Program addresses issues related to the interactions of hot plasmas with surrounding material surfaces. This includes wall conditioning procedures, studies of plasma-surface interactions, and implementation of impurity and particle control schemes. During the past year, activities were concentrated on preparation of wall conditioning techniques and plasma edge diagnostics for the Advanced Toroidal Facility (ATF), modeling and diagnostics preparation for the Tore Supra pump limiter, and H_α studies and preparation of a helium removal experiment on TEXTOR. Wall conditioning techniques in ATF include baking, glow discharge cleaning, electron cyclotron resonance (ECR) discharge cleaning, and gettering. For the first operational period of ATF, glow discharge and ECR discharge cleaning were employed. Mild baking was achieved during ECR discharge cleaning with 3 kW of power input. The progress of discharge cleaning was monitored with a computer-controlled residual gas analyzer. Plasma edge diagnostics prepared for the first phase of ATF operation include two instrumented limiters equipped with thermocouples and Langmuir probes, H_α monitors, charge-coupled device cameras, an infrared camera, an instrumented, movable divertor plate, and fast pressure gages.

The performance of a system of modular limiters for Tore Supra has been modeled in collaboration with Sandia National Laboratories, Albuquerque (SNLA). Limiters are being installed in a phased approach. An ATJ graphite limiter without pumping capabilities has been installed and will be used for the first six months of operation. It will be followed by a pyrolytic graphite limiter with a cooled base plate and pumping capability, which will also be used for about six months. Last, the fully cooled limiter head will be installed; it will tolerate high leading-edge fluxes and long pulse lengths. Diagnostics prepared for the pump limiter include fast pressure gages, an optical multichannel analyzer (OMA), and a high-heat-flux Langmuir probe (with SNLA). Data acquisition equipment, consisting of CAMAC hardware and a MicroVAX computer, and software for acquisition and analysis have been tested and shipped to Cadarache, France.

An array of six H_α detectors has been installed on TEXTOR for studies of particle confinement with the Advanced Limiter Test-II (ALT-II). First results have been obtained. A plan for the helium removal experiment with ALT-II has been developed in collaboration with the TEXTOR group. An OMA to be used for charge-exchange spectroscopy on helium has been purchased, tested, and shipped to TEXTOR.

4.1 WALL CONDITIONING IN ATF

P. K. Mioduszewski, R. A. Langley, J. E. Simpkins, T. S. Bigelow, and J. C. Glowienka

The Advanced Toroidal Facility (ATF) vacuum vessel has a surface area of 60 m^2 and a volume of approximately 10 m^3 . The pumping system comprises three turbomolecular pumps of 2200 L/s each; the effective pumping speed at the vessel is 2700 L/s for nitrogen. Typical global leak rates are $(1-5) \times 10^5 \text{ torr-L/s}$. Wall conditioning techniques in ATF include baking, glow discharge cleaning (G-DC), electron cyclotron resonance (ECR) discharge cleaning (ECR-DC), and gettering. For the initial operating phase, only G-DC and ECR-DC were used. Mild baking was achieved during ECR-DC with 3 kW of ECR input power.

Baking of the vessel to 150°C will be achieved by applying 440-V, 60-Hz power directly to the ATF helical windings.¹ The eddy currents induced in the vessel are estimated to produce 50 kW of Joule heating. In addition, ports and ducts will be heated by heating tapes. This baking system was not used during the initial operating period, but it has been installed and will be employed for the second operating period. Mild baking of the vessel to up to 50°C was achieved by 3 kW of ECR power during ECR-DC. Figure 4.1 shows a typical curve for the temperature of the vacuum vessel during and after overnight ECR-DC. When the power source is removed, the vessel temperature decays with a time constant of 40 min from an initial temperature of 50°C . This time constant becomes larger as the vessel temperature approaches ambient temperature.

Fig. 4.1. Typical wall temperature of the vacuum vessel during and after overnight ECR discharge cleaning.

For G-DC, a dc voltage of 500–800 V is applied to one stainless steel anode, which is inserted into the vessel. The total discharge current was measured to be 1–2 A. The glow can be initiated at 10–15 mtorr of hydrogen pressure and can be maintained in a stable condition at pressures as low as 0.5 mtorr. A 6-kW microwave source at a frequency of 2.45 GHz is used for ECR-DC. The necessary magnetic field at this frequency is 875 G, and the input power is typically 3 kW. Fill pressures of $(0.3\text{--}1) \times 10^{-4}$ torr of hydrogen are used.

The initial wall conditioning procedure consisted of several runs of G-DC (~12 h each), which removed mostly hydrocarbons and potential unipolar arcing sites, followed by ECR-DC every night and over weekends. Since G-DC was performed with the vacuum vessel at room temperature, the removal efficiency for water was very low. During ECR-DC the vessel temperature reached 50°C, and the water removal was somewhat more effective, although still very slow. Figure 4.2 shows some residual gas analyzer (RGA) data taken during a 14-h ECR-DC run. The figure shows the hydrogen, which is kept constant over the run, and the water and carbon monoxide levels, which decrease by approximately a factor of two. Baking the vessel at 150°C during the second operational period of ATF should greatly improve the water removal efficiency.

Fig. 4.2. RGA data taken during a 14-h ECR discharge cleaning run. The working gas (hydrogen) was kept constant; water (mass 18) and carbon monoxide (mass 28) decreased by a factor of two. The vessel temperature is shown in Fig. 4.1.

4.2 PLASMA EDGE STUDIES IN ATF

D. L. Hillis, T. Uckan, C. C. Klepper, P. K. Mioduszewski, and K. G. Young

A set of diagnostics is being prepared to study the configuration and parameters of the ATF edge plasma. Layout of the diagnostics system is guided by computer modeling of the plasma edge configuration. In a torsatron configuration such as ATF, the magnetic field configuration in the plasma edge forms stripes along which the plasma flows to the walls. Local plasma diagnostics are useful only when the global configuration is known. Therefore, imaging techniques will be used to determine the configuration of the edge plasma.

4.2.1 Imaging Techniques

Charge-coupled device (CCD) cameras with interference filters and an infrared (IR) camera, in combination with image-processing techniques, will be used to study plasma and energy flows in the edge. A schematic of the image acquisition and display hardware is shown in Fig. 4.3. The IR and CCD cameras, operated at the

Fig. 4.3. Schematic of the image processing acquisition and display system for ATF. A solid-state CCD camera (CCD) and IR cameras (IRC) are used to image the vessel wall and the plasma. Data from the cameras are digitized directly by a CAMAC module or a videocassette recorder (VCR). The images are redisplayed by a MicroVAX computer on television (TV) monitors.

standard video framing rate, are used to measure heat flux patterns to the vacuum vessel wall and visible light emission from the ionized plasma. These video cameras are coupled with fast acquisition and display systems, developed for a MicroVAX-II, which allow between-shot observation of the dynamic temperature and spatial extent of the plasma generated by ATF. The IR camera system provides acquisition of one 60×80 frame of 8-bit pixels every 16.7 ms via storage in a CAMAC module. The CCD data acquisition proceeds automatically, storing the video frames until its 12-bit, 1-megabyte CAMAC memory is filled. After analysis, transformation, and compression, selected portions of the data are stored on disk. Interactive display of experimental data and theoretical calculations is performed with software written in IDL (Interactive Data Language).

4.2.2 Instrumented Limiters

The instrumented limiter system in ATF, described in detail in ref. 2, consists of two modules, one at the top and one at the bottom of the vacuum vessel. Each module has a vertical stroke of 25 cm, and the toroidal separation between the two limiters is one field period, or 30° . The limiters are electrically insulated from the vacuum vessel and can be biased. Each module consists of 11 individual tiles, made of POCO AXF-5Q gas-purified graphite, mounted on a water-cooled stainless steel base plate. The tiles are shaped for constant heat deposition at a power flux e-folding length of 2 cm. They are equipped with thermocouples for measurements of the energy deposition profile and total deposited energy. The central tile incorporates Langmuir probes and a gas puff nozzle at the center. It can also be removed through a vacuum lock for materials studies.

The limiters will be used in conjunction with an IR camera, a visible spectrometer and a H_α detector to investigate the plasma edge. The system will provide radial and poloidal information on total energy deposition, time-resolved particle and power fluxes, and characteristic decay lengths during electron cyclotron heating (ECH) and neutral beam heating of plasmas. The limiter assembly is shown in Fig. 4.4.

4.2.3 Divertor Scoping Experiment

On Heliotron-E, plasma leaves the confined region in flux bundles ("divertor stripes") that cause localized heating and erosion on the vessel walls. To investigate this phenomenon in ATF and make use of the inherent divertor action, a large-diameter, movable graphite plate will be inserted in the vacuum vessel through one of the outboard horizontal ports ("Tennessee ports"). The arrangement is shown in Fig. 4.5(b). With top and bottom limiters removed, the particle and heat flow patterns on the graphite plate are measured with the CCD and IR cameras as functions of radial position. Inserting top and bottom limiters to the last closed flux surface and observing their influence on the flow patterns will provide information

ORNL-PHOTO 6143-87

Fig. 4.4. Photograph of the ATF instrumented limiter assembly.

on connection lengths in the edge plasma. Sufficiently long connection lengths will be a prerequisite for a modular divertor system.

4.2.4 Novel Langmuir Probe Techniques—Abstracts

4.2.4.1 “Asymmetric Double Langmuir Probe: Small Signal Application”³

T. Uckan

We discuss the asymmetric double Langmuir probe (ADLP) and demonstrate the possibility of using it to measure plasma temperature and density when it is

Fig. 4.5. Experimental arrangement of the divertor scoping experiment. (a) The plasma cross section with the instrumented limiters. (b) Cross section with the movable divertor plate.

operated in the region of small signal response. The area of one of the ADLP collectors is considerably larger than that of the other one. This probe can be operated at a relatively low applied voltage, $eV_a/T_e < 1$, and still provides sufficient information to determine plasma temperature and density. There is no need for a direct measurement of the ion saturation current, which can be on the order of a few amperes in a large fusion device. This reduces the requirements on the probe power supply.

4.2.4.2 "Asymmetric Double Langmuir Probe for Fast and Automatic Measurements of Plasma Temperature"⁴

T. Uckan

We present a fast technique for determining the plasma electron temperature T_e automatically from the small signal application of the ADLP when it is operated in the region where $-1 < eV_a/T_e < 1$. The method described here is based on simple time and rms averages of the probe current that results from a sinusoidally varying applied voltage V_a .

4.3 DIVERTOR CALCULATIONS FOR ATF

R. H. Fowler, R. N. Morris, and J. A. Rome

Particle flow from the well-confined plasma to the vacuum vessel wall has been studied by following field lines and particle orbits. A realistic multifilament model is used to compute the vacuum magnetic field, and a detailed model of the ATF vacuum vessel, including the ports, is used. The field lines and 1-keV particles were launched randomly in the poloidal and toroidal directions near the last closed flux surface. The field lines and particles are funneled by a natural divertor action and form narrow stripes on the vessel wall. The stripes are very similar for the field lines and 1-keV particles. Most particles intercept the walls tangentially. However, particles that enter the ports often hit perpendicularly. Figure 4.6 shows the field hits on the vacuum vessel as functions of the poloidal and toroidal angles for one field period. The solid lines are the outlines of the ports, the small crosses illustrate the coil troughs, and the markers represent the wall hits. The stripes expected on the divertor plate at the major radius position of 270 cm are shown in Fig. 4.7.

4.4 NEUTRAL PARTICLE TRANSPORT MODELING IN PUMP LIMITERS

L. W. Owen and P. K. Mioduszewski

The design of an efficient particle and heat removal system for steady-state operation of ATF requires knowledge of plasma transport in the scrapeoff layer (SOL) and neutral transport within the divertor/pump limiter chamber. The neutral particle and plasma transport are coupled through plasma-neutral interactions, particularly in the high neutral density environment surrounding limiters. The neutral particle transport code DEGAS, developed at Princeton Plasma Physics Laboratory (PPPL), and a simple one-dimensional (1-D) plasma fluid transport code are used in the design studies.

The extensive database of Langmuir probe and pressure measurements from the pump limiter experiment on the Impurity Study Experiment (ISX-B) was used

Fig. 4.6. Modeling of the magnetic field in the plasma edge. Interceptions of the field lines with the vacuum vessel are shown as a function of poloidal and toroidal angles for one field period.

Fig. 4.7. Field line interceptions on the divertor plate at $R = 270$ cm, forming "divertor stripes."

to benchmark DEGAS. This exercise was very productive in revealing key issues for improving both the modeling and the experimental diagnostics. Excellent agreement with the measured neutral pressure in the pump was obtained for high-temperature ($T_e > 30$ eV in the SOL), low-density ($n_e = 1 \times 10^{13} \text{ cm}^{-3}$) discharges. Lack of neutral pressure equilibrium in the pump, because of short discharge duration, precluded a meaningful comparison of calculated and measured pressures for high-density ($n_e > 2 \times 10^{13} \text{ cm}^{-3}$) discharges.

The ISX-B pump limiter was instrumented with two Langmuir probes, one on the entrance slot and one at the neutralizer plate. Typically, for high-density discharges in which the pump was inactive, the ion saturation current measured by the entrance probe was approximately a factor of two higher than that measured by the plate probe. The importance of resolving the origin of this difference led to a reexamination of the analysis of Langmuir probe data when the probe connection length is less than the ion collisional mean free path, with the result that the plasma densities inferred from the two probes are in reasonable agreement.

An important uncertainty in the interpretation of Langmuir probe data lies in the determination of the plasma flow velocity. A 1-D (parallel to the magnetic field) fluid transport code that solves the particle, momentum, and energy balance equations for the density, flow velocity, and electron and ion temperatures in the throat of a pump limiter has been developed and will be run iteratively with DEGAS. In this way, the characteristics of the plasma, as well as the neutral flow from and within the pump limiter/divertor chamber, can be estimated. The code will be generalized to include impurity flows and cross-field diffusion in the SOL.

4.5 INTERNATIONAL COLLABORATIONS ON PUMP LIMITERS

4.5.1 Tore Supra

C. C. Klepper, T. Uckan, P. K. Mioduszewski, and L. W. Owen

Details of the Tore Supra pump limiter experiments are given in ref. 5. ORNL is responsible for the experimental pump limiter program, and Sandia National Laboratories of Albuquerque (SNLA) is responsible for design and fabrication of the outboard module.

4.5.1.1 Modeling

During the past year, modeling and optimization of the performance of a system of modular limiters (in collaboration with SNLA) have been concluded. To predict the performance of one individual limiter module, neutral transport modeling with the DEGAS code was applied to the outboard pump limiter. For a particle flux into the pump limiter of $4 \times 10^{19} \text{ cm}^{-2} \cdot \text{s}^{-1}$ and an e-folding length of 1.6 cm for the particle flux, typical pressures of 2 mtorr were predicted in a realistic geometry.

4.5.1.2 System Definition: Abstract of "Modular Pump Limiter Systems for Large Tokamaks"⁶

T. Uckan, C. C. Klepper, P. K. Mioduszewski, and R. T. McGrath

Long-pulse (>10 -s) operation of large tokamaks with high-power (>10 -MW) heating and extensive external fueling will require correspondingly efficient particle exhaust for density control. A pump limiter can provide the needed exhaust capability by removing a small percentage of the particles which would otherwise be recycled. Single pump limiter modules have been operated successfully on ISX-B, the Poloidal Divertor Experiment (PDX), TEXTOR, and the Princeton Large Torus (PLT). An axisymmetric pump limiter is now being installed and will be studied in TEXTOR. A third type of pump limiter is a system that consists of several modules and exhibits performance different from that of a single module. To take advantage of the flexibility of a modular pump limiter system in a high-power, long-pulse device, the power load must be distributed among a number of modules. Because each added module changes the performance of all others, a set of design criteria must be defined for the overall system. The design parameters for the modules are then determined from the system requirements for particle and power removal. Design criteria and parameters are presented, and the impact on module design of the state of the art in engineering technology is discussed. The relationships between modules are considered from the standpoint of flux coverage and shadowing effects. The results are applied to the Tore Supra tokamak. A preliminary conceptual design for the Tore Supra pump limiter system is discussed, and the design parameters of the limiter modules are presented.

4.5.1.3 Fabrication

Fabrication of the horizontal module has presented some problems. To dissipate 3 kW/cm^2 in steady state, it was necessary to braze pyrolytic graphite to dispersion-hardened copper ("Glidcop") tubes, which turned out to be very difficult. To allow for more testing and to provide a reliable technique, it was decided to phase the pump limiter program. An uncooled ATJ graphite head without pumping capability will be used as a startup limiter for the first six months of operation. It will be replaced by a pyrolytic limiter head with cooling at the base plate only and pumping capability for the second six months. Finally, the full-performance limiter with pumping and stationary cooling during the discharge will be installed. The ATJ startup limiter had been installed at the end of this reporting period; first plasma is expected in March 1988.

4.5.1.4 Diagnostics and Data Acquisition

Global diagnostics for the pump limiter module include pressure gages for the total particle flux and water calorimetry for the total heat flux to the limiter module. For pressure measurements, Shultz-Phelps gages will be used. They will have

custom-made controllers with provisions for fast time response, buffered output for long cables, remote filament operation, and remote pressure range sensors.

For local measurements of the particle flux into the pump limiter throat, the neutralizer plate will be imaged onto a detection system that consists of a spectrometer/multichannel analyzer controlled via CAMAC by a MicroVAX computer. The system is fully developed and tested. For data acquisition and analysis, CAMAC hardware and a MicroVAX computer with two 70-megabyte hard disks have been equipped with all necessary software, tested, and shipped to Tore Supra.

4.5.2 TEXTOR

D. L. Hillis, T. Uckan, J. T. Hogan, C. C. Klepper, L. W. Owen, and P. K. Mioduszewski

4.5.2.1 H_α Measurements

During the past year, six H_α detectors have been fabricated and tested at ORNL and installed in TEXTOR. The goals of the H_α studies are to measure the total particle efflux from the plasma and to determine the global particle confinement time and its correlations with confinement regime and other plasma parameters. Because of the poloidal and toroidal asymmetries of in-vessel components, an array of six detectors has been installed to cover all major asymmetries of particle fluxes. Typical raw data for H_α intensities, along with the line-averaged density, are shown in Fig. 4.8. The data represent the particle fluxes to the wall and to the limiter blade. The global particle confinement time estimated from these data is 80 ms.

4.5.2.2 H_α Modeling

To obtain a more complete picture of the particle fluxes, neutral densities, and source rates, the H_α emission is modeled with the neutral transport code DEGAS. Figure 4.9 shows an initial modeling result for the H_α emission rate at the ALT-II limiter blade. The input is the parallel ion flux to the blade. The emission rate must be integrated along the observation chord in order to obtain the H_α light received by the detector. This work is in progress.

Detailed modeling of the H_α light distribution, including contributions due to the breakup of hydrocarbons (which may be important in carbonized machines), has been initiated with a three-dimensional Monte Carlo simulation of the neutral gas deposition. Before the code was applied to TEXTOR data, it was benchmarked with H_α data from the Texas Experimental Tokamak (TEXT).

It is a commonplace that particle confinement times increase with density in gas-fueled tokamaks at low density, then decline as the density is further increased. The usual interpretation of this behavior is that the opacity of dense plasma to neutrals localizes the ionization processes to the outer extremes of the confinement

Fig. 4.8. Typical traces of H_{α} emission and line-average density in TEXTOR as a function of time.

zone, leading to particle deposition in a regime with anomalous conduction losses. Hence, the fueling efficiency is lowered.

It should be noted that no direct experimental evidence has been presented for this localization behavior. Using the Monte Carlo model, we were able to fit poloidally resolved H_{α} profiles and to determine the flux-surface-averaged ionization source that enters the determination of the particle confinement time. As a result, we can determine the gas fueling efficiency in these discharges. Figure 4.10 shows the results of the modeling fitted to a TEXT density scan. In order to fit the data, it was necessary to assume that the incoming neutral energy was raised along with the plasma density. This assumption will be tested in experiments using detailed spectroscopic observations on TEXTOR, and the dependence of the radial diffusivity $D(r)$ will be extracted from the data.

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Fig. 4.9. Modeling of the H_α emission rate at the ALT-II limiter blade. Input is the parallel ion flux to the blade. (a) Poloidal grid. (b) H_α emission rate as a function of poloidal angle.

Fig. 4.10. Monte Carlo fit to H_{α} brightness for a TEXT density scan. Solid lines are the data; dashed lines, the numerical results. Brightness is shown as a function of major radius, for a viewing station 90° from the main limiter.

4.5.2.3 Helium-Removal Experiment

One goal of the ALT-II program is to assess the suitability of a pump limiter for helium ash exhaust in a fusion reactor. An experimental plan has been proposed and agreed upon with the TEXTOR group. In the first stage, helium in the plasma edge will be measured with the TEXTOR 30 keV lithium beam. In the second stage, a diagnostics/data acquisition system consisting of an optical multichannel analyzer

(OMA) and a MicroVAX computer will be installed to carry out charge-exchange spectroscopy of the central helium with the TEXTOR neutral beam injection system. Initial experiments with the lithium beam and preparation of the diagnostics have begun during this reporting period. The experimental arrangement of the lithium beam on the TEXTOR device⁷ is shown in Fig. 4.11.

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Fig. 4.11. Experimental arrangement of the 30-keV lithium beam on the TEXTOR device.

4.6 PLASMA-SURFACE INTERACTIONS

4.6.1 Graphite Outgassing Studies—Abstract of “Outgassing Properties of Various Graphites”⁸

J. E. Simpkins, P. K. Mioduszewski, and R. A. Strehlow

Thermal outgassing of graphite is of importance to experimental fusion devices because of its use in limiters and as a first wall material. Several commercial graphites have been studied with respect to their outgassing properties over the temperature range from 150°C to 1500°C. The apparatus uses induction heating with controlled feedback to permit a polythermal analysis to be conducted. Samples of GraphNol, Carbonne Lorraine, POCO, Stackpole 2020 graphites, and

carbon-carbon composites have been studied both in the "as received" condition and following purification or degassing and re-exposure to atmospheric contaminants. Compositions of the evolved gases have been found to vary significantly for different graphites during outgassing. This and differences in outgassing behavior are discussed in terms of surface complexes formed on graphite exposed to different atmospheres.

4.6.2 Graphite Conditioning and Recycling Experiments—Abstracts

4.6.2.1 "Helium-Ion-Induced Release of Hydrogen from Graphite"⁹

R. A. Langley

The ion-induced release of hydrogen from AXF-5Q graphite was studied for 350-eV helium ions. The hydrogen was implanted into the graphite with a low energy (~ 200 eV) and to high fluence. This achieved a thin (~ 10 -nm), saturated near-surface region. The release of hydrogen was measured as a function of helium fluence. A model that includes ion-induced detrapping, retrapping, and surface recombination was used to analyze the experimental data. A value of $(1.65 \pm 0.2) \times 10^{-16}$ cm² was obtained for the detrapping cross section, and a value of 0.5×10^{-14} cm⁴/s was obtained for the recombination coefficient. The hydrogen depletion depth was estimated to be 0.8 nm.

4.6.2.2 "Hydrogen Recycle from Graphite"¹⁰

R. E. Clausing and L. Heatherly

Understanding hydrogen recycle is critical to hydrogen density control in fusion experimental devices. Hydrogen recycle has been measured in the Recycle, Impurity, and Conditioning Simulator (RICS) plasma interaction simulator for both transient and steady-state conditions at temperatures from 50 to 350°C. Transient recycle coefficients range from less than 0.3 to more than 2, depending primarily on temperature, ion energy, and the plasma exposure immediately preceding the measurement. The amount of hydrogen readily available in the near surface to interact with the plasma bombardment is from 10^{16} to 10^{17} cm⁻². The initial recycle behavior changes considerably until the hydrogen ion fluence exceeds a few times 10^{16} cm⁻². After this initial conditioning has occurred, the short-term recycle behavior is similar to that of dense carbon films. The steady-state recycling from graphite is strongly influenced by the continuing formation of dense carbon films containing large amounts of hydrogen. These data help to explain, predict, and design the operation of present and future fusion machines.

4.6.2.3 Hydrogen Recycle and Isotope Exchange from Dense Carbon Films¹¹

R. E. Clausing and L. Heatherly

Dense carbon films were prepared by deposition from hydrogen plasmas to which methane was added. The initial hydrogen recycle coefficient from the films ranges from more than two to less than one. The films contain large amounts of hydrogen (up to 50 at. %). They adjust themselves to provide recycling coefficients near unity. Isotope changeover times tend to be long. The reservoir of hydrogen instantly available to the plasma to maintain or stabilize the recycle coefficient and isotopic composition of the plasma is 10^{15} cm^{-2} or greater depending on film preparation, temperature, and prior plasma exposure conditions. Simulator observations tend to support and improve the understanding of the observations in TEXTOR and the Joint European Torus (JET); however, they also point out the need for control of film deposition and operating parameters to provide desirable and reproducible properties. The films and the hydrogen isotopes they contain can be removed easily by plasma processes. Since the hydrogen in these films is relatively immobile except in the zone reached by energetic particles, or at temperatures above 400°C , dense carbon films may be useful in managing tritium recovery from near-term fusion experiments.

4.6.2.4 Graphite for Fusion Applications¹²

W. P. Eatherly,* R. E. Clausing, R. A. Strehlow, C. R. Kennedy,* and P. K. Mioduszewski

This report presents a consideration of graphite for fusion applications and makes specific recommendations of graphite grades or types. Graphite manufacture and properties are discussed to provide a rationale for the recommendations.

The plasma environment for possible fusion applications is reviewed. Considerations of energy deposition, leading to high temperatures along with significant thermal cycling, lead to requirements for high thermal-shock resistance, in addition to the low vapor pressure of solid carbon. Various phenomena are surveyed to provide a basic selection of properties for discussion.

The statistical character of graphite and its properties are surveyed with an emphasis on the non-Gaussian distribution of important properties such as fracture stress. The manufacture of graphite and the nature of graphite grades or types are discussed. A number of graphite properties that can be varied by manufacturing techniques are described. Graphite grades are recommended based on their properties, availability, and the extent of their databases. The use of a database in writing specifications for graphite is then discussed.

Chemical and surface properties are discussed with an emphasis on the surface properties, because of the large surface area of graphite relative to metals and other structural materials. The role of surface complexes and the reactions of graphite with hydrogen isotopes are described. Although the role of impurities is not clear

for fusion applications, their presence is possibly significant and also is described briefly.

Neutron damage and other radiation damage are not of pressing interest for near-term fusion applications. Irradiation damage would bear on longer-term applications and, consequently, is discussed briefly.

Graphite is seen to comprise a set of materials with a number of properties that can be controlled and adjusted over a wide range by the manufacturing process. This leads to specific recommendations for the application of graphite in fusion energy devices.

*Metals and Ceramics Division.

REFERENCES

1. R. A. Langley et al., "Vacuum Vessel Heating System for ATF," *J. Vac. Sci. Technol. A* **6** (3), 1288 (1988).
2. D. L. Hillis et al., "Plasma Edge Characterization: Diagnostics for ATF," pp. 178-81 in *Fusion Energy Division Annual Progress Report for the Period Ending December 31, 1986*, ORNL-6332, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., 1987.
3. T. Uckan, "Asymmetric Double Langmuir Probe: Small Signal Application," *Rev. Sci. Instrum.* **58**, 2260 (1987); also published as ORNL/TM-10391, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., November 1987.
4. T. Uckan, "Asymmetric Double Langmuir Probe for Fast and Automatic Measurements of Plasma Temperature," *Rev. Sci. Instrum.* **59**, 198 (1988); also published as ORNL/TM-10436, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., November 1987.
5. C. C. Klepper, P. K. Mioduszewski, and T. Uckan, "Diagnostics for the Tore Supra Pump Limiters," pp. 186-9 in *Fusion Energy Division Annual Progress Report for the Period Ending December 31, 1986*, ORNL-6332, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., 1987.
6. T. Uckan et al., "Modular Pump Limiter Systems for Large Tokamaks," *Fusion Technol.* **13**, 165 (1988); also published as ORNL/TM-10164, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., September 1987.
7. H. L. Bay et al., *First Direct Measurements of Low-Z Ion Concentrations in TEXTOR Using a High-Current Li-Injector*, Jül-2139, KFA Jülich, Jülich, Federal Republic of Germany, July 1987.
8. J. E. Simpkins, P. K. Mioduszewski, and R. A. Strehlow, "Outgassing Properties of Various Graphites," presented at the 34th National Symposium and Topical Conference of the American Vacuum Society, Anaheim, Calif., November 2-5, 1987.
9. R. A. Langley, "Helium-Ion-Induced Release of Hydrogen from Graphite," *J. Vac. Sci. Technol. A* **6** (3), 2119 (1988).
10. R. E. Clausing and L. Heatherly, "Hydrogen Recycle from Graphite," presented at the 34th National Symposium and Topical Conference of the American Vacuum Society, Anaheim, Calif., November 2-5, 1987.
11. R. E. Clausing and L. Heatherly, *Hydrogen Recycle and Isotope Exchange from Dense Carbon Films*, ORNL/TM-10310, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., March 1987.
12. W. P. Eatherly et al., *Graphite for Fusion Energy Applications*, ORNL/TM-10280, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., March 1987.

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Section 5

PLASMA TECHNOLOGY

H. H. Haselton, Section Head
D. W. Swain, Assistant Section Head

M. A. Akerman	S. C. Forrester	K. E. Rothe ¹
B. E. Argo	C. A. Foster	P. M. Ryan
S. E. Attenberger ¹	C. R. Foust	D. E. Schechter
F. W. Baity	W. L. Gardner	G. L. Schmidt ¹⁴
G. C. Barber	F. E. Gethers	D. D. Schuresko
V. E. Barnes	M. J. Gouge	R. C. Shanlever ³
D. E. Bartine ²	R. H. Goulding	G. T. Sherrod ¹⁵
L. R. Baylor ³	J. T. Greer	W. D. Shipley ³
P. F. Becher ⁴	G. R. Haste	D. W. Simmons
W. R. Becraft ⁵	P. P. Helton	F. Sluss
S. A. Bell	D. J. Hoffman	C. W. Sohns ¹⁶
T. S. Bigelow	W. A. Houlberg ¹¹	D. O. Sparks
R. A. Brown ⁶	H. T. Kerr ²	K. A. Stewart ¹¹
W. E. Bryan ³	H. E. Ketterer ¹	W. L. Stirling
J. L. Burke ⁷	H. D. Kimrey	C. K. Thomas ⁷
P. B. Burn ⁸	M. Kwon ¹²	D. H. Thompson ³
R. D. Burris ¹	R. L. Livesey	P. B. Thompson ³
E. J. Byrnes ⁸	J. B. Mankin ¹	C. C. Tsai
J. B. O. Caughman ⁹	B. S. Maxon ³	D. J. Webster ³
G. L. Chen	T. J. McManamy ³	E. R. Wells ⁷
S. K. Combs	P. S. Meszaros ¹	J. H. Whealton
J. F. Cox	S. L. Milora	G. A. White
W. K. Dagenhart	J. A. Moeller ⁵	T. L. White
E. G. Elliott	L. E. Morris ⁷	J. C. Whitson ¹
A. G. Evers	T. L. Owens ¹³	R. E. Wright
A. Fadnek	R. J. Raridon ¹	R. B. Wysor ³
P. W. Fisher ¹⁰	P. F. Rice	

1. Computing and Telecommunications Division, Martin Marietta Energy Systems, Inc.

2. Engineering Technology Division.

3. Engineering Division, Martin Marietta Energy Systems, Inc.

4. Metals and Ceramics Division.

5. Grumman Aerospace Corporation, Bethpage, N.Y.

6. Magnetism and Superconductivity Section.

7. Management Services Section.

8. Quality Department.

9. University of Illinois, Champaign.

10. Chemical Technology Division.

11. Plasma Theory Section.

12. Georgia Institute of Technology, Atlanta.

13. McDonnell Douglas Astronautics Company, St. Louis.

14. Princeton Plasma Physics Laboratory, Princeton, N.J.

15. Purchasing Division, Martin Marietta Energy Systems, Inc.

16. Instrumentation and Controls Division.

5. PLASMA TECHNOLOGY

SUMMARY OF ACTIVITIES

During 1987, the Plasma Technology Section placed increased emphasis on applications, with several large projects either completed or under way. Substantial progress was also made in technology development.

In the plasma fueling program, a significant portion of the work accomplished was related to international collaborations. This includes the delivery (one month ahead of schedule) and commissioning of a three-barrel repeating pneumatic pellet injector for the Joint European Torus (JET) in Culham, England, and the continuing work on the centrifugal injector for the Tore Supra tokamak in Cadarache, France. Initial results from JET experiments with the pellet injector have been very encouraging, with peak densities of $1.2 \times 10^{20} \text{ m}^{-3}$ achieved in ohmically heated discharges. Highlights of the plasma fueling development efforts include the completion and testing of the Tritium Proof-of-Principle pneumatic injector at ORNL and its installation on the Tritium Systems Test Assembly at Los Alamos National Laboratory, in support of deuterium-tritium operation on the Tokamak Fusion Test Reactor (TFTR). In addition, development work on advanced pellet acceleration methods continued with the construction of an electron-beam rocket pellet accelerator and the design and fabrication of a two-stage pneumatic gun.

As part of the rf technology program, a 4-MW compact loop antenna for heating in the ion cyclotron range of frequencies (ICRF) was constructed for use on TFTR. This antenna incorporates several advanced features, including a resonant double loop design, which provides integral matching, and a Faraday shield clad with graphite tiles. The antenna was tested in the ORNL Radio-Frequency Test Facility and delivered to Princeton Plasma Physics Laboratory in November 1987. In addition, design work was completed and component fabrication began on an ICRF antenna to be used on Tore Supra. This compact loop antenna, designed to operate for pulses of $>30 \text{ s}$, will incorporate several actively cooled components, including current straps and bumpers. As part of an experiment to investigate ways of improving ICRF coupling to plasmas during H-mode operation, the ORNL prototype cavity antenna on the Doublet III-D (DIII-D) tokamak at GA Technologies, San Diego, was returned to ORNL in November for simple modifications. These modifications were predicted to increase plasma loading, and the power-handling capabilities of the design, by a factor of 2. The antenna was reinstalled on DIII-D in December, with experiments scheduled to resume in January. Development work in the rf group included the construction and successful low-power testing of a full-size folded waveguide ICRF antenna, operating in the frequency range of 80-140 MHz. In addition, a successful effort was mounted to improve brazing techniques for graphite-clad Faraday shield tubes and to test the finished samples.

Negative ion source development for high-energy neutral particle beams also continued in 1987. A new source that uses transverse extraction of negative ions, VITEX-II, is being assembled. This source incorporates an internal magnetic field that makes it possible to drastically reduce the number of electrons extracted with the negative ions. Extraction currents of 50 to 100 mA of H^- are expected at a current density of 30 mA/cm². A Ringatron source, which uses longitudinal extraction, is now being fabricated. This design should produce a larger volume for negative ion formation and yield improvements in current density and brightness.

The Plasma Technology Section's modeling group provides modeling and computational support to the other groups in the section. A two-dimensional magneto-static code was developed to model compact loop antennas. Results from the code agreed very well with experimental measurements, and the code is being used to optimize compact loop antenna design. Other work in support of the rf program included modeling of folded waveguide antennas, high-power vacuum feedthroughs, and resonant coaxial structures. Modeling of a high-current-density electron beam interacting with a magnetic focusing field was undertaken in support of the electron-beam rocket pellet accelerator experiment in the plasma fueling group. The results were used to design the magnetic field coils for this experiment. The dynamics of intense beams, including nonlinear space charge and image charges, was studied for several accelerator subsystems of interest. The modeling group also provided extensive support to the negative ion source work in areas that included modeling sources and neutral beam current drive. A unique physics model developed for this work appears to provide, for the first time, reasonable agreement with experimental results and reliable predictions of experimental outcomes.

In summary, during 1987 the Plasma Technology Section continued to make important contributions in plasma heating and fueling technology to the magnetic fusion programs of the United States and other countries. The section's level of involvement with the Compact Ignition Tokamak and International Thermonuclear Engineering Reactor programs ensures the significance of its role in the years to come.

5.1 PLASMA FUELING PROGRAM

S. L. Milora

The ORNL Fueling Program has continued to play a major role in the magnetic fusion program in the United States and abroad. The research and development activities of the group continued along traditional lines with emphasis on two areas:

1. Continued development of the centrifuge and pneumatic pellet injector concepts, as embodied by construction of an advanced centrifuge device for the Tore Supra tokamak at Cadarache, France, completion of a new tritium pellet injector (TPI) facility to test tritium pellet fabrication and acceleration in

support of the deuterium-tritium (D-T) phase of operations on the Tokamak Fusion Test Reactor (TFTR) at Princeton Plasma Physics Laboratory (PPPL), and completion and commissioning of a new three-barrel repeating pneumatic injector for the Joint European Torus (JET) at Abingdon, England.

2. Development of advanced pellet injectors to explore the potential for pellet speeds above 2 km/s in anticipation of more demanding applications, such as the Compact Ignition Tokamak (CIT) and the International Thermonuclear Experimental Reactor (ITER). In this area, the plasma fueling group is pursuing several high-speed options, including a unique electron-beam (e-beam) rocket accelerator, the electrothermal gun, and the two-stage light gas gun.

In addition to pellet injector development, the group has increased its support role in magnetic fusion programs in the United States and abroad that include pellet injectors supplied by ORNL. Most notable in this area for 1987 were major collaborations with PPPL on TFTR, featuring the deuterium pellet injector (DPI) installed in 1986; with the JET Joint Undertaking, featuring the new three-barrel JET pellet injector (JPI) that was installed in April 1987; and with the Commissariat à l'Energie Atomique (CEA), featuring the Tore Supra centrifuge device, which is scheduled for delivery to the Tore Supra site in June 1988. The ORNL Plasma Fueling Program provides both operational support and expertise to these experimental programs through visits and assignment of staff to the collaborating laboratories.

5.1.1 Pellet Injector Development

5.1.1.1 Hydrogen electrothermal accelerator for plasma fueling

D. D. Schuresko

The development of a high-velocity pneumatic pellet accelerator, which operates with hydrogen plasma propellant, is aimed at extending the performance of present-day pneumatic pellet injectors to velocities of 2 to 5 km/s. A prototype accelerator, consisting of a vortex-stabilized arc discharge plasma generator coupled to the breech tube of a "pipe-gun" pneumatic pellet injector, has been developed and operated. The arc chamber is designed for arc initiation at 1 to 4 bar and is constructed from high-temperature materials. Electrical power is supplied to the arc from a capacitor bank supply and from an LC-line/pulse transformer supply that can produce 1-ms pulses at 5-kA currents into 0.1- Ω loads. The arc is triggered as hydrogen gas is admitted into the arc chamber; the ohmic dissipation increases the rate of rise of the gun breech pressure from 30 bar/ms to >100 bar/ms. Muzzle velocities increase from 1.3 km/s to 2.0 km/s for 10-mg hydrogen pellets; these increases represent conversion of 5 to 10% of the electrically dissipated energy to projectile kinetic energy. Technical progress has included

1. design and construction of the seven-stage pulse-forming network/transformer supply;

H₂ PELLETS

Fig. 5.2. Pellet diagnostics demonstrating the survival of H₂ pellets even with increased acceleration and shocks.

proposed a few years ago. Theoretical evaluation reveals that a practical device can be developed to perform the desired goals.

In the conceptual design, the mature technology of pellet extruder, electron gun, and electromagnet has been used for the α -beam accelerator development; however, the main uncertain factors affecting the device operation, such as the burn velocity of the hydrogen propellant stick and the heating of the exhaust gas, need to be

studied. To develop a practical and efficient pellet accelerator, a proof-of-principle (POP) device has been designed and fabricated for demonstrating pellet acceleration and studying these dominant factors.

The POP e-beam pellet accelerator (Fig. 5.3) consists of a pipe-gun-type pellet fabricator, an electron gun, a pellet accelerating column (including guide rails), and a set of axial magnets for e-beam compression and confinement. The design and development activities have been pursued with excellent progress. Computer modeling (see Sect. 5.4.2) confirms that the axial magnets can compress electron beams to achieve a current density above 300 A/cm^2 and contain the intense electron beam along the guide rails in the pellet acceleration column. The pellet fabrication and loading device has been operated reliably to produce pellets 4 mm in diameter by 12 mm long. Electron gun qualification has been initiated for forming 1-MW, 30-keV electron beams. The Medium-Energy Test Facility high-voltage supplies and switching tubes have been used to power the electron gun. The preliminary results are encouraging. For example, the gun has delivered high-density ($>70 \text{ A/cm}^2$) electron beams even without magnetic field compression. The continuous-wave (cw) graphite heater can heat a 2.5-cm-diam cathode to a temperature above 2000 K. Such a cathode has the potential to produce electron beams with several

OPRL DNG 87-3003 PED

Fig. 5.3. Design of the POP e-beam pellet accelerator.

hundred amperes. Thus, this cathode is suitable for the CIT-ITER class of e-beam pellet accelerator. The coils for the axial magnets have been fabricated and will be assembled soon.

5.1.1.3 Tritium proof-of-principle pellet injector

P. W. Fisher and S. L. Milora

The tritium POP (TPOP) injector is a pneumatic injector that uses the pipe-gun concept to freeze pellets directly in the injector barrel. The pipe gun is particularly good for tritium work because no excess tritium is needed to produce the pellet.

Figure 5.4 is a photograph of the apparatus. The glovebox at left contains the entire gun and gas handling system, which was designed and built for tritium service. The controls at right provide both manual and automatic operation of the entire system in the glovebox. Automatic controls are handled with an IBM PC-AT computer, and fast data acquisition is handled by a CAMAC system and a MicroVAX II computer.

ORNL-PHOTO 8853-87

Fig. 5.4. The TPOP system.

The system was completed and tested by ORNL in the autumn of 1987 and then shipped to Los Alamos National Laboratory and installed in the Tritium Systems Test Assembly in January 1988. While at ORNL, it was operated for several months just as it will be operated during tritium service. During this period, some 800 pellets were produced, and velocities of 1790 m/s were achieved with deuterium pellets. These results indicate that the TFTR and CIT requirement for 1500-m/s tritium pellets will be achievable with existing fast-valve technology.

5.1.1.4 Pneumatic acceleration

S. K. Combs, M. J. Gouge, and S. L. Milora

A generic pneumatic development facility has been equipped with the components required to carry out a wide range of research for pneumatic pellet injection; these components include vacuum systems, test chambers, hydrogen and deuterium feed systems, standard instrumentation (temperature controllers, etc.), and injector lines with data analysis tools (speed detectors and photographic stations). The prototype repeating injector¹ (previously used in initial fueling experiments on TFTR) has provided and will continue to provide a pneumatic test bed for repetitive gun concepts, such as those now applicable for JET and those needed for future applications (e.g., CIT and ITER). The facility will also support pipe-gun development aimed at the Princeton Beta Experiment, the Advanced Toroidal Facility (ATF), and, if needed, the TFTR TPI applications. The facility will also be used to investigate pneumatic techniques for achieving moderate increases in pellet speeds that can easily be retrofitted to TFTR and JET and used on future devices.

Recent efforts have concentrated on development of higher-pressure propellant valves for accelerating frozen hydrogen isotopes. The prototype valve² (Fig. 5.5) was developed for the repeating pneumatic injector (RPI) and was designed for 138 bar (2000 psi); this design has been used on all recent ORNL pneumatic injection systems. In recent tests, a modified valve with an enhanced power supply has performed at pressures of up to 221 bar (3200 psi), and data suggest that operation at even higher pressure can probably be achieved with minor design changes (the test limit of the facility is 345 bar). A new valve design can easily be retrofitted to existing systems (e.g., on JET, TFTR, or TPOP) to provide higher pellet speeds; extrapolations of experimental data suggest that speeds of ≥ 2 km/s are likely with deuterium pellets at an operating pressure of ≤ 345 bar (5000 psi). The inherent potential of this technology will be evaluated during 1988.

For investigating even higher pellet velocities, a small-scale, two-stage light gas gun is under construction (Fig. 5.6). The generic pneumatic facility provides most of the necessary tools for this research. The first stage (pump tube) consists of a 1.9-cm-diam piston with a 1-m acceleration length; the pellet, or projectile, is accelerated in a 1-m-long gun barrel. The initial objective is to demonstrate velocities in the 3.0-km/s range. Reliable, repetitive, high-velocity systems will eventually be required for fueling applications; this represents an extension of the repetitive pellet

Fig. 5.6. Schematic of two-stage light gas gun.

injection work that ORNL has been conducting since the early 1980s.¹ The performance, design, materials, and other elements of the system must be optimized to ensure the high level of reliability that is needed for fueling applications on future large tokamak devices. The two-stage, light gas gun concept is inherently capable of accelerating 10- to 50-mg pellets to velocities over 10 km/s, as demonstrated over the past 30 years in various hypervelocity research programs with room-temperature projectiles. Long-range goals of the two-stage, light gas gun effort are to determine inherent limits on pellet structure strength, to optimize pump tube piston motion to obtain near-constant acceleration at the limit of pellet integrity, and to design practical sabots for higher acceleration levels. This research will be conducted initially with single-shot, two-stage pipe guns.

In addition to the hardware development, several theoretical models have been implemented to interpret results from single- and two-stage pneumatic test facilities and to provide guidance on design of future development hardware. A Lagrangian interior ballistics code obtained from the Arnold Engineering Development Center (AEDC) has the following features.

- The code uses a Lagrangian formulation of the finite difference representation of the one-dimensional differential equations of continuity, motion, and energy.
- Shocks that form in the pump tube and barrel are treated by the artificial viscosity method of von Neumann and Richtmyer, which spreads out shocks due to dissipative effects such as viscosity and heat conduction.
- The code can model either real (variable specific heat) or ideal gases.
- Nonideal effects, such as piston friction and deformation, heat transfer from gas to wall, and smooth-wall or constant-factor gas friction, can be included.

The code models single-stage empirical results within 5 to 10% (Fig. 5.7) and predicts the performance of projectiles accelerated on the AEDC two-stage test range to within 5 to 8%. These numerical tools provide a valuable and efficient method for the design of future upgrades to single-stage light gas guns and for initial work on two-stage light gas guns.

5.1.1.5 Fueling for CIT and ITER

M. J. Gouge, S. L. Milora, and W. A. Houlberg

Responsibility for the CIT pellet injection system [area WBS-V of the CIT Work Breakdown Schedule (WBS)] is assigned to ORNL. The major thrusts of this activity are the following.

1. Coordinate mechanical, electrical, and control interfaces with other WBS areas to ensure that the injector system is consistent with the evolving CIT design.
2. Identify and resolve generic issues for the pellet injector system, such as hands-on maintenance (activation of components), safety standards and features, and tritium inventory requirements.
3. Ensure relevance of pellet development programs and ongoing tokamak experiments to the requirements of the CIT fueling system.

Fig. 5.7. Velocity of 4-mm deuterium pellets (47 torr-L) in a 1-m-long barrel as a function of breech pressure, as determined from experimental data and models.

During 1987, conceptual interfaces with other CIT systems were established, and the specifications for the pellet fueling system were resolved. The minimum specifications are achievable with modest improvements of existing technology.

The level of neutron activation of major injector components that results from streaming along the pellet guide tube was quantified. The local radiation levels permit extended hands-on maintenance; this is fortunate, since remote maintenance is problematic.

Tritium requirements for the pellet injector were estimated on the basis of WHIST simulations of CIT full-power shots. The advantages of efficient tritium pellet fabrication by the injector were highlighted, although the torus tritium content is the main driver of total site inventory and tritium shipment frequency if on-site hydrogenic isotope reprocessing is not possible.

The TPOP injector demonstrated acceleration of deuterium pellets to about 1790 m/s, as discussed in Sect. 5.1.1.3. This velocity corresponds to about 1500 m/s for tritium pellets, which is the minimum specification for the CIT injector.

The performance of pellet injectors operating at velocities ranging from 2 to 20 km/s in the high-temperature plasmas of devices such as ITER was assessed. Central penetration is not possible if existing pellet ablation scaling laws remain accurate for higher pellet velocities and plasma temperatures. Central fueling may,

however, be feasible if particle transport following initial pellet deposition allows inward flow arising from pinch-type transport terms. There is evidence of this effect on existing tokamaks (e.g., ASDEX). Ongoing and planned pellet experiments on TFTR, JET, and Tore Supra will provide considerable insight into the pellet deposition, particle transport, and profile peaking.

5.1.2 Pellet Injector Projects

5.1.2.1 JET pellet injector

S. K. Combs, F. E. Gethers, and S. L. Milora

A three-barrel RPI,^{3,4} shown in Figs. 5.8 and 5.9, was developed at ORNL as the principal component of a plasma fueling system for JET. This system supports a major collaborative program between the European Atomic Energy Community (EURATOM) and the United States on plasma fueling transport physics in the regime of high plasma density. The versatile injector consists of three independent, machine-gun-like mechanisms equipped with individual high-speed extruders to provide a continuous supply of solid deuterium to each gun assembly. The launcher features nominal pellet sizes of 2.7 mm, 4.0 mm, and 6.0 mm. The ideal volume-average density increments with these pellets are 0.58×10^{19} , 1.83×10^{19} , and $6.4 \times 10^{19} \text{ m}^{-3}$, respectively, in JET plasma volume, and the injector has been qualified at repetition rates of 5 Hz for the 2.7-mm pellets, 2.5 Hz for the 4.0-mm pellets, and 1 Hz for the 6.0-mm pellets. The guns can operate (individually or simultaneously) at their design repetition rates for 15-s pulses. Pellet speeds in the repeating mode average 1300 m/s; in the single-shot mode, the performance is close to 1500 m/s.

Along with the injector hardware, ORNL supplied the instrumentation and pellet diagnostics; the remote control system, which is based on an industrial programmable logic controller; and a MicroVAX/CAMAC-based operator interface and data acquisition system. The pellet injection system was qualified in extensive testing at ORNL before delivery, and it was shipped to JET one month ahead of schedule in April 1987. Completion of the installation by ORNL development specialists and initiation of the experimental program were delayed until September 1987 because of slow progress at JET on completion of the pellet injection system interfaces.

5.1.2.2 Tore Supra pellet injector/centrifuge upgrade

C. A. Foster, J. C. Whitson, and M. J. Gouge

The Tore Supra pellet injector is being built through a collaborative agreement between the U.S. Department of Energy (DOE), the Association EURATOM-CEA, and ORNL. Basic design for the injector is provided through an upgrade of the development centrifuge injector. The injector's performance goals are to freeze,

Fig. 5.8. Three-barrel repeating pneumatic injector for JET.

fabricate, and deliver with precise timing 10 to 30 variable-size pellets (1 to 10 torr-L each) per second at velocities of 800 to 1200 m/s for a tokamak pulse length of 30 s. The design of this pellet feed system is based on the results of development unit tests.

During 1987, progress was made both in generic centrifuge development and in fabrication and assembly of the Tore Supra injector. An upgraded pellet feed system that can operate for longer pulse lengths is being developed and will be added to the Tore Supra pellet injector when needed (1989-90).

ORNL-PHOTO 8041-87

Fig. 5.9. The JET injector during qualification tests at ORNL.

The acceleration system for the Tore Supra pellet injector was fully qualified in August 1987. The arbor was spun to design speeds with a drive system controlled by the CEA-supplied multibus control system. The arbor operated best at 127 Hz, which corresponds to a pellet speed of about 1250 m/s.

The CEA-supplied multibus control system components arrived at ORNL in mid-1987 and have been integrated into most of the injector subsystems (acceleration, vacuum pumping, etc.). Multibus control of the pellet feed subsystem, including cryogenic control, is being implemented.

The completion of mechanical assembly of the overall pellet injector was delayed from October 1987 to January 1988, largely because of the four-month strike of craft workers at ORNL during the summer of 1987. This delayed fabrication and assembly of the redesigned pellet feed system (Zamboni) to January 1988; this system was the critical item for overall device assembly. Despite the delay in completion of assembly, shipment of the centrifugal pellet injector to Tore Supra is still scheduled for May 1988.

5.1.2.3 Tritium pellet injector for TFTR

S. L. Milora, P. W. Fisher, and B. S. Maxon

Conceptual studies of alternative TPI designs that would interface with the igloo shield proposed by PPPL for use during tritium operation of TFTR were initiated

in the summer of 1987. The TPI gun design would be the basis for a new eight-shot pneumatic device with a limited tritium inventory (i.e., <2000 Ci), based on the pipe-gun technology being developed as part of the TPOP activity (Sect. 5.1.1.3).

The two TPI design concepts developed in 1987 are shown in Figs. 5.10 and 5.11. Preliminary evaluations concluded that the TPI with the smaller glovebox would be accepted for use on TFTR and could be provided at much lower cost (nearly one-half of the cost of the TPI based on the large glovebox concept) since it could use many of the components now being used in the existing DPI on TFTR.

Studies of the TPI were placed on hold in the latter part of 1987 pending final decisions by DOE on the need for this injector for TFTR.

5.1.3 Pellet Fueling Applications

5.1.3.1 Pellet ablation database: Summary of "Comparison of Hydrogenic Pellet Ablation Models with Experiment"⁵

M. J. Gouge, W. A. Houlberg, S. L. Milora, and D. D. Schuresko

A number of theories have been proposed over the past 15 years to describe the ablation of a solid hydrogenic pellet injected at velocities on the order of a few kilometers per second into a hot plasma. The most widely accepted theory is the neutral gas shielding model. Since its inception, this model has been expanded to include ablation by fast ions as well as electrons, realistic particle distribution functions, self-limiting ablation, and a cold ionized plasma shield beyond the ablating gas shield. Even the most recent versions of the model, however, do not provide a fully self-consistent treatment of the atomic processes of ionization and dissociation; therefore, the models have one or more free parameters that must be chosen based on results of pellet ablation experiments. Ablation measurements, including absolute pellet penetration and ablation profiles from the Impurity Study Experiment (ISX-B), Doublet III, the Poloidal Divertor Experiment, the Tokamak Fontenay-aux-Roses (TFR), T-10, and the Texas Experimental Tokamak (TEXT), were compared with existing pellet ablation models under a range of input assumptions. Agreement on penetration depth was best for the combined neutral gas/plasma shielding model⁶ with multiple (ten) electron energy groups and self-limiting collisionless ablation, although a wide variation in the plasma shield thickness (0.5 to 5 mm) was required to get best agreement with experimental penetration data. Shield thicknesses in this range have been inferred from past pellet experiments. No single ablation model gave good agreement on the shape of the ablation radial profile for all experiments, but the neutral gas, single electron energy group ablation model⁷ and the combined neutral gas/plasma shielding model with multiple energy groups had more success than the other models investigated. With the exception of the ISX-B data, the ablation database is relatively sparse. Coupled with experimental error bars on initial pellet size, electron temperature profiles, etc., this sparseness leads to large uncertainties in comparing ablation models with experiment. None of the present models predicts the large fluctuations seen in some

Fig. 5.10. TPI design concept, Mark I.

experimental ablation profiles (e.g., TFTR and TEXT). Existing and planned experiments on TFTR, JET, and Tore Supra should provide insight into these issues, in that an expanded pellet ablation database with better measurements of initial pellet size will be available.

5.1.3.2 JET preliminary experimental results

S. L. Milora

The three-barrel JPI system was delivered to JET in April 1987. Installation and commissioning by ORNL development specialists were completed in October 1987. Two permanent on-site staff members and visiting development specialists and physicists from the Plasma Technology and Plasma Theory sections represent ORNL in this collaboration.

Efforts focused on achieving reliable operation of the pellet injection system and initiating the experimental program. The primary objectives of the initial experiments are

1. to increase the transient and steady-state density attainable in JET and, in so doing, to reduce Z_{eff} and expand the range of JET parameters, and
2. to produce and sustain strongly peaked density profiles as targets for auxiliary heating (central and off-axis).

The second objective provides a basis for comparison with the results of strong off-axis heating obtained on TFTR and permits testing of diffusive transport and energy confinement models that predict improved confinement as a result of peaking of the density profile and improved heating efficiency with centrally peaked heating profiles.

As discussed in Sect. 5.1.2.1, the JPI is equipped with three independent injectors that provide wide flexibility in the fueling profile shape and pellet injection sequence. To date, the 4-mm gun has been qualified on JET at a 2-Hz repetition rate; the 2.7-mm gun, at a 4-Hz repetition rate. Pellet speeds in the repearing mode average 1300 m/s with ≤ 50 -m/s deviation from the average. Multiple 2.7- and 4-mm pellets have been injected into limiter and X-point discharges at up to 3 MA of plasma current. Increases in volume-average density close to the theoretical values have been observed, and, depending on the pellet size (or combination of sizes) and initial plasma conditions, plasmas with peak densities of $1.2 \times 10^{20} \text{ m}^{-3}$ have been achieved. With two to four 4-mm pellets spaced in time to achieve moderate penetration and density perturbation, broad density profiles have been produced [$n_e(0) = 4 \times 10^{19} \text{ m}^{-3}$]. Ion cyclotron heating power levels of up to 15 MW have been coupled to such profiles, producing a total stored energy of 6 MJ at a plasma current of 3.3 MA. Closer spacing of pellets resulted in pellet penetration to the plasma center and fueling of the discharge core. Strongly peaked electron density profiles, with $n_e(0) \geq 1.2 \times 10^{20} \text{ m}^{-3}$ immediately after pellet injection, have been achieved in ohmic discharges. Sawtooth oscillations have been suppressed for up to several seconds following the pellet injection phase. The central density can

decay slowly during this period, and a dense central plasma emerges with a half-width of ± 20 cm. Plasma density buildup has been demonstrated in the startup and flattop phases of ohmic limiter and X-point discharges using 2.7-mm pellets for pulse lengths exceeding 2.5 s. At an injection rate of 4 Hz, the density in these discharges increases linearly up to the density limit, and 50 to 70% of the pellet injector throughput is accounted for in the rate of rise of plasma particle inventory. Plasma density peaking with $n_e(0) = 1.2 \times 10^{20} \text{ m}^{-3}$ has been achieved in the current ramp phase by injecting a 4-mm pellet early in the discharge and following it with a 2.5-s burst of 2.7-mm pellets at 4 Hz.

5.1.3.3 TEXT pellet injection experiments

M. J. Gouge, D. D. Schuresko, and W. L. Rowan*

The four-shot pneumatic injector used on the Princeton Large Torus was dismantled and shipped to the University of Texas at Austin for use on TEXT in January 1987. Staff from ORNL modified the barrel diameter to 1 mm, consistent with the TEXT plasma inventory, and assisted TEXT staff in installation and initial operations during March and April 1987. During the experimental phase, enhanced confinement was correlated to large density increases (about 100%), suppression of sawtooth activity, and significant changes in microturbulence. Pellet injection is followed by peaking of $n_e(r)$ and $T_i(r)$, central impurity accumulation, and $T_e(r)$ reduction.⁸ From comparisons of pellet-fueled profiles and profiles with edge gas fueling that have similar average densities, reductions in transport due to the pellet perturbation are inferred.

*University of Texas, Austin.

5.2 RF DEVELOPMENT

D. W. Swain

The ORNL RF Development Program is funded by both the Development and Technology and the Confinement branches of DOE. The goals of this work are to

1. develop new or improved components for the generation, transmission, and launching of rf energy to heat plasmas;
2. design, fabricate, test, and install rf antennas and/or power systems for large fusion experiments; and
3. participate in experiments on rf heating in large confinement devices by collaborating with ongoing experimental programs.

The majority of our efforts are focused on the ion cyclotron range of frequencies (ICRF). This year has been an evolutionary one, during which the construction of

large antennas for confinement devices has taken precedence over the basic development activities that were our main emphasis in earlier years. We have also become involved in the applications of the devices to ongoing experiments.

Our basic development activities have continued, especially in the realm of improved Faraday shields that have also been used on our projects. The folded waveguide work has developed to the point that we are now testing a full-scale mock-up of a folded waveguide, with good results, and our rf modeling work has been used to design antenna structures and to improve existing structures so as to optimize the power handling capability of our antenna designs.

The year was dominated by the design, fabrication, and testing of a large antenna for the TFTR device. This antenna was delivered to PPPL in November. In addition, design and fabrication have been started on an antenna for the Tore Supra tokamak; this antenna will be delivered in the summer of 1988.

5.2.1 Basic Development

The development of concepts and components for high-power rf antennas in 1987 was driven primarily by the needs of applications such as the TFTR and Tore Supra compact loop antennas. Despite the heavy emphasis on the needs of these projects, advances were made over a broad range of topics, which also support the long-term rf technology needs of the division.

The Radio-Frequency Test Facility (RFTF), our neutral beam test facility, and numerous other materials facilities at ORNL were critical to the substantial progress made during the year in antenna component development. Applications covered capacitor development and testing, rf testing of graphite-clad Faraday shields in a magnetized plasma, and various thermal and mechanical tests of critical elements of the TFTR and Tore Supra antennas.

5.2.1.1 Faraday shield development

D. J. Hoffman

This year marked the first use of a Faraday shield covered with graphite tiles on an antenna exposed to a combination of plasma, magnetic fields, and neutral gas. This was first accomplished using a Faraday shield mounted on the high-power development antenna. Although we initially feared that the graphite would adsorb gas between pulses and release it during the rf discharge, experiments in RFTF showed that rf, graphite, and gas are compatible. After conditioning, the antenna behaved flawlessly. The graphite did not adversely affect antenna performance, even in the presence of plasmas. Later in the year, these promising results were reconfirmed when the TFTR antenna was tested. Both antennas operated at the full voltages, currents, and electric field strengths necessary to meet design specifications and the power-handling requirements of fusion heating applications.

Successful use of Faraday shielded antennas in current and future large tokamaks requires the shield structures to withstand large mechanical forces and high thermal loads. The need for greater reliability is simultaneously growing because the cost of hardware failure is increasing and because events like water leakage could pose a health hazard. We have substantially increased the amount of hardware testing involved in the development of these devices in order to prevent such occurrences. We are now testing Faraday shield tubes and welded assemblies to their full rated thermal loads, disruption loads, and stresses. Generally, 100,000 cycles of these kinds of tests are desired; however, the thermal tests are limited to 10,000 cycles because of time constraints. Our tests have indicated that critical welds in the Faraday shield can be relied on for the full number of worst-case mechanical loads. Tube brazements can survive maximum anticipated disruption loads (43 J/cm^2 in 20 ms) for thousands of cycles, and tubes subjected to five times disruption thermal loads have survived >5000 cycles. The rated thermal loads seem to be manageable: tests of the development antenna in RFTF and tests in the beam facilities show that long-pulse 200-W/cm^2 loads are reliably handled by the shield structures.

We have also tested uncooled Faraday shield elements, in continuing collaboration with the TEXTOR project, carried out at the Kernforschungsanlage (KFA) Jülich, Jülich, Federal Republic of Germany. These tests help us assess the limits of passive cooling in such structures. As a development group, we are principally concerned with the design of actively cooled shields, which will be required in fusion devices of the future. However, tests that we have performed on the TEXTOR shield show that designs incorporating passively cooled Inconel support frames and molybdenum-based, graphite-coated shield elements can meet today's requirements, although they fail when pushed much beyond these requirements.

5.2.1.2 Antenna components

D. J. Hoffman

The antennas that we have designed at ORNL are compact loop antennas, typically incorporating capacitive matching structures. The compact loops, which integrate antenna motion into the antenna design, required development work on two critical elements: the capacitive structures and the antenna protection bumpers that shield the antenna from toroidal heat loads. In both cases, two approaches were developed to address both the near-term and the long-term needs of the program.

In the resonant double loop (RDL) antenna design, the capacitors are probably the power-limiting element. To meet the near-term needs of TFTR, a capacitor was designed at ORNL to operate at a maximum of 50 kV with moderate internal electric fields (43 kV/cm maximum). This capacitor can carry more than 800 A for 2- μ s pulses. The low electric field requirement limited the range of available capacitance to $\approx 6:1$. We built a prototype and tested it on our "capacitor killer" to the maximum required voltages and pulse lengths. Tests of two such capacitors incorporated into the TFTR antenna indicated reliable operation at 65 kV; the ultimate limit may be higher than that, but we did not try to push beyond that voltage.

The longer lead time for the Tore Supra antenna allowed us to use a commercial capacitor, built to our specifications by Comet Ltd. of Switzerland, for this design. The peak fields in this capacitor are much higher (100 kV/cm) at the maximum 50-kV rating. The maximum current specification of 750 A rms at 80 MHz was thought to be the most difficult to meet because of a Tore Supra requirement for continuous operation. The capacitor survived cw operation on the capacitor killer at the full rated current. To ensure that the high internal electric field could be sustained, we adapted a smaller version of the capacitor to the development antenna, which was installed in RFTF. This capacitor was operated to the full rated electric field under the various conditions that RFTF can impose. These tests indicated that the Comet capacitor could fulfill its design specifications and that the Tore Supra antenna design based on these capacitors was sound.

The protection bumpers for the antennas must tolerate 1 kW/cm² for the duration of the plasma pulse. The short pulses for TFTR allow some inertial cooling of the bumpers, while the 210-s Tore Supra discharges require internal active cooling. We performed a series of thermal tests to prove that the TFTR bumpers can take 10,000 cycles and ultimately used a design based on our test results. For Tore Supra, the need for real-time cooling forced a radical design change. Figure 5.12 shows a graphite bumper tile brazed to a molybdenum substrate, which in turn is brazed to copper cooling tubes. A two-step brazing process is involved. The graphite is

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Fig. 5.12. Cross section of manifold/bumper in Faraday shield assembly.

first brazed to the molybdenum, and the molybdenum is then brazed to the copper tubes with a different braze alloy and at somewhat lower braze temperature. Sample bumpers have been fabricated using this procedure and tested on the neutral beam test facility. The maximum power density attained without damaging the bumper was a factor of two above the design value.

Other antenna components that received our attention were the high-power vacuum feedthrough and the ceramic supports for the vacuum coaxial line. The ceramic supports are located in the coaxial feed lines near the current straps. Although the voltage is low at this point, the structure is not optimized for voltage standoff. We designed and tested a straight vacuum feedthrough to prove this concept. It sustained >30 kV cw on a 3-in. coaxial line (14 kV is required in the TFTR design). This very inexpensive and simple feedthrough is currently being used on the capacitor killer and the folded waveguide antenna at ORNL and on a beam accelerator at Los Alamos.

Continuing tests on our original high-power feedthrough included a number of mechanical tests to qualify its use on the antennas for TFTR and Tore Supra. Analysis of the ceramic-metal interface and of the internal stresses in the ceramic will be conducted in 1988. Four more of these feedthroughs were purchased by the TEXTOR group at KFA Jülich.

5.2.1.3 Folded waveguide

T. L. Owens and G. R. Haste

A full-scale model of the folded waveguide launcher⁹ was built of aluminum parts. The outside dimensions of this model were $300 \times 70 \times 30$ cm. With nine internal vanes, the model was designed to operate in the range from 78 to 140 MHz. The significant features of the device are shown in Fig. 5.13. At the front, a polarizing plate serves to block the ends of five of the folds, leaving the other five folds open to radiate. At the rear, a movable back plate can be driven by rods attached to the back plate and a driver plate. Since the resonant frequency is determined by the length of the folded waveguide, the motion of the back plate is used to tune the device to the desired frequency. Power is coupled into the folded waveguide with a coaxial line at the side. The center conductor of the coaxial line touches the edge of the center vane with a sliding contact. The position of the sliding contact can be varied to control the coupling, or matching, to the folded waveguide.

Testing of the full-scale model confirmed the predicted performance of the device. With the front polarizing plate replaced by a solid plate, the magnitude and direction of the magnetic fields just inside the device were determined; they are shown in Figs. 5.14 and 5.15, respectively. The magnitude is greatest at the center and falls to zero at the outer edges, and the direction of the magnetic field alternates from one fold to the next. The reason for covering alternate folds is clear: so that all of the fields coupled out through the apertures have the same direction. Figure 5.16 shows the magnetic field as measured on the outside of the polarizing plate. The fields in front of the apertures are as expected and follow the behavior

Fig. 5.13. Folded waveguide coupler.

Fig. 5.14. Scan along path length just inside a blank plate covering the front of the folded waveguide.

of the fields inside the folded waveguide. A somewhat surprising feature is that the fields in front of the blocked-off regions are nearly equal to those in front of the apertures, as a result of the currents induced on the outside of the plate between the apertures.

The electric field is expected to be at a maximum at the edge of the center vane, midway between the front and back plates. When the device was tested at high

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Fig. 5.15. Field direction inside the folded waveguide.

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Fig. 5.16. Scan of $H_{\parallel}$ along path length, showing that fields in front of the apertures are equal to those in front of the plates.

power in air, it broke down (arced) at the point where the highest electric field was expected and at a value of 15 kV/cm, which is typically the breakdown strength of air.

The spatial variation of the magnetic field was determined at greater distances from the front of the folded waveguide and compared with that for an RDI antenna that had nearly the same transverse dimensions as the full-scale model. The field variation was almost the same for the two antennas, both radially and in the transverse directions.¹⁰ As a result, the effects of these antennas on a plasma are expected to be the same.

The encouraging results from the full-scale model prompted an effort to make it vacuum compatible in order to assess its performance with higher rf power. A two-stage effort was planned: first vacuum operation, then operation with launch into the RFTF plasma. The second stage is indicated in Fig. 5.17, which shows the folded waveguide inside a vacuum chamber that in turn is attached to the RFTF.

Some modifications and fabrication were begun in order to allow the testing at higher power. The natural oxide coating on the aluminum leads to a high secondary electron yield, which favors multipactor discharges, so the aluminum parts were sent to be coated with copper. This change in the outer surface was expected to minimize the potential for multipactor discharges. Some minor modifications to the structure were made to eliminate trapped air volumes and thereby make the structure more vacuum compatible. The vacuum enclosure was designed and sent out for fabrication. The high-power testing, with the new and modified parts, is expected to begin in early 1988.

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Fig. 5.17. Test configuration for the folded waveguide.

5.2.2 RF Projects

5.2.2.1 TFTR antenna

W. L. Gardner and D. J. Hoffman

A 4-MW launcher was designed, built, and tested for use on TFTR. The launcher was delivered to PPPL in late November 1987 and will be installed on

TFTR in early January 1988. Experiments using this launcher are scheduled to begin when TFTR operations resume in the spring of 1988. Figure 5.18 is a photograph of the TFTR launcher before shipment.

ORNL-PHOTO 9981-87

Fig. 5.18. The TFTR antenna.

This launcher is the first to use the RDL antenna design, which was pioneered at ORNL.¹¹ The design consists of a partial-turn current strap with an asymmetric feedpoint and vacuum variable capacitors located at each end. The current strap and capacitors form a resonant structure that is matched to the transmitter output impedance ($50\ \Omega$) at the feedpoint. This integral matching feature eliminates the need for additional matching stubs and substantially reduces the current and voltage levels at the vacuum feedthrough. In addition, the design is compact (the launcher is completely installed in a single port) and can handle high power levels.

The launcher itself consists of two RDLs that can be driven independently of one another. Each is tunable from 37 to 68 MHz and can handle a power level of 2 MW (4 MW total) for a duration of 2 s, with pulses spaced 300 s apart. The launching structure is movable radially over a distance of 11 cm, allowing considerable control over the amount of plasma coupling (and thus antenna loading) produced.

An important component of the ORNL TFTR launcher is the actively cooled Faraday shield, incorporating two tiers of high-strength Inconel tubes welded into an Inconel support frame. As shown in Fig. 5.19, the outer tier of tubes is covered by semicylindrical graphite tiles for impurity control. The shield is designed to withstand average heat fluxes of $200\ \text{W}/\text{cm}^2$ and peak loads of $9000\ \text{W}/\text{cm}^2$ during a disruption. Cooling is provided by high-pressure demineralized water.

Fig. 5.19. Artist's rendering of the TFTR antenna.

Before being shipped to PPPL, the launcher was tested in the RFTF. It was demonstrated that the launcher can handle a peak voltage level of 65 kV, which is somewhat higher than that required for 4-MW operation at anticipated loading levels in the TFTR device.

5.2.2.2 Tore Supra antenna

F. W. Baity

The Tore Supra tokamak¹² is a large device with a major radius of 2.36 m, a minor radius of 0.8 m, a plasma current of 1.7 MA, and a magnetic field on axis of 4.5 T. Its main objectives are to provide experience with superconducting magnet systems and to study the characteristics of long-pulse plasmas heated by a variety of auxiliary heating schemes. Initial plasma operation in Tore Supra is scheduled for early 1988.

The ICRF antenna for Tore Supra must operate over a frequency range from 35 to 80 MHz for pulse lengths of ≥ 30 s at a power level of 2 MW per loop. The antenna is inserted through a 60- by 70-cm horizontal port and can be moved radially over 30 cm. This antenna is the most ambitious RDL design attempted to date, given the extensive cooling required by the long-pulse operation and the wide frequency range. The design¹³⁻¹⁶ is the result of a collaborative effort between ORNL and the Centre d'Etudes Nucléaires de Cadarache. A cross section through one loop is shown in Fig. 5.20. The antenna is shaped to match the plasma curvature under nominal operating conditions. Both the face and the edges of the Faraday shield

Fig. 5.20. Long-pulse ICRF antenna for Tore Supra.

are covered with water-cooled graphite and can withstand a plasma heat flux of up to 1 kW/cm^2 . Each loop is tuned and matched to the $30\text{-}\Omega$ impedance of the transmission line feeding the antenna by means of two vacuum variable capacitors, designed and built for this application by Comet Ltd.

A preliminary design review was held in Oak Ridge in February 1987; the final design review, in Cadarache in June 1987. Contracts for fabrication of the major subassemblies were placed in October 1987, with completion set for early 1988. The antenna will be assembled and tested in the RFTF at ORNL, and then shipped to France for installation during the summer of 1988. Heating experiments will begin in the fall of 1988.

5.2.2.3 High-power rf supply system

G. C. Barber

The modified 821-D power system from the Fusion Materials Irradiation Test (FMIT) facility was delivered for installation in mid-February 1987. Installation and checkout were completed, and a few hundred kilowatts of rf power were achieved by March 31, 1987. During an attempt to drive the system to full power output, the X-2170-D vacuum tube failed. Analysis of the tube failure indicated overheating

of the cathode and plate, inadequate cooling of these structures, or a combination of both. The tube was replaced with a standard Eimac K-2170, and a power level of 1.2 MW was achieved. The air cooling of the cathode and water cooling of the anode will be improved before the system is driven beyond these parameters.

The coaxial transmission line system—consisting of 9-in. couplers, phase shifters, voltage standing wave ratio (VSWR) tuner, and transmission line—was installed successfully. It was tested for proper operation at low power and interfaced with the RFTF for antenna tests. The 821-D transmitter system was used to test the TFTR antenna during the latter part of the year. Since initiation of these tests, the system has operated more than 250 plate hours without failure.

5.2.3 Applications and Collaborations

5.2.3.1 Fast-wave ICRF antenna for Doublet III-D

F. W. Baity

Measurements of plasma loading on Doublet III-D (DIII-D) continued with the low-power prototype cavity antenna designed and built by ORNL.^{14,17-19} The decrease in the plasma loading resistance of the fast-wave ICRF antenna that occurs at the transition from L-mode operation to H-mode operation pushes the capability of the antenna to its limits. The present antenna was designed to match an expected plasma loading resistance range from 1 to 5 Ω , which is approximately what is measured during L-mode operation of DIII-D. During the H-mode, the observed loading resistance is in the range from 0.5 to 2 Ω . The power limit with the present antenna geometry, using state-of-the-art capacitors, would be about 1 MW; however, fairly simple modifications to the present geometry were undertaken, based on recent antenna modeling results, to increase the antenna loading, and the power limit, by approximately a power of two. These modifications were completed during the November-December vacuum opening. The amount of the increase in loading will be determined experimentally during 1988, before the design of a 2-MW fast wave antenna for DIII-D is completed.

5.2.3.2 Ion cyclotron heating system for CIT

D. W. Swain

The CIT is a small, high-field tokamak that is scheduled to be constructed for PPPL, with operation beginning in 1996. As lead laboratory for rf development, ORNL has been charged with the responsibility for the design and, ultimately, the fabrication and testing of the CIT ion cyclotron heating system.

The baseline design for CIT calls for 10 MW of rf heating in the frequency range from 60 to 110 MHz. There is provision for additional heating, if required. The initial ICRF heating power will be supplied by modifying six existing FMIT transmitters to cover the required frequency range, each transmitter generating at

least 2 MW at 95 MHz (the design frequency for the system). The ICRF heating strategy is being planned to accommodate operation over the range from 70 to 100% of the design magnetic field. This permits both initial low-field testing and full-field operation, during which ignition conditions will be achieved.

The present conceptual design for the antenna consists of an RDL structure, similar to the structures built for TFTR and Tore Supra. Tuning elements at the ends of this structure are envisioned as being shorted stubs sharing the tokamak vacuum. An alternative is to replace the shorted stubs with the more standard vacuum capacitor. There are three antenna modules, each of which can be installed and removed through a midplane port in CIT. Each module carries two loops, one on top of the other. The antenna is electrically shielded from the plasma by a graphite-coated Faraday shield similar to those used on the Tore Supra and TFTR antennas. An artist's rendition of the proposed antenna module is shown in Fig. 5.21.

In addition to the antenna design, a layout of all equipment (transmitters, transmission lines, dummy loads, etc.) that will be needed in the CIT experiment has been completed, and interfaces with the other elements of the project (e.g., cooling water, electricity, instrumentation and controls) have been carried out.

ORNL-PHOTO 8257-88A

Fig. 5.21. Proposed antenna module for CIT.

5.3 NEGATIVE ION BEAM DEVELOPMENT

M. A. Akerman, G. C. Barber, W. R. Becraft, W. K. Dagenhart, H. H. Haselton, P. M. Ryan, D. E. Schechter, C. C. Tsai, W. L. Stirling, and J. H. Whealton

During 1987, we have continued to develop volume sources with emphasis on negative ion extraction and high brightness. This work has included both experimental and theoretical investigations. An additional area of concentration has been the development of high-energy, high-current beam lines for providing current drive and heating at the core of a tokamak reactor.

5.3.1 Results of VITEX POP Source

M. A. Akerman, W. K. Dagenhart, D. E. Schechter, W. L. Stirling, and J. H. Whealton

A POP negative ion source, which produces negative hydrogen ion beams by a process of volume ionization with transverse extraction (VITEX), has been operated at the Negative Ion Test Facility. In this source,²⁰⁻²² an intense hydrogen arc column is created by a Penning discharge in a strong magnetic field. The positive ions and excited molecules diffuse out of the arc column into the anode plasma region, are attached by the cold plasma electrons, and are dissociated into negative ions. This is an effective process for producing negative ions. The source performance varies with the source parameters; typical performance of a VITEX POP source is shown in Table 5.1. As shown in Fig. 5.22, the current density of negative ion beams is a decreasing function of the area of the ion-emitting aperture.

Table 5.1. Performance of existing and scaled negative ion sources

Parameter	Achieved		
	Ova. aperture, 12.7 by 38.1 mm	Slit aperture, 1 by 20 mm	VITEX scaled
Ion	H ⁻	H ⁻	D ⁻
Energy, keV	13	14	100
Current, A	0.1	0.03	1.5
Current density, mA/cm ²	32	150	15
Pulse length, s	0.1-10	0.1-10	dc
Duty factor, %	>10	>10	dc
Extraction area, cm ²	3.1	0.2	100
Source pressure, mtorr	20	200	5
Gas load, torr·L/s	2.4	2.4	<20
Normalized rms			
X	0.02	0.013	<0.2
Y	0.03	0.017	<0.2
Ion temperature, eV	<0.88	0.58 ^a	

^a An ion temperature of 0.12 eV was measured for low-current-density beams.

Fig. 5.22. Effect of extraction area on beam current density.

This feature could be associated with the nonuniformity of the negative ion density or with the plasma sheath. Effects of other parameters—such as the gas feed, the negatively biased potential of the plasma grid at which negative ions are emitted, and the width of the anode plasma region from the arc column to the plasma grid—have been investigated and optimized for increasing the negative ion output. The typical ion temperature is about 0.6 eV for current densities of a few tens of milliamperes per square centimeter. For ion beams with low current density (a few milliamperes per square centimeter) and low accelerator aberrations, the measured ion temperature was as low as 0.12 eV. The details of these exciting results are given in refs. 23 and 24. These source characteristics are favorable for developing cw VITEX sources for high-power, multi-megaelectron-volt neutral particle beam injectors. Such injectors are considered to be the prime candidate for current drive on next-generation fusion reactors such as ITER.

5.3.2 VITEX-II Source

M. A. Akerman

On the basis of the good experimental results from the VITEX POP source,^{21,22} a new source, designated VITEX-II, has been designed and built. Figure 5.23 is

ORNL-PHOTO 00747-88

Fig. 5.23. VITEX-II source.

a photograph of the VITEX-II source. The new source has its own self-contained magnetic field to guide the reflex discharge, filter out the hot electrons from the negative ion production region, reduce the number of electrons extracted with the negative ions, and enable the recovery of most of the electrons that are extracted with the negative ions at about 10% of the ion extraction energy. A biased plasma grid aids in enhancing the negative ion extraction density. A second plasma control has been installed so that the grid's effect on the negative ion generation process can be investigated. The discharge uses two hot-filament electron feeds and can supply a 200-V, 100-A arc in steady state. An extraction current of 50 to 100 mA of H^- is expected at a current density near 30 mA/cm^2 for pulses in the range from milliseconds to seconds. The beam energy will be 40 keV. Extracted electron currents of about 0.5 mA are expected, of which most will be recovered at 6-keV energy. Calculations indicate that the initial emittance will be about $0.015 \pi\text{-cm-mrad}$ for a circular beam. Initial beam experiments will begin in February 1988.

5.3.3 Ringatron Development

W. L. Stirling, J. H. Whealton, and M. A. Akerman

During this reporting period, the Ringatron concept,²⁵ briefly mentioned in last year's annual report, has been funded for experimental study. A mechanical design has been completed, and parts are being fabricated. The Ringatron promises to be a high-brightness negative ion source applicable to fusion.

As shown in Fig. 5.24, the Ringatron consists of a Penning discharge localized near the outer wall of a cylinder, from which excited species migrate toward the relatively cool center. As migration occurs, an optimum location will exist for creation of negative ions. This optimum location can be made to exist at the center of the cylinder by optimizing the gas pressure, the diameter of the cylinder, and the current in the discharge. Negative ions will be extracted from the center of

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Fig. 5.24. Ringatron concept.

the cylinder with coaxial magnetic and electric fields oriented along the cylinder's axis. This source should provide a much larger volume from which negative ions can be extracted, less transverse energy spread in the extracted beam, high current density, and high brightness.

5.3.4 Research and Development of High-Energy Particle Beams for Current Drive, Heating, and Alpha Particle Diagnostics

W. R. Becraft, M. A. Akerman, H. H. Haselton, P. M. Ryan, W. L. Stirling, and J. H. Whealton

The key issue for ITER and for tokamak reactors is steady-state operation, with the attendant requirement for plasma current drive. Of the current drive concepts under serious consideration, only neutral beams hold real promise for driving current effectively at the plasma densities expected in ITER. Furthermore, these beams have a strong advantage in that they can drive currents in the core of the plasma and may contribute significantly to stable operation. Neutral beams at energies of 1 to 3 MeV are also promising because of their simple configurations and their reliance only on rf power systems.

The most credible diagnostic for determining conditions in a fusing plasma by measurement of the velocity and possibly the spatial distribution functions of confined alpha particles is a neutral beam of high-energy lithium, carbon, or oxygen atoms. A research and development program under way at ORNL is applicable to the formulation of such diagnostics for CIT, ITER, and other ignited systems, in that the ion sources and rf acceleration schemes will be similar. A conceptual design for a diagnostic beam line is shown in Fig. 5.25. Nominal exit parameters for this beam are as follows:

Current	7.2 A
Energy	3 MeV
Beam radius	3.5 cm
Length	22 m
Power	21.6 MW
Efficiency	38-80%

Present conceptual designs are being extended through detailed system and component design analysis and through the development and testing of negative ion injectors, rf quadrupole (RFQ) accelerators, and neutralizers, which are the major elements of systems suitable for plasma current drive, heating, and alpha particle diagnostics.

Fig. 5.25. Conceptual design of a diagnostic beam line for an Engineering Test Reactor.

5.4 PLASMA TECHNOLOGY MODELING

J. H. Whealton, P. M. Ryan, R. J. Raridon, P. S. Meszaros, K. E. Rothe, B. D. Murphy,* M. Bacal,[†] G. E. McMichael,[‡] T. L. Owens, and W. R. Becraft

Activities in modeling during 1987 include (1) several levels of description optimization for ICRF antennas, Faraday shields, feedthroughs, and transmission lines; (2) full nonlinear, three-dimensional (3-D) level of descriptions of the plasma sheath near an ICRF antenna/Faraday shield, (3) design of e-beam rocket accelerator for ultrafast pellet acceleration; (4) analysis of the extraction of a liquid-metal ion source; (5) studies of 3-D extraction optics of negative ion sources, including those of Lawrence Berkeley Laboratory, Culham Laboratory in England, the Ecole Polytechnique de Palaiseau in France, Los Alamos National Laboratory, the Japan Atomic Energy Research Institute (JAERI), and ORNL; (6) analysis of a new volume negative ion source, the Ringatron, which is configured to produce beams with especially high current density; (7) analysis and optimization of space-charge-dominated beam transport subsystems, such as the funnel and certain low-energy beam transport (LEBT) devices; and (8) analysis of neutral beam heating and current drive

systems, taking into account the nonlinear dynamics of beam acceleration, combination, and neutralization. These activities support existing and proposed programs in ICRF physics and technology, plasma fueling, neutral beam heating and current drive, and neutral beam diagnostics.

*Computing and Telecommunications Division, Martin Marietta Energy Systems, Inc.

†Ecole Polytechnique, Palaiseau, France.

‡Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada.

5.4.1 RF Modeling

5.4.1.1 Modeling of ICRF launchers and related sources

P. M. Ryan, K. E. Rothe, D. J. Hoffman, and J. H. Whealton

The power transmission limits due to electric field breakdown in the folded waveguide launcher were investigated with a two-dimensional (2-D) electrostatic analysis in the vicinity of the vane tip. This approach is both efficient and accurate, since only a small portion of the total device need be considered and the potential along the conductor is nearly constant over the distances involved. The electrostatic approximation improves as the number of folds is increased.

Figure 5.26 shows equipotential contours surrounding a vane with a thickness $2R$, a tip radius R , a gap between tip and wall B , and an intervane gap G . Figure 5.27 shows the normalized power transmission for a waveguide launcher with three uniformly spaced vanes (four folds) as a function of tip radius and tip-to-wall gap. The power transmission peaks for $R/G \approx 0.8$. Increasing B/G also increases the power transmission, although the increase is modest beyond $B/G \approx 1.2$.

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Fig. 5.26. Equipotential contours in the vicinity of a folded waveguide vane tip.

Fig. 5.27. Power transmission through a waveguide with three uniformly spaced vanes as a function of normalized vane tip radius R/G and tip-to-wall gap B/G . Power transmission is assumed to be limited by voltage gradient (electric field) breakdowns.

A 30- Ω rf feedthrough with a very low VSWR was designed with the ORNL 2-D Laplace transmission line analysis²⁶ and has been successfully operated. The transmission line section of the analysis was modified to include ohmic losses and has been used to analyze resonant coaxial structures such as the high-voltage breakdown tester and the capacitor killer.

The 2-D magnetostatic analysis²⁷ was modified and applied to the CIT resonant loop antenna geometry. Engineering parameters such as strap inductance, radiation resistance, and strap ohmic resistance are now routinely calculated and used to

optimize antenna designs on the basis of voltage and current limits. The calculations agree very well with laboratory measurements.

The load factor R , defined as the ratio of the antenna loading resistance to the plasma surface resistance, increases with cavity depth and decreases with strap width. On the other hand, the power loading per strap volt, which is proportional to R/L^2 (where L is the normalized strap inductance), increases as the strap width is increased and is relatively independent of cavity depth. Combining these two effects with the appropriate strap length, plasma impedance, operating frequency, and current and voltage limits allows optimum design points to be identified, as in Fig. 5.28.

Fig. 5.28. Effects of current and voltage limits on power coupling and optimum design points.

5.4.1.2 Plasma sheath near ICRF antenna/Faraday shield plasma

J. H. Whealton, P. M. Ryan, R. J. Raridon, and P. S. Meszaros

The plasma sheath near an ICRF antenna has become an issue because such antennas have been suspected of being impurity sources and possibly inhibiting rf propagation in a high-density plasma. The theoretical basis for our description of the plasma sheath is given in Fig. 5.29, which shows the theoretical domain of the ICRF antenna problem and the existing theories that lie near this domain. The theories labeled R1, R2, R3, R1B, and R4, which lie nearest the domain, were all developed at ORNL and produce the best approach to a satisfactory theory for the ICRF plasma edge. The problem is fully 3-D and very nonlinear, and it must be treated on ion time scales.

Fig. 5.29. The domains of theories encompassing the region where an ICRH antenna Faraday shield is expected to exist, plotted in three-dimensional space. The horizontal axis gives the dimensionality of boundary conditions and image charges. The vertical axis gives the degree of nonlinearity. The depth axis gives the time scales of the various theories. The ion cyclotron frequency time lies near the front face on this scale; the ICRH antenna sheath appears as a blob in the upper right-hand corner. The three theory domains denoted R1, R4, and R5 are only once removed from the domain necessary for consideration of the ICRH antenna Faraday shield. The domains of R2 and R3 are two steps removed. All of these theories were developed at ORNL. The domains of theories developed at other laboratories are shown for comparison.

5.4.2 Electron Beam Modeling

P. M. Ryan, R. J. Raridon, C. A. Foster, C. C. Tsai, and J. H. Whealton

A modeling effort supported the e-beam rocket accelerator experiment²⁸ in the pellet fueling program (Sect. 5.1.1.2). A $2\frac{1}{2}$ -dimensional Vlasov-Poisson analysis was used to design the electrodes and magnetic field patterns needed to accelerate, control, and focus a high-perveance electron beam. An example calculation is shown in Fig. 5.30. (The magnetic field axis of the main solenoid coil is at the bottom of all three plots.) The accelerator structure for one off-axis cathode is shown in Fig. 5.30(a). The cathode field needed to control the space-charge of a 30-A/cm^2 beam through a 0.75-m -long, 30-keV accelerator is 1160 G . Figures 5.30(b) and 5.30(c) trace the electron trajectories of the 30-keV , 8.5-A beam through the first 50 cm of the main solenoid coil [Fig. 5.30(b) has an expanded vertical dimension to magnify electron gyrations]. The main solenoid has a maximum field of $14,470\text{ G}$,

(ALL DIMENSIONS IN cm)

Fig. 5.30. Example of electron beam design analysis. (a) Accelerator with field of 1160 G at cathode, $J = 30 \text{ A/cm}^2$, $V = 30 \text{ kV}$. (b) Electron trajectories through compressional magnetic field, with vertical dimension magnified to show detail. (c) Electron trajectories in realistic geometry, with an area compression of 12.4.

giving a beam compression factor of 12.4. This analysis has been used to design and analyze the auxiliary shaping coils as well as the main solenoid coil.

5.4.3 Ion Source Modeling

5.4.3.1 Liquid-metal ion source extraction

P. M. Ryan, J. H. Whealton, P. S. Meszaros, K. E. Rothe, G. D. Alton,* and H. T. Kerr

A liquid-metal ion source was considered in detail, with emphasis on the beam rms production due to optical aberrations in the extractor. Like all known experiments, this ion source is dominated by aberrations, which have prevented realization of its potential.

*Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada.

5.4.3.2 Volume negative ion source extraction

J. H. Whealton, R. J. Raridon, P. S. Meszaros, and W. L. Stirling

An analysis produced during the year was the first to replicate experimental results; Fig. 5.31 indicates the agreement with unambiguous experimental determinations. The analysis capitalizes on the difference between negative ion extraction and positive ion extraction,²⁹⁻³¹ for which there is an adequate and verified

Fig. 5.31. Negative ion current measured from a Faraday cup as a function of perveance (data of R. Stevens, Los Alamos National Laboratory, obtained with a small volume-produced negative ion source from Lawrence Berkeley Laboratory) for currents of 100, 200, and 300 A, compared with the theoretical model developed at ORNL (solid line), which includes the physics of negative ion sheaths. At very low perveance (A), there is a slow falloff as a function of voltage (or inverse perveance). At an intermediate high voltage, which corresponds to a low perveance, there is a horizontal plateau. At very high perveance or lower voltages, there is a sudden sharp falloff (C and D). The model reproduces the horizontal plateau and the drops at very low and very high perveance; it is deficient in the region where the slow falloff begins (B) because it assumes an ion temperature of zero. (Experimentally, this falloff becomes more gradual with increasing ion temperature.) This is the first such agreement between theory and output from a volume-produced negative ion source.

analysis.³²⁻³⁴ For negative ion extraction, the presheath fields are dominated by the plasma positive ion's attempt at charge neutrality, compared with the case of positive ion extraction. Figure 5.32 illustrates the predictive value of the analysis, which accurately predicted the output of the Culham negative ion source (one-third of that claimed). This analysis was extended to three dimensions in position space with all boundary image charges considered and a self-consistent, fully implicit computation of the sheath. Calculations have also been performed on the Culham, Berkeley (Mark II), and ORNL (VITEX) sources. Many issues are being addressed. These sources are candidates for neutral beam generation for current drive, but their emittance is an unknown quantity, since the extraction geometry is like that of positive ion sources 30 years ago.

5.4.3.3 Ringatrons

J. H. Whealton, W. L. Stirling, K. E. Rothe, and P. M. Ryan

The Ringatron, a new volume negative ion source, has been configured as shown in Fig. 5.33. The geometric attributes shown may produce a current density higher

Fig. 5.32. H^- beam current measurements and ORNL theory. The 1986 experimental data are drain current measurements; the interpreted result was 135 mA of current from a Culham negative ion source. The ORNL theory, developed in 1987, suggested that the space charge limit of this source was only 50 mA, approximately one-third of that claimed. When the beam current was later measured directly with a Faraday cup, the result was 50 mA, consistent with the ORNL theory. In this case, the theory accurately predicted the experimental results.

Fig. 5.33. Isometric view of the components of a Ringatron ion source.

than that now available by a significant factor. Extraction along the magnetic field may reduce the rms transverse emittance to levels below those from transverse magnetic extraction sources. Reference 25 describes the details of this analysis and its relationship to earlier work.

5.4.4 Nonlinear Beam Dynamics

5.4.4.1 Analysis of beam transport funnel and LEBT

J. H. Whealton, R. J. Raridon, T. L. Owens, and W. R. Becraft

The funnel is a device for combining two bunched beams longitudinally by means of timed forces applied so as to synchronize the beams. A critical subsystem for this device is the rf deflector, which is a fully 3-D device, as shown in Fig. 5.34. In modeling of this subsystem, significant unexpected longitudinal emittance growth was discovered, and nonlinear longitudinal lenses were invented to reduce this growth.

Fig. 5.34. The rf deflector.

The LEBT is a device for transporting the emissions from an ion source into the acceptance of an accelerator. Space-charge forces are characteristically high in such a device. One subsystem in the LEBT is the column where the beam is accelerated from 20 to 100 keV in a dc accelerator. The source for the LEBT that we considered produces beams that are not cylindrically symmetric. We investigated the emittance growth of these beams when they traverse a cylindrically symmetric column. A schematic is shown in Fig. 5.35. A square beam with corresponding emittance is shown in Fig. 5.36. This is a considerable enhancement over the emittance produced by a circular beam. Merely removing the corners of a square beam does not cure the emittance growth; this indicates that the emittance of the core of the beam is enhanced by the nonlinear space-charge forces that arise as a result of the corners. These observations, which were produced from a fully 3-D, Vlasov-Poisson steady-state analysis, are consistent with the experimental findings, which until now were not fully understood.

5.4.4.2 Neutral beam current drive system

J. H. Whealton, B. D. Murphy,* P. M. Ryan, H. H. Haselton, G. M. McMichael,[†] and M. A. Akerman

A neutral beam current drive system based on an RFQ was examined in detail. Several options were considered. The most promising appears to include a four-rod RFQ, a plasma neutralizer, a negative ion source, an LEBT, and a beam dump.

Fig. 5.35. Emittance growth of beam traversing a cylindrically symmetric column.

Two multiple-channel RFQ options for a 40-MW system are shown in Fig. 5.37. The negative ion source under development by JAERI appears to be ready for adaptation to this system. A suitable LEBT is being developed. A plasma neutralizer developed at JAYCOR has the necessary low power input, low gas output, and high neutralization efficiency. A conceptualization of the entire neutral beam line is shown in Fig. 5.38. Details of the ion source, the LEBT, and the RFQ entrance are presented. The output beam is approximately 10 cm in diameter; this is significant, given the access limitations to most confinement devices.

*Computing and Telecommunications Division, Martin Marietta Energy Systems, Inc.

†Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada.

Fig. 5.36. Emittance growth of a square beam.

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CURRENT	1A	1/2A
ENERGY	2 MeV	2 MeV
FREQUENCY	23 MHz	65 MHz
POWER	80 MW	80 MW
BEAM AREA	2.8 M ²	0.6 M ²
NEUTRAL BEAM DIVERGENCE (NO TELESCOPE)	10 mrad	3 mrad

Fig. 5.37. Two multiple-channel RFQs.

Fig. 5.38. Neutral beam current drive system.

REFERENCES

1. S. K. Combs et al., "Repeating Pneumatic Hydrogen Pellet Injector for Plasma Fueling," *Rev. Sci. Instrum.* **56**, 1173 (1985).
2. S. L. Milora, S. K. Combs, and C. R. Foust, "Fast-Opening Magnetic Valve for High-Pressure Gas," *Rev. Sci. Instrum.* **57**, 2356 (1986).
3. S. L. Milora et al., "Design of a Repeating Pneumatic Pellet Injector for the Joint European Torus," in *Proceedings of the IEEE 12th Symposium on Fusion Engineering, Monterey, 1987*, Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1987.
4. S. K. Combs et al., "A Three-Barrel Repeating Pneumatic Pellet Injector for Plasma Fueling of the Joint European Torus," presented at the 34th National Symposium of the American Vacuum Society, Anaheim, California, November 2-5, 1987; proceedings to be published in *J. Vac. Sci. Technol.*
5. M. J. Gouge et al., "Comparison of Hydrogenic Pellet Ablation Models with Experiment," *Bull. Am. Phys. Soc.* **30**, 1840 (1987).
6. W. A. Houlberg, S. L. Milora, and S. E. Attenberger, *Neutral and Plasma Shielding Model for Pellet Ablation*, ORNL/TM-10556, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., October 1987.
7. S. L. Milora, *New Algorithm for Computing the Ablation of Hydrogenic Pellets in Hot Plasmas*, ORNL/TM-8616, Union Carbide Corp. Nuclear Div., Oak Ridge Natl. Lab., April 1983.
8. W. L. Rowan et al., "Enhanced Confinement Following Pellet Injection into the Texas Experimental Tokamak (TEXT)," *Bull. Am. Phys. Soc.* **30**, 1841 (1987).
9. T. L. Owens, "A Folded Waveguide Coupler for Plasma Heating in the Ion Cyclotron Range of Frequencies," *IEEE Trans. Plasma Sci.* PS-14, 934 (1986).
10. T. L. Owens et al., "Experimental Comparison of Folded Waveguide and Loop Couplers for ICRF Heating," *Bull. Am. Phys. Soc.* **32**, 1952 (1987).
11. T. L. Owens, F. W. Baity, and D. J. Hoffman, "ICRF Antenna and Feedthrough Development at ORNL," *Radio Frequency Plasma Heating: AIP Conf. Proc.* **129**, 95 (1985).
12. R. Aymar, "Status Report on Tore Supra," p. 185 in *Proceedings of the 14th Symposium on Fusion Technology (Avignon, France, September, 1986)*, Vol. 1, Pergamon Press, Oxford, 1987.
13. W. R. Becraft et al., "Compact Loop Launcher Design Study for Tore Supra," p. 161 in *Proceedings of the 13th European Conference on Controlled Fusion and Plasma Heating (Schliersee, Federal Republic of Germany, April, 1986)*: *Europhys. Conf. Abstr.* 10C, Part II, European Physical Society, 1986.
14. F. W. Baity et al., "Progress in ICRF Heating Technology and Designs for Future Large Tokamak Heating Systems," p. 743 in *Proceedings of the 14th Symposium on Fusion Technology (Avignon, France, September, 1986)*, Vol. 1, Pergamon Press, Oxford, 1987.
15. D. J. Hoffman et al., "The Design of High-Power ICRF Antennas for TFTR and Tore Supra," *Applications of Radio-Frequency Power to Plasmas: AIP Conf. Proc.* **159**, 302 (1987).

16. F. W. Baity et al., "The Design of a High-Power, Long-Pulse Antenna for Tore Supra," *Bull. Am. Phys. Soc.* **32**, 1952 (1987).
17. D. J. Hoffman et al., "ICRH Coupling in DIII-D," p. 141 in *Proceedings of the 13th European Conference on Controlled Fusion and Plasma Heating (Schliersee, Federal Republic of Germany, April, 1986): Europhys. Conf. Abstr.* 10C, Part II, European Physical Society, 1986.
18. M. J. Mayberry et al., "Coupling Tests of an ICRF Compact Loop Antenna on DIII-D," *Bull. Am. Phys. Soc.* **31**, 1418 (1986).
19. Y. Uesugi et al., "Coupling Characteristics of an ICRF Compact Loop Antenna on DIII-D," *Bull. Am. Phys. Soc.* **32**, 1901 (1987).
20. W. L. Stirling, W. K. Dagenhart, and C. C. Tsai, *Volume H⁻ Generation with the SITEX Source in the VITEX Reflex Mode Without Cesium*, ORNL/TM-9753, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., 1986.
21. C. C. Tsai et al., "Discharge Characteristics of a Plasma Generator for SITEX and VITEX Ion Sources," *Production and Neutralization of Negative Ions and Beams: AIP Conf. Proc.* **158**, 194-205 (1987).
22. W. K. Dagenhart et al., "Accelerated Beam Experiments with the ORNL SITEX and VITEX H⁻/D⁻ Sources," *Production and Neutralization of Negative Ions and Beams: AIP Conf. Proc.* **158**, 271-81 (1987).
23. J. J. Donaghy et al., *Emission of the ORNL Negative Ion Source*, ORNL/TM-10186, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., November 1987.
24. C. C. Tsai et al., *Design Considerations for a Negative Ion Source for DC Operation of High-Power, Multi-Megaelectron-Volt Neutral Beams*, ORNL/TM-10644, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., March 1988.
25. J. H. Whealton et al., "High Brightness Ion Source: The Penning Ringatron," *Production and Neutralization of Negative Ions and Beams: AIP Conf. Proc.* **158**, 404-18 (1987).
26. J. H. Whealton et al., "Theory of Feedthroughs: Wave Transmission and Voltage Characteristics of High-Power Current Feeds for ICRH," *Fusion Technol.* **8**, 400 (1985).
27. G. L. Chen et al., "Resonant Loop Antenna Design with a 2-D Steady-State Analysis," *Application of RF Power to Plasmas*, S. Bernabei and R. W. Motley, eds., *AIP Conf. Proc.* **159**, 382 (1987).
28. C. A. Foster, M. M. Menon, and J. H. Whealton, "E-Beam Rocket Pellet Accelerator," *Bull. Am. Phys. Soc.* **31**, 1599 (1986).
29. J. H. Whealton, "Accelerator for Negative Ion Sources," presented at the IAEA Technical Committee Meeting on Negative Ion Beam Heating, Grenoble, France, March 21, 1985.
30. J. H. Whealton, M. A. Bell, and R. J. Raridon, "Extraction and Acceleration of Negative Ion Beams from Volume Produced Sources, Including Those of Allison, Stirling, and Bacal," presented at the Second European Workshop on the Production and Application of Light Negative Ions, Ecole Polytechnique, Palaiseau, France, March 5-7, 1986.

31. J. H. Whealton, "Review of Computer Modeling of Negative Ion Beam Formation," *Production and Neutralization of Negative Ions and Beams: AIP Conf. Proc.* **158**, 482-506 (1987).
32. J. H. Whealton and J. C. Whitson, "Space Charge Ion Optics Including Extraction from a Plasma," *Part. Accel.* **10**, 325 (1980).
33. J. H. Whealton, "Ion Optics Arithmetic," *Nucl. Instrum. Methods* **189**, 55 (1981).
34. J. H. Whealton, R. W. McGaffey, and P. S. Meszaros, "A Finite Difference 3-D Poisson-Vlasov Algorithm for Ions Extracted from a Plasma," *J. Comput. Phys.* **63**, 20 (1986).

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Section 6

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**SUPERCONDUCTING MAGNET
DEVELOPMENT**

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10

P. N. Haubenreich, Manager, Large Coil Program
M. S. Lubell, Head, Magnetics and Superconductivity Section

O. D. Ballinger	B. Jakob ⁵	S. W. Schwenterly
L. R. Baylor ¹	D. L. James	L. S. Scruggs ⁷
R. E. Bohanan	T. Kato ⁵	S. S. Shen
R. L. Brown	W. J. Kenney	B. C. Smith
J. A. Clinard ²	M. W. Keller ⁶	R. E. Stamps
L. Dresner	J. O. Kiggans	Y. Takahashi ⁴
J. F. Ellis	J. W. Lue	A. R. Ulbricht ³
D. T. Fehling	J. N. Luton, Jr.	S. F. Vaughan ⁷
W. A. Fietz	W. Maurer ³	C. A. Wallace
J. M. Finger	J. N. Money	C. T. Wilson ¹
W. M. Fletcher ¹	K. Okuno ⁴	R. E. Wintenberg ⁸
G. M. Friesinger ³	T. C. Patrick	R. J. Wood ¹
S. D. Gauss ³	W. J. Redmond	F. Wuechner ³
R. L. Hendren	L. Riester	K. Yoshida ⁴
C. R. Howell	J. P. Rudd	K. L. Zell ⁷
F. Iida ⁴	C. R. Schaich	J. A. Zichy ⁵

-
1. Engineering Division, Martin Marietta Energy Systems, Inc.
 2. Engineering Technology Division.
 3. Assignee from Kernforschungszentrum Karlsruhe, Karlsruhe, Federal Republic of Germany.
 4. Assignee from Japan Atomic Energy Research Institute, Ibaraki, Japan.
 5. Assignee from Swiss Institute for Nuclear Research (now Paul Scherrer Institute), Villigen, Switzerland.
 6. ORAU Student Research Participant, June-August 1987.
 7. Program/section secretary.
 8. Instrumentation and Controls Division.

6. SUPERCONDUCTING MAGNET DEVELOPMENT

SUMMARY OF ACTIVITIES

In 1987 the principal activity in this area continued to be the international Large Coil Task (LCT), in which ORNL served as the Operating Agent. The LCT program of testing six different superconducting toroidal field coils was successfully completed, and repatriation of the three foreign test coils was begun. Tests of each coil at design current and magnetic field in 1986 were followed this year by extended-condition tests that delineated the operating margins actually achieved in the design and construction of the coils. These tests and some coil safety tests that were added to the program produced gratifying, informative results. Operation was concluded with warmup of the 420-t test stand from liquid helium temperature. After being sealed for 22 months, the surrounding vacuum tank was opened in October. The Japanese coil was removed and packed for shipment, and preparations were made to do the same for the EURATOM and Swiss coils, as requested by their owners. ORNL scientific/technical staff members continued their evaluation of results and preparation of an LCT summary report in collaboration with representatives of other participants. Most of the test facility operators transferred to other positions at ORNL. As LCT activities diminished, efforts of the ORNL magnetics group began to shift to long-range tasks in fusion magnet development.

6.1 LARGE COIL TASK

During 1987 the International Fusion Superconducting Magnet Test Facility (IFSMTF) continued to serve, as it had for the preceding nine years, as the focal point for the collaboration of the United States, the European Atomic Energy Community (EURATOM), Japan, and Switzerland in the development of toroidal field magnet systems for fusion applications. On-site activities peaked in 1987 as the test program pushed all coils to their design limits and beyond.

Typical representation at the test facility was three to five persons from Japan, two to four from EURATOM, and one or two from Switzerland. Testing followed the program outline previously adopted by all participants in the Large Coil Task (LCT). An on-site committee that included representatives of each LCT participant oversaw the day-to-day activities.

LCT project officers and the LCT executive committee met twice in Oak Ridge in 1987. The principal topics were review of progress, the sequence of remaining tests (including new coil safety tests), and plans for final tasks (summary report

and preparation of coils for shipment). All LCT participants agreed that the test program had been quite successful in achieving technical goals and that the international collaboration had been highly effective.

6.2 FACILITY OPERATION AND MAINTENANCE

6.2.1 Overview

The facility was operated continuously from January through September in support of the coil test program. By the time the tank that housed the test stand was opened in October, it had been continuously under vacuum for 21 months. Between the initial cooldown and the final warmup, the test stand was continuously at cryogenic temperatures (liquid nitrogen or below) for 19 months. This extended operation produced significant information on performance, reliability, and sources of problems in a facility with some features that are relevant to the superconducting magnet systems needed for fusion power stations of the future. The overall availability of the facility for coil testing was quite creditable. Despite various problems related to the cryogenics, the availability from January to the end of active testing in September was 54%.

Operations in 1987 began with startup following a two-week shutdown of the helium refrigerator for regeneration of purifier beds and other scheduled maintenance tasks. During this shutdown, the test stand had slowly warmed to the temperature of the surrounding liquid-nitrogen-cooled cold wall. The subsequent cooldown was prolonged by new heat leaks, which resulted from air leakage into the vacuum jacket on a helium distribution line and increased conduction through multiple electrical connections to the pulse coil system that had been made during the shutdown. These conditions were remedied, and active coil testing resumed on February 2 with pulsed-field tests of the Swiss (CH) coil.

Operation of the pulsed-field coils at the CH test position was a technical milestone, as it required the unlocking, rotation, precise location, and locking of the multiton assembly with its flexible umbilical cord of coolant lines and instrumentation leads. These operations and the makeup of electrical power contacts at the new location had to be done by remote control, with the equipment at extremely cold temperatures (around 10 to 20 K for the actuators).

After the successful tests of the CH coil with superimposed pulsed fields in the first half of February, the pulse coil assembly was moved again. During this move to the bore of the Japanese (JA) coil, the helium-actuated cylinders for unlocking, rotating, and locking the assembly developed a serious problem. Piston seal leakage resulted in a helium leak into the tank vacuum. The assembly was moved to the JA station and locked there, but not before heat transfer due to the rise in tank pressure had boiled helium out of the coils, thereby causing a week's delay. Acting upon advice from ORNL, the U.S. Department of Energy (DOE) notified other LCT participants that to avoid possible excessive delay and cost in further attempts at movement, requirements for pulsed-field testing of the U.S. coils would

be withdrawn. Other LCT participants also concluded that relocation of the pulse coils was impractical and agreed to revise the test program accordingly.

After pulsed-field tests of the JA coil, the long-planned extended-condition tests of coils began. The first test, of the Westinghouse (WH) coil, was designed to elucidate the tolerance of its Nb_3Sn conductor to variations in temperature of the forced-flow helium coolant. For this test the refrigerator was adjusted to provide the highest attainable temperature to the WH coil while maintaining the standard coolant temperatures at the other coils [3.8 K to the EURATOM (EU) and CH coils, 4.2 K to the bath-cooled JA, General Dynamics (GD), and General Electric (GE)/ORNL coils]. With its helium inlet at 8 K, the WH coil current was raised to 18 kA, just above its nominal design current at 4 K.

After the "high-temperature" test operation, the next series of tests entailed experimental operation of single coils at currents well above their design values. This test series determined the achievable limits on coil current in self-field of the WH, GE/ORNL, JA, GD, and EU coils. (The CH coil test was deferred because no CH representative was on site at the time.) The EU coil reached the 140% current that its owners had set as their test objective. The other coils attained currents between 120 and 139% before the tests were terminated by incipient or actual quenches.

The WH coil was tested to investigate the behavior of its Nb_3Sn conductor as the magnetic field neared the highest attainable value in a six-coil test (without operating background coils beyond previously tested levels). This testing, with all six coils at extraordinarily high currents, taxed the capacity of the helium refrigeration system well beyond previous operations. Coil test operation was repeatedly interrupted by six-coil dumps from high current that were initiated by causes outside the WH coil. Each time, several days were required to recover the helium boiled off when the test stand was heated by magnetic field transients during the dump. The test was concluded on May 31, when the WH coil reached a field of 8.6 T (at the reference point in the horizontal midplane of the winding) with a current of 112% of its 8-T design value.

During the first week of June, one pulse coil was driven to twice the nominal current to test the JA coil in an asymmetric pulsed field. During this test, the nitrogen leakage into the vacuum tank sharply increased. While this event was being investigated, operation of the helium refrigerator was interrupted by freezing of air that had gradually leaked into portions of the helium system operating at subatmospheric pressure. The system was cleaned up, but before coil tests could be resumed, a seal on a helium compressor shaft failed and much air was drawn into the helium system. These problems and the cleanup and recovery occupied most of June and July.

Coil tests resumed on July 29 with a test of the JA coil at high field. The coil reached its owners' goal of 8.7 T with current at 108% of the 8-T design value. From then through the end of the coil test program on September 4, there was almost no delay due to problems with facility operation. The cryogenic system operated without further incident. (Nitrogen leakage into the vacuum tank from a still-undetermined source continued to be abnormally high, but the nitrogen froze

out on helium-cooled components without causing any evident problem, other than somewhat enhanced heat transport to the test stand.) Additional liquid helium was procured from an external source during some six-coil test periods when it was especially beneficial in avoiding delays for recuperation of the liquid reserve. Combined with extended working hours for the coil experimenters, this enabled a dramatic increase in the pace of the experiments during the final five weeks of the test program.

Three extended-condition tests of the CH coil were performed during the first week of August. First was a high-current, single-coil test that ended in a quench at 119% of design current. Next, the coil was operated with a drastically reduced helium flow rate up to full current. Finally, in a six-coil test to maximum field, the CH coil quenched just as it reached its goal of an 8.9-T reference field at 110% of design current. Tests of other coils at extraordinarily high fields continued, and in four days both the EU and the GE/ORNL coils were operated in separate six-coil tests up to 9.0 T at the reference points (9.1 to 9.2 T at the peak field points in the small-radius sectors of the coils).

The next series of tests explored the mechanical and electrical behavior of the coils (and, incidentally, the strains in the test stand structure) under abnormally high out-of-plane loading. For these tests, five coils were operated to high currents while one coil (adjacent to the two coils being tested) was kept deenergized. Each of the six coils was so tested in one or both directions during a 10-d period.

On August 20, the high-current test of the CH coil was repeated. This time the coil operated without quenching at 120% current, even when simulated nuclear heating was applied.

The next eight days were devoted to coil safety tests. Beginning in May 1987, the LCT participants had studied and planned for tests to investigate the feasibility of delaying and controlling superconducting magnet shutdown under certain adverse circumstances. These tests included operation and orderly shutdown of the EU coil after total stoppage of coil coolant flow. The EU coil was operated at full current for 1 h after flow stoppage, then ramped to zero with no problem. The test and ramp without flow took 1 h. In other tests, the WH coil was operated under current-sharing (marginally superconducting) conditions while heat pulses were applied to investigate quench propagation in this type of forced-flow conductor.

After a 3-d interruption caused by a plant power outage, coil testing was concluded with two days of intense activity. Stable operation with all six coils at 8.5-T reference fields was first demonstrated. Next the GD and JA coils were tested to their reference fields, 8.8 and 8.9 T respectively. The next day the CH coil was tested with out-of-plane loads of up to 17 MN. Then came the last planned test, the "maximum-torus" test. The coil currents were adjusted to make the peak fields in all six coils as nearly equal as practicable. Coil currents were then ramped up together until a spontaneous quench occurred, originating in the WH coil. At this point, the peak fields in the six coils ranged from 9.0 to 9.2 T, with currents between 98 and 108% of their 8-T design values.

The magnetically stored energy of the array at the time of the final dump was 944 MJ, of which more than 90% was dissipated in the dump resistors. The remainder appeared as heat in the coils, which constituted the first step in the planned warmup of the test stand. Active warming by circulating helium was delayed until the 400-kg accumulation of frozen nitrogen on test stand surfaces had evaporated and been evacuated. Circulation of warmed helium began on September 10, and by September 22 the test stand temperature was approaching 270 K.

The next two weeks were spent in measuring leak rates from helium and nitrogen systems. This required achieving a suitably low tank pressure, which was made difficult by the effects of water that had accumulated as a result of air inleakage during the 22 months that the tank had been continuously under vacuum. When leakage from each helium and nitrogen system inside the vacuum tank was finally measured, there was no detectable increase over the rates measured in 1985.

The vacuum tank lid was removed on October 9, after all observed temperatures in the test stand were above the dewpoint of the atmosphere in the building. The first week after the tank was opened was spent in inspections. With the exception of the pulse coil drive mechanism, the test stand was generally in good condition. Only minor effects of the extended-condition tests were evident. For example, some structural gaps had increased to 2 mm because of the expected plastic deformation during out-of-plane loading. Observations were recorded, and installation of work platforms and removal of in-tank equipment began on October 19.

All three non-U.S. participants in LCT wished to repatriate their coils. Procedures for removal, testing, and packaging of the coils were worked out between the owners and ORNL. Owners made arrangements for shipping and also provided technical personnel to monitor and participate in work on the coils.

In preparation for removal of the JA coil, which the Japan Atomic Energy Research Institute (JAERI) had requested at the earliest practicable date, sensor leads, helium lines, and superconducting buses were cut; wedges, upper collar, and shims were removed; the pulse coil assembly was rotated; and a sector of the ring gear in the JA coil bore was removed. Japanese representatives actively participated with Martin Marietta Energy Systems, Inc., craftsmen in this work. On November 2 the JA coil was lifted out of the test stand and attached to the base of its shipping crate, which had been rebuilt. After electrical tests of the JA coil showed that no damage had been incurred by any of the experiments, the coil was packaged for shipment. On November 16 it was loaded onto a highway transporter and left the Y-12 Plant for Savannah, Georgia, on the first leg of its journey back to Japan.

Removal of the EU coil entailed disconnecting and capping numerous capillary tubes and helium and vacuum connections. This was done under the direct supervision of an engineer from Kernforschungszentrum Karlsruhe (KfK); on December 15 the coil was lifted out of the tank and mounted on its shipping crate, which had been preserved. Plans were made for completion of the testing, preparation, and packaging of the EU coil when KfK representatives returned after year-end holidays in Europe.

Preliminary work on disconnecting the CH coil was begun, and plans were made for removal of this coil with the active participation of a Brown Boveri et Cie (BBC) field engineer in January 1988.

All foreign participants in the coil testing and analysis activities left Oak Ridge and returned to their home laboratories before the end of December. Before departing, they had participated in analysis of almost all the test data and had made a substantial start on writing the LCT Summary Report.

Disbanding of the IFSMTF operations group proceeded rapidly, and most of the operators were reassigned to other positions at ORNL by the end of December.

A plan was developed to use selected equipment from the IFSMTF in other activities in the fusion program at ORNL; the cryogenic systems were preserved for possible future recommissioning.

6.2.2 Availability of the Test Facility

The purpose of the IFSMTF was to create the conditions and to provide the supporting services required for coil testing activities. Therefore, for the IFSMTF, "availability" can be defined as the condition of the facility that permits coil testing activities to proceed. Coil testing activities by definition include not only the energizing of the coils but also the normal tasks required either before or after a period of coil operation. They also include recuperation from the testing, overnight and weekend rest for the people doing the testing, and liquefaction of helium boiled off as a consequence of the testing. An availability factor for a time period can be defined as the ratio of days that the system is available to the total days in the period. Figure 6.1 shows monthly availability factors during the entire six-coil test period.

The availability of the IFSMTF turned out to be better than many of the expectations recorded in the minutes of LCT meetings. (It would be of interest to compare the availability actually achieved with a prediction based on a detailed analysis of the systems and the best data on reliability of individual components. However, no such analysis has ever been made.) These expectations were formed on the basis of each participant's view of the facility design and equipment quality, plus the participant's past experience with facilities that were more or less similar. LCT project officers, after much discussion, agreed in 1984 that an availability factor of 50% was "a reasonably optimistic goal." The achieved factor for the 22 months of operation with six coils was 57%.

The only major element of the facility that became inoperative during the program was the system for remotely moving and locating the pulse coil assembly in the bore of the test coils. Although this breakdown prevented pulsed-field testing of the U.S. coils and, therefore, had a significant effect on achievement of program goals, it did not seriously reduce the availability factor computed for the six-coil operating period, because only a few days were spent in efforts to make the system keep on working after its use in the non-U.S. coil tests. The basic problem was

Fig. 6.1. IFSMTF availability factor for each month of operation with six coils.

simple, albeit difficult to solve: good sealing of a helium-actuated piston at very low temperature.

6.3 COIL TESTING AND ANALYSIS

6.3.1 Coil Tests

On October 24, 1985, the last of the six coils was installed and the vacuum tank lid was put on for the preliminary pumpdown. After room-temperature leaks were found and repaired, preliminary cooling was started to find the cryogenic leaks that invariably occur in such a complicated system. All of these leaks were repaired and pumpdown was started early in January 1986. Cooling commenced on January 18, and the WH coil was superconducting one month later. The test program began in early March and was carried out over an 18-month period, ending on September 3, 1987, with a maximum-field torus test in which all of the coils were energized simultaneously to a 9-T magnetic field. During this testing period, the system remained continuously at cryogenic temperature. Occasional excursions in

temperature occurred, with some as high as liquid nitrogen temperature (due either to problems with the cryogenic system or to coil dumps of the full array from high current). At such times it took from two days to a few weeks to recool the facility to helium temperature.

6.3.1.1 Single-coil design-point tests

The coil tests were arranged in a sequence of increasing severity with the electrical and thermal tests performed first, followed by pulsed-field experiments and ending with the mechanical tests. The data for the GE/ORNL coil presented in Fig. 6.2 illustrate the sequence of current and field tests that were performed for

Fig. 6.2. Load lines for the GE/ORNL coil.

each coil. First, the coil was tested by itself to full design current (which in the case of the GE/ORNL coil was 10,500 A). In this test (sometimes called the Standard test), the solenoidal forces on a D-shaped coil led to severe deformation of the structural case, with the horizontal bore increasing and the vertical bore decreasing. The calculation of these dimensional changes by a relatively simple finite-element model agreed very well (within 10%) with the measurements made on the GD and JA coils by moving-coil differential transformers placed in the bore of the coils.¹

In the single-coil design-point tests, all six coils reached 100% design current at $B_{\max} = 6.4$ T on the first try, without training or any quench due to bedding down of the winding, and the WH coil was energized to 100% design current at a helium inlet temperature of 8 K.

6.3.1.2 Six-coil design-point tests

The next series of tests was the six-coil design-point (Standard-1) tests, during which each coil was tested in turn to full rated current at a reference field of 8 T. For these tests, the other five coils were treated as background coils and energized to about 80% of their rated currents. A special synchronized reference signal drive was constructed to control each power supply so that all coils could be simultaneously charged to a different percentage of their rated currents. The settings were continuously variable from 0 to 140% of current ratings. Four of the power supplies delivered 16 kA and ± 12 V, and two were rated at 25 kA and ± 12 V. The reference field was calculated for the innermost turn at the midplane of the straight section of the D-shaped coil. The computer program FANDF,² which was written for this calculation, allowed for the differences between the coils in current density, ampere turns, and geometry (see Fig. 6.3). Thus, for each coil to attain a reference field of 8 T, different sets of currents were required for the other five background coils. These ranged from 72% for the CH coil test to 91% for the WH coil test; for the other four coils, background coil currents were close to 80%. For the WH coil, the last coil tested, the background currents and thus the reference field were already so high that this test was performed as the so-called symmetric torus test. The currents in each coil were adjusted so that all six coils achieved an 8-T reference field simultaneously. To accomplish this, the WH coil actually had to be run at 101.4% of rated current, while the other five were energized to between 88 and 95% of their rated current (on average, 91%). This test could be performed with confidence since each coil already had achieved an 8-T reference field at 100% design current. Each coil manufacturer also provided a calculation for the ratio of the maximum field in the corner region to the reference field. For a coil by itself (single-coil test) this ratio was accurately calculated, but for operation in the six-coil torus the ratio was not accurately calculated, and a program similar to FANDF is being prepared. The inaccuracy arises from the assumption by each coil manufacturer that all the other coils were identical to its own for the torus calculation. For this reason, all tests were performed for the *reference field*. In Fig. 6.4, the field distribution around the circumference of the inner turn is shown for the WH coil for both single-coil (solenoidal) and six-coil toroidal operation. This distribution is typical

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Fig. 6.3. LCT full-array model for field and force analysis.

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Fig. 6.4. Field variation from inside turn in middle of straight section of outside perimeter for WH coil.

of all the coils. The difference between the maximum field in the corner region and the reference field is 20.5% for the single-coil configuration and 3% for the toroidal configuration. The angular variation is much less in single-coil operation, and the minimum in toroidal operation is similar to the maximum field value in single-coil operation.

In the six-coil design-point test, all six coils achieved 100% design current at $B_{ref} = 8$ T without any training, including the adiabatically stabilized EU and CH coils.

6.3.1.3 Single-coil extended-current tests

After all the electrical and thermal tests (described in Sect. 6.3.2) at the design point (100% rated current and 8-T reference field) were completed, single-coil extended-current tests (Alt-C tests) were conducted with the aim of determining the *maximum current* above rated current that each coil could carry (with the ultimate level set at 140% because of design limits on deformation of the structure).

The results of the Alt-C tests are shown in Table 6.1. Three of the experiments resulted in a quench of the test coil. The EU coil was the only one to achieve the 140% level, and this resulted in a maximum field of 9 T. The stored energy was 200 MJ, or about twice that at the design point (Standard test).

Table 6.1. Single-coil extended-current tests

	Coil					
	EU	WH	GE/ORNL	GD	JA	CH
Cooling ^a	FF	FF	PB	PB	PB	FF
Ratio of operating current to rated current	140	131	139	120	138	120
I_{op}/I_{rated} , %						
Operating current I_{op} , A	15,949	23,200	14,591	12,240	14,061	15,600
Inlet temperature T_{in} , K	3.73	3.90	4.33	4.33	4.33	3.72
Outlet temperature T_{out} , K	3.97	5.50	4.33	4.33	4.33	3.94
Reference field ^b B_{ref} , T	7.76	6.83	7.70	6.79	7.73	6.92
Maximum field B_{max} , T	9.01	8.23	8.89	7.72	8.81	7.86
Ratio of maximum field to reference field	115.3	120.5	115.5	113.6	113.9	113.5
B_{max}/B_{ref} , %						
Stored energy E_s , MJ	200	202	193	136	198	123

^aFF = forced-flow, PB = pool-boiling.

^bInnermost turn at midplane of straight section.

The GE/ORNL coil reached 139% of rated current without undergoing a quench, but the current drive was stopped when the onset of current sharing was observed (see Fig. 6.5). To verify that this was the reason for the increase in the coil compensation voltage, the current was reduced until the voltage decreased to zero and then slowly increased stepwise until the exponential voltage rise was reached. It was a pleasant surprise to encounter current sharing well above the cryostable limit.

The JA coil achieved 138% of rated current, at which point the critical current in the high-field-grade conductor was exceeded and the coil quenched. The actual critical current in the conductor, which was at a temperature between 4.3 and 4.4 K according to the pressure inside the coil, was very close to the short-sample data extrapolated to 4.4 K. The coil was too stable in all the experiments to have quenched for any other reason.

Before the test of the GD coil, it was decided to limit the current to 120% of the rated current because a higher dump voltage could not be tolerated. The breakdown voltage to ground had slowly decreased with time for this coil and, as a result, the dump resistor was lowered to 26 m Ω , the minimum safe value (dump voltage = 265 V). The coil was brought to 120% and, when the current ramp was stopped to permit a flat-top for data acquisition, the coil quenched. A study revealed that the quench originated in the grade III conductor (low-field grade). The critical current had been exceeded. The current in this conductor was not as high as one would have expected from short-sample measurements, even compensating for operation at higher temperature. The performance of this coil in subsequent experiments

Fig. 6.5. Voltage across GE/ORNL coil, showing the onset of the resistive state.

was not in jeopardy, because the field distribution for operation in a toroidal test was actually lower for the grade III conductor than in the solenoidal test, even when the reference field was more than 2 T higher (see Figs. 6.6 and 6.7). Unlike similar braided conductor used in both GD and JA coils, monolithic subelements used in both the EU and GE/ORNL coils exceeded short-sample expectations. The conductors are shown in Fig. 6.8.

The CH coil also had a limit of 120% of rated current, which was set by the fabricator (BBC) to avoid excessive deformation of the structure. During the later stages of the testing program for some thermal experiments, the CH coil was charged to 120% of rated current without a quench. However, during the Alt-C tests the coil exhibited some sort of training effect for two successive charging attempts, which ended in quenches at 111% and 119%. Both quenches originated in the end pancake, possibly an indication of delamination of potted conductor or motion between the winding and structure.

The WH coil was energized to 131% of rated current, at which point the resistive power dissipation in the coil was over 600 W and the coil quenched. The cryogenic

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Fig. 6.6. Field distribution in midplane of GD coil in single-coil operation to 119% design current.

Fig. 6.7. Field distribution in midplane of GD coil in toroidal test configuration to a reference field of 9 T.

system could not handle such an additional load, and the output temperature continuously increased throughout the experiment, as shown in Fig. 6.9. The resistive power dissipation was calculated resistively from the compensation voltage across the coil (clearly discernible above the noise at 12 kA), as well as thermodynamically from temperature and mass flow measurements. For the mass flow measurement, steady-state conditions must be established, and the first point taken was at 11 kA. Figure 6.10, which shows the power dissipation vs current for the WH coil, indicates that the onset of resistance is at about 10 kA or 56% of the rated current and only about 30% of the expected critical current. It is remarkable that the coil could be operated some 13 kA above the first appearance of resistance.

In the Alt-C tests, all six coils achieved at least 120% design current. The EU coil achieved 140% at 9 T; the GE/ORNL coil, 139% at 8.9 T; and the JA coil, 138% at 8.8 T.

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INTERNAL FORCED-FLOW COOLING
3.8 K-1.5 MPa

EXTERNAL BATH COOLING
4.2 K-0.1 MPa

Fig. 6.8. Photographs of (a) GE/ORNL, (b) JA, (c) CH, (d) EU, (e) GD, and (f) WH conductors.

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Fig. 6.9. Current and temperatures for WH single-coil extended test.

Fig. 6.10. Resistive power dissipation in WH coil measured resistively and thermodynamically in single-coil extended test.

6.3.1.4 Six-coil extended-field tests

The results of the Alt-C tests, along with knowledge of the critical current, enabled us to design the six-coil extended-field (Alt-A) tests. The purpose of these tests was to achieve the *maximum field* for each test coil without exceeding the limits of the background coils. For example, the GE/ORNL single-coil extended test achieved 14,591 A at a maximum field of 8.9 T. Since current sharing was reached, this point is the critical current. With known empirical rules,³ the current was extrapolated to higher fields. A six-coil test designed to reach a 9-T reference field was successfully performed with the five background coils set at various currents, which averaged out to 94% of their rated current. A maximum field of 9.2 T was achieved stably without a quench, although the final current of 11,447 A was close to the critical current limit.

Similar tests were done one after the other for all six coils. The results are summarized in Table 6.2. All the NbTi coils achieved a 9-T maximum field. The

Table 6.2. Results from six-coil extended-field tests

	Coil ^a					
	EU	WH ^b	GE/ORNL	GD	JA	CH ^c
Ratio of operating current to rated current I_{op}/I_{rated} , %	114	112	109	100	107	110
Operating current I_{op} , A	13,000	19,827	11,447	10,230	10,958	14,303
Average current in background coils $\langle I \rangle$, %	91	94	94	99	97	87
Reference field B_{ref} , T	9.01	8.64	9.03	8.78	8.85	8.85
Maximum field ^d B_{max} , T	9.1	8.9	9.2	9.0	9.1	9.0
Ratio of maximum field to reference field B_{max}/B_{ref} , %	101	103	102	102	102.2	101.3
Stored energy E_S , MJ	788	829	827	858	858	630

^aInlet and outlet temperatures for the forced-flow coils and bath temperatures for the pool-boiling coils are similar to those in Table 6.1.

^bTest ended in a quench.

^cThese values were taken when current ramp was stopped; the system drifted up some 40 G, and the test ended in a quench.

^dProbably only one figure should be considered significant until the toroidal field calculation is complete.

Nb_3Sn WH coil reached an 8.9-T maximum field and quenched when the resistive power dissipation was close to 600 W. The CH coil results were reached after the current ramp was stopped, but the system continued to drift up in current (until the voltage decreased to almost zero). After a few minutes, another 5 A and 40 G were added to the CH coil, and it quenched. Movement in the toroidal array resulted from the very substantial out-of-plane forces as well as the central forces that were present in all six-coil tests. These movements are seen by all the coils (simultaneously measured by the compensated voltage across all the coils), but only the end pancakes of the CH coil received enough motion to develop a normal region, resulting in a quench. The coil was not designed to be cryostable. Frictional heating external to the conductor is removed by the helium only after it passes through the conductor (see Fig. 6.8). The EU conductor, which also operated above the cryostable limit, is designed so that the helium intercepts any externally generated heat before it reaches the superconductor.

The results for the other four coils were achieved without a quench. The pool-boiling coils were operated at a higher average temperature (4.3 K) than the two NbTi forced-flow coils (3.83 K), so it is all the more pleasing that they achieved the same maximum field.

In the Alt-A tests, all three NbTi pool-boiling coils achieved 9 T at 4.3 K. Both NbTi force-cooled coils achieved 9 T at (3.8 K), and the Nb_3Sn force-cooled coil achieved 8.9 T at (4.7 K).

6.3.1.5 Symmetric torus test

Near the end of the program, after the Alt-A tests were completed, we repeated the symmetric torus test with the aim of achieving 8.5 T simultaneously on all the coils, in much the same manner as the earlier 8.0-T symmetric torus test. This was done after all the mechanical and safety tests were completed, and it was so successful that we were encouraged to try a torus test in which a maximum field of 9 T could be achieved, at least on some of the coils. Finally, on the last day of experimenting, we ran the symmetric torus test again with some adjustment in the current settings so that, while the symmetry was lost with regard to the reference field, the highest maximum field could be obtained on each coil. This test was also successful, and all coils simultaneously reached 9.0 T or more. The load line for the GE/ORNL coil is indicated in Fig. 6.2 and is labeled "max torus test." We ran this test at the extrapolated critical current value. This was possible because the pressure in the pool-boiling coils was reduced to 15 psi for this test; thus, we did not expect to reach current sharing in the GE/ORNL coil or to exceed the critical current in either the JA or the GD coil. The settings are shown in Table 6.3. After the current ramp was stopped and data were taken, the inlet and outlet temperatures of the WH coil continued to rise, and the whole system quenched from a total stored energy of 944 MJ. Subsequent examination indicated that no damage occurred as a result of the full-torus dump from such a high setting (50% greater stored energy than the design value).

Table 6.3. Current distributions and forces for the maximum-field torus test ($E_s = 944$ MJ)

	Coil					
	EU	WH	GE/ORNL	GD	JA	CH
Rated current, A	11,400	17,760	10,500	10,200	10,220	13,000
Ratio of operating current to rated current	106	108	106	98	106	99
I_{op}/I_{rated} , %						
Inlet temperature, K	3.80	3.90	4.26	4.26	4.26	3.80
Outlet temperature, K	3.95	5.10	4.26	4.26	4.26	4.20
Reference field, T	9.09	8.75	9.06	8.78	8.90	8.98
Maximum field, T	9.2	9.0	9.2	9.0	9.1	9.1
Out-of-plane force, ^a MN	-11	1.2	10	-0.15	1.6	-1.1
Central force, MN	57	66	53	51	53	46

^aNegative value indicates clockwise direction looking down on torus.

The most interesting result was a mechanical movement, which was induced in the system by the widely differing dump time constants of the coils. The GD coil had a much longer time constant than any of the other coils. This meant that the dynamic out-of-plane forces were most severe for its two neighbors, the GE/ORNL and the JA coils. In Fig. 6.11, the out-of-plane forces are shown as a function of time. The JA coil initially had a 1.6-MN force in the direction of the GD coil at the moment of the quench; this force increased to 16 MN some 22 s after the initiation of the quench. The GE/ORNL coil had a positive out-of-plane force of 10 MN initially that underwent a change over about 30 s to a negative force (in the direction of the GD coil) of 12 MN. The fact that the windings and structure of both coils apparently suffered no damage is a tribute to the designers and manufacturers of these coils. No superconducting magnet had ever before been subjected to dynamic forces of such magnitudes. The only apparent effect was that the gaps between the coil and the bucking post for both the GE/ORNL and JA coils were the largest of all the coils after the system was warmed and the lid was removed for inspection.

In summary, during the maximum-field torus test, all six coils simultaneously attained a maximum field of at least 9 T. The total stored energy was 944 MJ.

6.3.2 Coil Performance

Residual resistivity ratio

The WH conductor had an extremely high residual resistivity ratio (RRR), indicating that the diffusion barrier was effective and that the copper was annealed

Fig. 6.11. Out-of-plane forces as a function of time during the dump of the torus from a stored energy of 944 MJ.

during the heat treatment for the formation of the Nb_3Sn . The GD conductor also had a high RRR, showing the advantage of separate fabrication of the cable and matrix.

Sensors

There was never any indication that the sensors on any coil created any shorts. This was true even for the GE/ORNL coil, which had shorts that were eliminated before the experimental program began.

Joint losses

The joint losses for all six coils were low and agreed closely with calculations.

System dumps

The effects of coil dumps (induced current and voltages and changing out-of-plane loads) could be accurately calculated. About 96% of the stored energy was removed by the dump resistor for four of the coils. Only 77% could be removed from the WH coil because of the large eddy currents induced on the shorted aluminum structure. Similarly, only 88% was removed from the CH coil because of a copper cooling tube on the structure, which provided a path for induced eddy currents.

Hot-spot measurements

Hot-spot measurements were made for the pool-boiling GE coil and the forced-flow WH coil. Measured values were less than the adiabatic calculation, lending encouragement for extrapolation to reactor-size magnets.

Stability tests

The pool-boiling coils were all cryostable at the design point. The energy needed to drive a half-turn (5 m) or a whole turn (10 m) normal was one to two orders of magnitude larger than that calculated on the basis of known enthalpy. The WH coil was extremely stable (stability margin between 1 and 1.9 J/cm³, depending on the location of the heater) at the design point, even though it was operating well above current sharing.

Simulated nuclear heating

The pool-boiling coils were stable at the design point with power densities of 50 mW/cm³ sustained for 60 s over 50 m of conductor. The nominal Engineering Power Reactor (EPR) requirement was 10 mW/cm³. The forced-flow CH coil could handle continuous heating of 300 W with local dissipation exceeding the Next European Torus (NET) requirement by a factor of 2.

Current sharing

For the first time, current sharing (CS) measurements were carried out on large coils (EU and WH). The CS measurements could be performed on the EU coil above the cryostatic stability limit without initiating thermal runaway. On the WH coil, the CS measurements indicated severe degradation of the conductor current.

Forced-flow cooling requirement

In a test to determine forced-flow cooling requirements, the flow for the EU coil was stopped at the design point for 10 min, and then the coil was ramped down without a quench being initiated. In all, the coil was without active cooling for 1 h.

AC losses

The magnitude of the ac losses measured on three coils was low (18 ± 3 W) and within expectations. However, the lack of any field (and current) dependence is not fully explained. Analysis is still in progress.

Acoustic emission

The acoustic emission (AE) noise emanated mostly from movement of the winding, but there was some from the structure. The pool-boiling coils had more AE

than the forced-flow EU coil (potted conductor) or the WH coil (conductor contained in grooves). The virgin runs were always noisier than subsequent charging, indicating compacting (bedding down) of the winding pack. There was better correlation between AE and compensated voltage for the forced-flow coils than for the pool-boiling coils, indicating that the winding and structure do not communicate as well in pool-boiling coils.

Mechanical loads

The mechanical response of all the coils under the extreme central loads (46 to 66 MN) during the toroidal tests and the out-of-plane loads (19 to 27 MN) during the Alt-B tests (five coils energized and one off) was excellent.

Winding motion

Motion existed in all the coils, but it did not affect the performance of any of the coils except the CH coil, which quenched on some occasions when it was energized to very high currents.

Displacement

Displacement measurements (DMs) were qualitatively as expected, but the magnitudes were not well predicted, and the differences among the coils are not fully understood. The behavior and magnitude of bore displacements were as predicted. The three pool-boiling coils showed surprising differences in winding pack displacements. None of the coils is elastic, and some hysteresis was found. The forced-flow potted EU coil deformed more like a solid body than the pool-boiling coils. In the out-of-plane load test, the DMs of the winding pack showed differences between the two sides when the same total net force was reversed. These differences result from the different field distributions that a coil experiences on each side.

Strain

Our ability to calculate the magnitude of strains is not very good. The strains on the pool-boiling conductors were higher and the case strains lower than anticipated. These results, with the AE data, indicate that the transmission of forces between the winding and the structure is poor. The only strain data on the conductor of the forced-flow coils is from the WH conductor, which had lower strains than the pool-boiling conductors, indicating good coupling to the grooves in the plates. Case strains for the EU and CH potted coils were also higher than for the pool-boiling coils, again indicating good transmission of the forces from the windings. Some nonlinear strains were noted on the subelements of the GE/ORNL conductor, but not on the core of the conductor, which behaved like the other pool-boiling conductors. This may be an indication of delamination of some subelements. However, this did not affect the stability or performance of the coil.

6.3.3 Facility Performance

Despite the fact that the refrigerator capacity was marginal, the test stand was maintained at cryogenic temperature throughout the 20-month period of cooling and testing.

Subatmospheric operation of the auxiliary cold box over an extended period was verified to be practical. The inlet temperature to forced-flow coils can be 3.7 K.

Cooling and warming of the test stand were carried out expeditiously and smoothly. No large thermal stresses or displacements were noted. No flow distribution problems were observed for any of the pool-boiling coils.

The remainder of the facility (vacuum pumps, power supplies, electronics, data acquisition system, computers, etc.) worked reliably with very good overall availability. The diagnostic sensors on both the facility components and the coils held up remarkably well, with fewer than 5% becoming unusable over the course of the experiment.

6.4 CONCLUSIONS

All six LCT coils exceeded their design goals. The NbTi coils performed at least as well as the Nb₃Sn WH coil. Substantial improvement is needed in the performance of the Nb₃Sn conductor to meet the winding pack current density and field level required for the International Thermonuclear Experimental Reactor (ITER).

The LCT results indicate that either a forced-flow or a pool-boiling design could be extrapolated to a reactor-size magnet. The advantages usually ascribed to forced-flow potted magnets (ease in providing very high discharge voltages, transmission of the winding forces to the structural case, and cooling of the conductor) were supported by the results. The advantages usually ascribed to pool-boiling magnets (exceptional cryostability, ability to absorb large nuclear heating, and ease in cooling) were also verified.

Four state-of-the-art advances were made:

- These are the largest coils (in size, weight, or stored energy) ever to produce 9 T or, for that matter, 8 T.
- The EU and CH coils are the largest adiabatically stabilized coils ever made.
- The WH coil is the largest Nb₃Sn coil ever made.
- The WH coil is the largest coil ever to be operated at full design current and 8 K.

REFERENCES

1. J. F. Ellis and P. L. Walstrom, "Moving Coil Linear Variable Differential Transformer," *Rev. Sci. Instrum.* **49**, 398-400 (1978).
2. T. J. McManamy, Engineering Division, Martin Marietta Energy Systems, Inc., private communication, 1987.
3. M. S. Lubell, *IEEE Trans. Magn.* **MAG-19**, 754-7 (1983).

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Section 7

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ADVANCED SYSTEMS PROGRAM

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T. E. Shannon¹

R. G. Blattner²	J. D. Galambos⁶	J. A. Moeller³
T. G. Brown³	P. L. Goranson¹	J. F. Monday¹
M. K. Bullock²	G. E. Gorker³	W. D. Nelson¹²
L. C. Caldwell⁴	I. Gomes⁸	Y-K. M. Peng
J. K. Carty⁵	J. R. Haines⁹	R. L. Reid¹
W. R. Clark¹	D. L. Henderson¹⁰	B. W. Riemer³
W. K. Cooper	B. D. Henegar⁴	R. O. Sayer⁶
L. S. Dale⁴	D. R. Hicks¹	E. C. Selcow³
L. Deleanu⁶	T. Horie¹¹	P. T. Spampinato³
C. A. Flanagan⁷	S. S. Kalsi³	D. J. Strickler⁶
P. J. Fogarty¹	V. D. Lee⁹	S. L. Thomson¹³
R. A. Fortner⁴	D. C. Lousteau¹	J. J. Yugo¹²
	J. B. Miller⁸	

-
1. Engineering Division, Martin Marietta Energy Systems, Inc.
 2. American Technical Associates, Knoxville, Tenn.
 3. Grumman Aerospace Corporation, Bethpage, N.Y.
 4. Section secretary.
 5. Bits & Bytes, Oak Ridge, Tenn.
 6. Computing and Telecommunications Division, Martin Marietta Energy Systems, Inc.
 7. Westinghouse Electric Corporation, Madison, Pa.
 8. The University of Tennessee, Knoxville.
 9. McDonnell Douglas Astronautics Company, St. Louis.
 10. Engineering Physics and Mathematics Division.
 11. Japan Atomic Energy Research Institute, Tokai, Japan.
 12. TRW, Inc., Redondo Beach, Calif.
 13. Bechtel National, Inc., San Francisco.

7. ADVANCED SYSTEMS PROGRAM

SUMMARY OF ACTIVITIES

The Advanced Systems Program has been organized as a focal point for design studies of future fusion experiments. The Fusion Engineering Design Center (FEDC) is the major engineering resource for the program. This group of 25 to 30 persons consists of roughly equal numbers of ORNL researchers and outside industrial participants. Since its formation in 1979, the Design Center has played a leading role in the design of next-generation devices.

From January through September 1987, the principal activity of the Advanced Systems Program was the Compact Ignition Tokamak (CIT) project, with limited resources applied to support of the design studies for the Tokamak Ignition/Burn Experimental Reactor (TIBER II) and the International Tokamak Reactor (INTOR). Activities in preparation for the International Thermonuclear Experimental Reactor (ITER) Project were initiated, with the Design Center taking a key role in the overall design team. Since the CIT was expected to become a capital project in the FY 1988 national budget, a typical ORNL project organization was put in place to manage this large effort through 1996.

As part of the national design team under the leadership of Princeton Plasma Physics Laboratory, ORNL has been a major contributor to the CIT project since its beginning in 1985. In 1987, this included lead responsibility for design integration and six Work Breakdown Schedule elements: ex-vessel remote maintenance, ion cyclotron resonance heating, shielding, external structure, vacuum systems, and fueling.

The Design Center supported the TIBER II design effort, led by Lawrence Livermore National Laboratory, in several key areas, including configuration development, facilities, remote maintenance, cost estimating, first wall and divertor design, fueling system design, and toroidal field magnet design. In addition to these design activities, a new systems code called TETRA was developed, under the direction of the Design Center, for use in the TIBER II design point selection.

The Design Center also continued to lead the engineering activities for the INTOR program. Interest in this program increased because of the planned ITER project, which will include the same international participants. These efforts, along with the assignment of one FEDC staff member to work with the Fusion Engineering Reactor design team in Japan, reinforced the Design Center's position as the primary point of interaction between the major international design teams and the U.S. reactor studies program. These efforts on the TIBER II and INTOR design studies have led to an expanded role for the Design Center in the ITER project.

7.1 ACTIVITIES IN SUPPORT OF THE COMPACT IGNITION TOKAMAK

As the next major step in the U.S. fusion program, the Compact Ignition Tokamak (CIT) has the objective of reaching ignition in order to address the scientific issues associated with ignited plasma regimes. The role of the Fusion Engineering Design Center (FEDC) in developing the conceptual design for the CIT is described in this section.

7.1.1 Design Integration

The core configuration of the present CIT device is an outgrowth of the ignition studies carried out during FY 1986. A number of characteristic features evolved during this phase, which resulted in three distinguishable candidate design options: a hydraulic preload system used to apply a preload to the inner leg of the toroidal field (TF) coil; a sliding joint located near the TF coil inboard leg, which acts to decouple the vertical load of the outboard region of the TF coil from the inner leg; and a conventional TF coil design that incorporates a copper-Inconel sandwich construction to optimize the resistance and strength of the coil. Figure 7.1 illustrates these design options and highlights their characteristic features. Further design and structural analysis showed that the sliding-joint approach was less effective than the preload method in unloading the TF coil inner leg. The joint extended beyond the straight section of the TF coil; current was therefore able to flow around the corner, and an appreciable amount of vertical load thus remained in the TF coil inner leg.

Fig. 7.1. Design options for the CIT core configuration.

The baseline design configuration established in 1987 combined the features of the hydraulic preload concept and the composite copper-Inconel TF coil design. The machine size has evolved during the preconceptual design period because of physics and engineering refinements. The present baseline machine has a major radius of 1.75 m. It has more margin with respect to q and volt-seconds, has more reasonable vacuum vessel and first wall envelope space, and does not rely on an active preload system to achieve normal operating conditions. The preload structure is designed to allow the TF system to operate at 12 T; however, the system can operate independently of any preload at 10 T to meet normal operating parameters.

The details of the CIT device core are shown in Fig. 7.2, which highlights the copper-Inconel ohmic heating (OH) solenoid and TF coil inner leg, the exterior poloidal field (PF) coils, and the interior control coils. The TF coils are modified Bitter plates with inner legs made of a composite of explosion-bonded copper and Inconel. A partial case supports the upper, lower, and outboard leg sections. The TF and PF coils are precooled with nitrogen and undergo an adiabatic temperature rise during a pulse. The solenoid coils are a double-pancake type of winding cut from a single laminated plate of explosion-bonded Inconel-copper-Inconel. The

Fig. 7.2. CIT device core.

vacuum vessel assembly is prefabricated as two 180° sectors that are inserted into two TF coil half-assemblies and joined in situ by welding. The vacuum vessel has 16 large horizontal ports and 16 pairs of circular vertical ports, top and bottom. The vessel assembly is cooled by forced nitrogen gas that passes through poloidal cooling channels welded to the outside of the vessel. Trade-offs were made between circular and rectangular test cells, and the circular cell was selected, primarily from a cost standpoint. The CIT device-test cell interface is illustrated in Fig. 7.3. A pellet injection system and a diagnostic neutral beam are housed outside the test cell; midplane tubes connect these components to the vacuum vessel. The device core is housed in a thermally insulated cryostat. Upper and lower glass epoxy compression blocks and stainless steel support plates are located between the tokamak device core and the preload structure. The compression blocks transmit the preload to the TF coil inner leg while insulating the cold coils from the warm support plate and preload structure. In an early preload structural design, sized for a preload of 2.27×10^7 kg (50 million lb) (see Fig. 7.1), a hydraulic assembly was located between the upper compression block and the support plate attached to the preload structure. The hydraulic cylinders were located in a direct load path to the preload structure; however, their position made them difficult to replace and limited their area, requiring an operating pressure of 206.7 MPa (30,000 psi). Design changes were needed to correct this situation. The CIT physics requirements

Fig. 7.3. Plan view of CIT device and test cell.

were also modified to include operation at 12 T, imposing a design requirement of 5.22×10^7 kg (115 million lb) on the preload structure to unload the TF coil inner leg. Figure 7.4 shows the revised preload structural design that was developed to meet these changes. The present structure consists of thick plates and built-up I-beams. An intermediate structure is located between the device core and the hydraulic cylinders, so that the cylinders can be placed in the basement of the test cell (improving maintenance) and their area can be increased. In this revised design, the hydraulic pressure is reduced to less than 68.9 MPa (10,000 psi).

A close-fitting, 1.8-m-thick, borated-concrete igloo shield surrounds the device core. It is designed to minimize penetrations through the shield and to maximize the ease of access to internal components. Most peripheral components are located between the igloo shield and the device thermal boundary. The igloo shield reduces

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Fig. 7.4. Preload structural design.

air activation and allows personnel access to and hands-on maintenance within the test cell 24 h after shutdown. Figure 7.5 shows the device core and press structure with a typically configured shield. Several configurations are being considered to optimize access and maximize device component maintenance.

Ex-vessel remote maintenance tasks in the test cell are done with a bridge-mounted manipulator system and a mobile telerobot. In-vessel remote maintenance tasks (replacing graphite tiles and divertor plates, leak detection, and welding) are done with two articulated-boom manipulators. They operate under vacuum and are stored behind a shield plug and vacuum isolation valve.

Fig. 7.5. Isometric view of CIT device core.

7.1.2 Ex-Vessel Remote Maintenance

Because deuterium-tritium (D-T) fuel will be used in CIT, remote handling technology is required for most maintenance and disassembly operations. The general sequence of operations for component maintenance is shown in Fig. 7.6. As described in ref. 1, design activities in this area during 1987 focused on establishing interfaces between equipment and the facility design, developing the requirements for manipulator systems, and using mock-up demonstrations to support the tokamak configuration design.

Fig. 7.6. Equipment maintenance sequence.

The major thrust of the work for 1987 was to define the maintenance requirements closely enough to identify major impacts on the facility configuration. These studies included evaluation of (1) remote handling and manipulator transport systems, (2) access to machine components that require remote maintenance, and (3) requirements for transport, decontamination, and repair or disposal of failed components. The progress of this work is described in ref. 1.

The prime candidates for remote handling and manipulator transport systems were a bridge-mounted manipulator with a telescoping mast (Fig. 7.7) and a floor-mounted system with an articulated boom. The bridge-mounted system was selected for the baseline configuration; it provides full coverage of the test cell without interference from floor-mounted machine components.

Fig. 7.7. Bridge-mounted manipulator for CIT test cell.

The use of partial mock-ups has been extremely valuable in studying problems of access and has had an impact on the development of the machine configuration. Work during 1988 will emphasize development of manipulator systems, preliminary design of facilities-related equipment, and the continued use of full-size mock-ups.

7.1.3 Ion Cyclotron Resonance Heating System

Developing a conceptual design for the ion cyclotron resonance heating (ICRH) system for CIT was the joint responsibility of the Design Center and the Plasma Technology Section of the Fusion Energy Division. The CIT conceptual design studies are described in detail in Sect. 5 of this report.

7.1.4 Nuclear Analysis

The high neutron wall loadings ($4\text{--}5\text{ MW/m}^2$) associated with the operation of CIT require consideration of neutronics-related issues in the overall system design. The most critical radiation concern in the CIT design process relates to the

numerous penetrations in the device. The pellet injector, a major component, has a line-of-sight penetration through the igloo shield and the test cell wall. A nuclear analysis was performed to determine the feasibility of personnel access to and hands-on maintenance of the injector, as required by all current options for this component. This analysis is described in detail in ref. 2.

Figure 7.8 shows the pellet injector system and the relationship of the techniques used in the analysis. A coupled Monte Carlo/discrete-ordinates analysis was performed to determine the neutron flux entering the test cell, and the dose response rates from the neutron-induced activation inside the pellet injector glovebox were then determined at 0.5 h, 1 h, and 24 h after shutdown.

Fig. 7.8. Pellet injector configuration, with relationship of techniques used in shielding analysis.

A 10° sector of the tokamak geometry was modeled with the Monte Carlo code MCNP. The angular 14-MeV neutron current, estimated at a distance of 187 cm from the mouth of the port, was used as the source for the penetration in the igloo shield. The neutron source in the plasma corresponds to production of 5×10^{20} neutrons per pulse, but because of the small solid angle subtended in this geometry, only 7.4×10^8 neutrons enter the pellet injector during each pulse.

The glovebox configuration was modeled as shown in Fig. 7.9; dose calculations were made in the six locations labeled A through F, and the results are presented in Table 7.1. Operating conditions assumed for these calculations were a 5-s pulse length, a 1-h interval between pulses, and 15 pulses per day. The first set of calculations assumes 10 consecutive days of operation; the second set, 200 consecutive days for a total of 3000 pulses, which gives a conservative upper bound on the activation. The results of the study indicate that dose rates after shutdown from neutron-induced activation inside the glovebox do not present a concern for personnel access.

Fig. 7.9. Model of glovebox configuration. Locations of dose calculations are labeled A-F.

Table 7.1. Shutdown dose rates in the glovebox (mrem/h)

Position	10-d scenario			200-d scenario		
	0.5 h	1 h	24 h	0.5 h	1 h	24 h
A	2.4×10^{-2}	2.1×10^{-2}	6.6×10^{-4}	2.8×10^{-2}	2.4×10^{-2}	4.2×10^{-3}
B	1.3×10^{-3}	1.1×10^{-3}	3.5×10^{-5}	1.4×10^{-3}	1.3×10^{-3}	2.3×10^{-4}
C	2.5×10^{-4}	2.0×10^{-4}	7.7×10^{-6}	2.8×10^{-4}	2.3×10^{-4}	4.3×10^{-6}
D	1.8×10^{-4}	1.6×10^{-4}	5.0×10^{-6}	2.1×10^{-4}	1.9×10^{-4}	3.2×10^{-5}
E	7.7×10^{-5}	6.7×10^{-5}	2.1×10^{-6}	8.8×10^{-5}	7.8×10^{-5}	1.3×10^{-5}
F	2.4×10^{-5}	2.1×10^{-5}	6.3×10^{-7}	2.8×10^{-5}	2.4×10^{-5}	3.9×10^{-6}

7.1.5 External Structure and Hydraulic Press

The concept of preloading the TF coils of the tokamak to achieve a more compact device has been advanced in other tokamak design studies, notably those of the Ignitor concept.³ In the CIT design studies, the preloading concept is incorporated through a totally external preloading system. In essence, the CIT tokamak is installed in the jaws of a hydraulic press. Hydraulic pressure is used to apply a vertical preload to the inner leg of the TF coils. The preload is the force required to react exactly the vertical separating force normally reacted by the inner leg of the TF coil. With the preload, the inner leg of the TF coil is under essentially zero vertical tensile stress when the coils are carrying the maximum current during the flat-top period of the operating cycle.

The evolution of the external press design parallels the design evolution of the CIT device, as described in ref. 4. Over the life of the conceptual design study for CIT, parameters for the device have varied considerably. As understanding of physics and engineering issues evolved, the major radius changed from 1.08 m to 1.75 m, and the field on axis changed from 12.6 T to 12 T.

When these parameters changed, the required preload more than doubled to 5.22×10^7 kg. This load, coupled with the large spans in the beams necessitated by the larger machine size, demanded a structure that used the mass in the structure more efficiently. The tension link concept, shown in Fig. 7.4, was adopted to meet that need.

The tension link concept featured three main beam structures—top, bottom, and base—with the top and bottom beams connected by tension links on each end. The base beam was mounted in the floor of the CIT test cell and supported the deadweight of the CIT machine plus the press structure. The three webs joining the top and bottom flanges formed a double box beam, which is very rigid and stable.

Two options were considered for the hydraulic system for this concept. The first used 27 hydraulic cylinders with a piston diameter of 66.55 cm operating at 55.17 MPa (8000 psi); the second used 3 large hydraulic cylinders with a piston diameter of 183.52 cm operating at a pressure of 65.52 MPa (9500 psi). The height of the cylinders was 76.2 cm to allow clearance for removing and installing the V-packing seals and bushings. The design travel of the cylinders was 10.16 cm. The hydraulic system applied a total preload of 5.22×10^7 kg to the TF inner leg, producing a compressive stress of 246 MPa (35,000 psi). The system bleed-off capability made it possible to maintain a constant load of 5.22×10^7 kg when the TF inner leg grows in height because of the temperature increase.

The column-and-sleeve concept, shown in Figs. 7.10 and 7.11, is an extension of the tension link concept and is the present baseline press design. Preloading the columns in tension during initial installation of the press reduces the stress range, protecting the columns from fatigue during its life. Each column is preloaded to a load of 7.48×10^6 kg with hydraulic oil-filled nuts. During preloading of the CIT device, the final load in each column is 1.303×10^7 kg. This results in a minimum stress in each column from the initial preload of 162 MPa (23,500 psi) and a maximum stress of 322 MPa (46,700 psi) during the CIT preloading. The hydraulic oil-filled nuts require a special design, because their size and load capacity are larger than any existing design.

The hydraulic system is essentially the same as the second option considered for the tension link concept; the height of each cylinder is increased to 108 cm to allow clearance for installing the V-packing and bushings. Design travel remains at 10.16 cm. The cost estimate for this concept is \$20 million.

7.1.6 Vacuum System

The CIT will require an ultrahigh-vacuum (UHV) pumping system to evacuate the plasma chamber from atmospheric pressure to low pressure and to maintain

Fig. 7.10. The column-and-sleeve concept.

Fig. 7.11. The CIT device core in the column-and-sleeve structure.

the required torus vacuum levels during bakeout, discharge cleaning, and pulsed burn operation. The major performance goal of the vacuum pumping system is the achievement of a base pressure of less than 1×10^{-8} torr. The pumped stream, which will contain tritium, must not be exposed to lubricating fluids or organic seal materials.

The CIT vacuum pumping system includes the UHV pumping system for the torus, the diagnostic high-vacuum pumping system, the forepump and roughing pump system, vacuum system bakeout, pump ducts, differential pumping and leak detection, local instrumentation and control system, and cryostat pumping system. The design and performance of the UHV pumps, the forepumps and roughing pumps, and the pump ducts are described in detail in ref. 5.

The reference design for the torus vacuum pumps, valves, and ducts is shown in Figs. 7.12 and 7.13. The vacuum pumps and isolation valves are located in the test cell basement; the duct and shield configuration is intended to allow some hands-on

Fig. 7.12. CIT vacuum pumping system (elevation view).

Fig. 7.13. CIT vacuum pumping system (plan view).

maintenance. The size and cross-sectional shape of the duct change in several places as it extends from the torus to the 1-m-diam plenum in the basement. There are two 90° elbows in the duct. All flanges and valves are specified to be all-metal with metal seals.

Six smaller ducts lead from the plenum to six 2000-L/s magnetic-bearing turbo-molecular pumps (TMPs). Only five of these pumps are assumed to be operational, with the sixth included for redundancy. Because TMPs typically have a relatively low hydrogen compression ratio, a second stage consisting of two 300-L/s magnetic-bearing TMPs (one for redundancy) is provided. Magnetic shielding constructed of 0.1-m-thick carbon steel is placed around each TMP to limit the eddy current heating of the turbine blades, which rotate at a high speed.

Two 600-m³/h mechanical Normetex scroll pumps (one for redundancy) are used for roughing and for backing the second-stage TMPs. These are dry rotary, ejection-type mechanical pumps with no sealing lubricant exposed to the vacuum environment.

Because the exhaust is handled in a throughput instead of holdup fashion with no organic seal or lubricant materials exposed to the vacuum stream, large inventories of tritium, which would be vulnerable to release during an accident and which could inhibit maintenance of the vacuum pumping equipment, are avoided.

The net speed of the system was calculated to be $5.0 \text{ m}^3/\text{s}$ for hydrogen and $2.6 \text{ m}^3/\text{s}$ for nitrogen. The base pressure that can be achieved in the torus is assumed to be limited by outgassing of the stainless steel vacuum vessel and pump duct and the graphite surfaces of the first wall and divertor armor. Because the ducts have a significant surface area, the outgassing from duct walls was modeled with a source distributed along the duct. The estimated total pressure in the torus was $7.9 \times 10^{-7} \text{ Pa}$ ($6.0 \times 10^{-9} \text{ torr}$), which meets the goal of less than $1.3 \times 10^{-6} \text{ Pa}$.

The cost impacts of the equipment selections for this design were estimated during the evaluation of design options. The net cost penalty for an all-metal, oil-free torus vacuum pumping system is estimated to be \$780,000. The reduction in cost for safety-related equipment with this design was not determined, but it could significantly offset the cost penalty.

In summary, design efforts to date show that an all-metal, oil-free vacuum pumping system appears feasible. The key issues are reliability and the cost penalties associated with this approach. A research and development (R&D) program to operate two of these pumps for two years is under consideration. Although the cost of this system could be significantly reduced by using components with organic seals and oil-lubricated pumps, the safety concerns and added cost to safety systems are judged to outweigh the cost penalties.

7.1.7 Fueling

The funding for the R&D, design, and fabrication of the pellet injector system for CIT will be provided by the Development and Technology Division of the U.S. Department of Energy (DOE). Funding to support interface activities between the ORNL pellet injector group and the project was provided in 1987 and is scheduled to continue through the entire CIT design phase. Activities during 1987 in support of the CIT conceptual design studies of the pellet injector were a joint effort between the Design Center and the Plasma Technology Section of the Fusion Energy Division and are described in Sect. 5 of this report.

7.1.8 Magnetics/Disruption Simulation Studies

The level of energy confinement required for ignition in CIT leads to a high-field ($B_t = 10 \text{ T}$) device with a large plasma current ($I_p = 9 \text{ MA}$). System studies have resulted in a baseline design with major radius $R = 1.75 \text{ m}$, minor radius $a = 0.55 \text{ m}$, elongation $b/a = 2.0$, and $q = 3.5$, where elongation and q are measured at the 95% flux surface. The PF system for CIT is designed for double-null divertor operation at $4.5 \text{ MA} < I_p < 9.0 \text{ MA}$. Device physics specifications require that

higher power supply requirements. The power supply requirements and TF coil preload levels for the internal PF coil option are more sensitive to enhanced field levels than those of the external PF coil option because of the much larger TF coils associated with the internal option.

7.2 ACTIVITIES IN SUPPORT OF INTOR, TIBER, AND ITER

During 1987, the Design Center had key responsibility in several areas for support of the Engineering Test Reactor (ETR) studies aimed at the Tokamak Ignition/Burn Experimental Reactor (TIBER II) studies led by Lawrence Livermore National Laboratory (LLNL). These responsibilities included systems analysis, cost estimating, configuration development, facilities design, remote maintenance equipment design, first wall and divertor design, and fueling system design. This work has evolved into lead roles in several of these areas for the FY 1988 International Thermonuclear Experimental Reactor (ITER) project. The Design Center also continued to play a major role in the International Tokamak Reactor (INTOR) studies, with several staff members involved in leading engineering, systems analysis, remote maintenance and configuration, and physics studies. Design Center activities in support of all three ETR projects (INTOR, TIBER, and ITER) are discussed.

7.2.1 Systems Analysis

Systems analysis activities in support of ETR-type devices at the Design Center during 1987 were focused on the development of a new tokamak systems code. This code, called TETRA, was developed in a joint effort by participants from the Design Center, Argonne National Laboratory, Los Alamos National Laboratory, LLNL, ORNL, TRW, Inc., and the Canadian Fusion Fuels Technology Project. The first version of this code was constructed to model devices similar to the TIBER device. It has been used to support the TIBER II studies and to perform a comparative analysis of next-generation INTOR-like designs.

7.2.1.1 Systems code architecture

The TETRA code is similar in concept to the code described in Ref. 8 in consisting of modules that are executed and controlled by a driver routine. TETRA also has a feature that allows for optimization. A detailed description of the code architecture is given in ref. 9.

The modules, each describing a system or component of a tokamak reactor, are shown in the Tokamak Reactor Systems flow diagram (Fig. 7.14). The modules downstream depend on those upstream to supply input (e.g., the energy storage module requires input from the magnet modules and the plasma heating modules).

Fig. 7.14. Tokamak reactor systems flow diagram.

The overall ETR systems code schematic is shown in Fig. 7.15. The systems code is controlled by an optimizer or nonlinear equation solver. All modules from Fig. 7.14 serve as a function generator and are represented as a single block (labeled Tokamak Reactor Systems) in Fig. 7.15. This block returns to the driver computed values of physics and engineering quantities, which are used in evaluating specified constraints. If constraints are not satisfied within tolerance, the driver changes specified variables for iteration and recalls the Tokamak Reactor Systems modules until convergence criteria are satisfied. When the optimizer option is used, the variables are iterated within prescribed bounds until the constraints are satisfied and a maximum or minimum selected figure of merit (such as cost or major radius) is achieved.

7.2.1.2 Comparative analysis of next-generation INTOR-like designs

The International Fusion Research Council recommended that the INTOR Workshop conduct a critical analysis of the INTOR-like designs. In addition to INTOR,¹⁰ these include the next generation tokamaks now under development: the Next European Torus (NET) in the European Community,¹¹ the Fusion Engineering Reactor (FER) in Japan,¹² the OTR in the U.S.S.R.,¹³ and TIBER in the United States.¹⁴ As part of this overall effort, a series of comparative analysis calculations was performed with TETRA. These calculations are described in detail in ref. 15. Each design was benchmarked by the code, numerous sensitivity calculations were

Fig. 7.15. ETR systems code schematic.

performed to examine the specific impact of each design choice on a given design, and relative cost comparisons were developed.

The TETRA systems code was used to replicate each design to check the ability of the code to reproduce the design performance. The geometry and dimensions of the designs are given in Table 7.4, and typical results from the benchmark calculations are given in Table 7.5. They show that the code reproduced the various designs with reasonable accuracy. For some of the comparisons, detailed aspects of a given design may not have been well represented because of an inability to precisely

Table 7.4. Geometry and dimensions of INTOR-like designs

	INTOR	NET	FER	TIBER	OTR
Major radius, m	5.0	5.18	4.42	3.0	6.3
Minor radius, m	1.2	1.35	1.25	0.83	1.5
Plasma current, MA	8.0	10.2	8.7	10.0	8.0
Field on axis, T	5.5	5.0	4.6	5.55	5.8
D-T density, 10^{20} m^{-3}	1.4	1.3	1.0	0.8	1.4
Temperature, keV	10.0	10.0	12.0	16	8.0
TF coil thickness, m	67	70	68	49	110

Table 7.5. Comparison of design and calculated performance parameters

	INTOR	NET	FER	TIBER	OTR
Maximum toroidal field, T					
Design	~11	11.4	12	12	12
Calculation	10.8	10.8	10.0	11.1	11.8
Magnetic energy, GJ					
Design	25	25	14	4	45
Calculation	19.9	22.2	11.6	5	38.7
Current density in TF coil winding pack J_{wp}					
Design	2540	2200	3300	4000	3500
Calculation*	2970	2467	2990	4390	3055
Maximum field in OH solenoid, T					
Design	8	11	12	14	8
Calculation	8.8	10.1	10.9	13.8	7.6
Fusion power, MW					
Design	585	650	406	314	500
Calculation	584	652	405	308	504
Wall load, MW/m²					
Design	1.3	1.0	1.1	1.1	0.8
Calculation	1.2	0.99	0.9	1.2	0.7
Beta, %					
Design	4.9	5.6	5.3	6.0	3.2
Calculation	5.0	5.6	6.6	7.0	3.5
Required volt-seconds					
Design	112	181	50	58	200
Calculation	119	149	140	66	184

* Assumes Westinghouse Nb₃Sn conductor design.

represent a given feature or concept in the code, a different definition of terms, or different assumptions about how to represent a feature, concept, or parameter.

Two types of sensitivity analysis were performed. In the first, designated global analysis, the impact of replacing in toto the physics or the engineering assumptions and design constraints of one design with those of another design was determined. The purpose was to find the major aspect of a design that contributes most to the general definition of that design. In the second type of sensitivity study, the impact on a given design of making a single change in the physics, engineering, or general features was determined. The purpose was to find the individual changes that appear to have the greatest impact on a given design.

Figure 7.16 shows the results of a global substitution series of calculations that examined the impact of using NET physics and TIBER engineering. The results indicate a change to a much lower aspect ratio design and to a much lower field on axis. The major radius is about 3.4 m, which is much closer to the nominal TIBER value than the NET value. This result suggests that all of the physics assumptions and design constraints combined produce a relatively small change in major radius for these two designs.

Fig. 7.16. Comparison of TIBER and NET.

In one series of individual sensitivity analyses, calculations were performed to determine the individual impact of selected differences between the INTOR and TIBER designs. Individual changes in the plasma major radius were investigated, starting with a calculation of INTOR and progressively making changes until the major physics and engineering assumptions and design constraints were those of TIBER. The changes listed in Table 7.6 have a relatively large impact (>20-cm change) on the major radius; others have a substantially smaller impact.

The net effect of these changes is a reduction in major radius of about 2 m, which is the difference between the nominal INTOR major radius and the TIBER value. This is illustrated in Fig. 7.17. Caution should be taken in the interpretation, however, since the effect of one change was obtained by making that change only and holding all other assumptions fixed; it is not certain that the results should add up to produce the integrated net change. Nevertheless, each item clearly has a significant impact on the device size.

Table 7.6. Changes with large impact on major radius

	Difference in major radius (cm)
Change in inboard shield thickness from 80 cm (INTOR) to 48 cm (TIBER)	-70
Change in inner TF leg thickness, as a result of change from INTOR winding pack current density to TIBER winding pack current density	-30
Change in inboard plasma scrapeoff thickness from 20 cm (INTOR) to 6 cm (TIBER)	-35
Change in inboard gaps other than scrapeoff, from 15 cm (INTOR) to 2 cm (TIBER)	-25
Change in divertor configuration from single null and elongation of 1.88 (INTOR) to double null and elongation of 2.4 (TIBER)	-50
Change in operating mode from inductive start and burn (INTOR) to noninductive current drive and $Q > 5$ (TIBER)	-45
Change in coefficient in Troyon beta formulation from 4 (INTOR) to 3.1 (TIBER)	+50

Fig. 7.17. Comparison of INTOR and TIBER.

The systems code cost routine was used to estimate the relative cost of each design. The relative costs are based only on an estimate of the total direct capital cost of the designs and include no indirect, contingency, escalation, or development costs. Also, no operating costs are included. The results (Fig. 7.18) are given as cost normalized to INTOR.

Fig. 7.18. Comparison of direct cost for INTOR-like devices.

The results of this study demonstrate the ability of systems analysis to replicate the five INTOR-like designs with good accuracy. This capability is very encouraging, since the objectives and features of the five designs vary widely. The results also indicate the value of sensitivity analysis to provide insights to the designers on the impacts of various aspects of the design. Such results can be used by a design team to provide guidance at the early stages of a design. Global sensitivity analysis can provide some broad overview insights, and the impact of individual changes on the relative capital cost of a given design can be estimated. Such results are important ingredients at the early stages of a design when various options are being explored.

7.2.2 Configuration Development

Design scoping studies were completed on concepts for the TIBER vacuum tank. In the baseline configuration, shown in Fig. 7.19, a single external vacuum tank is used for both the plasma and coil vacuum boundary. A cylindrical tank approximately 7.5 m in radius and 11 m tall, topped with a torispherical head, is required. With TIBER's horizontal maintenance scheme, limited-life components (i.e., the divertors and test modules) are installed through approximately 2-m² ports at the machine vertical centerline. The size of these ports in turn limits access for

Fig. 7.19. Baseline configuration for TIBER II vacuum tank.

removal of the longer-life shield components and necessitates segmentation of the shield into four poloidal sectors. Consequently, two concepts for a vacuum tank are being pursued: a conventional cylindrical structure with the required ports, and a demountable concept in which a stationary frame has large removable wall panels that contain the ports. The second concept would provide the maximum opening between the TF coils for installation and removal of the longer-life components.

The torispherical head is common to both concepts and was sized using the pressure vessel code assuming a Class 2 rating and type 315L stainless steel construction. The required wall thickness was determined to be 3.2 cm (1.25 in.). For the cylindrical side wall, also assumed to be constructed of type 315L stainless steel, buckling constraints determine the required thickness. Several feasible solutions for wall thickness at different distances between reinforcement rings were found for side loads only. For these cases, it was determined that the axial load generated from supporting the dome lowered the critical buckling pressure on the side walls by 15%. Parametric studies were then carried out using the much simpler equations that define buckling, considering only the radial loading. The actual factor of safety can then be assumed to be approximately 15% lower than that calculated. Figure 7.20 shows the required wall thickness as a function of the number of segments or, conversely, the distance between supports. The reference design uses seven sectors, chosen as the best fit considering the constraints of the overall layout. A net safety factor of 3 is then obtained for a 1.9-cm-thick wall.

The columns required to support the dome, as well as the side plates in the second concept, have been sized. Sixteen columns, lying in the same circumferential

Fig. 7.20. Required wall thickness as a function of number of vertical sectors. Buckling criteria: $R = 7.6$ m (300 in.), height = 11 m (433 in.).

plane as the TF coils, are needed. If 51-cm-wide box columns (the same width as the TF coils) are used, they must be 76 cm (30 in.) deep with 5-cm-thick walls.

7.2.3 Facilities and Maintenance for TIBER II

The Design Center had the lead responsibility for developing the facilities design and remote maintenance approach for TIBER II. Facilities for TIBER II include the plant buildings and structures, the reactor maintenance equipment, and the general arrangement of the plant buildings and services. The major structures are the reactor building and the reactor maintenance building. Figure 7.21 shows the overall site plan. The reactor building provides a controlled environment for the tokamak and adjacent supporting equipment. The building arrangement allows space for maintenance operations and equipment and includes transportation corridors and laydown areas.

The reactor building is a part of the confinement system that controls the release of radioactive material from the plant, and it must meet safety criteria for routine and accidental releases. It is designed to operate with a filtered exhaust and at a slightly negative pressure so that any atmospheric leakage is inward.

The reactor building is sized to house the tokamak and its adjacent supporting systems and to allow space for maintenance operations. A basic building size of 20 m from the center of the tokamak to the wall (7.5 m for the cryostat, 6.5 m for the

Fig. 7.21. Site plan for TIBER II facilities.

retracted divertor, and 6 m for the handling machine and clearances) is required to allow this operation. A square building with 40-m sides was found to allow laydown of the vacuum vessel dome or PF coils in any corner. This minimum-size building was selected for the baseline design. The building height of 35 m allows operation of a crane with a capacity of 2×10^5 kg and lifting of a TF coil above the vacuum vessel with clearances.

The reactor building is connected directly at grade level to the maintenance building by a transfer chamber $4 \times 10 \times 8$ m high, as shown in Fig. 7.22. Next to the transfer chamber is a maintenance equipment storage area, $8 \times 11 \times 8$ m high. The upper portion of the west wall can be raised to allow the building crane to travel into a crane storage and maintenance area above the neutral beam source room, as shown in Fig. 7.23. The movable portion of the wall retracts into a pocket in the roof.

The reactor building basement contains the heat transport and vacuum systems for the tokamak, as well as cable and pipe galleries. The basement is laid out to accommodate remote operations and is connected directly to the maintenance building by an air lock and transfer corridor. Space around the vacuum tank allows up to 1.0 m of shielding, if required.

The reactor maintenance building provides facilities for the inspection, testing, and repair of reactor components, including the test modules and maintenance tools and equipment, and for the preparation of radioactive material and waste for shipment and disposal. Decontamination, atmosphere control, and shielding are provided to ensure the safety of the operating personnel and to control the release of radioactive material from the building.

Fig. 7.22. Major TIBER II facilities (plan view).

Fig. 7.23. Major TIBER II facilities (elevation view).

A major design consideration for all parts of the plant that contain activated or contaminated material is contamination control (i.e., preventing the spread of radioactive material between areas). Transfer of components between the reactor building and the maintenance building at grade and basement levels is through air locks. A decontamination chamber, including a Freon-spray-cleaning system, is provided at this interface to clean components being transferred in either direction. Other decontamination chambers can be incorporated between hot cell areas as required.

The conceptual design and analysis of the maintenance procedures for TIBER II were completed, and the application of the results to help define the ITER configuration was initiated. This work resulted from the cooperative effort between the Design Center and the Canadian Fusion Fuels Technology Program and is documented in ref. 16.

The recommended procedures for internal module removal are based on a track-mounted strongback, which is contained in a vacuum chamber that can be attached to the main tokamak vacuum vessel. The nuclear test modules are supported by rollers and withdrawn on a track. The divertor modules cannot be withdrawn horizontally as one piece in the TIBER II configuration. Relocating the magnets to allow direct divertor removal and removing the inner and outer divertor plates separately were evaluated. The in-vessel manipulator used to replace first wall and limiter tiles is also contained in a vacuum chamber.

7.2.4 Cost Estimating

To develop an estimate of the cost for the TIBER II design, the FEDC cost database was reviewed in detail. The results were combined with new cost scaling information generated as part of the systems code development work, and approximately 100 cost scaling algorithms were integrated into the TETRA systems code. The TIBER II cost estimate drawn from this work is summarized in Table 7.7.

The total direct cost of TIBER II was estimated to be about \$1500 million; the total constructed cost, \$2500 million. Estimates using the same methods were prepared for INTOR and a NET-like design; these costs are compared to estimates published by the other studies (with currency conversions and escalation) in Fig. 7.24. The results agree well with the INTOR estimates by the U.S. team and are somewhat higher than the estimates by the NET team. The models used in these studies will be used for the economic evaluation of ITER options. In the next phase of ITER, the cost analysis task will concentrate on the development of the database and on comparison of costing methods and models with those of the other ITER participants.

7.2.5 First Wall and Divertor Design Studies

Design studies for the TIBER II first wall and divertor led to material selection and a set of final specifications for the baseline design. These studies included

Table 7.7. TIBER II cost summary

Account	Description	Cost (millions of dollars)	
21	Structures	165	
211	Site improvements	12.0	
212	Reactor building	37.4	
214	Maintenance building	50.0	
215	Tritium building	26.1	
216	Electrical building	8.0	
217	Other buildings	31.3	
22	Reactor equipment	1218	
221	Reactor system	255.7	
221.1	First wall	18.0	
221.3	Shield	160.6	
221.4	Structure	27.6	
221.5	Divertor	49.5	
222	Magnets	228.1	
222.1	TF coils	106.1	
222.2	Outer PF coils	58.2	
222.3	Inner PF coils	34.4	
222.4	Solenoid	29.4	
223	Power injection	270.0	
223.1	ECRH system	30.0	
223.2	Lower hybrid system	60.0	
223.3	Neutral beam system	180.0	
224	Vacuum system	25.7	
225	Power conditioning	100.4	
225.1	TF coil power supply	13.8	
225.2	PF coil power supply	42.9	
225.3	Energy storage	43.7	
226	Heat transport	64.9	
226.1	Reactor cooling	14.8	
226.2	Cryogenic system	34.0	
226.3	Auxiliary cooling	16.1	
227	Fuel handling	103.2	
227.1	Fuel injection	37.1	
227.2	Fuel processing	7.3	
227.3	Fuel storage	6.7	
227.4	Atmospheric recovery	27.1	
227.5	Water recovery	25.0	
228	Instrumentation	100.0	
229	Maintenance equipment	70.0	
24	Electric plant	46	
25	Miscellaneous plant	26	
26	Heat rejection system	15	
Total direct cost		1470	
Indirect cost		510	
Contingency		451	
Constructed cost		2431

Fig. 7.24. Constructed cost as a function of major radius, estimated for INTOR, NET, and TIBER II.

consideration of thermal/mechanical response, sputtering erosion, and disruption-induced melting and vaporization erosion. Various materials were evaluated for use as armor and structural materials.

Mechanically attached graphite (or carbon-carbon composite) armor tiles were recommended for use on the inboard first wall because (1) radiation cooling appears adequate and (2) the erosion lifetime of graphite armor should exceed the lifetime of the TIBER II device. In addition, an armor design concept using a mechanical attachment allows remote replacement of damaged tiles without removal of the entire shield sector.

The outboard first wall is constructed of either a bare stainless steel/blanket structure or graphite armor mechanically attached to the stainless steel. A bare stainless steel structure with a thickness of about 8 mm has a marginally adequate erosion lifetime and, of course, results in the simplest design concept. A lower-risk approach is to line the entire first wall with graphite armor. Although this adds complexity to the first wall design, the potential for replacing the mechanically attached tiles in situ with remote manipulators is an attractive design feature.

The two leading candidates for the TIBER II divertor plate armor material are graphite and tungsten. Because both materials have major issues that may lead to unacceptable performance, it is difficult to choose between them. For the purpose of continuing through the design process, tungsten is recommended because of its superior sputtering erosion performance. However, for tungsten to be a viable option, the edge temperature must be maintained below 40 eV during all operating phases, and most of the melt layer formed during disruptions must remain intact. The other issue that has been identified for tungsten is the potential for transferring

this high- Z material to other regions of the first wall, leading to a plasma-material compatibility problem. This transfer could occur through movement of ionized tungsten that has been sputtered or by condensation of vaporized material following a disruption.

The key issue in the performance of graphite as a divertor plate material is redeposition of sputtered material. A reasonable lifetime is possible only if redeposition is an extremely effective mechanism. The major advantages of graphite are its small erosion rate by sublimation during disruptions and its compatibility with the first wall material.

7.2.6 Fueling System Design for TIBER II

The TIBER II fuel system controls the fuel mixture, injection rate, and depth of injection into the plasma during all phases of operation: the startup, intermediate, and power ranges of operation. Fuel gas injectors are used during startup, D-T pellet injectors during intermediate-range operation, and high-velocity D-T pellet or D-T plasma injectors in the power range.

Multiple gas injectors are recommended for optimum gas distribution and system availability. The current specifications call for three pairs of fast-response gas injection valves, with flow control ranges of 0.5–5 torr·L/s and 5–50 torr·L/s and an availability of 98% for one year of operation. Distribution valves are needed in each channel for selecting the gas composition. All valves must be radiation hardened and must operate in high magnetic fields (pulsed and steady-state). The fuel control valves should be located in vertical ports where they will be accessible for remote maintenance or replacement; this would also increase the space available for blanket modules and plasma diagnostics. Transport time between the flow control valves and the plasma should be minimized to enhance the use of automatic control.

For intermediate-range fueling, two D-T pellet injectors that operate with 98% availability for one year of operation are needed. These injectors should produce pellet velocities of 0.5 to 1.5 km/s at injection rates of 2 Hz during steady-state operation and 5 Hz during transients with 2.5-mg pellets. Further development of existing pneumatic or centrifugal injectors to improve their availability and accommodate tritium operation should satisfy these requirements. The maximum holdup inventory per injector should be <20 mg, and double-boundary tritium containment is required to minimize the risk of radiation contamination of other systems. Additional requirements include torus isolation valves so that injectors can be serviced without breaking the torus vacuum, adequate radiation shielding to permit hands-on maintenance, and electrical isolation of pellet injection tubes from the torus to minimize the impact of plasma disruptions.

The intermediate-range injectors can be used in the power range but must be supplemented with a pellet accelerator to produce the needed fueling velocities. Two alternatives—laser-driven acceleration of pellets launched from the intermediate-range injectors and use of a plasma gun to inject compact toroids (CTs) of fuel plasma—are under consideration. Laser-driven pellets must have an entry velocity

of 70 km/s; CTs, an entry velocity of 700 km/s. In addition, it must be possible to inject pellets at controlled velocities from 5 to 100% of the required velocity. Any impurities in the fuel system must be separated from the fuel before it reaches the plasma. Experimental evidence indicates that the required velocities can be attained, but considerable R&D is needed; in addition, acceleration parameters must be optimized to minimize system cost and energy and power consumption.

REFERENCES

1. P. T. Spampinato and D. Macdonald, "Ex-Vessel Remote Maintenance for the Compact Ignition Tokamak," in *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, Calif., November 1986*, Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1987.
2. E. C. Selcow, P. N. Stevens, I. C. Gomes, and L. M. Gomes, "Radiation Analysis of the CIT Pellet Injector System and Its Impact on Personnel Access," in *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, Calif., November 1986*, Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1987.
3. B. Coppi, "Physics and Technology of Ignition Experiments," in *Proceedings of the 11th Symposium on Fusion Engineering, Austin, Texas, November 1985*, Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1985; see also "Ignitor" section in *Interim Report on the Assessment of Engineering Issues for Compact High Field Ignition Devices*, C. A. Flanagan, ed., ORNL/FEDC-86/1, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., April 1986.
4. V. D. Lee, "Configuration Development of a Hydraulic Press for Preloading the Toroidal Field Coils of the Compact Ignition Tokamak," in *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, Calif., November 1986*, Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1987.
5. J. R. Haines, "Design of a Tritium-Compatible Vacuum Pumping System for the Compact Ignition Tokamak," in *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, Calif., November 1986*, Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1987.
6. J. D. Galambos, D. J. Strickler, and Y-K. M. Peng, "System Code Comparison of Internal and External PF Coil CITs," in *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, Calif., November 1986*, Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1987.
7. J. D. Galambos, D. T. Blackfield, Y-K. M. Peng, R. L. Reid, D. J. Strickler, and E. Selcow, "System Studies of Compact Ignition Tokamaks," *Fusion Technol.* **13**, 93 (1988).
8. R. L. Reid et al., *The Tokamak Systems Code*, ORNL/FEDC-84/9, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., April 1986.
9. R. L. Reid and J. D. Galambos, "Architecture of the ETR Systems Code," in *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, Calif., November 1986*, Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1987.
10. INTOR, *International Tokamak Reactor: Phase Two A, Part II*, International Atomic Energy Agency, Vienna, 1986.
11. R. Toschi, "The Next European Torus," *Nucl. Eng. Design/Fusion* **3**(4), 325 (1986).
12. Japan Atomic Energy Research Institute, "The Fusion Experimental Reactor (FER)," in *Proceedings of the INTOR-Related Specialists Meeting on Information on Engineering Test Reactor Design Concepts*, to be published by the International Atomic Energy Agency, Vienna (1988).

13. I. V. Kurchatov Institute of Atomic Energy, "OTR," in *Proceedings of the INTOR-Related Specialists Meeting on Information on Engineering Test Reactor Design Concepts*, to be published by the International Atomic Energy Agency, Vienna (1988).

14. C. D. Henning et al., *TIBER—Tokamak Ignition/Burn Experimental Reactor, Final Design Report*, UCID-20589, Lawrence Livermore Natl. Lab., Livermore, Calif., November 1986.

15. C. A. Flanagan, J. D. Galambos, and Y-K. M. Peng, "Comparative Analysis of Next-Generation INTOR-Like Devices," in *Proceedings of the 12th Symposium on Fusion Engineering, Monterey, Calif., November 1986*, Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1987.

16. *TIBER II/Future ITER Maintenance Needs*, Report 878004-03-00, Canadian Fusion Fuels Technology Project, Mississauga, Ontario, Canada, September 1987.

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Section 8

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**MATERIALS RESEARCH
AND DEVELOPMENT**

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E. E. Bloom¹
Fusion Materials Program Manager

D. J. Alexander¹	L. K. Mansur¹
D. N. Braski¹	P. J. Maziasz¹
R. E. Clausing¹	A. F. Rowcliffe¹
W. R. Corwin¹	I. I. Siman-Tov³
W. P. Eatherly¹	R. E. Stoller¹
M. L. Grossbeck¹	T. Sawai²
S. Hamada²	M. Suzuki²
L. Heatherly¹	K. R. Thoms³
J. A. Horak¹	P. F. Tortorelli¹
R. L. Kluch¹	J. M. Vitek¹
A. W. Longest³	S. J. Zinkle¹

¹Metals and Ceramics Division.

²Japan Atomic Energy Research Institute, Ibaraki-ken, Japan.

³Engineering Technology Division.

8. MATERIALS RESEARCH AND DEVELOPMENT

SUMMARY OF ACTIVITIES

The focus of the Fusion Materials Program is the development of materials for use in components of a fusion reactor that will be exposed to high neutron fluences during their design life.

Austenitic and martensitic steels and vanadium alloys are being developed for first-wall and blanket structural applications; copper alloys, graphite, and carbon-carbon composites for high-heat-flux components; and ceramics for electrical insulators, rf windows, and possible structural applications.

The research on structural alloys has two points of focus: (1) development of Fe-Cr-Ni austenitic stainless steels for near-term applications and (2) development of Fe-Cr-Mn austenitic stainless steels, Fe-Cr-W-V martensitic steels, and vanadium alloys as low-activation structural alloys that would significantly reduce the waste disposal burden of fusion power reactors in the longer term.

Through the years, Fe-Cr-Ni austenitic steels with significantly improved resistance to radiation damage have been developed. These alloys are the leading candidates for use in near-term applications in reactors because of their advanced state of development and commercial practice. Typical of the improved austenitic steels is the prime candidate alloy (PCA), which is an Fe-15Cr-15Ni-1.5Mo austenitic alloy with controlled additions of Ti, Si, C, and P. In a collaborative program with the Japan Atomic Energy Research Institute, of which the fourth year has been completed, we are investigating the effects of fusion reactor radiation damage levels on the engineering properties of PCA (the U.S. composition) and JPCA (the Japanese composition, which is slightly different from PCA). Central to this effort is the irradiation of these alloys in mixed-spectrum reactors, such as the High-Flux Isotope Reactor (HFIR), with tailoring of the neutron spectrum to produce damage levels [transmutation-produced helium and displacements per atom (dpa)] equivalent to those produced in a fusion reactor spectrum. In the past year we have obtained the first results, at damage levels of 8-15 dpa, which clearly show that microstructural evolution, swelling, and irradiation creep are strong functions of the He:dpa ratio. Correct simulation of this parameter is thus crucial in the determination of the response of alloys in the fusion neutron spectrum. The extended shutdown of HFIR (which has been the cornerstone irradiation facility, allowing us to achieve the range of temperatures, damage rates, and He:dpa ratios characteristic of a fusion reactor) has caused a major delay in the U.S. and U.S.-Japan collaborative programs on austenitic stainless steels.

Development of low-activation austenitic and ferritic steels requires that metallurgically important elements such as Ni, Mo, Nb, and N be removed or reduced to

levels that are relatively low compared with those used in commercially available alloys. With the Fe-Cr-Mn alloy system, we have focused our initial research on obtaining fully austenitic base ternary compositions with no ferrite or martensite present. This phase of the research is complete, with Fe-(12-14)%Cr-(20-25)%Mn identified as the most stable austenitic ternary composition. This composition will now be developed for high-temperature strength, phase stability, and radiation damage resistance.

Commercially available 9Cr-1MoVNb and 12Cr-1MoVW martensitic steels are being used to scope the basic radiation response of this class of alloys at fusion reactor damage levels. As with the austenitic steels, we find that the microstructural evolution during irradiation is sensitive to the He:dpa production ratio. To develop low-activation martensitic steels, tungsten is proposed as a substitute for molybdenum, and niobium is replaced by tantalum and vanadium. An initial series of Cr-W steels that is analogous to the Cr-Mo steels has been produced. Microstructural examination, tempering studies, tensile tests, and Charpy impact tests indicate that three Cr-W steels with 9 to 12% chromium are comparable to the 9Cr-1MoVNb and 12Cr-1MoVW steels.

Vanadium and the alloying elements normally used in vanadium alloys (e.g., Ti, Cr, and Si) are acceptable from the viewpoint of producing low-activation alloys. Research on vanadium alloys is presently focused on scoping radiation response. The elevated-temperature tritium trick is used to introduce fusion-relevant helium levels, and subsequent irradiation in the Experimental Breeder Reactor-II and the Fast Flux Test Facility creates displacement damage. Four alloys have been included in our investigations (V-15Cr-5Ti, V-20Ti, V-3Ti-1Si, and Vanstar 7). The effects of irradiation on mechanical properties are strongly dependent on alloy composition. Irradiation at 420°C to approximately 30 dpa completely embrittles V-15Cr-5Ti, with the fracture mode changing from ductile to cleavage. In comparison, the V-3Ti-1Si alloy retains high ductility and a ductile fracture mode.

Critical elements of the alloy development effort are research on corrosion and compatibility and the investigation of the basic mechanism of radiation damage. Corrosion and compatibility studies have the objectives of (1) establishing compatible combinations of structural material, coolant, and tritium breeder and (2) understanding the mechanisms of corrosion and mass transfer to provide a basis for predicting corrosion and mass transfer kinetics in a reactor system. Recent emphasis has been placed on the corrosion of low-activation austenitic and martensitic steels in lithium and Pb-Li systems. Research on radiation damage mechanisms includes the development of theoretical models and the conducting of basic experiments, leading to a mechanistic understanding of radiation effects in materials and providing a foundation for the design of radiation-resistant materials.

8.1 ALLOY DEVELOPMENT FOR IRRADIATION PERFORMANCE

8.1.1 Austenitic Stainless Steels—Abstracts

8.1.1.1 "Microstructural Development of Austenitic Stainless Steels Irradiated in HFIR"¹

M. P. Tanaka,* S. Hamada, A. Hishinuma,* and P. J. Maziasz

Microstructural developments of titanium-modified austenitic stainless steel have been determined from the irradiation in the High Flux Isotope Reactor (HFIR) with special interests in fusion application. The data have been obtained to a peak fluence corresponding to approximately 34 displacements per atom (dpa) and helium concentration of 2500 appm for irradiation temperatures between 300 and 600°C.

Microstructure of the materials after the irradiation at temperatures of 300 and 400°C suggests that mutual stability of the radiation-enhanced precipitates (MC and $M_{23}C_6$ in this case) and associated fine bubbles (subcritical, gas-driven cavities) has contributed to the extension of the transient regime of swelling to higher fluence than 34 dpa. At higher irradiation temperatures of 500 and 600°C, however, the conversion of small cavities to large voids (supercritical, bias-driven cavities) has occurred partly at this 34-dpa damage level because biases of dislocation have increased as a result of decreased formation of the precipitates on the dislocation line.

*Japan Atomic Energy Research Institute, Ibaraki-ken, Japan.

8.1.1.2 "Temperature Dependence of Swelling in Type 316 Stainless Steel Irradiated in HFIR"²

S. Hamada, P. J. Maziasz, M. P. Tanaka,* M. Suzuki, and A. Hishinuma*

The object of this experiment is to investigate for fusion applications the temperature dependence of swelling in solution-annealed (SA) and cold-worked (CW) type 316 stainless steel irradiated to 30 and 50 dpa at 300 to 600°C in HFIR. At irradiation temperatures of 400°C and below, a high concentration (2 to $4 \times 10^{23} \text{ m}^{-3}$) of small bubbles (1.5 to 4.5 nm diam) formed uniformly throughout the matrix. Swelling was very low ($<0.2\%$) in both materials irradiated to 30 dpa. In the SA 316, cavity size increased and the number density decreased with increasing irradiation temperature above 500°C. At 600°C, most of the cavities were voids. Maximum swelling ($\sim 1\%$) occurred at 500°C. On the other hand, in 20% CW specimens, cavities were much smaller, with diameters of 6 and 9 nm at 500 and 600°C, respectively. The cavity number density at both 500 and 600°C ($\sim 1 \times 10^{22} \text{ m}^{-3}$)

was about one order of magnitude less than at 400°C. Swelling increased slightly as irradiation temperature increased, peaking at 600°C (0.3%). These results indicate that the SA material has the same level of swelling resistance as the CW material at irradiation of 400°C and below.

*Japan Atomic Energy Research Institute, Ibaraki-ken, Japan.

8.1.1.3 "Postirradiation Tensile and Fatigue Behaviors of Austenitic PCA Stainless Steel Irradiated in HFIR"³

M. P. Tanaka,* S. Hamada, A. Hishinuma,* and M. L. Grossbeck

The program of U.S.-Japan collaborative testing in HFIR and the Oak Ridge Research Reactor (ORR) is now nearly final stage of phase I period, which is intended to investigate the response of the U.S. and Japanese prime candidate alloys (PCA and JPCA) for fusion application to high level of neutron damage and helium concentration. The Japan Atomic Energy Research Institute (JAERI) put special emphasis on the investigation of SA material to avoid the weldability problem in CW material. Tensile and fatigue properties of the JPCA, which was irradiated up to 34 dpa and 2500 appm helium concentration, will be reported in this paper.

The JPCA in both the SA and CW conditions was hardened to nearly similar strength after the HFIR at all irradiation temperature. The total elongation of the JPCA in both conditions was decreased at 400°C and 600°C because of increased hardening and helium embrittlement, respectively. The ductility of the JPCA remained, however, above 5% in total elongation at all test-temperature range. The fatigue life of the CW PCA was reduced by the irradiation hardening. The reduction of the fatigue life is, however, only a factor of 10 to 50 at 430°C.

These data suggest that the SA JPCA could have the same level of mechanical properties as the CW materials in high level of neutron damage and helium concentration. So SA material could be used as blanket structural materials for fusion reactor in well-specified condition.

*Japan Atomic Energy Research Institute, Ibaraki-ken, Japan.

8.1.1.4 "Irradiation Creep in Type 316 Stainless Steel and U.S.-PCA with Fusion Reactor He: dpa Levels"⁴

M. L. Grossbeck and J. A. Horak

Although an extensive database exists for irradiation creep in fast reactors, there is very little information on irradiation creep in environments where helium is generated simultaneously with displacement damage. A spectrally tailored experiment,

MFE-4, was designed for ORR, which contained pressurized tubes of both AISI 316 stainless steel and a titanium-modified steel (PCA). A nearly constant He:dpa ratio of ~ 12 was achieved by successively changing absorbers from water to aluminum to hafnium. The tubes were pressurized with helium to stress levels ranging from 20 to 470 MPa depending upon temperature. Actively controlled and continuously monitored temperatures of 330, 400, 500, and 600°C were investigated. The tubes were examined by laser profilometry at damage levels of 5 and 12 dpa.

The average creep rates or total creep strains were found to be linear with stress below an effective stress level of about 200 MPa for all temperatures. At 330°C, both alloys exhibited a transition to a higher creep rate at a stress level of about 200 MPa. This behavior has been observed in austenitic stainless steels and, in fact, in type 316 stainless steel and PCA in data reported by Puigh et al. The transition in creep rate is most clearly identified by Wassilew, who interpreted the phenomenon as a transition from SIPA creep to climb-assisted glide creep. The transition stress decreases with increasing temperature. However, since the experiment was designed such that the tubes would not rupture prior to an exposure of 50 dpa, stresses at 400, 500, and 600°C were sufficiently low to be within the SIPA creep regime. In the stress regime investigated, the PCA (heat K-280) experienced a higher creep rate than the type 316 stainless steel (U.S. fusion reference heat X15893). This is in contrast to the observations of Puigh, who found the creep rate of PCA (heat K-280) to be lower than that of type 316 stainless steel (U.S. breeder heats 81600 and 93591). This discrepancy is believed to result from heat-to-heat variations in the type 316 stainless steel.

8.1.2 Ferritic Steels—Abstracts

8.1.2.1 "Effect of Nickel Content of 9Cr-1MoVNb and 12Cr-1MoVW Steels on the Aging and Irradiation Response of Impact Properties"⁵

W. R. Corwin, J. M. Vitek, and R. L. Klueh

Irradiating nickel-containing alloys in a mixed-spectrum reactor can simulate both transmutation helium and displacement damage expected in a fusion reactor first wall. Impact properties of 9Cr-1MoVNb and 12Cr-1MoVW steels doped with nickel were determined in the as-heat-treated, thermally aged, and irradiated conditions to determine if nickel doping affects the behavior. The irradiation was carried out in a fast-spectrum reactor which produces only an insignificant amount of helium during irradiation, thereby evaluating the effect of nickel alone. Only limited property changes resulted from thermal aging or irradiation to 12 dpa at 450 to 550°C. Irradiation of the 12Cr-1MoVW steel at 390°C produced severe degradation of impact properties. Nickel additions affect the unirradiated material properties, but subsequent radiation-induced changes were similar. The results indicate that nickel doping and subsequent irradiation in a mixed-spectrum reactor is a viable method for simulating irradiation effects in a fusion reactor first wall.

8.1.2.2 "Postirradiation Tensile Behavior of Nickel-Doped Ferritic Steels"⁶

R. L. Kluch and J. M. Vitek

Tensile specimens of normalized-and-tempered 9Cr-1MoVNb, 9Cr-1MoVNb-2Ni, 12Cr-1MoVW, 12Cr-1MoVW-1Ni, and 12Cr-1MoVW-2Ni steels were irradiated in HFIR at 300, 400, and 500°C to displacement damage levels of up to ~11 dpa. The nickel was added to the ferritic steels to produce helium by a two-step (n, α) reaction during irradiation in this mixed-spectrum reactor. Up to 103 appm He was produced in the steels with 2% Ni. Irradiation at 300 and 400°C caused an increase in strength of all the steels relative to the strength both in the normalized-and-tempered condition and after aging of the normalized-and-tempered steel for a time period similar to that in the reactor. The strength increases were accompanied by a loss of ductility. At 500°C, there was little change in the strength properties of the steels. The results at 300 and 400°C indicate an effect of helium on the strength increases; no helium effect was apparent for the specimens irradiated at 500°C.

8.1.2.3 "Reduced-Activation Ferritic Steels: A Comparison with Cr-Mo Steels"⁷

R. L. Kluch and P. J. Maziasz

The ferritic steels now being considered for fusion-reactor applications are the Cr-Mo steels; these include the 2 $\frac{1}{4}$ Cr-1Mo, 9Cr-1MoVNb, and 12Cr-1MoVW steels. Irradiation of alloys that contain molybdenum, nickel, or niobium in a fusion environment produces long-lived radioactive isotopes, which lead to difficult radioactive waste disposal problems once the structure is removed from service. Such problems can be reduced by developing steels that contain only elements that produce radioactive isotopes that decay to low levels in a reasonable time (tens of years instead of hundreds or thousands of years). Because tungsten is found to behave like molybdenum in simple steels, it is being proposed to replace molybdenum. To replace niobium, a greater use of vanadium has been proposed; tantalum is also a possible replacement for niobium.

An initial series of reduced-activation steels has been produced. Eight experimental Cr-W heats were produced, analogous to Cr-Mo steels presently of interest for fusion applications. The compositions have been selected so as to determine the effect of chromium, tungsten, and vanadium on the properties of the steels. Concentrations range from 2 $\frac{1}{4}$ to 12% Cr, 0 to 2% W, and 0 to 0.25% V; one alloy contained 0.07% Ta. Tempering and microstructural studies have been completed on these alloys, and tensile and impact tests have been conducted. The results have been compared with properties for 2 $\frac{1}{4}$ Cr-1Mo, 9Cr-1MoVNb, and 12Cr-1MoVW steels.

The tempering studies and the tensile tests have shown that there is a range of Cr-W-V compositions that give unirradiated properties similar to the Cr-Mo steels.

Impact properties are also comparable. The results from the studies on the initial heats have demonstrated that Cr-W steels can be produced with properties that are similar to those of the Cr-Mo steels. With a continued development program, it is felt that steels with properties superior to those of the Cr-Mo steels can be developed.

8.1.2.4 "Corrosion of Ferritic Steels by Molten Lithium: Influence of Competing Thermal Gradient Mass Transfer and Surface Product Reactions"⁸

P. F. Tortorelli

Both standard and "low-activation" ferritic steels were exposed to thermally convective lithium for various periods of time. Results from these experiments showed that the shape of the mass transfer profile of Fe-12Cr-1MoVW steel (as measured by weight changes) changed substantially as the maximum loop temperature was raised from 500 to 600°C. Furthermore, for a particular loop experiment, changes in the structure and composition of the exposed surfaces did not reflect typical mass transfer tendencies for all elements: the chromium surface concentration was often a maximum at intermediate temperatures, while nickel (present at low concentrations in the starting material) and manganese (found in some of the low-activation alloys) tended to be transported to the coldest part of the loop. Such data were interpreted in terms of a qualitative model in which there are different dominant reactions for the various constituents of the ferritic steels (for example, chromium product formation involving nitrogen and/or carbon and solubility-driven elemental transport of manganese). As with other alloy systems, such competing reactions complicate the characterization of the corrosion and mass transfer of these steels in lithium. Nevertheless, the overall corrosion rate of this type of steel was relatively low. However, because of thermal gradient mass transfer, the low-activation ferritic steels containing significant concentrations of manganese tended to have higher dissolution rates than those of similar steels with very low manganese contents.

8.1.2.5 "Void Formation and Helium Effects in 9Cr-1MoVNb and 12Cr-1MoVW Steels Irradiated in FFTF and HFIR at 400°C"⁹

P. J. Maziasz and R. L. Klueh

Previous work has shown that void formation in 9Cr-1MoVNb and 12Cr-1MoVW martensitic steels irradiated in HFIR to ~38 dpa reached a maximum at 400°C. Increased formation of subcritical bubbles and bias-driven voids was also found in 9Cr and 12Cr steels doped with up to 2 wt % Ni to increase helium generation during HFIR irradiation. This work expands the previous comparison by

including samples of both doped and undoped 9Cr-1MoVNb and 12Cr-1MoVW steels irradiated in the Fast Flux Test Facility (FFTF) at about 420°C to 47 dpa. The comparison of HFIR- with FFTF-irradiated samples of the various steels provides convincing evidence that helium is a primary agent that causes voids to form in these steels. HFIR irradiation to ~38 dpa produces 32 to 87 appm He in the undoped steels and 410 to 440 appm He in the steels with 2 wt % Ni added. By contrast, FFTF irradiation of these steels to 47 dpa produces only about 5 appm He.

Very few voids were found in 9Cr-1MoVNb steels irradiated in FFTF, and none were found in the 12Cr-1MoVW steels. By comparison, void formation increased with increased helium level in HFIR, particularly in the 9Cr steels. Apart from the void formation differences, there was little difference in microstructure between the samples irradiated in HFIR and those in FFTF. Alloy additions of nickel did affect precipitate and subgrain structure evolution in the 9Cr-1MoVNb steel during irradiation in both reactors but had little detectable effect in the 12Cr-1MoVW steels. Irradiation at 400°C caused instability of the as-tempered precipitate and subgrain structure in both the 9Cr-1MoVNb and the 9Cr-1MoVNb-2Ni steels and caused copious additional precipitation of coarse $M_{23}C_6$ and fine M_6C in the nickel-doped steel. However, HFIR and FFTF irradiation produced essentially the same precipitates in both 9Cr steels. While the ferritic steels are indeed quite swelling resistant during fast reactor irradiation, the strong increase in void formation with helium content is of concern and is currently being studied at higher fluences.

8.1.2.6 "Impact Properties of 9Cr and 12Cr Steels After Low-Temperature Irradiation"¹⁰

R. L. Klueh, J. M. Vitek, and W. R. Corwin

Irradiation of ferritic steels can cause a large increase in the ductile-brittle transition temperature (DBTT) and a decrease in the upper-shelf energy. Three irradiation capsules containing miniature Charpy V-notch impact specimens of 9Cr-1MoVNb and 12Cr-1MoVW steels and these steels with 1 and 2% Ni additions were irradiated in HFIR at the reactor coolant temperature of ~55°C. One capsule was irradiated to $\sim 0.91 \times 10^{26}$ n/m² to produce a displacement damage level of ~5 dpa, and the second and third capsules were irradiated to $\sim 9.3 \times 10^{26}$ n/m² and ~10 dpa. Nickel was added to the steels to study the effect of helium on properties.

Postirradiation impact testing indicated that irradiation caused the DBTT to increase, with the largest increase ~125°C. The 9Cr-1MoVNb steels with or without nickel showed a larger increase than the 12Cr-1MoVW steels, with and without nickel. The difference between the 9Cr and 12Cr steels was the most notable effect; the effect of nickel (and perhaps helium) was a secondary effect. These same steels were previously irradiated at higher temperatures. At 390°C, the 12Cr-1MoVW steels showed a substantially larger increase in DBTT than the 9Cr-1MoVNb steels. It thus appears that the effect of irradiation temperature on the DBTT of the 9Cr-1MoVNb steel is such that there is little change at temperatures above ~300°C;

the increase in DBTT then becomes greater as the temperature decreases. On the other hand, the 12Cr-1MoVW steel shows a maximum increase at $\sim 400^{\circ}\text{C}$ and the amount of the DBTT increase becomes less at higher and lower temperatures.

8.1.3 Vanadium Alloys—Abstract of “Doping of Vanadium Alloys with Helium Using Tritium”¹¹

D. N. Braski

Vanadium alloys are currently being evaluated for possible future application as a structural first wall for a fusion reactor. Major concerns are the displacement damage and high rates of helium production in a first wall caused by the 14-MeV neutrons from the plasma. To study the effect of helium on the microstructure and to simulate its effect in irradiation experiments, various vanadium alloys have been doped with helium using the “tritium trick” procedure. Vanadium alloy specimens were heated at 400°C in a stainless steel retort with tritium at 53 kPa (400 torr). Helium concentration was controlled by holding the specimens under these conditions for a predetermined time to allow the tritium, which is quite soluble in vanadium, to diffuse into the pressure and increasing the temperature in the retort to 700°C . This removed the remaining tritium from the specimens and left the insoluble ^3He behind in the microstructure. The microstructure of V-15Cr-5Ti (wt %) doped with 293 appm ^3He contained bubbles in the matrix and grain boundaries. Small (2-nm-diam) bubbles and clusters of bubbles punched out dislocation loops in the matrix due to their high internal pressure. Larger bubbles formed on preexisting carbide particles in the grain boundaries and matrix. Large rafts of bubbles were observed in the V-20Ti (wt %) alloy. It is believed that these bubbles were associated with the formation of titanium tritide during tritiation. The tritide would have decomposed during the degassing treatment at 700°C , thus leaving the bubbles in its place. This result suggests that titanium may not be uniformly distributed in the alloy, even though a prior solution-annealing treatment was used. Helium in the grain boundaries was found to cause intergranular separation in the vanadium alloys, so methods of promoting better accommodation of helium in the microstructure are being developed.

8.1.4 Copper Alloys—Abstracts

8.1.4.1 “Microstructure and Properties of Copper Alloys Following 14-MeV Neutron Irradiation”¹²

S. J. Zinkle

The microstructure of copper and three single-phase copper alloys (Cu-5%Al, Cu-5%Mn, Cu-5%Ni) has been examined following a room-temperature 14-MeV neutron irradiation up to a maximum fluence of $2 \times 10^{21} \text{ n/m}^2$ ($\sim 10^{-3} \text{ dpa}$). The

irradiation produced small defect clusters, many of which were resolvable as stacking fault tetrahedra (SFTs) or triangle loops. Alloying did not affect the overall cluster density or size distribution, but it did cause a significant reduction in the density of SFTs and triangle loops. The overall defect cluster size was independent of fluence with a mean and most probable diameter of ~ 2.6 and ~ 1.7 nm, respectively. There was no evidence of direct cascade overlap in this study. Cascade overlap effects are estimated to become significant for fluences $\sim 10^{22}$ n/m². The overall defect cluster density was found to vary as $N \sim \sqrt{\phi t}$ with a short transition period for all four metals. Reexamination of published data indicates that this relationship may be broadly applicable over the irradiation temperature range of 80 to 400 K. Logarithmic plots of the cluster density vs fluence showed anomalous curvature due to the nonlinear defect survival rate. Logarithmic plots should not be used exclusively to determine the fluence dependence of radiation damage processes.

8.1.4.2 "Surviving Defect Fraction in 14-MeV Neutron-Irradiated Copper"¹³

S. J. Zinkle

The number of point defects that are produced and remain as a result of an energetic displacement cascade is of fundamental importance to radiation effects studies. There have been a number of experimental studies of defect production efficiency and the fraction of freely migrating defects produced during irradiation. These two parameters are independent of fluence and for a given material depend only on the irradiation temperature and primary knock-on spectrum. On the other hand, the surviving defect fraction (η) depends on the number of sinks and defect clusters that are present at a given time during the irradiation and therefore generally decreases with increasing fluence. When coupled with appropriate radiation damage models, the interdependence of the three parameters mentioned provides a significant insight into the basic mechanisms of point defect production, migration, and clustering.

We have measured the surviving defect fraction (η) in copper following a 14-MeV neutron irradiation at room temperature over the fluence range of 1×10^{20} to 3×10^{21} n/m² (0.04 to 1×10^{-3} dpa). Electron microscopy and electrical resistivity measurements were performed to give two independent measurements of η at each fluence level. The agreement between the two methods was good. The surviving defect fraction decreased with increasing fluence (from 12 to 5%) over the fluence range that was studied. Microhardness measurements made on the same specimens suggest that the barrier strength of loops (β) may be dependent on fluence at these low fluence levels.

8.1.5 Radiation Damage Mechanisms—Abstracts

8.1.5.1 *Microstructural Evolution in Fast-Neutron-Irradiated Austenitic Stainless Steels*¹⁴

R. E. Stoller

The general field of neutron irradiation effects is very broad. The present work has focused on the specific problem of fast-neutron-induced radiation damage to austenitic stainless steels. These steels are used as structural materials in current fast fission reactors and are proposed for use in future fusion reactors. Two primary components of the radiation damage are atomic displacements (in units of displacements per atom, or dpa) and the generation of helium by nuclear transmutation reactions. The radiation environment can be characterized by the ratio of helium to displacement production, the so-called He:dpa ratio. Radiation damage is evidenced microscopically by a complex microstructural evolution and macroscopically by density changes and altered mechanical properties. The purpose of this work was to provide additional understanding about mechanisms that determine microstructural evolution in current fast reactor environments and to identify the sensitivity of this evolution to changes in the He:dpa ratio. This latter sensitivity is of interest because the He:dpa ratio in a fusion reactor first wall will be about 30 times that in fast reactor fuel cladding.

The approach followed in the present work was to use a combination of theoretical and experimental analysis. The experimental component of the work primarily involved the examination by transmission electron microscopy of specimens of a model austenitic alloy that had been irradiated in ORR. Some of these specimens had been implanted with helium and subsequently annealed at various temperatures prior to irradiation. The as-implanted-and-aged microstructures were also characterized. A major aspect of the theoretical work was the development of a comprehensive model of microstructural evolution. This included explicit models for the evolution of the major extended defects observed in neutron-irradiated steels: cavities, Frank faulted loops, and the dislocation network.

8.1.5.2 "Mechanical Property Changes Induced in Structural Alloys by Neutron Irradiations with Different Helium to Displacement Ratios"¹⁵

L. K. Mansur and M. L. Grossbeck

Effects of neutron irradiation on mechanical properties are central to the materials engineering of fusion reactors. In order to provide the base of understanding,

as well as technological data for these phenomena, irradiations in a fusion reactor spectrum are most desirable. Unfortunately, all of the required characteristics of such a spectrum are not presently available in existing test facilities. However, two of the relevant manifestations of the high-energy fusion neutron spectrum, namely high displacement damage levels and very high helium contents induced by (n, α) transmutation reactions, can be achieved by manipulations of fission reactor irradiations. Effects of helium interaction with displacement damage can be explored over He:dpa ratios ranging from a few tenths to nearly 100, and, in particular, the He:dpa ratios expected in fusion reactors can be reproduced. This work involves comparisons of fast- and mixed-spectrum reactor irradiations of nickel- or boron-bearing alloys, alloys whose isotopic composition or neutron spectrum environment has been artificially adjusted, or alloys subjected to helium injection by accelerator irradiation or tritium decay.

Examples of recent results for austenitic stainless steels, ferritic/martensitic steels, and vanadium alloys are reviewed. Tensile, creep, creep-rupture, and fatigue properties are discussed. Understanding of these results in terms of defect and microstructural mechanisms is explored. While drastic degradation of mechanical properties by helium has been observed, it is generally found that the presence and severity of degradation are dictated by alloy composition, microstructure, test conditions, and other controllable parameters.

8.1.5.3 "Defect Microstructures in fcc Metals Irradiated near Room Temperature"¹⁶

S. J. Zinkle and R. L. Sindelar*

Irradiation of fcc metals near room temperature with energetic particles produces clusters of point defects that were originally termed "black spot" defects. In recent years, high-resolution studies of these defect clusters have been able to identify specific cluster types, such as the SFT, in several metals.

This paper compares the defect cluster microstructures of two fcc metals following low-dose (<1 -dpa) neutron irradiation at temperatures near room temperature. Pure copper was irradiated with 14-MeV neutrons at 25°C ($0.22T_m$) to a fluence of 2×10^{21} n/m² ($\sim 10^{-3}$ dpa). Type 304L stainless steel was irradiated in a thermal reactor at $\sim 100^\circ\text{C}$ ($0.20T_m$) to a fast fluence of 8×10^{24} n/m² (~ 0.5 dpa). Elastic continuum calculations predict that the SFT should be the most stable vacancy defect configuration for both of these metals. A significant fraction of the defect clusters in copper are resolvable as SFTs. However, there are no distinctly visible SFTs among the defect clusters in the irradiated stainless steel specimen. Possible causes of this difference are discussed, including solute and helium effects and the effect of homologous irradiation temperature on the probability of faulted loop dissociation to an SFT.

*Savannah River Laboratory, Aiken, South Carolina.

8.2 FACILITIES DEVELOPMENT

8.2.1 HFIR Facility—Abstract of "HFIR Irradiation Facilities Improvements—An Update on the HIFI Project"¹⁷

K. R. Thoms, G. R. Hicks, B. H. Montgomery, I. I. Siman-Tov, and C. D. West

The HFIR Irradiation Facilities Improvements (HIFI) Project is nearing completion. In August 1986, phase I of the project was completed, providing the capability to perform instrumented irradiation experiments in the target region of HFIR. Thus, the irradiation positions with the highest continuous neutron fluxes available in the world are no longer limited to uninstrumented experiments with their inherent uncertainty in knowledge of actual irradiation conditions. Phase II of the project is presently on schedule for completion in June 1987. At that time, the number and size of large removable beryllium (RB*) irradiation positions will be increased from four 37-mm positions to eight 48-mm positions.

The completion of phase I included the installation of a new target basket, target tower, and target tower hole plug. The previously existing hydraulic rabbit tube assembly was moved from the center of the target region to the point of an equilateral triangle; the other two points locate the positions where instrumented experiments can now be operated. Along with the components necessary to provide instrumentation to target capsules, a new quick-access hatch was installed. This hatch has eight penetrations which directly line up with the eight positions of the new RB* penetrations being fabricated as part of phase II.

In conjunction with the installation of phase I components, the first instrumented target capsule was installed to determine more accurately the probable temperature in the uninstrumented target capsules previously irradiated as part of the U.S.-Japan fusion materials program. Preliminary data from this experiment indicate close agreement with expected temperatures during the first two cycles of operation in all positions except those at the extreme ends of the capsule. During the third and fourth cycles of the planned five-cycle irradiation, temperatures rose significantly, and several hypotheses are presently being investigated to explain this anomaly. At the end of the fourth cycle, the HFIR was shut down for an extended period to investigate the embrittlement of the reactor pressure vessel. The capsule is awaiting reactor restart to complete the final cycle of irradiation.

A detailed description of components installed during phases I and II will be presented. Data from planned gamma heating rate measurements in the new RB* facilities and information from the operation of the first instrumented target capsule will also be presented.

8.2.2 Irradiation Experiments—Abstracts

8.2.2.1 "Spectrally and Isotopically Tailored Experiments to Control Helium Generation in Austenitic Stainless Steels"¹⁸

A. F. Rowcliffe, P. J. Maziasz, M. L. Grossbeck, and M. P. Tanaka*

For applications in near-term fusion machines such as the proposed International Thermonuclear Experimental Reactor (ITER), the major radiation effects-related issues for austenitic stainless steels are dimensional stability and fracture toughness in the range 100 to 400°C, for neutron doses up to 20 to 30 dpa. For longer-range applications, it will be necessary to develop steels with adequate creep strength, dimensional stability, and fracture toughness at temperatures up to 600°C with neutron doses in the region of 100 dpa. Irradiation parameters known to affect these properties are temperature, damage rate, gaseous and solid transmutation rates, and the nature of the primary damage. The closest approach to the fusion radiation environment currently available in the United States is through the use of spectrally tailored or isotopically tailored experiments in water-cooled mixed-spectrum reactors, such as HFIR and ORR. Experiments are described which utilize these techniques in addressing radiation effects-related issues for both near-term and long-term fusion machines.

Comparison of the initial results from the spectrally tailored experiment MFE 4A/4B with earlier results from experiments in FFTF (He:dpa < 1) and in HFIR (He:dpa ~ 70) demonstrates a strong dependence of swelling behavior on radiation environment. For a titanium-modified steel (PCA), both CW and annealed, void swelling at 400 and 500°C occurred much more rapidly in a spectrally tailored environment in ORR than in experiments in either HFIR or FFTF. In the SA material, ~2.7% swelling occurred at 500°C at a fluence of only ~11 dpa. To make a realistic assessment of swelling behavior, the importance of utilizing a radiation environment that simultaneously reproduces the helium generation and damage rates typical of the fusion environment is emphasized. Irradiation creep, strength, and ductility appear to be less sensitive to these irradiation parameters, at least at low doses.

*Japan Atomic Energy Research Institute, Ibaraki-ken, Japan.

8.2.2.2 "Design of Spectral-Tailored Fusion Reactor Materials Experiments in the HFIR RB* Capsule Irradiation Facility"¹⁹

A. W. Longest, J. E. Corum,[†] and K. R. Thoms

Design of four spectral-tailored capsules to irradiate magnetic fusion energy (MFE) materials specimens in the new HFIR RB* facility at temperatures of 60, 200, 330, and 400°C, respectively, has been completed. These designs incorporate

provisions for removal, examination, and reencapsulation of the MFE specimens at intermediate exposure levels en route to a target exposure level of 30 dpa.

The HFIR RB* capsule irradiation facility will allow spectral tailoring of the neutron flux by placement of appropriate neutron absorber shields around the in-core section of the capsule. Hafnium shields will be used for the present U.S.-Japan collaborative MFE materials testing program to tailor the neutron spectrum to closely match the helium production:atom displacement ratio (14 ppm He/dpa) expected in a fusion reactor first wall. Other features of the new RB* capsule irradiation facility which have been incorporated into the capsule designs include (1) straight access into any of the eight 46-mm-diam positions, (2) standard capsule lead tube design, and (3) 180° capsule rotation at the end of each reactor cycle to provide uniform exposure to all specimens at a given elevation.

The MFE capsule containment tube (38.1 mm OD) will be made of 6061-T6 aluminum in the in-core region and type 304L stainless steel in the upper region. An oxide dispersion-strengthened aluminum alloy containing 6 to 8 wt% Al_2O_3 has been selected for the specimen holder to provide adequate strength and dimensional stability under the planned irradiation conditions; this alloy also meets requirements of high thermal conductivity (close to that of aluminum) and reasonably low density (2.74 g/cm^3). With the exception of the 60°C capsule, where the test specimens will be in direct contact with the reactor cooling water, the specimen temperatures (monitored by 24 thermocouples) will be controlled by varying the thermal conductance of a small gas gap region between the specimen holder and the containment tube.

These MFE capsule irradiations in the new HFIR RB* facility are expected to begin in early 1988.

†Midwest Technical, Inc., under subcontract 85B-73978C.

8.3 MATERIALS COMPATIBILITY—ABSTRACT OF “FUNDAMENTALS OF HIGH-TEMPERATURE CORROSION IN LIQUID METALS”²⁰

P. F. Tortorelli

The different corrosion reactions that can occur in liquid-metal environments were reviewed. In the most general sense, these were classified into categories of dissolution, impurity and interstitial reactions (corrosion product formation and elemental transfer), alloying, and compound reduction. In addition to definitions and descriptions of these types of reactions, considerations in materials selection based on an understanding of the various liquid-metal corrosion phenomena were discussed.

8.4 FUSION MATERIALS HANDBOOK

J. W. Davis*

The materials handbook is divided into two volumes. Volume 1 is essentially an engineering database for use in design, analysis, and material selection of components or structures for fusion reactors. It contains "engineering-type" curves along with extrapolations of data and comparison of material properties. Volume 2 is a supporting documentation book that contains the assumptions regarding the development of the data pages contained in Vol. 1, as well as the actual raw data. This new volume is intended to function as a material property database for use in experiment design. Efforts continued to be directed toward placing all of the data used to develop the engineering curves in Vol. 1 into Vol. 2. This involves generating roughly 200 new data pages for Vol. 2. In addition to these activities, new data pages are being developed for inclusion in Vol. 1. These data pages should be supportive of the design activities for the Compact Ignition Tokamak and the Engineering Test Reactor and cover first wall, high heat flux, and magnet components. Materials involved consist of the austenitic steel PCA, the ferritic steel HT-9, vanadium alloy V-15Cr-5Ti, pure copper and copper alloys Cu-Al₂O₃ and Cu-Be-Ni, silicon carbide, and the magnet case steels 304 and 21Cr-6Ni-9Mn. The publication package will consist of approximately 60 data pages. Along with preparation of data pages, work is also progressing on the development of a computerized material property database.

*McDonnell Douglas Astronautics Company, St. Louis.

REFERENCES

1. M. P. Tanaka et al., "Microstructural Development of Austenitic Stainless Steels Irradiated in HFIR," presented at the Third International Conference on Fusion Reactor Materials, Karlsruhe, Federal Republic of Germany, October 4-8, 1987, to be published in the proceedings.
2. S. Hamada et al., "Temperature Dependence of Swelling in Type 316 Stainless Steel Irradiated in HFIR," presented at the Third International Conference on Fusion Reactor Materials, Karlsruhe, Federal Republic of Germany, October 4-8, 1987, to be published in the proceedings.
3. M. P. Tanaka et al., "Postirradiation Tensile and Fatigue Behaviors of Austenitic PCA Stainless Steels Irradiated in HFIR," Third International Conference on Fusion Reactor Materials, Karlsruhe, Federal Republic of Germany, October 4-8, 1987, to be published in the proceedings.
4. M. L. Grossbeck and J. A. Horak, "Irradiation Creep in Type 316 Stainless Steel and U.S.-PCA with Fusion Reactor He:dpa Levels," presented at the Third International Conference on Fusion Reactor Materials, Karlsruhe, Federal Republic of Germany, October 4-8, 1987, to be published in the proceedings.
5. W. R. Corwin, J. M. Vitek, and R. L. Klueh, "Effect of Nickel Content of 9Cr-1MoVNb and 12Cr-1MoVW steels on the Aging and Irradiation Response of Impact Properties," *J. Nucl. Mater.* 149, 312-20 (1987).
6. R. L. Klueh and J. M. Vitek, "Postirradiation Tensile Behavior of Nickel-Doped Ferritic Steels," *J. Nucl. Mater.* 150, 272-80 (1987).
7. R. L. Klueh and P. J. Maziasz, "Reduced-Activation Ferritic Steels: A Comparison with Cr-Mo Steels," presented at the Third International Conference on Fusion Reactor Materials, Karlsruhe, Federal Republic of Germany, October 4-8, 1987, to be published in the proceedings.
8. P. F. Tortorelli, "Corrosion of Ferritic Steels by Molten Lithium: Influence of Competing Thermal Gradient Mass Transfer and Surface Product Reactions," presented at the Third International Conference on Fusion Reactor Materials, Karlsruhe, Federal Republic of Germany, October 4-8, 1987, to be published in the proceedings.
9. P. J. Maziasz and R. L. Klueh, "Void Formation and Helium Effects in 9Cr-1MoVNb and 12Cr-1MoVW Steels Irradiated in FFTF and HFIR at 400°C," presented at the Third International Conference on Fusion Reactor Materials, Karlsruhe, Federal Republic of Germany, October 4-8, 1987, to be published in the proceedings.
10. R. L. Klueh, J. M. Vitek, and W. R. Corwin, "Impact Properties of 9-Cr and 12-Cr Steels After Low-Temperature Irradiation," presented at the Third International Conference on Fusion Reactor Materials, Karlsruhe, Federal Republic of Germany, October 4-8, 1987, to be published in the proceedings.
11. D. N. Braski, "Doping of Vanadium Alloys with Helium Using Tritium," pp. 218-19 in *Proceedings of the 45th Annual Meeting of the Electron Microscopy Society of America, Baltimore, Maryland, August 2-7, 1987*, ed. G. W. Bailey, San Francisco Press, San Francisco, 1987.

12. S. J. Zinkle, "Microstructure and Properties of Copper Alloys Following 14-MeV Neutron Irradiation," *J. Nucl. Mater.* 150, 140-58 (1987).

13. S. J. Zinkle, "Surviving Defect Fraction in 14-MeV Neutron-Irradiated Copper," presented at the Third International Conference on Fusion Reactor Materials, Karlsruhe, Federal Republic of Germany, October 4-8, 1987, to be published in the proceedings.

14. R. E. Stoller, *Microstructural Evolution in Fast-Neutron-Irradiated Austenitic Stainless Steels*, ORNL-6430, December 1987.

15. L. K. Mansur and M. L. Grossbeck, "Mechanical Property Changes Induced in Structural Alloys by Neutron Irradiations with Different Helium to Displacement Ratios," presented at the Third International Conference on Fusion Reactor Materials, Karlsruhe, Federal Republic of Germany, October 4-8, 1987, to be published in the proceedings.

16. S. J. Zinkle and R. L. Sindelar, "Defect Microstructures in fcc Metals Irradiated Near Room Temperature," presented at the Third International Conference on Fusion Reactor Materials, Karlsruhe, Federal Republic of Germany, October 4-8, 1987, to be published in the proceedings.

17. K. R. Thoms et al., "HFIR Irradiation Facilities Improvements—An Update on the HIFI Project," presented at the Third International Conference on Fusion Reactor Materials, Karlsruhe, Federal Republic of Germany, October 4-8, 1987, to be published in the proceedings.

18. A. F. Rowcliffe et al., "Spectrally and Isotopically Tailored Experiments to Control Helium Generation in Austenitic Stainless Steels," presented at the Third International Conference on Fusion Reactor Materials, Karlsruhe, Federal Republic of Germany, October 4-8, 1987, to be published in the proceedings.

19. A. W. Longest, J. E. Corum, and K. R. Thoms, "Design of Spectral-Tailored Fusion Reactor Materials Experiments in the HFIR RB* Capsule Irradiation Facility," presented at the Third International Conference on Fusion Reactor Materials, Karlsruhe, Federal Republic of Germany, October 4-8, 1987, to be published in the proceedings.

20. P. F. Tortorelli, "Fundamentals of High-Temperature Corrosion in Liquid Metals," pp. 56-60 in *Metals Handbook*, 9th ed., Vol. 13: *Corrosion*, ed. J. Johnson, R. T. Kieppura, and D. A. Humphries, American Society of Metals, Metals Park, Ohio, September 1987.

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Section 9

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NEUTRON TRANSPORT

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R. G. Alsmiller, Jr.¹

J. M. Barnes²

J. Bartley¹

C. Y. Fu¹

T. A. Gabriel¹

D. M. Hetrick²

D. C. Larson¹

R. W. Roussin¹

R. T. Santoro¹

D. K. Trubey¹

J. E. White¹

¹Engineering Physics and Mathematics Division.

²Computing and Telecommunications Division, Martin Marietta Energy Systems, Inc.

9. NEUTRON TRANSPORT

SUMMARY OF ACTIVITIES

The neutron transport program includes three elements: analyses, cross-section evaluation and processing, and the work of the Radiation Shielding Information Center (RSIC).

The analysis program, at present, is part of a joint U.S.-Japan neutronics program and is directed at validating available computer codes and cross-section data by comparing calculated results with experimental data obtained from the Fusion Neutron Source facility at the Japan Atomic Energy Research Institute. The evaluation and processing program is directed at producing accurate cross-section data for materials that are of specific interest to fusion reactor designers. Staff members of the RSIC serve as technical consultants to the fusion energy research community, as well as a variety of other research communities, on all matters related to neutron transport.

9.1 ANALYSES

9.1.1 Comparison of Calculated Results with Experimental Data for the Tritium Production Rates in a Li_2O Assembly

R. T. Santoro, R. G. Alsmiller, Jr., J. M. Barnes, and T. A. Gabriel

The Monte Carlo codes MORSE¹ and MCNP² have been used to calculate the tritium production from ~14-MeV neutron reactions in a Li_2O assembly.³ Tritium production from neutron reactions with ^6Li and ^7Li nuclei was calculated along the central axis of a 0.60-m-diameter by 0.60-m-long assembly and four additional assemblies where sheets of type 304 stainless steel and polyethylene were placed in front of the Li_2O to simulate first wall and coolant materials. The calculated data are compared with measured data obtained from the Fusion Neutron Source (FNS) at the Japan Atomic Energy Research Institute. The calculated data reproduce the measured data in shape but differ from the measured data by 10-20% in the case of ^6Li and by as much as 30% at some spatial locations for the ^7Li tritium production.

9.1.2 Comparison of Calculated and Experimental Data for Source Characteristics, Reaction Rate Distributions, and Tritium Production Rates in a $\text{Li}_2\text{O-Li}_2\text{CO}_3$ Assembly

R. T. Santoro, R. G. Alsmiller, Jr., J. M. Barnes, and T. A. Gabriel

Monte Carlo calculations are being performed to estimate the induced activation in selected foils for the purpose of characterizing the spatial distribution of the neutrons emitted from the FNS rotating deuterium target. In addition, calculations are being made to determine the tritium production from the reaction of energetic neutrons with the ^6Li and ^7Li isotopes in Li_2O , which is being used as the fertile material. In contrast to the previous series of experiments³ (Phase I), the Li_2O in these experiments was surrounded by Li_2CO_3 , so the measured data are not significantly influenced by room return. All of the calculations are being carried out with the Monte Carlo code MORSE.

The analysis is being performed using a detailed representation of the Phase II experimental geometry, including the rotating target assembly. The radiation transport cross sections used in the analysis are taken from the VITAMIN-E library⁴ (ENDF/B-V) and collapsed from the 174-neutron, 38-gamma-ray group structure to a more readily usable 53-neutron, 21-gamma-ray group format. The ^6Li and ^7Li tritium breeding cross-section data are also taken from the ENDF/B-V files; the ^7Li data are those currently recommended by Los Alamos National Laboratory (Young evaluation).

The deuterium-tritium (D-T) neutron distribution (angle energy) from the target was determined using the kinematics for the reactions of deuterons in titanium-tritide. The induced activation was calculated in foil packages that were distributed throughout the experimental assembly. The agreement between the measured and calculated responses is generally favorable for the threshold-type reactions, but it is less favorable for reactions at thermal energies.

9.2 DATA EVALUATION AND PROCESSING FOR FUSION NEUTRONIC DATA NEEDS

D. C. Larson, C. Y. Fu, D. M. Hetrick, and J. E. White

Evaluated and processed neutron cross-section data are produced to meet the needs of fusion reactor designers. Nuclear data needs for the Magnetic Fusion Energy Program are given in ref. 5 and include evaluated cross sections for copper, nickel, and chromium. This year, calculations for all isotopes of chromium and nickel were completed, and assembly of complete isotopic evaluations for chromium and nickel was initiated. Isotopic evaluations of chromium, nickel, and copper will be available by May 1988 for inclusion in the evaluated data file ENDF/B-VI. This will be the first version of ENDF in which special attention has been paid to data of

priority to fusion energy. Also available for ENDF/B-VI will be isotopic evaluations of iron and an evaluation for natural lead. All of this work has been jointly funded by the Offices of Fusion Energy, Basic Energy Sciences, and Nuclear Physics in the U.S. Department of Energy and the Defense Nuclear Agency.

Evaluated cross sections must be processed into forms that can be used in radiation transport computer codes. The focus of this effort has been the development of VITAMIN-E,⁴ a 174-neutron, 38-gamma-ray group cross-section library. It can be used in conjunction with the AMPX-II system⁶ to derive cross-section data suited to a particular application.

A continuing effort is under way to maintain VITAMIN-E and the relevant AMPX-II computing technology on the computers of the National Magnetic Fusion Energy Computing Center at Lawrence Livermore National Laboratory. The VITAMIN-E data and AMPX-II computing technology are also available from the Radiation Shielding Information Center (RSIC) at ORNL.

9.3 RADIATION SHIELDING INFORMATION CENTER

R. W. Roussin, D. K. Trubey, J. E. White, and J. Bartley

The Radiation Shielding Information Center serves an international community by responding to inquiries about radiation transport problems. Staff members provide guidance by drawing on a technical database that includes a computerized literature file, a collection of complex computer programs, and a substantial body of nuclear data libraries pertinent to the solution of such problems.

Acquiring the needed computer-based technology base requires the collaboration of the neutronics community with RSIC staff members to collect, organize, process, evaluate, and package relevant technology developed in the community. This technology is disseminated throughout the community with a mechanism for feedback of experience through use, which results in an improved product. The resulting technology base provides an overall advancement of the state of the art.

A sample of some recent products of this information cycle process illustrates the international character of the RSIC community. The Japan Atomic Energy Research Institute contributed a new version of CCC-410/THIDA2, a code system for calculation of transmutation, activation, decay heat, and dose rates. That installation also provided DLC-123/DDXLIB, a multigroup, doubly differential database for radiation transport calculations. Los Alamos National Laboratory contributed a new version of the general-purpose Monte Carlo code CCC-200/MCNP and a separate cross-section library, DLC-105/MCNPDAT. The Kernforschungsanlage (KFA), Jülich, Federal Republic of Germany, provided a new version of a high-energy transport code, CCC-496/HETC-KFA, originally developed at ORNL. Lawrence Livermore National Laboratory provided a new version of the nuclear model code PSR-146/ALICE and Sandia National Laboratory a new version of the electron-photon cascade Monte Carlo code CCC-467/ITS. The University of Tokyo provided CCC-501/SUSD, a cross-section sensitivity and uncertainty analysis system, and CCC-511/TRISTAN, a three-dimensional discrete ordinates code. Oak Ridge National

Laboratory provided an updated version of the DLC-113/VITAMIN-E fine-group cross-section library and the DLC-126/PVE photon library for multigroup radiation transport calculations.

This selection represents a small portion of the total activity of the center. Information processing (including evaluation and packaging) is a daily function. In addition to a comprehensive literature database, RSIC-packaged products include 131 data packages (DLC), 522 neutronics and shielding code packages (CCC), and 247 data processing and other miscellaneous code packages (PSR).

REFERENCES

1. M. B. Emmett, *The MORSE Monte Carlo Radiation Transport System*, ORNL-4744, Union Carbide Corp. Nuclear Div., Oak Ridge National Laboratory, 1975.
2. Los Alamos Monte Carlo Group, *MCNP—A General-Purpose Monte Carlo Code for Neutron and Photon Transport*, LA-7396-M (Rev. Version 2B), Los Alamos National Laboratory, Los Alamos, N.M., 1981.
3. T. Nakamura and M. A. Abdou, "Summary of Recent Results from the JAERI/U.S. Fusion Neutronics Phase I Experiments," *Fusion Technol.* 10, 541 (1986).
4. R. W. Roussin et al., *VITAMIN-E: A Coupled 174-Neutron, 38-Gamma-Ray Multigroup Cross-Section Library for Deriving Application-Dependent Working Libraries for Radiation Transport Calculations* [computer program], available from the Radiation Shielding Information Center, Engineering Physics and Mathematics Division, Oak Ridge National Laboratory, as DLC-113/VITAMIN-E.
5. *Proceedings of the Fifth Coordination Meeting of Participants in the Office of Basic Energy Sciences Program to Meet High Priority Nuclear Data Needs of the Office of Fusion Energy, Argonne, Illinois, September 17-19, 1986*, Appendix D, DOE/ER/02490-4, U.S. DOE, 1986.
6. N. M. Greene et al., *AMPX: A Modular Code System for Generating Coupled Multigroup Neutron Gamma Libraries from ENDF/B*, ORNL-3706, Union Carbide Corp. Nuclear Div., Oak Ridge National Laboratory, 1976.

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Section 10

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**MANAGEMENT SERVICES,
QUALITY ASSURANCE,
AND SAFETY**

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Management Services

V. C. Kruzic

D. R. Alford
L. R. Ballard
B. J. Beem¹
T. H. Brady²
D. P. Brooks
J. L. Burke
W. K. Cooper
M. W. Darnell³
J. M. Finger
M. L. Givens^{3,4}
H. W. Jernigan
J. R. Jernigan^{1,4}
C. H. Johnson³

D. Y. Johnson³
L. M. Johnson
C. C. Jones
S. G. Kimmett
A. J. King¹
T-C. Liu³
L. E. Morris
J. C. Neeley³
M. B. Nestor
J. C. Parrott³
L. A. Pollard^{1,4}
J. O. Richardson
G. G. Ross^{3,4}

E. M. Ruckart
S. K. Sanders¹
S. R. Schwartz³
D. G. Sharp
G. G. Shearin
B. J. Smith³
S. L. Smyrl³
P. A. Sumner³
C. K. Thomas^{*}
R. M. Watkins³
E. R. Wells^{*}
B. J. Williams³
N. Y. Wright^{1,4}

Quality Assurance

E. J. Byrnes⁵

G. F. Bowles⁵
L. M. Jordan⁵

Safety

E. R. Wells^{*}

^{*}Dual capacity.

1. Section secretary.
2. Finance and Materials Division, Martin Marietta Energy Systems, Inc.
3. Information Resources Organisation, Martin Marietta Energy Systems, Inc.
4. Part-time.
5. Quality Department.

10. MANAGEMENT SERVICES, QUALITY ASSURANCE, AND SAFETY

SUMMARY OF ACTIVITIES

Broad technical and administrative support for the programmatic research and development activities of the Fusion Energy Division is provided by the Management Services Section and by the division's Quality Assurance (QA) and Safety programs.

The Management Services Section provides support in the following areas:

- General personnel administration, material and service procurement, subcontracting, and coordination of national and international agreements.
- Nonprogrammatic engineering services for support systems and equipment; identification, planning, and coordination of general plant project and facility improvements; coordination of maintenance and production shop work; labor relations; and telecommunications.
- Financial management.
- Library services and resources.
- Publications services.

Support is provided through effective communication with division programmatic staff and through the coordination of resources from disciplines outside the division.

The QA activity in the division emphasizes the development and documentation of a QA program that conforms to national standards, the review and approval of engineering documents, supplier surveillance, identification and documentation of nonconforming items, audits, and QA assessments/plans.

The division's safety activities include a formal safety program and environmental protection services. Efforts devoted to the removal of hazardous wastes from division facilities continued during 1987.

10.1 MANAGEMENT SERVICES

10.1.1 General Administration Services

10.1.1.1 Personnel

On December 31, 1987, the Fusion Energy Division had 170 employees, compared with 180 on December 31, 1986. Figure 10.1 shows the composition of the division's scientific staff. Attrition from the division during 1987 consisted of 3 retirements, 2 resignations, and 16 transfers to other divisions. Thus, 11 employees joined the division during the year. About half of the new employees are women or

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Fig. 10.1. Fusion Energy Division professional staff by discipline.

members of minority groups; this demonstrates the division's continuing commitment to affirmative action.

The University and College Co-Op Program sponsored three electrical engineering students, one each from Tennessee Technological University, the University of Tennessee, and Virginia Polytechnic Institute and State University; one nuclear engineering student from the Georgia Institute of Technology; and two computer communications students from the University of Tennessee. Eleven technical students participated in summer programs; six of them were sponsored by Oak Ridge Associated Universities.

Long-term foreign and domestic arrangements were made for seven staff members during 1987. Apartments near Princeton Plasma Physics Laboratory (PPPL) continued to be rented during most of the fiscal year for use by ORNL staff members working at PPPL. The division was host to 81 scientific guests and subcontractor personnel; 42 of these were foreign participants, 30 of whom were associated with the Large Coil Task (LCT).

Personnel development activities received continued emphasis. These included job-related seminars, scientific workshops, educational studies, and employee training courses.

10.1.1.2 Procurement and subcontracts

During 1987, the division's procurement group processed 2171 requisitions with a total value of about \$5.4 million. Throughout the year, this group actively monitored an average of 600 to 700 open purchase orders. In addition, 186 shipping orders were processed. These included the shipment of equipment to Abingdon, England, for use on the the Joint European Torus (JET) and to Cadarache, France, for use on Tore Supra.

Industrial participation through subcontracts to the division approximated \$2.7 million in 1987. Almost all of the subcontract cost (\$2.5 million) was applicable to the ORNL Fusion Program.

The initial phase of a procurement status database was implemented about midyear. The primary goals of this real-time information system are to provide users with the status of individual procurements and to serve as an effective tool for cost control.

10.1.1.3 International agreements and collaboration

The division participated in numerous personnel exchanges and collaborations during 1987. The Management Services Section (MSS) played a key role in organizing these activities, with responsibility for coordinating administrative, legal, and protocol matters for outbound Fusion Program representatives and inbound foreign guests.

In this capacity, MSS staff members interacted with the ORNL Foreign National Office, the ORNL and Y-12 Plant security organizations, the Legal Department and the Office of the Comptroller and Treasurer of Martin Marietta Energy Systems, and the Washington and Oak Ridge Operations offices of DOE, as well as other support and service organizations. Responsibilities included ensuring adherence to general laboratory and company policies and to federal procedures and laws, monitoring the processing of paperwork to ensure timeliness and accuracy, obtaining the necessary approvals, and generally supporting the satisfactory implementation of exchanges, cooperative programs, and collaborations.

The division's collaborative activities are described in detail in other sections of this report. The following review demonstrates the scope of these efforts.

As part of the U.S.-Japan cooperative program on fusion research, exchanges with the Heliotron-E group at the Kyoto University Plasma Physics Laboratory involved the in-depth analysis of electron cyclotron heating (ECH) data and critical assessment of hard X-ray generation on Heliotron-E. A visiting scientist from Kyoto University participated in the division's benchmark calculations of energetic orbit losses in Heliotron-E.

The division made significant contributions to the development of the Australian stellarator program through a collaboration with the Australian National University, Canberra. Interactions with visiting scientists from the Max-Planck-Institut für Plasmaphysik furthered the development of transport codes and the formulation of considerations for a common database on stellarators, pursuant to the International Energy Agency (IEA) Implementing Agreement for Cooperation in Development of the Stellarator Concept.

Under a collaborative agreement between the U.S. DOE and the European Atomic Energy Agency (EURATOM), ORNL was assigned the task of designing, fabricating, assembling, testing, and installing a three-barrel, repetitive pneumatic pellet launcher system for JET. The division successfully delivered this system in April, one month ahead of schedule. The system has operated reliably and is playing a key role in the JET experimental program.

The Large Coil Task (LCT) is a multinational effort, organized under the auspices of IEA, to demonstrate the operation of superconducting magnets on a scale relevant to future fusion devices. The specific objectives of this effort include stable operation of coils under simulated nuclear heating loads and demonstration of the ability of each coil to withstand stresses induced by background fields from other coils. The test program, carried out on the International Fusion Superconducting Magnet Test Facility (IFSMTF), was successfully concluded in September. The coils achieved a world's record in magnetic fields, and all scheduled major milestones were attained. The experimental information and test data gained from the LCT, to be published in a summary report, will be useful in the development of advanced conductors and in the design of future devices.

The division participates in a collaboration between the Federal Republic of Germany, Japan, and the United States on the TEXTOR tokamak in Jülich, Federal Republic of Germany, and is responsible for defining, preparing, and implementing a helium removal experiment for the Advanced Limiter Test-II program. This experiment, scheduled for 1988, will simulate the removal of helium ash from the plasma core of a tokamak reactor via a pumped belt limiter; significant progress was made during the year.

The division is also a key contributor to the collaboration between the United States and the Commissariat à l'Energie Atomique on the Tore Supra tokamak. A prototype particle control limiter, built at OPNL, has been installed on Tore Supra, and a centrifugal pellet injector and an rf heating antenna are under construction. The first long-term assignment of a division staff member to Tore Supra is scheduled to begin in early 1988.

As part of the U.S.-U.S.S.R. fusion research exchange program, a division staff member visited the Kharkov Physical-Technical Institute to apply ECH theory to the Uragan-III device, and two senior researchers from the U.S.S.R. visited the division for collaborative work on the Advanced Toroidal Facility (ATF). A joint U.S.-U.S.S.R. stellarator research planning meeting, held in Moscow, further illustrates the two countries' commitment to joint research.

In a collaboration sponsored by the International Atomic Energy Agency, the United States, the U.S.S.R., the European Community, and Japan are developing a conceptual design for an International Thermonuclear Experimental Reactor (ITER), with the objective of demonstrating the scientific and technological feasibility of fusion. The division is well represented in this collaboration; actual work on the design phase is scheduled to begin in 1988.

10.1.2 Engineering Services

The Engineering Services Group coordinates all engineering work performed on general facilities additions, modifications, and repairs in the division. Active work to improve the physical plant facilities, despite limited resources, continued during

1987. The Engineering Services Group worked closely with the Engineering Division of Martin Marietta Energy Systems, Inc., and with Fusion Energy Division researchers to develop consistent, practical long-range plans for needed improvements. In this reporting period, a new laboratory for pellet injector assembly work was completed, and construction began on the third phase of a six-phase effort to improve the air-handling systems in Bldg. 9201-2. Phase 4 of this effort is scheduled for 1988, as is the initiation of the first phase of an upgrade of the 440-V electrical distribution system.

The demineralized water system in Bldg. 9201-2 provides cooling water for ATF, the Radio-Frequency Test Facility (RFTF), and other test facilities and for the building air conditioners. During 1987, the Engineering Services Group undertook the major task of removing all of the mechanically balanced water-pump impeller-shaft assemblies from this system, balancing the assemblies, and reinstalling them. Half of the assemblies had been reinstalled by year's end. Detailed drawings of the system were prepared and analyzed by an outside contractor to facilitate planning for present and future operating and maintenance needs.

Two 11,000-gal liquid nitrogen storage tanks were installed at Bldg. 9204-1 to serve the IFSMTF. These tanks eliminated the need for the obsolete 4000-gal trailers that had been used for both storage and delivery for many years. With the larger tanks, costs were lower and operational efficiency increased. When the IFSMTF was decommissioned, one of the tanks was installed at Bldg. 9201-2, where it serves ATF and RFTF. These improvements, carried out as part of a Performance Improvement Process (PIP) project, received a PIP Award from Energy Systems.

The Engineering Services Group oversaw 151 fabrication jobs, with a total cost of \$1,100,000, for the division. Of these jobs, 53 went to the ORNL shops, 27 to the Y-12 Plant, 20 to the Oak Ridge Gaseous Diffusion Plant, and 21 to outside shops. A computer-based system was developed to report fabrication progress and costs to managers in the Energy Systems Engineering Division and the Fusion Energy Division.

Other achievements during the year included establishing a loan equipment area for division personnel; developing a procedure for improved control of nuclear materials and deuterium bottles; actively participating in the Y-12 Plant inventory effort, during which many accountable items were located and identified; and working with key ORNL personnel to make the ORNL Space Report more useful to the division. The group continued to coordinate the division's 400 telephones, with the goals of improving service and lowering costs.

Storage of used materials for future research projects continues to be a problem as space formerly allocated to the division is reclaimed by the Y-12 Plant. The division plans a comprehensive study of the use of laboratory, office, and storage space in 1988. This study could identify some areas of relief for the division's storage problems.

The Engineering Services Group produced a time-lapse film of the on-site construction of the ATF device. This film provides a complete record for historical and documentation purposes.

10.1.3 Financial Services

The Financial Office is a functional part of the Management Services Section and provides financial management support for administrative, engineering, and research personnel in areas that include budget preparation, cost scheduling, and variance analysis. The office also provides meaningful and appropriate accounting and cost control. Interaction with division management is an essential part of administering the budget, accounting policies, and procedures. Table 10.1 and Fig. 10.2 show the funding trends for the ORNL Fusion Program.

**Table 10.1. Fusion Program expense funding (in thousands of dollars)--
budget outlay**

Activity	FY 1985 Actual cost	FY 1986 Actual cost	FY 1987 Actual cost	FY 1988 Funding as of February 1988	FY 1989 Budget submission	FY 1990 Budget submission
Applied plasma physics						
Fusion plasma research	\$3,116	\$2,355	\$2,303	\$2,405	\$2,575	\$2,700
Experimental plasma research	1,410	1,152	1,194	1,220	1,320	1,410
National MFE computer network	443	203	370	380	360	360
Technical program support	189	248	168	61	0	0
	\$5,158	\$3,958	\$4,035	\$4,066	\$4,255	\$4,470
Confinement systems						
Research operation	\$12,589	\$13,301	\$16,212	\$17,478	\$18,050	\$18,785
Major device fabrication	6,768	8,992	1,960	492	0	0
Magnetic mirror research operations	1,134	1,263	1,953	290	2,853	2,355
Compact Ignition Tokamak support	0	0	835	2,475	2,400	2,350
Technical program support	0	12	0	0	100	100
	\$20,491	\$23,568	\$20,960	\$20,735	\$23,403	\$23,590
Development and technology						
Magnetic systems	\$13,589	\$10,553	\$7,450	\$2,170	\$1,200	\$1,600
Plasma engineering	3,896	3,745	5,672	7,065	6,725	7,105
Reactor systems	478	351	310	170	177	184
Environment and safety	10	83	69	80	50	50
Reactor materials	6,928	6,957	5,193	4,922	5,303	5,138
Fusion Engineering Design Center	4,781	4,548	3,285	2,570	2,968	3,182
	\$29,682	\$26,237	\$21,979	\$16,977	\$16,443	\$17,259
TOTAL ORNL FUNDING	\$55,331	\$53,763	\$46,974	\$41,778	\$44,101	\$45,319

10.1.4 Library Services

In addition to providing library services such as online searching, reference assistance, and circulation of materials, the Fusion Energy Library introduced several new services during 1987.

Fig. 10.2. Fusion Program expense funding (B/O). (Does not include Compact Ignition Tokamak budgets.)

A dedicated, direct-access terminal to the Library Information Online Network (LION) was installed in the Magnetics and Superconductivity Reading Room in Bldg. 9204-1.

The library gained access to two new information resources: LEGI-SLATE, an online database that allows access to full-text legislative and regulatory information, and PI-NET, the Physical Information Network of the American Physical Society, which includes news releases, online orders, and a weekly electronic news bulletin.

The library began subscribing to "Fast Track," a monthly publication in audio-tape format. These tapes are summaries of best-selling business books.

New space for housing materials overflowing from the Fusion Energy Library was acquired in Bldg. 9201-2, close to the library. Materials that were formerly stored in scattered areas are now consolidated in the library annex.

10.1.5 Publications Services

The Fusion Energy Division Publications Office (FEDPO) provides the division with editing, writing, composition, conventional and computer graphics, document makeup, and reproduction services. It also serves as liaison with the Laboratory Records Department of the Information Resources Organization (IRO) for clearance processing of all documents prepared by division staff.

FEDPO staff handled a total of 197 jobs during 1987; these included journal articles, conference papers, reports, a thesis, and a book. In addition, 318 presentations (abstracts and viewgraph packages) were cleared. Much of this material is listed in Appendix 1.

At the request of a senior member of the division's research staff, a PIP project was initiated during the year to find faster ways of publishing the division's research. The result was the development and implementation of a preprint option, approved by ORNL, for journal articles and conference papers.

During the year, the FEDPO conducted training classes for division secretaries to help them improve their document preparation skills. In addition, planning began for a technical writing class for division research staff.

Electronic publishing—preparation of text, graphics, and sometimes complete documents using computers—made steady advances in the division in 1987. In response to the division's commitment to electronic publishing, the FEDPO acquired four new Macintosh SE personal computers (PCs) and an Abaton scanner during the year. Editors in the publications office use these Macintosh PCs, the division's computer system, and the IRO Text Management System for much of their editing and writing. During the year, compositors continued to expand their knowledge and skill in using the TeX formatter available on the division's VAX cluster; they also learned several word processing packages used with the Macintosh SE and IBM PCs. Implementation of an AppleTalk[®] network—connecting FEDPO's population of Macintosh PCs and the Apple LaserWriter printer—provided an additional resource for rapid preparation of camera-ready documents and graphics of high quality.

The Graphics Section of the publications office produced 3,234 drawings and revisions, 447 visuals, 7,866 Pos prints and viewgraphs, and 1,243 miscellaneous items during 1987. Over one-third of the drawings and revisions and over two-thirds of the visuals were produced using the MAPPER program on the division's computer system. During the year, the section's illustrators were trained in several software packages for the Macintosh SEs. In addition, the Abaton scanner, which works in conjunction with the Macintosh SE, was put into heavy use by the Graphics staff.

These capabilities reflect FEDPO's commitment to aid division staff in the production of high-quality documents in an expeditious and cost-effective manner.

10.2 QUALITY ASSURANCE

In June 1987, all quality assurance (QA) personnel at ORNL began reporting directly to the ORNL Quality Manager. Since that time, the division's QA manager has reported administratively to the ORNL Quality Manager and programmatically to the director of Fusion Energy Division. The two QA specialists in the division continue to report to the division's QA manager.

10.2.1 QA Program Development

The QA group began revising the division's QA procedures. At the end of the year, two revised procedures had been issued and one was being reviewed. Revision of all procedures should be completed in 1988.

A QA training program was developed for the division. The program consists of an orientation session, which includes a general overview of NQA-1 and its application to the division, and other sessions on specific division QA procedures.

10.2.2 QA Program Implementation

The division QA staff reviewed engineering and procurement documents, including drawings and specifications that define technical requirements for items to be fabricated, to ensure that these documents clearly defined the QA requirements to be met. Staff members made a number of trips to suppliers during the year to ensure that major components for division projects were being manufactured correctly; personnel from the division and from the Engineering Division of Energy Systems also participated in these efforts.

During the year, 22 nonconformance reports, 1 quality investigation report, and 16 deviation reports were written to identify and document nonconformances so that problems could be resolved. Staff members also performed five audits and vendor surveillances during the year.

A QA Assessment/Plan (QAA/P) is used to identify and evaluate the risk of failure in quality or other areas, to determine if special QA activities are needed to monitor this risk, and to reduce the risk of failure to an acceptable level. Three QAA/Ps were developed during 1987; there were nine active QAA/Ps at year's end.

10.3 SAFETY AND ENVIRONMENTAL PROTECTION

10.3.1 Safety

The division places a high priority on safety awareness and on correcting safety problems. Safety meetings were held every two months, and attendance was mandatory for division staff. The division director, division safety officer, and/or a designee attended the monthly Y-12 Plant safety meetings, and reports on these meetings were made to the section heads and program managers. Monthly inspections were conducted by each section and quarterly inspections were made by the division director.

A committee was formed to evaluate all areas of Bldg. 9201-2 to determine where safety glasses should be required. The committee decided that fencing should be placed around some areas to restrict access and that signs should be installed to identify restricted areas.

All items proposed for safety action were resolved, with the exception of safety on Bear Creek Road and local sidewalk replacement.

A division staff member represented the ORNL divisions at the Y-12 Plant on the Y-12 Traffic Committee. During the year, this committee resolved many in-plant traffic problems and assisted the Energy Systems Engineering Division in implementing the new security barriers on Bear Creek Road. High mast lighting, raised pavement markers, and improved pavement striping were placed on Bear Creek Road, and the idea of retaining a traffic professional to assist in evaluating the need for further improvements was accepted.

The startup of ATF mandated general safety orientation for all personnel with access to the facility. The audiovisual group worked with facility operators and research staff to produce a 23-min videotape for safety training. This videotape records the content of the safety training and has been widely recognized as an effective tool for this purpose. The audiovisual group also produced a videotape documenting the arrival and preliminary fitting of the ATF vacuum vessel. This videotape was viewed by DOE Office of Fusion Energy and Oak Ridge Operations Office staff; it was instrumental in the process of gaining approval to proceed with final installation of the vacuum vessel.

The building video system was used to focus employee attention on a broad range of safety items on a daily basis. These items included use of seat belts and safety glasses, hazardous driving conditions in the Y-12 Plant, and off-the-job safety. Approximately 60 messages were displayed for a total of 680 hours.

10.3.2 Environment

Increased emphasis at all levels on environmental concerns has resulted in several new activities and programs in this area. Two division staff members attended a course on Resource Conservation and Recovery Act (RCRA) regulations for handling hazardous materials and other short courses on environmental regulation and procedures. Achievements during 1987 included control of storage drums stored inside and outside the building, better control of environmental waste, and a waste minimization activity report.

Appendix 1

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BOOKS AND JOURNAL ARTICLES

- N. D. Alikakos and K. C. Shaing, "On the Singular Limit for a Class of Problems Modelling Phase Transitions," *SIAM J. Math. Anal.* **18**, 1453-62 (1987)
- S. E. Attenberger, W. A. Houlberg, and S. P. Hirshman, "Some Practical Considerations Involving Spectral Representations of 3D Plasma Equilibria," *J. Comput. Phys.* **72**, 435-48 (1987)
- D. B. Batchelor, M. D. Carter, G. L. Chen, and C. L. Hedrick, "Coupled Model of Wave Damping, Quasilinear Heating, and Radial Transport Applied to Bumpy Tori," *Phys. Rev. Lett.* **58**, 2664-67 (1987)
- A. Bayliss, L. F. Ibañez, and J. T. Hogan, "Classical Transport in Nonaxisymmetric Toroidal Magnetic Confinement Geometries," *Plasma Phys. Controlled Fusion* **29**, 957-68 (1987)
- C. D. Beidler, W. N. G. Hitchon, W. I. van Rij, S. P. Hirshman, and J. L. Shohet, "Unified Theory of Ripple Transport in Stellarators," *Phys. Rev. Lett.* **58**, 1745-7 (1987)
- P. G. Carolan, B. P. Duval, A. R. Field, S. J. Fielding, N. C. Hawkes, N. J. Peacock, G. Fussman, G. Janeschits, J. Hoffman, K. H. Behringer, and R. C. Isler, "Charge-Exchange-Excited Line Radiation in a Tokamak (ASDEX) with Neutral-Particle-Beam Injection," *Phys. Rev. A* **35**, 3454-71 (1987)
- B. A. Carreras, "Low-Aspect-Ratio Torsatrons," *Comments Plasma Phys. Controlled Fusion* **11**, 139-46 (1987)
- B. A. Carreras, L. Garcia, and P. H. Diamond, "Theory of Resistive Pressure-Gradient-Driven Turbulence," *Phys. Fluids* **30**, 1388-1400 (1987)
- M. D. Carter, D. B. Batchelor, and A. C. England, "Second Harmonic Electron Cyclotron Breakdown in Stellarators," *Nucl. Fusion* **27**, 985 (1987)
- S. K. Combs, S. L. Milora, C. R. Foust, L. R. Baylor, G. C. Barber, R. D. Burris, P. W. Fisher, C. A. Foster, R. V. Lunsford, G. L. Schmidt, D. D. Schuresko, T. Senko, R. C. Shanley, W. D. Shipley, D. O. Sparks, K. A. Stewart, and R. B. Wysor, "Eight-Shot Pneumatic Pellet Injection System for the Tokamak Fusion Test Reactor," *Rev. Sci. Instrum.* **58**, 1195-1203 (1987)
- W. A. Cooper and S. P. Hirshman, "Axisymmetric MHD Equilibria with Isothermal Toroidal Mass Flow by Variational Steepest Descent Moments Method," *Plasma Phys. Controlled Fusion* **29**, 933-43 (1987)
- W. A. Cooper, S. P. Hirshman, and M. C. Depassier, "Inverse Moments Equilibria for Helical Anisotropic Systems," *Phys. Fluids* **30**, 3532-9 (1987)
- W. R. Corwin, J. M. Vitek, and R. L. Klueh, "Effect of Nickel Content of 9Cr-1MoVNb and 12Cr-1MoVW Steels on the Aging and Irradiation Response of Impact Properties," *J. Nucl. Mater.* **149**, 312-320 (1987)
- E. C. Crume, Jr., C. O. Beasley, Jr., S. P. Hirshman, and W. I. van Rij, "Neoclassical Transport Coefficients for Finite-Aspect-Ratio and Bean-Shaped Tokamak Plasmas," *Phys. Fluids* **30**, 1152-9 (1987)
- A. E. Dabiri, "Economic Considerations of Commercial Tokamak Options," *Fusion Technol.* **12**, 238 (1987)
- P. H. Diamond and B. A. Carreras, "On Mixing Length Theory and Saturated Turbulence," *Comments Plasma Phys. Controlled Fusion* **10**, 271 (1987)
- J. K. Dickens, J. W. McConnell, K. M. Chase, H. W. Hendel, E. B. Nieschmidt, and F. Y. Tsang, "Measurements of the Neutron and Gamma-Ray Fluences in the TFTR Test Cell Due to a Point Source Simulating D-T Fusion Plasma Neutron Production," *Fusion Technol.* **12**, 270 (1987)
- A. Fruchtman, K. Riedel, D. B. Batchelor, and H. Weitzner, "A Kinetic Full Wave Theory of Strong Spatial Damping of Electron Cyclotron Waves in Nearly Parallel Stratified Plasmas," *Phys. Fluids* **30**, 115-28 (1987)
- R. C. Goldfinger and D. B. Batchelor, "Theory of Electron Cyclotron Heating in the ATF Torsatron," *Nucl. Fusion* **27**, 31 (1987)
- D. C. Gregory, L. J. Wang, F. W. Meyer, and K. Rinn, "Electron-Impact Ionization of Iron Ions: Fe^{11+} , Fe^{13+} , and Fe^{15+} ," *Phys. Rev. A* **35**, 3256-64 (1987)
- D. C. Griffin, M. S. Pindola, and C. Bottcher, "Distorted-Wave Calculations of the Electron-Impact Ionization of Highly Ionized Na-Like Ions," *Phys. Rev. A* **35**, 3642-53 (1987)

- T. S. Hahm, P. H. Diamond, P. W. Terry, L. Garcia, and B. A. Carreras, "Role of Impurity Dynamics in Resistivity-Gradient-Driven Turbulence and Tokamak Edge Plasma Phenomena," *Phys. Fluids* **30**, 1452-65 (1987)
- R. J. Hastie, T. C. Hender, B. A. Carreras, L. A. Charlton, and J. A. Holmes, "Stability of Ideal and Resistive Internal Kink Modes in Toroidal Geometry," *Phys. Fluids* **30**, 1756-66 (1987)
- R. J. Hawryluk, V. Arunasalam, J. D. Bell, M. G. Bell, M. Bitter, W. R. Blanchard, F. Boody, N. Brets, R. Budny, C. E. Bush, J. D. Callen, J. L. Cecchi, S. Cohen, R. J. Colchin, S. K. Combs, J. Coonrod, S. L. Davis, D. Dimock, H. F. Dylla, P. C. Efthimion, L. C. Emerson, A. C. England, H. P. Eubank, R. Fonck, E. Fredrickson, R. J. Goldston, L. R. Grisham, B. Grek, R. Groebner, H. Hendel, K. W. Hall, D. L. Hillis, E. Hinnov, S. Hiroe, R. Hulse, H. Hsuan, D. Johnson, L.-C. Johnson, R. Kaita, R. Kamperschroer, S. M. Kaye, S. Kilpatrick, H. Kugel, P. H. LaMarche, R. Little, C. H. Ma, D. M. Manos, D. Mansfield, R. T. McCann, M. McCarthy, D. C. McCune, K. McGuire, D. M. Meade, S. S. Medley, S. L. Møller, D. R. Mikkelsen, W. Morris, D. Mueller, M. Murakami, E. Nieschmidt, D. K. Owens, V. K. Paré, H. Park, B. Prichard, A. Ramsey, D. A. Rasmussen, M. H. Redi, A. L. Roquemore, N. R. Sauthoff, J. Schivell, G. L. Schmidt, S. D. Scott, S. Sesnic, M. Shimada, J. E. Simpkins, J. Sinnis, F. Stauffer, B. Stratton, G. D. Tait, G. Taylor, C. E. Thomas, H. H. Towner, M. Ulrickson, S. von Goeler, R. Wieland, J. B. Wilgen, M. Williams, K. L. Wong, S. Yoshikawa, K. M. Young, M. C. Zarnstorff, and S. Zweben, "Experimental Results from the TFTR Tokamak," *Philos. Trans. R. Soc. London A: Math. Phys. Sci.* **322**, 147-62 (1987)
- C. L. Hedrick and L. W. Owen, "Poloidally Asymmetric Electrostatic Potentials in Closed Line Bumpy Toroids," *Phys. Fluids* **30**, 657-69 (1987)
- C. L. Hedrick, L. W. Owen, B. H. Quon, and R. A. Dandl, "Diamagnetic Wells in Axisymmetric Mirrors," *Phys. Fluids* **30**, 1860-8 (1987)
- W. W. Heidbrink, S. L. Milora, G. L. Schmidt, W. Schneider, and A. Ramsey, "Neutron and Hard X-Ray Measurements during Pellet Deposition in TFTR," *Nucl. Fusion* **27**, 3 (1987)
- T. C. Hender, B. A. Carreras, and V. E. Lynch, "Helic Equilibria," *Nucl. Fusion* **27**, 2161 (1987)
- S. Hiroe, "The Role of the Non-Maxwellian Electron Distribution in Tandem Mirror Experiments," *Comments Plasma Phys. Controlled Fusion* **11**, 95-117 (1987)
- S. Hiroe, G. R. Haste, Jr., J. S. Tolliver, B. H. Quon, K. A. Connor, J. R. Goyer, and L. Solensten, "Convective Contributions to Local Power Loss in a Bumpy Torus," *Phys. Fluids* **30**, 2870-6 (1987)
- S. Hiroe, J. C. Glowienka, D. L. Hillis, J. B. Wilgen, G. L. Chen, J. A. Cobble, A. M. El Nadi, J. R. Goyer, L. Solensten, W. H. Casson, O. E. Hankins, and B. H. Quon, "Effect of Electric Fields and Fluctuations on Confinement in a Bumpy Torus," *Phys. Fluids* **30**, 847-56 (1987)
- W. A. Houlberg, "Volt-Second Consumption in Tokamaks with Sawtooth Activity," *Nucl. Fusion* **27**, 1009-1020 (1987)
- R. C. Isler, "A Review of Charge-Exchange Spectroscopy and Applications to Fusion Plasmas," *Phys. Scr.* **35**, 650-61 (1987)
- R. L. Klueh and J. M. Vitek, "Postirradiation Behavior of Nickel-Doped Ferritic Steels," *J. Nucl. Mater.* **150**, 272-80 (1987)
- E. A. Lazarus and G. H. Neilson, "Solutions to the Tokamak Circuit Equations with Force Balance for a Massless Plasma," *Nucl. Fusion* **27**, 383-96 (1987)
- D. K. Mansfield, H. K. Park, L. C. Johnson, H. M. Anderson, R. Chouinard, V. S. Foote, C. H. Ma, and B. J. Clifton, "Multichannel Far-Infrared Laser Interferometer for Electron Density Measurements on the Tokamak Fusion Test Reactor," *Appl. Opt.* **26**, 4469-74 (1987)
- P. W. Meyer, C. C. Havener, K. J. Snowdon, S. H. Overbury, D. M. Zehner, and W. Heiland, "Observation of the Neutralization of Highly Charged Ions Interacting With a Metal Surface," *Phys. Rev. A* **35**, 3176-79 (1987)
- P. K. Mioduszewski, R. C. Isler, J. E. Simpkins, P. H. Edmonds, E. A. Lazarus, C. H. Ma, and M. Murakami, "Improvement of Plasma Performance with Chromium Gettering in ISX-B," *Nucl. Fusion* **27**, 195 (1987)

- R. N. Morris, R. H. Fowler, J. A. Rome, and T. J. Schlagel, "Advanced Toroidal Facility Neutral Beam Injection: Optimization of Beam Alignment and Aperturing," *Fusion Technol.* **12**, 281 (1987)
- G. H. Neilson and J. H. Harris, "Harmonic Analysis for Magnetic Configuration Control in Experimental Stellarator Devices," *Nucl. Fusion* **27**, 711-24 (1987)
- H. Okuda and S. Hiroe, "Diffusion of a Plasma Subject to Neutral Beam Injection," *Phys. Fluids* **30**, 1160-8 (1987)
- M. S. Pindzola and D. C. Griffin, "Double Auger Processes in the Electron-Impact Ionization of Lithiumlike Ions," *Phys. Rev. A* **36**, 2628-32 (1987)
- M. S. Pindzola, C. Bottcher, and D. C. Griffin, "Indirect Processes in the Electron Impact Ionisation of Ca^+ Using an LS-Term-Dependent Close-Coupling Method," *J. Phys. B* **20**, 3535-46 (1987)
- D. Post, G. Bateman, W. Houlberg, L. Bromberg, D. Cohn, P. Colestock, M. Hughes, D. Ignat, R. Izzo, S. Jardin, C. Kieras-Phillips, L. P. Ku, G. Kuo-Petravic, B. Lipschultz, R. Parker, C. Paulson, Y.-K. M. Peng, M. Petravic, M. Phillips, N. Pomphrey, J. Schmidt, D. Strickler, A. Todd, N. Uckan, R. White, S. Wolfe, and K. Young, "Physics Aspects of the Compact Ignition Tokamak," *Phys. Scr.* **T16**, 89-106 (1987)
- K. Rinn, D. C. Gregory, L. J. Wang, R. A. Phaneuf, and A. Müller, "Electron-Impact Ionization of O^{5+} : Improved Measurements," *Phys. Rev. A* **36**, 595-98 (1987)
- E. Rodriguez-Solano Ribiero and K. C. Shaing, "Calculation of Neoclassical Fluxes in the Plateau Regime for Nonaxisymmetric Toroidal Plasmas," *Phys. Fluids* **30**, 462-6 (1987)
- R. W. Roussin and D. K. Trubey, "Radiation Shielding and Protection," pp. 596-632 in *Encyclopedia of Physical Science and Technology*, vol. 2, R. Meyers, ed., Academic Press, Inc., Orlando, Florida, 1987
- P. M. Ryan, W. L. Stirling, J. H. Whealton, and I. Alexeff, "Direct Recovery of Ion Beam Energy Using Magnetic Electron Suppression: I. Analysis of ORNL Energy Recovery Experiments," *Nucl. Instrum. Methods A* **261**, 556-72 (1987)
- R. T. Santoro, J. M. Barnes, R. G. Alsmiller, Jr., M. B. Emmett, and J. D. Drischler, "Comparisons of Calculated and Measured Spectral Distributions of Neutrons from a 14-MeV Neutron Source Inside the Tokamak Fusion Test Reactor," *Fusion Technol.* **11**, 420 (1987)
- D. P. Schissel, J. Baur, G. Bramson, A. Kellman, R. T. Snider, R. Stockdale, S. S. Wojtowicz, and C. A. Foster, "Results of Pellet Fueled Discharges on the Doublet III Tokamak," *Nucl. Fusion* **27**, 1063-73 (1987)
- K. C. Shaing, "Physical Mechanism of Plasma Currents Induced by Waves," *Plasma Phys. Controlled Fusion* **29**, 1637-41 (1987)
- J. Sheffield, "The ATF—ORNL's New Fusion Device to Begin Operation Soon," *ORNL Rev.* **20**(4), 16-18 (1987).
- J. Sheffield, "Magnetic Fusion Progress: A History and Review," *ORNL Rev.* **20**(4), 1-13 (1987).
- J. E. Simpkins, W. R. Blanchard, H. F. Dylla, P. H. LaMarche, "Residual Effects of Chromium Gettering on the Outgassing Behavior of a Stainless Steel Vacuum Vessel" *J. Nucl. Mater.* **145-47**, 348-52 (1987)
- W. M. Stacey, Jr., C. C. Baker, P. L. Colestock, C. A. Flanagan, R. F. Mattas, Y.-K. M. Peng, D. F. Post, D. L. Smith, P. T. Spampinato, and R. J. Thome, "U.S. Contribution to the Phase 2A, Part 2 International Tokamak Reactor Workshop, 1983-1985, June 1985," *Fusion Technol.* **11**, 317 (1987)
- B. C. Stratton, A. T. Ramsey, P. P. Boody, C. E. Bush, R. J. Fonck, R. J. Groebner, R. A. Hulse, R. K. Richards, and J. Schivell, "Spectroscopic Study of Impurity Behavior in Neutral Beam Heated and Ohmically Heated TFTR Discharges," *Nucl. Fusion* **27**, 1147-64 (1987)
- J. S. Tolliver and C. L. Hedrick, "Monte Carlo Estimates of Particle and Energy Confinement Times in a Bumpy Torus and a Bumpy Square with Poloidal Electric Fields," *Phys. Fluids* **30**, 870-7 (1987)
- P. F. Tortorelli, "Fundamentals of High-Temperature Corrosion in Liquid Metals," pp. 56-60 in *Metals Handbook*, 9th ed., Vol. 13: *Corrosion*, J. Johnson, R. T. Kierpura, and D. A. Humphries, eds., American Society for Metals, Metals Park, Ohio, 1987.

- T. Uchan, "Asymmetric Double Langmuir Probe: Small Signal Application," *Rev. Sci. Instrum.* **58**, 2260-63 (1987)
- T. Uchan, "Plasma-Materials Interactions Test Facility," *Rev. Sci. Instrum.* **58**, 17 (1987)
- S. J. Zinkle, "Microstructure and Properties of Copper Alloys Following 14-MeV Neutron Irradiation," *J. Nucl. Mater.* **150**, 140-58 (1987)

PRESENTATIONS

January

- CIT Confinement Workshop, Princeton, New Jersey, January 17-20, 1987**
 W. A. Houlberg, "JET Pellets"
- U.S./Japan Exchange Workshop on MHD Stability of Strongly Shaped Tokamaks and Paths to High Beta, San Diego, California, January 19-23, 1987**
 L. A. Charlton, B. A. Carreras, J. A. Holmes, and V. E. Lynch, "Fully Toroidal $m = 1$ Resistive MHD Studies"
- J. T. Hogan, J. A. Holmes, B. A. Carreras, L. A. Charlton, C. O. Beasley, S. P. Hirshman, and W. I. van Rij, "Ideal MHD Stability of Low-Aspect-Ratio Shaped Plasmas"
- G. H. Neilson, "A Retrospective on High Beta Studies in ISX-B"
- D. A. Spong, D. J. Sigmar, and J. J. Ramos, "Effects of Energetic Alpha Populations on Ballooning Stability of Shaped Tokamaks"
- Meeting on Lawrence Livermore National Laboratory Engineering Test Reactor Effort, Lawrence Livermore National Laboratory, Livermore, California, January 27, 1987**
 M. W. Rosenthal, M. J. Saltmarsh, J. Sheffield, T. Shannon, and L. A. Berry, "Proposals for ORNL Support to TIBER"

February

- Workshop on Turbulence in Confined Plasmas, The University of Texas at Austin, Austin, Texas, February 2-4, 1987**
 G. S. Lee, L. Garcia, B. A. Carreras, and P. H. Diamond, "Effects of a Sheared Radial Electric Field on Resistivity-Gradient-Driven Turbulence in Tokamak Edge Plasmas"
- CIT Electromagnetics Meeting (Poloidal Field Systems Workshop), Princeton Plasma Physics Laboratory, Princeton, New Jersey, February 3, 1987**
 D. J. Strickler, "Poloidal Magnetics of a Divertor CIT"
- Biannual Plasma Physics Meeting of the Australian Institute of Nuclear Sciences and Engineering, Lucas Heights, Australia, February 8-11, 1987**
 B. A. Carreras, "Three-Dimensional MHD Calculations"
- TIBER/ETR Design Review Meeting, Lawrence Livermore National Laboratory, Livermore, California, February 9-12, 1987**
 C. A. Flanagan, "ETR/INTOR"
- G. E. Gorker, "DT Fueling Systems"
- Y.-K. M. Peng, "Status of the ETR Systems Code Development and Design Space Studies"
- S. L. Thomson, "Cost Basis of TIBER"
- U.S./Japan Exchange Q-70, Lawrence Livermore National Laboratory, Livermore, California, February 23-26, 1987**
 G. E. Gorker and W. D. Nelson, "Electrical Systems for TIBER"
- Y.-K. M. Peng, "ETR Systems Analysis in the United States"
- R. L. Reid, "Code Integration and FEDC Modules"
- S. L. Thomson, "ETF/TIBER Plant Systems"
- U.S. Congressional Hearing on Magnetic Fusion, conducted by the Energy, Research and Development Subcommittee of the House Science, Space, and Technology Committee, Washington, D.C., February 24, 1987**
 J. Sheffield, "Testimony on Magnetic Fusion to the Energy, Research and Development Subcommittee of the House Science, Space and Technology Committee"
- Magnetic Fusion Advisory Committee Meeting, Georgia Institute of Technology, Atlanta, Georgia, February 24-25, 1987**
 J. F. Lyon and M. Murakami, "Review of the Advanced Toroidal Facility Program"
- TMS-AIME Annual Meeting, Denver, Colorado, February 24-27, 1987**
 R. L. Klueh, "Ferritic Steels for Fusion Reactor Applications"

- P. J. Maziasz, "Irradiation-Produced Precipitate and Microstructural Evolution in 9Cr-1MoVNb Steel at 300 to 600°C"

March

U.S.-Japan Workshop on Divertors and Limiters, Nagoya, Japan, March 9-12, 1987

D. L. Hillis, P. K. Mioduszewski, J. A. Rome, R. H. Fowler, O. Motojima, T. Mizuuchi, N. Noda, T. Mutoh, H. Zushi, A. Iiyoshi, and K. Uo, "Pump Limiter and Divertor Scoping Studies on the Heliotron-E Device"

P. K. Mioduszewski, "Divertor and Limiter Studies on ATF"

P. K. Mioduszewski, "Particle Control in Fusion Devices"

P. K. Mioduszewski, "Particle Control Studies in Tore Supra"

ETR Tokamak Systems Code Meeting, Fusion Engineering Design Center, Oak Ridge, Tennessee, March 10-11, 1987

G. E. Gorker, "TF Coil Power Conversion (TFPOWER.COD)"

D. J. Strickler, "Poloidal Magnetics Module--Interfacing MHD Equilibria with the ETR Systems Code"

DOE Review Meeting, Fusion Engineering Design Center, Oak Ridge, Tennessee, March 16, 1987

Y.-K. M. Peng, "CIT Systems Analysis and Plasma Engineering"

Y.-K. M. Peng, "ETR/TIBER/INTOR Systems Code Development Status and Systems Analysis"

1987 Particle Accelerator Conference, Washington, D.C., March 16-19, 1987. Abstracts published in *Bull. Am. Phys. Soc.* **32** (1982).

F. W. Meyer and J. W. Hale, "Operation of the ORNL ECR Source"

J. H. Whealton, R. J. Raridon, M. A. Bell, K. E. Rothe, and B. D. Murphy, "Ion Beam Dynamics in High Intensity RFQ LINAC," p. 189

U.S.-Japan Workshop on Assessment of Spectroscopic Data for Temperature and Density Measurements, Nagoya, Japan, March 17-20, 1987

R. C. Isler, "Spectral Diagnostics for Temperature and Density Measurements on ATF"

MINIMARS Review Meeting, Fusion Engineering Design Center, Oak Ridge, Tennessee, March 18-19, 1987

G. E. Gorker, "Fuel System"

G. E. Gorker and D. C. Keeton, "Heat Transport and Power Conversion Systems"

G. E. Gorker and D. C. Keeton, "Power Balance and Electrical Systems"

American Nuclear Society Topical Meeting on Remote Systems and Robotics in Hostile Environments, Pasco, Washington, March 29-April 2, 1987. Proceedings published by the American Nuclear Society.

P. T. Spampinato and E. R. Hager, "Maintenance Features of the Compact Ignition Tokamak Fusion Reactor," p. 550

CIT PF Design Meeting, Princeton Plasma Physics Laboratory, Princeton, New Jersey, March 31, 1987

J. Galambos, "System Code Studies of Internal vs External PF Coil CITs"

D. J. Strickler, "Internal/External Coil Control and Flexibility"

April

Annual Controlled Fusion Theory Conference: 1987 Sherwood Meeting, San Diego, California, April 5-8, 1987. Abstract booklets distributed to conference attendees.

D. B. Batchelor, E. F. Jaeger, and P. L. Colestock, "Ion Cyclotron Emission Calculations Using a 2D Full Wave Numerical Code," paper 2D19

C. O. Beasley, Jr., J. T. Hogan, W. I. van Rij, and S. P. Hirshman, "Ion Heat Conductivity and Bootstrap Current in Low-Aspect-Ratio Tokamaks," paper 3B11

B. A. Carreras, "Ideal and Resistive MHD Stability of Tokamak Plasmas"

- M. D. Carter and D. B. Batchelor, "Effects of Fast Ion Sources on Lower Hybrid Current Drive," paper 3B7
- L. A. Charlton, B. A. Carreras, J. A. Holmes, V. E. Lynch, R. J. Hastie, and T. C. Hender, "Fully Toroidal MHD Nonlinear Studies of the $m = 1$ Fast Sawtooth Crash," paper 1B1
- G. L. Chen, P. M. Ryan, D. J. Hoffman, J. H. Whealton, and D. W. Swain, "Theoretical Study of ORNL-Designed TFTR ICRH Antenna," paper 1C34
- E. C. Crume, K. C. Shaing, J. S. Tolliver, S. P. Hirshman, and W. I. van Rij, "Bootstrap Current in Nonaxisymmetric Toroidal Plasmas," paper 2C1
- N. Dominguez, B. A. Carreras, V. E. Lynch, and S. P. Hirshman, "Ideal Mercier Stability in 3 Dimensions," paper 2C7
- C. L. Hedrick, J. S. Tolliver, and J. R. Cary, "Transitions from Passing to Trapped in Stellarators and Rippled Tokamaks," paper 2C24
- S. P. Hirshman and P. Merkel, "Free-Boundary Helias Stellarator Equilibria," paper 2B4
- J. T. Hogan, J. A. Holmes, and E. A. Lazarus, "Shape Optimisation of Low-Aspect Ratio Tokamaks," paper 3B9
- J. A. Holmes, B. A. Carreras, L. A. Charlton, V. E. Lynch, R. J. Hastie, and T. C. Hender, "Compressibility and Temperature Effects in Toroidal MHD"
- E. F. Jaeger, D. B. Batchelor, H. Weitzner, and P. L. Colestock, "Global ICRF Modeling in Large Non-Circular Tokamak Plasmas with Finite Temperature," paper 2C11
- F. Kazeminejad, R. Sydora, J. M. Dawson, J. N. Leboeuf, and F. Brunel, "A Hybrid Vlasov-Fluid Model of Kinetic Ions and Massless Fluid Electrons," paper 1D32
- J. N. Leboeuf, G. S. Lee, D. R. Thayer, and P. H. Diamond, "Ion Temperature Gradient Driven Drift Waves: Particle Simulation and Theory," paper 3B18
- G. S. Lee, B. A. Carreras, and P. H. Diamond, "Frequency Spectrum of Resistivity-Gradient-Driven Turbulence Due to Sheared Radial Electric Field," paper 3A5
- V. E. Lynch, J. S. Tolliver, K. C. Shaing, and B. A. Carreras, "Optimization of the Bootstrap Current in Stellarators," paper 2D18
- C. K. Phillips, P. L. Colestock, G. W. Hammett, D. G. Swanson, D. B. Batchelor, E. F. Jaeger, D. N. Smithe, and P. Bonoli, "ICRF Modelling Studies for TFTR," paper 2D4
- K. C. Shaing, "Transport Theory for Fluctuating Electric Fields in Toroidal Plasmas," paper 2D3
- D. A. Spong, D. J. Sigmar, and J. J. Ramos, "Stability Properties of Shaped Tokamaks with Energetic Alpha Populations," paper 2C23
- TIBER-NET Design Review and Exchange, Lawrence Livermore National Laboratory, Livermore, California, April 6-10, 1987**
- S. S. Kalsi, "Eddy-Current Losses in TIBER TF Coils"
- D. C. Lousteau, "Alternate Configuration"
- Y.-K. M. Peng, "U.S. TIBER/ETR Systems Analysis"
- S. L. Thomson, "TIBER-II Cost Models and Estimates"
- Fusion Power Associates Annual Meeting and Symposium--Applications of Laser, Particle Beam and RF Power Technologies, Pleasanton, California, April 8-9, 1987. Edited transcripts published in *J. Fusion Energy* 6 (1987).**
- H. H. Haselton, "Applications of Neutral Beam and RF Technologies," pp. 345-50
- J. P. Clarke, S. O. Dean, J. Sheffield, D. Meade, D. O. Overskei, and R. Linford, "Status of Magnetic Fusion," pp. 391-99
- ETR Design Review Meeting, Lawrence Livermore National Laboratory, Livermore, California, April 9-10, 1987**
- G. E. Gorker, "DT Fueling Systems"
- Y.-K. M. Peng, "Status and Results of Systems Code Development and Analysis"
- U.S.-Japan 1987 Exchanges and the Summit Nations TWP Meeting, Nagoya, Japan, April 10-15, 1987**
- J. F. Lyon, "World Stellarator Program"
- Spring Meeting of the American Physical Society, Crystal City, Virginia, April 20-23, 1987**
- B. A. Carreras, "Ideal and Resistive MHD Stability of Tokamak Plasmas"

ANS Topical Conference on Theory and Practices in Radiation Protection and Shielding, Knoxville, Tennessee, April 22-24, 1987. Proceedings published by the American Nuclear Society, 1987.

C. V. Parks, B. L. Broadhead, R. W. Roussin, J. C. Gauthey, S. N. Cramer, and B. L. Kirk, "Intercomparison of Cross-Section Libraries Used for Spent Fuel Cask Shielding Analysis," vol. 2, p. 559

E. C. Selcow, "One- and Two-Dimensional Radiation Analysis of the Compact Ignition Tokamak"

IRI Study Group 9A, Williamsburg, Virginia, April 22-24, 1987

Y-K. M. Peng, "The STX Experience in the Culture of U.S. Magnetic Fusion Energy R&D"

Fusion Power Associates Symposium on Fusion Energy Development: The International Effort, Washington, D.C., April 24-25, 1987. Edited transcripts published in *J. Fusion Energy* 6 (1987).

R. L. Hirsch, E. Storm, W. R. Ellis, T. K. Fowler, D. Keefe, M. McCormack, J. A. Schmidt, and J. Sheffield, "Prospects for Fusion Power: Panel Discussion," pp. 159-77

JET-U.S. Joint Working Meeting on Pellet Injection for JET, Abingdon, England, April 27-May 15, 1987

S. L. Milora, "JET Injector—ORNL Launcher"

S. L. Milora, "Review of Pellet Results Relevant to JET"

W. A. Houlberg, "JET Predictive Transport Modeling with Multiple Pellets"

ETR Systems Code Meeting, Fusion Engineering Design Center, Oak Ridge, Tennessee, April 29-30, 1987

G. E. Gerker, "Magnet Power Conversion Systems"

R. L. Reid, "Meeting Objectives"

CIT PF System Workshop, Princeton Plasma Physics Laboratory, Princeton, New Jersey, April 30, 1987

D. J. Strickler and R. O. Sayer, "External PF Coil Current Distributions for the $R = 1.75$ m CIT"

May

7th APS Topical Conference on Applications of Radio-Frequency Power to Plasmas, Kissimmee, Florida, May 4-6, 1987. Proceedings published as *Applications of Radio-Frequency Power to Plasmas*, S. Bernabei and R. W. Motley, eds., *AIP Conf. Proc.* 159 (1987).

F. W. Baity, "Modeling of Compact Loop Antennas"

D. B. Batchelor, E. F. Jaeger, and P. L. Colestock, "Ion Cyclotron Emission Calculations Using a 2D Full Wave Numerical Code"

W. R. Becraft, J. H. Whealton, H. H. Haselton, L. A. Berry, B. D. Murphy, P. M. Ryan, R. J. Raridon, and K. E. Rothe, "Central Production of ICRH in Dense Plasmas by Coherent Ionization of a Weakly Relativistic Gas"

G. L. Chen, P. M. Ryan, D. J. Hoffman, F. W. Baity, D. W. Swain, and J. H. Whealton, "Resonant Loop Antenna Design with a 2-D Steady-State Analysis," p. 382

W. L. Gardner, T. S. Bigelow, G. R. Haste, D. J. Hoffman, and R. L. Livesey, "ICRH Antenna Development on the ORNL RF Test Facility"

R. C. Goldfinger, S. E. Attenberger, J. S. Tolliver, D. B. Batchelor, and W. A. Houlberg, "Generation of Plasma Equilibria Using the RAYS Code Coupled to WIIIST"

R. C. Goldfinger and D. B. Batchelor, "Second Harmonic Electron Cyclotron Heating Calculations for the ATF Toratron"

D. J. Hoffman, F. W. Baity, W. E. Bryan, G. L. Chen, K. H. Luk, T. L. Owens, J. M. Ray, P. M. Ryan, D. W. Swain, and J. C. Walls, "The Design of High-Power ICRF Antennas for TFTR and Tore Supra," p. 302

E. F. Jaeger, D. B. Batchelor, H. Weitzner, and P. L. Colestock, "Global ICRH Modeling in Large Noncircular Tokamak Plasmas with Finite Temperature"

M. J. Mayberry, F. W. Baity, D. J. Hoffman, J. Luxon, T. L. Owens, and R. Prater, "Coupling of an ICRF Compact Loop Antenna to H-Mode Plasmas in DIII-D"

- T. L. Owens, G. L. Chen, G. R. Haste, and P. M. Ryan, "Tests of a High-Power Folded Waveguide Coupler for ICRF Heating"
- H. Weitzner, K. Imre, and D. B. Batchelor, "Wave Propagation at Ion Cyclotron Resonance in Large Toroids," p. 358
- J. H. Whealton, R. J. Raridon, K. E. Rothe, and P. M. Ryan, "Self-Consistent Multi-Dimensional Model of the Plasma Edge Near an ICRF Antenna— A Nonlinear Limit"
- First Meeting of the US-EC Fusion Bilateral Coordinating Committee, Brussels, Belgium, May 6-7, 1987**
- J. Sheffield, "The Ignition Physics Study Group Supports the Compact Ignition Tokamak and Engineering Test Reactor Programs"
- 34th International Technical Communication Conference, Denver, Colorado, May 10-13, 1987. Proceedings published by the Society for Technical Communication, Washington, D.C., May 1987.**
- M. B. Nestor, "The Eternal Triangle: Author, Editor, Reader," pp. WE-81 WF-82
- 5th Conference on Real-Time Computer Applications in Nuclear, Particle and Plasma Physics, San Francisco, California, May 12-15, 1987. Proceedings published in *IEEE Trans. Nucl. Sci.* NS-34 (1987).**
- L. R. Baylor, W. R. DeVan, and J. N. Sumner, "The ATF Status and Control System"
- J. D. Bell and V. K. Paré, "Upgrade of MHD Data Acquisition System from ISX-B to ATF"
- D. E. Greenwood, "SAMS—The Synchronization and Monitoring System for ATF Data Acquisition," p. 912
- K. L. Kannan and L. R. Baylor, "The ATF Data Management System," p. 921
- K. A. Stewart, L. R. Baylor, D. E. Greenwood, K. L. Kannan, D. R. Overby, W. R. Wing, J. N. Sumner, and W. R. DeVan, "The Data Acquisition and Control Systems for ATF: An Overview," p. 739
- IRI Advanced Study Group 7B, Overcoming Roadblocks to R&D Goals, Chicago, Illinois, May 13-15, 1987**
- O. B. Morgan, "Overcoming Matrix Organization Problems in R&D"
- ETR Technical Oversight Committee (ETOC) Meeting, Princeton, New Jersey, May 18, 1987**
- Y.-K. M. Peng, S. Thomson, L. Reid, J. Galambos, and L. Deleanu, "TIBER Cost and Design"
- Final MINIMARS Design Review Meeting, Toronto, Ontario, Canada, May 20-21, 1987**
- G. E. Gorker, "Fuel Pellet Injection System"
- G. E. Gorker, "Heat Transport System"
- G. E. Gorker, "Power Conversion System"
- 18th Annual Meeting of the Division of Atomic, Molecular, and Optical Physics, American Physical Society, Cambridge, Massachusetts, May 18-20, 1987. Abstracts published in *Bull. Am. Phys. Soc.* 32 (1987).**
- D. C. Griffin and M. S. Pindzola, "Double Auger Processes in Electron-Ion Scattering," p. 1274
- C. C. Havener, M. S. Huq, and R. A. Phaneuf, "Low-Energy Electron Capture Cross Sections for $O^5 + H$ and $N^5 + H$ Using Merged Beams," p. 1226
- P. W. Meyer, C. C. Havener, R. A. Phaneuf, J. K. Swenson, N. Stolterfoht, and S. M. Shafroth, "Electron Correlation Effects in Slow, Double-Electron Capture Collisions Involving Multicharged Ions," p. 1222
- L. J. Wang, K. Rinn, and D. C. Gregory, "Electron-Impact Ionization Cross Section Measurements for Ni^{5+} , Ni^{6+} , and Ni^{7+} ," p. 1273
- 1987 U.S./U.S.S.R. Exchange Agreement, Kharkov, USSR, May 25-June 9, 1987**
- M. D. Carter and D. B. Batchelor, "Effects of Fast Ion Sources on Lower Hybrid Current Drive"
- M. D. Carter, D. B. Batchelor, and A. C. England, "Second Harmonic Electron Cyclotron Breakdown in Stellarators"
- M. D. Carter, D. B. Batchelor, C. L. Hedrick, and G. L. Chen, "Effects of Transport and RF Heating on the Lowest Order Distribution Function"

June

- 1987 IEEE International Conference on Plasma Science, Arlington, Virginia, June 1-3, 1987.** Abstracts published by the Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1987.
- D. A. Rasmussen, "Application of Fusion-Related Electron Temperature and Density Diagnostics to Plasmas of Commercial Interest"
- Engineering Review Board Meeting, Princeton Plasma Physics Laboratory, Princeton, New Jersey, June 9, 1987**
- P. T. Spampinato, "Six Months R&D Review for WBS K"
- Cryogenic Engineering Conference, St. Charles, Illinois, June 14-18, 1987.** Proceedings published in *Adv. Cryog. Eng.* **33** (1987).
- L. Dresner, "Quench Detection by Fluid Dynamic Means in Cable-In-Conduit Superconductors," pp. 167-74
- J. W. Luc, W. A. Fietz, J. N. Luton, S. W. Schwenterly, R. E. Stamps, D. H. Thompson, C. T. Wilson, and T. Kato, "Operating Experience of the IFSMTF Vapor-Cooled Lead System," pp. 259-66
- S. W. Schwenterly, "Design and Testing of Electrical Insulation for Superconducting Coils," pp. 271-81
- S. W. Schwenterly, W. A. Fietz, and R. E. Stamps, "Operation of a Helium Refrigerator with Six Large Superconducting Coils in the IFSMTF"
- Workshop on Alpha Particle Effects in ETR, Washington, D.C., June 15-16, 1987.** Proceedings published in *Fusion Technol.* **13** (1988).
- D. A. Spong, D. J. Sigmar, and J. J. Ramos, "Modification of Tokamak Ballooning Stability Boundaries by Alpha Populations," p. 428
- N. A. Uckan, J. S. Tolliver, W. A. Houlberg, and S. E. Attenberger, "Influence of Fast Alpha Diffusion and Thermal Alpha Buildup on Tokamak Reactor Performance," p. 411
- TIBER II/ETR/ITER Review Meeting, Fusion Engineering Design Center, Oak Ridge, Tennessee, June 16-19, 1987**
- G. E. Gorker, "Fueling Systems"
- G. E. Gorker, "TF and PF Magnet Power Conversion"
- Y-K. M. Peng, "Systems Code, Cost Scaling Code, and Systems Analysis"
- JAERI-U.S. DOE Workshop on Fusion Blanket Neutronics, Tokai, Japan, June 16-19, 1987**
- R. T. Santoro, R. G. Alsmiller, Jr., J. M. Barnes, and T. A. Gabriel, "Monte Carlo Analysis of FNS Phase I Experiments"
- R. T. Santoro, R. G. Alsmiller, Jr., J. M. Barnes, and T. A. Gabriel, "Monte Carlo Analysis of the FNS Phase II Experiments"
- 14th European Conference on Controlled Fusion and Plasma Physics, Madrid, Spain, June 22-26, 1987.** Proceedings published as *Europhys. Conf. Abstr.* **11D**, Parts I and II (1987).
- S. A. Cohen, J. Ehrenberg, D. V. Bartlett, D. J. Campbell, A. D. Cheetham, L. de Kock, A. Gondhalekar, N. Gottardi, R. Granetz, W. Houlberg, H. Jaekel, E. Lazzaro, P. Morgan, J. O'Rourke, M. Pick, M. P. Stamp, D. D. R. Summers, E. van der Goot, M. Watkins, and A. Weller, "Edge Dynamics in Pellet-Fuelled Inner-Wall JET Discharges," Part II, p. 694 (1987)
- D. J. Hoffman, F. W. Baity, M. J. Mayberry, and D. W. Swain, "ICRF Coupling on DIII-D and the Implications on ICRF Technology Development"
- J. P. Lyon, B. A. Carreras, T. C. Jernigan, R. L. Johnson, M. Murakami, and G. H. Neilson, "Status of the ATF Torsatron Program"
- J. P. Lyon, B. A. Carreras, S. L. Painter, J. S. Tolliver, and I. N. Sviatoslavsky, "Low-Aspect-Ratio Torsatron Reactor and ATF-II Studies"
- D. H. McNeill, G. J. Greene, J. D. Newburger, D. K. Owens, G. L. Schmidt, and D. D. Schuresko, "Measurement of Plasma Parameters in the Luminous Regions of Pellets Injected into Tokamaks"

- S. L. Milora, S. K. Combs, C. A. Foster, D. D. Schuresko, M. J. Gouge, P. W. Fisher, C. R. Foust, F. E. Gethers, H. H. Haselton, D. W. Simmons, and J. C. Whitson, "Pellet Injector Research at ORNL"
- R. Parker, D. Post, G. Bateman, M. Bell, P. Colestock, J. Helton, W. Houlberg, M. Hughes, D. Ignat, S. Jardin, J. Johnson, S. Kaye, C. Kieras-Phillips, L-P. Ku, G. Kuo-Petravic, B. Lipschultz, J. Manickam, M. Peng, M. Petravic, M. Phillips, M. Porkolab, N. Pomphrey, J. Ramos, J. Schmidt, D. Sigmar, R. Stambaugh, D. Stotler, D. Strickler, A. Todd, N. Uckan, J. Wesley, and K. Young, "Physics Considerations for the Compact Ignition Tokamak," Part I, p. 301
- D. D. Schuresko, S. L. Milora, S. K. Combs, C. A. Foster, P. W. Fisher, R. E. Argo, G. C. Barber, C. R. Foust, F. E. Gethers, M. J. Gouge, H. H. Haselton, J. E. Moeller, N. S. Ponte, D. W. Simmons, and J. H. Whitson, "Pellet Injector Research at ORNL," Part I, p. 327
- D. W. Swain, F. W. Baity, W. E. Bryan, D. J. Hoffman, T. L. Owens, and J. J. Yugo, "Technology Development of Antennas for Ion Cyclotron Heating Experiments in Fusion Devices"
- M. L. Watkins, W. A. Houlberg, A. D. Cheetham, A. Gondhalekar, R. Granetz, F. Hendriks, J. O'Rourke, and P. N. Stubberfield, "A Model for Pellet Ablation in JET," Part I, p. 201
- INTOR Review Meeting, Georgia Institute of Technology, Atlanta, Georgia, June 25-26, 1987**
- Y-K. M. Peng, "Homework Tasks for Group B: Operational Limits and Confinement"
- P. T. Spampinato, "Critical Issue E Has Concluded Its Activities for Configuration and Maintenance Issues for Phase Two A, Part 3"

July

- INTOR Workshop, Phase Two A, Part 3, Session XV, Vienna, Austria, July 13-24, 1987**
- C. A. Flanagan, "Summary of U.S. Contributions to INTOR Workshop: Analysis of INTOR-Like Designs"
- P. T. Spampinato, "Chapter VII, Section 2. Vertical and Horizontal Access Configurations"
- P. T. Spampinato, "Interim Report for Critical Issue E—Configuration and Maintenance"
- IAEA Technical Committee Meeting on Negative Ion Sources, Culham, England, July 15-17, 1987**
- J. H. Whealton, W. R. Becraft, B. D. Murphy, and H. H. Haselton, "A 3 MeV Neutral Beam System for Current Drive"
- J. H. Whealton, H. H. Haselton, W. R. Becraft, B. D. Murphy, P. M. Ryan, M. A. Akerman, and G. E. McMichael, "High Energy (2 MeV) Neutral Beam Systems for Current Drive in Tokamak Reactors"
- J. H. Whealton, K. E. Rothe, P. S. Meszaros, and R. J. Raridon, "Validated Negative Ion Source Modeling"
- 15th International Conference on the Physics of Electronic and Atomic Collisions (ICPEAC), Brighton, England, July 22-28, 1987**
- F. W. Meyer, D. C. Griffin, C. C. Havener, M. S. Huq, R. A. Phaneuf, J. K. Swenson, and N. Stolterfoht, "Correlation Effects on Double Electron Capture in Highly-Charged, Low-Energy Ion-Atomic Collisions" (invited paper)
- Conference on Atomic Collisions in Fusion, Oxford, England, July 30 August 1, 1987**
- R. C. Isler, "Diagnostic Experiments Involving Charge Exchange in Fusion Research"

August

- 45th Annual Meeting of the Electron Microscopy Society of America, Baltimore, August 2-7, 1987.** Proceedings published by San Francisco Press, San Francisco, 1987, G. W. Bailey, ed.
- D. N. Braski, "Doping of Vanadium Alloys with Helium Using Tritium," pp. 218-9

Sixth International Conference on Mathematical Modelling, Washington University, St. Louis, Missouri, August 4-7, 1987

- L. Dresner, "Similarity Solutions of Nonlinear Partial Differential Equations Invariant to a Family of Affine Groups"

Tenth International Conference on Structural Mechanics in Reactor Technology (SMiRT 10), Lausanne, Switzerland, August 17-21, 1987. Transactions published as *Mechanical and Thermal Problems of Fusion Reactors*, F. H. Witmann, ed., North-Holland, Amsterdam, 1987.

- M. S. Lubell, J. W. Luc, T. J. McManamy, J. N. Luton, and S. S. Shen, "A Review of the Structural Aspects of the Large Coil Task," pp. 41-53

TIBER/ETR Meeting, Lawrence Livermore National Laboratory, Livermore, California, August 19, 1987

- R. L. Reid, "Systems Code Status"

Fusion Power Associates Meeting and Symposium on Fusion Energy Development: Breakeven and Beyond, Princeton Plasma Physics Laboratory, Princeton, New Jersey, August 27-28, 1987

- J. Sheffield, "The Role of Stellarators in the Advanced Toroidal Program"

U.S./U.S.S.R. Fusion Materials Workshop, Oak Ridge, Tennessee, August 31 September 4, 1987

- D. N. Braski, "The Effect of Neutron Irradiation on the Tensile Properties and Microstructure of Several Vanadium Alloys"

- B. A. Chin, H. T. Lin, M. L. Grossbeck, and S. H. Goods, "Welding of Helium-Doped Type 316 Stainless Steel"

- M. L. Grossbeck, "Irradiation Creep in the U.S. Fusion Alloy PCA at Fusion He/dpa Levels"

- R. I. Klueh, "Manganese-Stabilized Austenitic Stainless Steels for Fusion Applications"

- P. J. Maziasz and R. L. Klueh, "Swelling Behavior of Ferritic/Martensitic Steels"

- A. F. Rowcliffe, "Overview of ORNL Program"

September

CIT PF Design Meeting, Princeton Plasma Physics Laboratory, Princeton, New Jersey, September 15, 1987

- R. O. Sayer, "Calculation of Radial and Vertical Forces on the CIT 1.75 m Vacuum Vessel for Several TSC Disruption Scenarios"

- D. J. Strickier, "Poloidal Magnetics Studies on Swept Divertor and Internal Coil Issues"

Joint Workshop on Electron Cyclotron Emissions and Electron Cyclotron Resonance Heating (EC-6), Oxford, England, September 16-18, 1987

- T. L. White, T. S. Bigelow, and H. D. Kimrey, "Initial High-Power Testing of the ATF ECH System"

ICCS Workshop, Boston, Massachusetts, September 17-18, 1987

- L. Dresner, D. T. Fehling, M. S. Lubell, J. W. Luc, J. N. Luton, T. J. McManamy, S. S. Shen, and C. T. Wilson, "Stability Tests of the Westinghouse Coil in the International Fusion Superconducting Magnet Test Facility (IFSMTF)"

12th Conference on the Numerical Simulation of Plasmas, San Francisco, September 20-24, 1987

- R. C. Goldfinger and D. B. Batchelor, "Ray Tracing in ATF Using 3-D Splines"

- J. A. Holmes, L. A. Charlton, B. A. Carreras, and V. E. Lynch, "Fully Implicit Three-Dimensional MHD Stability and Evolution in Toroidal Geometry"

- V. E. Lynch, B. A. Carreras, J. B. Drake, H. R. Hicks, and W. F. Lawkins, "Implementation of a 3-D Nonlinear MHD Calculation on the Intel Hypercube"

- P. M. Lyster and J. N. Leboeuf, "A Fluid-Particle Simulation Model for Plasma Instabilities"

- J. Schutkeker, T. Tajima, W. Horton, T. Kamimura, D. Barnes, and J. Leboeuf, "Simulation of the Kelvin-Helmholtz Instability with Electrostatic Implicit Particle Code"

Ignition Physics Study Group Meeting, San Diego, California, September 21, 1987

R. A. Dory, M. S. Chu, J. Greene, J. Helton, J. K. Lee, R. Stambaugh, A. Turnbull, M. Phillips, A. Todd, F. Troyon, W. A. Cooper, B. A. Carreras, J. Hogan, J. Ramos, D. Sigmar, M. Chance, S. Jardin, J. Manickam, and P. Rutherford, "Ignition Physics Study Group Subcommittee for MHD Theory—Status Report"

M. Greenwald and J. Sheffield, "Density Limits and Fueling—Data Base Assessment 1985–1987"

J. Sheffield, "The Ignition Physics Study Group Supports the Compact Ignition Tokamak and Engineering Test Reactor Programs"

Tenth International Conference on Magnet Technology (MT-10), Boston, Massachusetts, September 21–25, 1987. Proceedings to be published in *IEEE Transactions on Magnetics*.

L. Dresner, D. T. Fehling, M. S. Lubell, J. W. Lue, J. N. Luton, T. J. McManamy, S. S. Shen, and C. T. Wilson, "Stability Tests of the Westinghouse Coil in the International Fusion Superconducting Magnet Test Facility (IFSMTF)"

G. Friesinger, S. Gauss, P. Komarek, M. S. Lubell, T. J. McManamy, W. Maurer, S. S. Shen, L. Siewerdt, A. Ulbricht, F. Wuchner, and G. Zahn, "Testing of the Euratom LCT Coil in the Toroidal Arrangement of the International Fusion Superconducting Magnet Test Facility Without External Pulsed Fields (Standard I) and With Them (Standard II) and an Extended Single-Coil Test"

M. S. Lubell, J. A. Clinard, L. Dresner, W. A. Fietz, W. M. Fletcher, P. N. Haubenreich, J. W. Lue, J. N. Luton, T. J. McManamy, S. W. Schwenterly, S. S. Shen, R. E. Stamps, C. T. Wilson, R. E. Wintenberg, R. J. Wood, A. Ulbricht, G. M. Friesinger, F. Wuechner, K. Okuno, T. Kato, F. Iida, Y. Takahashi, H. Tsuji, T. Hiyama, J. A. Zichy, and B. Jakob, "The IEA-Large Coil Task Test Results in IFSMTF"

K. Okuno, T. Kato, Y. Takahashi, F. Iida, H. Tsuji, T. Hiyama, S. Shimamoto, S. S. Shen, J. W. Lue, and M. S. Lubell, "Experimental Results on the Japanese LCT Coil in IFSMTF: Pulsed Field Tests and Extended-Condition Tests"

S. S. Shen, L. Dresner, M. S. Lubell, J. W. Lue, J. N. Luton, T. J. McManamy, C. T. Wilson, and R. E. Wintenberg, "Test Results of the U.S.-LCT Pool-Boiling Coils in the International Fusion Superconducting Magnet Test Facility (IFSMTF)"

Committee on Magnetic Fusion in Energy Policy, National Research Council, National Academy of Sciences, Washington, D.C., September 24, 1987

J. Sheffield, "Economics of Fusion Reactors"

U.S.-Japan Workshop on Plasma Modeling with MHD and Particle Simulation, Napa, California, September 25–26, 1987

P. M. Lyster and J. N. Leboeuf, "A New Fluid-Particle Simulation Model for Plasma Instabilities"

6th Topical Conference on Atomic Processes in Plasmas, Santa Fe, New Mexico, September 28–October 2, 1987

R. C. Isler and R. E. Olson, "Charge Transfer from Excited Hydrogen Atoms to C^{6+} and O^{6+} "

October

European Liquid Metal Workshop, Fontenay-aux-Roses, France, October 1–2, 1987

P. P. Tortorelli, "Microstructural Influences on the Corrosion of Austenitic Stainless Steel by Pb-17 at. % Li"

P. P. Tortorelli, G. E. Bell, and E. J. Lawrence, "Effectiveness of Filtering, Cold Trapping, and Hot Gettering for Lithium Purification"

Third International Conference on Fusion Reactor Materials (ICFRM-3), Karlsruhe, Federal Republic of Germany, October 4–8, 1987. Proceedings to be published in *J. Nucl. Mater.*

M. L. Grossbeck and J. A. Horak, "Irradiation Creep in Type 316 Stainless Steel and U.S. PCA with Fusion Reactor He:dpa Levels"

S. Hamada, P. J. Maziasz, M. P. Tanaka, M. Suzuki, and A. Hishinuma, "Temperature Dependence of Swelling in Type 316 Stainless Steel Irradiated in HFIR"

- R. L. Klueh and P. J. Maziasz, "Reduced-Activation Ferritic Steels: A Comparison with Cr-Mo Steels"
- R. L. Klueh, J. M. Vitek, and W. R. Corwin, "Impact Properties of 9 Cr and 12 Cr Steels After Low-Temperature Irradiation"
- A. W. Longest, J. E. Corum, and K. R. Thoms, "Design of Spectral-Tailored Fusion Reactor Materials Experiments in the HFIR RB* Capsule Irradiation Facility"
- L. K. Mansur and M. L. Grossbeck, "Mechanical Property Changes Induced in Structural Alloys by Neutron Irradiations with Different Helium to Displacement Ratios"
- P. J. Maziasz and R. L. Klueh, "Void Formation and Helium Effects in 9Cr-1Mo-VNb and 12Cr-1Mo-VW Steels Irradiated in FFTF and HFIR at 400°C"
- A. F. Rowcliffe, P. J. Maziasz, M. L. Grossbeck, and M. P. Tanaka, "Spectrally and Isotopically Tailored Experiments to Control Helium Generation in Austenitic Stainless Steels"
- R. E. Stoller, P. J. Maziasz, A. F. Rowcliffe, and M. P. Tanaka, "Swelling Behavior of Austenitic Stainless Steels in a Spectrally Tailored Reactor Experiment: Implications for Near-Term Fusion Machines"
- M. P. Tanaka, S. Hamada, A. Hishinuma, and P. J. Maziasz, "Microstructural Development of Austenitic Steels Irradiated in HFIR"
- M. P. Tanaka, S. Hamada, A. Hishinuma, and M. L. Grossbeck, "Postirradiation Tensile and Fatigue Behaviors of Austenitic PCA Stainless Steels Irradiated in HFIR"
- K. R. Thoms, G. R. Hicks, B. H. Montgomery, I. I. Siman-Tov, and C. D. West, "HFIR Irradiation Facilities Improvements - An Update on the HIFI Project"
- P. F. Tortorelli, "Corrosion of Ferritic Steels by Molten Lithium: Influence of Competing Thermal Gradient Mass Transfer and Surface Product Reactions"
- S. J. Zinkle, "Surviving Defect Fraction in 14-MeV Neutron-Irradiated Copper"
- S. J. Zinkle and R. L. Sindelar, "Defect Microstructures in fcc Metals Irradiated near Room Temperature"
- ICRF/Edge Physics Workshop, Oak Ridge, Tennessee, October 6-7, 1987**
- D. B. Batchelor, "ICRF/EDGE Workshop Overview and Summary"
- M. D. Carter, "Electrostatic Effects on Electrons Near ICRH Antennas"
- J. T. Hogan, "Modeling Considerations for Selected RF-Plasma Edge Effects"
- J. H. Whealton, P. M. Ryan, and R. J. Raridon, "Nonlinear Multidimensional Collisionless Plasma Sheath Dynamics"
- IEEE 12th Symposium on Fusion Engineering, Monterey, California, October 12-16, 1987. Proceedings published by the Institute of Electrical and Electronics Engineers, Piscataway, N.J., 1987.**
- W. R. Becraft, J. H. Whealton, M. A. Akerman, G. E. McMichael, B. D. Murphy, P. M. Ryan, H. H. Hazelton, and W. L. Stirling, "Plasma Current Drive With 1- to 3-MeV Neutral Beams: An Efficient, Reactor-Relevant Approach"
- A. Y. Brovman and L. E. Nickels, "Optimum Power Supplies for a Pulsed Power System"
- T. G. Brown, "The Configuration Development of the Compact Ignition Tokamak Device"
- W. E. Bryan, F. W. Baily, D. J. Hoffman, and J. M. Ray, "ORNL Compact Loop Antenna Design for TFTR and Tore Supra"
- K. K. Chipley and G. N. Frey, "Fabrication and Installation of the Vacuum Vessel for the Advanced Toroidal Facility"
- M. J. Cole, J. W. Whitson, and B. J. Banks, "Fabrication of the Helical Field Coil Components for the Advanced Toroidal Facility"
- C. A. Flanagan, J. D. Galambos, and Y-K. M. Peng, "Comparative Analysis of Next-Generation INTOR-Like Designs"
- J. D. Galambos, D. J. Strickler, and Y-K. M. Peng, "Systems Code Comparison of Internal and External PF Coil CITs"
- G. E. Gorker, J. R. Haines, and W. D. Nelson, "Fueling System Design for the TIBER II ETR Reactor"
- C. L. Hahn, T. Uckan, P. K. Mioduszewski, and P. H. Edmonds, "Advanced Toroidal Facility Graphite Rail Limiter"

- J. R. Haines, "Design of a Tritium-Compatible Vacuum Pumping System for the Compact Ignition Tokamak"
- C. J. Hammonds and J. A. Mayhall, "Advanced Toroidal Facility Vacuum Vessel Stress Analysis"
- P. N. Haubenreich, P. Komarek, S. Shimamoto, and G. Vecsey, "Productive International Collaboration in the Large Coil Task"
- S. S. Kalsi, D. C. Lousteau, and J. R. Miller, "Design Considerations for ITER Toroidal Field Coils"
- V. D. Lee, "Configuration Development of a Hydraulic Press for Preloading the Toroidal Field Coils of the Compact Ignition Tokamak"
- J. W. Lue, L. Dresner, D. T. Fehling, M. S. Lubell, J. N. Luton, T. J. McManamy, S. S. Shen, C. T. Wilson, and R. E. Wintenberg, "Hot-Spot Measurements on the U.S.-LCT Coils in the IFSMTF"
- T. J. McManamy, R. D. Benson, R. L. Brown, G. H. Henkel, E. A. Lazarus, and D. E. Williamson, "Design and Fabrication of a Prototype Solenoid for the Spherical Torus Experiment," Vol. 1, pp. 350-52
- M. M. Menon, P. H. Edmonds, and C. L. Hahs, "A Calorimeter for Measuring the Neutral Beam Power Reaching the Plasma," pp. 1119-21
- S. L. Milora, S. K. Combs, L. R. Baylor, C. R. Foust, F. E. Gethers, and D. O. Sparks, "Design of a Repeating Pneumatic Injector for the Joint European Torus"
- B. E. Nelson for the ATF Team, "Final Assembly of the Advanced Toroidal Facility"
- Y-K. M. Peng, J. D. Galambos, R. L. Reid, D. J. Strickler, S. Kalsi, and L. Deleanu, "Initial Results of Systems Analysis of the ETR/ITER Design Space"
- D. Post, R. Parker, G. Bateman, M. Bell, P. Colestock, L. Grisham, J. Helton, W. A. Houlberg, M. Hughes, J. Johnson, B. Lipschultz, J. Manickam, A. Miller, C. Phillips, M. Phillips, N. Pomphrey, M. Porkolab, J. Ramos, D. Ross, D. Sigmar, D. Stotler, D. Strickler, R. Stambaugh, A. Todd, N. Uckan, and J. Wesley, "The Physics Aspects of the CIT Design"
- W. H. Power, F. W. Baity, and D. J. Hoffman, "Capacitor Analysis for RF Antennas"
- R. L. Reid and J. D. Galambos, "Architecture of the ETR Systems Code"
- S. L. Salem, M. Y. Lee, and G. Listvinsky, "Electromagnetic Loads and Structural Response of the CIT Vacuum Vessel to Plasma Disruptions"
- D. E. Schechter, F. Sluss, and D. J. Hoffman, "Brazing of Ceramic and Graphite to Metal in the Fabrication of ICRF Antenna and Feedthrough Components"
- E. C. Selcow, P. N. Stevens, I. C. Gomes, and L. M. Gomes, "Radiation Analysis of the CIT Pellet Injector System and Its Impact on Personnel Access"
- T. E. Shannon, "The Compact Ignition Tokamak: Project Overview"
- S. S. Shen, L. R. Baylor, L. Dresner, D. T. Fehling, M. S. Lubell, J. W. Lue, J. N. Luton, T. J. McManamy, C. T. Wilson, R. E. Wintenberg, R. J. Wood, A. R. Ulbricht, F. Wuechner, G. M. Friesinger, K. Okuno, T. Kato, Y. Takahashi, F. Iida, J. A. Zichy, and B. Jakob, "Measurements of Electromagnetic Properties of LCT Coils in IFSMTF"
- W. D. Shipley, R. R. Kindsfater, and D. A. Rasmussen, "Mechanical Design Aspects of the Advanced Toroidal Facility Thomson Scattering Diagnostic"
- P. T. Spampinato and D. Macdonald, "Ex-Vessel Remote Maintenance Design for the Compact Ignition Tokamak"
- D. J. Strickler, Y-K. M. Peng, R. O. Sayer, S. C. Jardin, and A. M. Rotolante, "Poloidal Magnetics and Divertor Strike Point Control in the Compact Ignition Tokamak," Vol. 2, p. 1424
- D. J. Taylor, F. W. Baity, W. E. Bryan, D. J. Hoffman, R. L. McIlwain, and J. M. Ray, "ORNL Compact Loop Antenna Design for TFTR and Tore Supra"
- S. L. Thomson and J. D. Blevins, "Facilities Design for TIBER-II"
- C. C. Tsai, W. L. Stirling, M. A. Akerman, W. K. Dagenhart, H. H. Haselton, P. M. Ryan, D. E. Schechter, J. H. Whealton, and W. R. Beecraft, "Design Considerations for a Negative Ion Source for DC Operation of High-Power, Multi-Megaelectron-Volt Neutral Beams"
- N. A. Uckan, "Synchrotron Radiation Losses in ETRs," Vol. 2, pp. 1394-97

- N. A. Uckan, W. A. Houlberg, S. E. Attenberger, R. A. Dory, D. A. Spong, J. S. Tolliver, and J. Sheffield, "Physics Analysis of the TBER-II Engineering Test Reactor," Vol. 2, pp. 1428-33
- N. A. Uckan and H. C. Howe, "Transport Simulations of Ohmic Ignition Experiment IGNITEX," Vol. 2, pp. 1398-1401
- T. Uckan, C. C. Klepper, and P. K. Mioduszewski, "Design Considerations of Modular Pump Limiter Systems for Large Tokamaks"
- J. J. Weede and G. Listvinsky, "Thermal Aspects of the CIT Divertor and First Wall"
- J. J. Yugo, P. L. Goranson, D. W. Swain, F. W. Baity, and R. Vesey, "Design of an Ion Cyclotron Resonance Heating System for the Compact Ignition Tokamak"
- 40th Annual Gaseous Electronics Conference, Atlanta, Georgia, October 13-16, 1987.** Abstracts published in *Bull. Am. Phys. Soc.* **32** (1987).
- C. Bottcher, D. C. Griffin, and M. S. Pindzola, "Ionization in Collisions Between Electrons and Complex Ions" (invited paper), p. 141
- R. A. Phaneuf, "Measurement of Electron-Impact Ionization Cross Sections for Ions," p. 153
- International Conference on Materials for Nuclear Reactor Core Applications, Bristol, England, October 27-29, 1987**
- P. J. Maziasz, "Radiation-Induced Phase Formation and Stability in Neutron-Irradiated Steels"
- Third International Symposium on Laser-Aided Plasma Diagnostics, Los Angeles, California, October 28-30, 1987**
- C. H. Ma and D. P. Hutchinson, "Feasibility Study of an Infrared Interferometer/Polarimeter System for CIT" (invited paper)

November

- 34th National Symposium and Topical Conference of the American Vacuum Society, Anaheim, California, November 2-5, 1987.** Proceedings published in *J. Vac. Sci. Technol. A* **6** (3), Parts I and II (1988).
- C. E. Bush, J. Schivell, D. H. McNeill, S. S. Medley, H. W. Hendel, R. A. Hulse, A. T. Ramsey, B. C. Stratton, H. F. Dylla, B. Grek, D. W. Johnson, G. Taylor, M. Ulrickson, and R. M. Wieland, "Characteristics of Radiated Power for Various Tokamak Fusion Test Reactor Regimes," p. 2004
- R. E. Clausing, R. Causey, W. Hsu, L. Heatherly, R. A. Langley, P. K. Mioduszewski, and J. E. Simpkins, "The 'Retention' of Hydrogen in Graphite During Plasma Experiments"
- R. E. Clausing and L. Heatherly, "Hydrogen Recycle from Graphite"
- S. K. Combs, S. L. Milora, L. R. Baylor, C. R. Foust, F. E. Gethers, and D. O. Sparks, "A Three-Barrel Repeating Pneumatic Pellet Injector for Plasma Fueling of the Joint European Torus," p. 1901
- P. W. Fisher, S. K. Combs, C. A. Foster, C. R. Foust, M. J. Gouge, S. L. Milora, and D. D. Schuresko, "Tritium Pellet Fueling for Fusion Reactors"
- C. A. Foster, D. E. Schechter, and P. M. Ryan, "Electron Beam Rocket Pellet Accelerator"
- C. A. Foster, C. W. Sohns, and D. W. Simmons, "Variable Mass Pellet Feed Device for Centrifuge Injector"
- L. Heatherly and R. E. Clausing, "Formation and Removal of Diamond-Like Hard Carbon Films Using Glow Discharge and Microwave Plasmas"
- R. A. Langley, "Helium-Ion-Induced Release of Hydrogen from Graphite," p. 2119
- R. A. Langley, G. H. Neilson, A. M. Alhan, E. Slaughter, J. N. Sumner, and J. A. White, "Vacuum Vessel Heating System for the Advanced Toroidal Facility," p. 1288
- R. L. Livesey, T. S. Bigelow, W. L. Gardner, D. J. Hoffman, and T. L. Owens, "RF Vacuum Breakdown"
- P. K. Mioduszewski, J. E. Simpkins, and T. Uckan, "Summary Abstract: Plasma-Induced Residual Gas Transients," p. 2008
- J. E. Simpkins, P. K. Mioduszewski, and R. A. Strehlow, "Outgassing Properties of Various Graphites"

29th Annual Meeting of the American Physical Society Division of Plasma Physics, San Diego, November 2-6, 1987. Abstracts published in *Bull. Am. Phys. Soc.* 32 (1987).

- S. C. Aceto, A. Carnevali, K. A. Connor, J. F. Lewis, J. C. Glowienka, and W. D. Shipley, "The ATF Heavy Ion Beam Probe," p. 1916
- V. Arunasalam, P. C. Efthimion, E. Fredrickson, R. J. Goldston, K. McGuire, G. Taylor, J. Wilgen, and F. J. Stauffer, "On the Self-Consistency of the Principle of Profile Consistency Results for Sawtooth Tokamak Discharges," p. 1806
- S. E. Attenberger, N. A. Uckan, W. A. Houlberg, and J. S. Tolliver, "Plasma Performance Analysis of Current-Driven Tokamak Reactors," p. 1760
- F. W. Baity, W. E. Bryan, D. J. Hoffman, and J. M. Ray, "The Design of a High-Power, Long-Pulse Antenna for Tore Supra," p. 1552
- C. O. Beasley and C. L. Hedrick, "Comparison of Analytic and Numerical Transport Coefficients in the $1/\nu$ Regime for Stellarators and Torsatrons," p. 1836
- J. D. Bell, V. K. Paré, and J. H. Harris, "MHD Data Acquisition System for ATF," p. 1915
- C. A. Bennett, D. P. Hutchinson, and R. K. Richards, "Selective Absorption of CO_2 Laser Radiation Using Hot CO_2 ," p. 1870
- B. D. Blackwell, B. A. Carreras, L. E. Sharp, X-H. Shi, and N. Takeuchi, "The Helic Configuration: Magnetic Design and Experiment," p. 1835
- R. Budny, M. Bell, C. Bush, E. Fredrickson, R. Goldston, H. Hsuan, K. McGuire, W. Morris, H. Park, A. Ramsey, J. Schivell, S. Scott, and G. Taylor, "q-Transitions in TFTR," p. 1741
- C. E. Bush, J. D. Strachan, J. Schivell, S. S. Medley, G. Taylor, H. H. Towner, R. M. Wieland, M. G. Bell, P. C. Efthimion, B. Grek, D. W. Johnson, D. K. Mansfield, D. H. McNeill, W. Morris, D. Mueller, H. Park, and S. Yoshikawa, "Confinement, Scaling, and Dynamics of Neutral Beam Heated Detached Plasmas on TFTR," p. 1927
- M. D. Carter, D. B. Batchelor, and E. F. Jaeger, "Fokker-Planck Calculations of Ion Bernstein Wave Absorption," p. 1949
- J. R. Cary and C. L. Hedrick, "Corrections to the Stellarator Particle Invariants," p. 1836
- A. Cavallo, G. Taylor, P. C. Efthimion, and J. Wilgen, "Central Electron Power Deposition from Slope of Sawtooth Measurements Using the TFTR Twenty Channel Grating Polychromator," p. 1804
- L. A. Charlton, B. A. Carreras, J. A. Holmes, and V. E. Lynch, "The Effects of Compressibility on Full Nonlinear Resistive MHD Tokamak Calculations in Toroidal Geometry," p. 1774
- R. J. Colchin, F. S. B. Anderson, C. C. Eberle, A. C. England, J. H. Harris, D. K. Lee, and D. L. Million, "Magnetic Field Verification in ATF," p. 1880
- S. K. Combs, S. L. Milora, C. R. Foust, and F. E. Gethers, "Repeating Three-Barrel Pellet Injector for the Joint European Torus (JET)," p. 1840
- W. K. Dagenhart, W. L. Stirling, M. J. Gouge, C. C. Tsai, and J. H. Whealton, "A Light Mass Alpha Particle Diagnostic Neutral Beam Line," p. 1870
- N. Dominguez, B. A. Carreras, and V. E. Lynch, "3-D Stability of Low- n MHD Modes," p. 1915
- R. A. Dory, B. A. Carreras, V. E. Lynch, J. P. Lyon, and J. Sheffield, "Systematics of Stellarator Reactor Designs Based on the Torsatron Coils," p. 1916
- R. A. Dory, H. C. Howe, J. A. Rome, K. C. Shaing, and N. A. Uckan, "Current Drive by Opposing Energetic Neutral Beams," p. 1956
- P. C. Efthimion, D. W. Johnson, N. L. Bretz, M. Bitter, C. E. Bush, B. Grek, K. W. Hill, R. J. Goldston, R. J. Fonck, H. Park, A. T. Ramsey, B. C. Stratton, F. J. Stauffer, G. Taylor, and R. M. Wieland, "Recent Confinement Studies of Ohmically-Heated Helium Plasmas," p. 1809
- A. C. England, J. H. Harris, T. C. Jernigan, R. N. Morris, M. Murakami, G. H. Neilson, D. A. Rasmussen, J. A. Rome, M. J. Saltmarsh, O. Motojima, H. Okada, and K. Uo, "Runaway Suppression and Monitoring in Torsatrons," p. 1880
- R. H. Fowler, J. A. Rome, R. N. Morris, and K. Hanatani, "Benchmarks of Neutral Beam Injection Codes for Stellarators," p. 1835

- R. F. Gandy, G. J. Hartwell, M. A. Henderson, J. D. Hanson, D. G. Swanson, C. J. Bush, R. J. Colchin, A. C. England, and D. K. Lee, "Magnetic Surface Mapping with Phosphor-Coated Screens on the Auburn Torsatron," p. 1834
- W. L. Gardner, T. S. Bigelow, G. R. Haste, D. J. Hoffman, R. L. Livesey, and P. M. Ryan, "ICH Development Activities on the ORNL RF Test Facility," p. 1952
- R. C. Goldfinger and D. B. Batchelor, "Modeling of Ion Bernstein Wave Propagation in ATF," p. 1914
- A. Gondhalekar, A. Cheetham, S. A. Cohen, W. Houlberg, T. T. C. Jones, P. D. Morgan, J. O'Rourke, K. Sonnenberg, and M. Watkins, "Control of Density Profile and Particle Exhaust in JET," p. 1838
- R. P. Gormley, P. N. Stevens, R. R. Kindsfater, D. A. Rasmussen, M. Murakami, S. L. Painter, P. S. Hays, T. L. Clark, and C. E. Thomas, "Spectral Calibration of the Thomson Scattering System," p. 1916
- M. J. Gouge, W. A. Houlberg, S. L. Milora, and D. D. Schuresko, "A Comparison of Hydrogenic Pellet Ablation Models with Experiment," p. 1840
- G. W. Hammett, P. L. Colestock, W. A. Houlberg, and C. K. Phillips, "ICRF Modeling for CIT and TFTR," p. 1922
- J. H. Han, J. N. Leboeuf, and P. H. Diamond, "Particle Simulation of Low Frequency Fluctuations in Finite Beta Plasmas," p. 1889
- J. H. Harris, G. H. Neilson, D. K. Lee, S. P. Hirshman, H. C. Howe, and R. N. Morris, "Magnetic Configuration Control in the Advanced Toroidal Facility," p. 1879
- C. L. Hedrick, J. S. Tolliver, and J. R. Cary, "Comparison of Analytic and Full Guiding Center Behavior at a Trapped-Passing Interface in Stellarators," p. 1836
- S. Hiroe, M. Murakami, P. C. Efthimion, R. Goldston, B. Grek, D. W. Johnson, H. Towner, R. Yoshino, M. Zarnstorff, and the TFTR Group, "Scale Length Study in TFTR," p. 1806
- D. J. Hoffman, T. S. Bigelow, W. E. Bryan, W. L. Gardner, J. M. Ray, P. M. Ryan, and D. J. Taylor, "Tests and Design of the ORNL Antenna for TFTR," p. 1952
- J. T. Hogan and C. C. Klepper, "Particle Deposition Effects on τ_p Scaling," p. 1944
- J. A. Holmes, B. A. Carreras, L. A. Charlton, and V. E. Lynch, "MHD Stability and Evolution for Very Low Shear and Hollow Safety Factor Profiles in Toroidal Geometry," p. 1772
- W. A. Houlberg, S. E. Attenberger, and S. L. Milora, "Pellet Ablation by Fast Hydrogen Ions and Alphas," p. 1760
- H. T. Hunter, D. P. Hutchinson, and R. K. Richards, "A High Power Pulsed CO₂ Laser Source for Alpha Particle Measurement by Thomson Scattering," p. 1870
- D. P. Hutchinson, W. H. Casson, and C. H. Ma, "A Multichannel Far-Infrared Interferometer on ATF," p. 1916
- K. Imre, D. C. Stevens, H. Weitzner, and D. B. Batchelor, "ICRH in Large Tokamaks," p. 1949
- E. F. Jaeger, D. B. Batchelor, and P. L. Colestock, "Cyclotron Emission from Energetic Ions in Tokamaks," p. 1778
- F. Kazeminejad, J. M. Dawson, R. Sydora, J. N. Leboeuf, and P. Brunel, "Interaction of a Neutral Gas and an Ambient Plasma," p. 1724
- R. R. Kindsfater, S. Hiroe, C. E. Bush, J. H. Harris, G. R. Haste, R. C. Isler, J. B. Wilgen, V. Corson, G. Renda, and J. Schivell, "Radiated Power from ATF ECH Target Plasma," p. 1916
- C. C. Klepper, P. K. Mioduszewski, and T. Uckan, "Physics Considerations in the Design of the Outboard Pump Limiter for Tore Supra," p. 1944
- J. N. Leboeuf, B. A. Carreras, P. H. Diamond, and G. S. Lee, "Ion Pressure Gradient Driven Turbulence," p. 1891
- D. K. Lee, J. H. Harris, and R. J. Colchin, "Field Error Correction for the Advanced Toroidal Facility," p. 1915
- G. S. Lee, B. A. Carreras, and P. H. Diamond, "Study of Resistive Pressure-Gradient-Driven Turbulence with Temperature Evolution," p. 1921

- I. S. Lehrman, P. L. Colestock, G. J. Greene, D. H. McNeill, M. Ono, J. R. Wilson, D. N. Smithe, J. L. Shohet, G. R. Haste, T. L. Owens, D. J. Hoffman, and D. W. Swain, "ICRF Antenna Near Fields and Their Effect on the Edge Plasma," p. 1950
- M. S. Lubell, "Status of Superconducting Magnet Technology," p. 1933
- J. F. Lyon, F. W. Baity, B. A. Carreras, R. J. Colchin, J. L. Dunlap, J. H. Harris, R. C. Isler, T. C. Jernigan, M. Murakami, M. Menon, P. K. Mioduszewski, G. H. Neilson, D. A. Rasmussen, M. J. Saltmarsh, T. L. White, and W. R. Wing, "ATF Physics Program," p. 1879
- P. M. Lyster, P. H. Diamond, J. N. Leboeuf, G. S. Lee, and B. A. Carreras, "Particle-Fluid Model of Low Frequency Plasma Instabilities," p. 1892
- C. H. Ma and D. P. Hutchinson, "An Infrared Interferometer/Polarimeter System for CIT," p. 1870
- P. K. Mioduszewski, J. C. Glowienka, T. C. Jernigan, R. A. Langley, G. H. Neilson, and J. E. Simpkins, "Initial Cleanup of the ATF Plasma Vessel," p. 1914
- M. Murakami, H. C. Howe, S. E. Attenberger, J. H. Harris, W. A. Houlberg, K. L. Kannan, D. K. Lee, R. N. Morris, and G. H. Neilson, "Confinement Analysis for ATF," p. 1880
- G. H. Neilson, T. C. Jernigan, P. H. Edmonds, R. D. Foskett, J. C. Glowienka, R. L. Johnson, R. A. Langley, P. K. Mioduszewski, and M. J. Saltmarsh, "The Advanced Toroidal Facility and its Initial Operation," p. 1879
- H. Okuda and S. Hiroe, "Neutral Injection and Plasma Diffusion in a Tokamak," p. 1919
- T. L. Owens, G. L. Chen, G. R. Haste, and P. M. Ryan, "Experimental Comparison of Folded Waveguide and Loop Couplers for ICRF Heating," p. 1952
- S. L. Painter, B. A. Carreras, V. E. Lynch, J. F. Lyon, J. S. Tolliver, and I. N. Sviatoslavsky, "Studies of Low-Aspect-Ratio Torsatron Reactors and ATF-II," p. 1916
- V. K. Paré, J. H. Harris, J. L. Dunlap, and J. D. Bell, "MHD Diagnostics for ATF," p. 1915
- Y-K. M. Peng, D. J. Strickler, and J. T. Hogan, "Correlation of MHD Stability with Mean-Field Safety Factor," p. 1763
- J. J. Ramos, D. A. Spong, and D. J. Sigmar, "Alpha Particle Ballooning Mode Studies," p. 1771
- D. A. Rasmussen, A. C. England, C. C. Eberle, W. R. DeVan, R. R. Kindsfather, R. N. Morris, J. A. Rome, M. J. Saltmarsh, and R. B. Wysor, "Suppression of X-Rays Generated by Runaway Electrons in ATF," p. 1914
- R. K. Richards, H. T. Hunter, and D. P. Hutchinson, "A CO₂ Laser Thomson Scattering Diagnostic for CIT Alpha Particle Measurements," p. 1922
- J. A. Rome, A. J. Spejewski, and S. P. Hirshman, "Stellarator Design by Surface Shape Optimization," p. 1836
- A. L. Roquemore, G. M. Gammel, J. H. Kamperschroer, H. W. Kugel, and R. A. Langley, "Fractional Energy Components of the U.S. Common Long Pulse Source," p. 1929
- W. L. Rowan, M. E. Austin, R. D. Bengtson, R. V. Bravenec, D. L. Brower, R. D. Durst, R. F. Gandy, S. P. Fan, S. K. Kim, J. C. Forster, M. J. Gouge, Y. X. He, N. C. Luhmann, Jr., S. C. McCool, A. G. Meigs, A. Ouroua, D. M. Patterson, W. A. Peebles, P. E. Phillips, T. L. Rhodes, B. Richards, Ch. P. Ritz, P. M. Schoch, D. D. Schuresko, K. W. Wenzel, J. C. Wiley, and A. J. Wootton, "Enhanced Confinement Following Pellet Injection into the Texas Experimental Tokamak (TEXT)," p. 1841
- P. M. Ryan, D. J. Hoffman, G. L. Chen, and F. W. Baity, "Ohmic Losses and Magnetic Shielding in the TFTR Antenna Faraday Shield," p. 1952
- J. Schivell, C. E. Bush, R. A. Hulse, D. K. Mansfield, H. K. Park, A. T. Ramsey, G. L. Schmidt, F. J. Stauffer, B. C. Stratton, G. Taylor, and J. Timberlake, "Central Radiation Losses at High Density in TFTR," p. 1808
- G. L. Schmidt, R. A. Hulse, F. S. McDermott, D. H. McNeill, S. L. Milora, D. K. Owens, H. Park, M. H. Redi, J. Schivell, and the TFTR Group, "Results from Pellet Injection Experiments on TFTR," p. 1741
- D. D. Schuresko, S. L. Milora, S. K. Combs, C. A. Foster, P. W. Fisher, B. E. Argo, G. C. Barber, C. R. Foust, N. S. Ponte, and J. H. Whitson, "High-Velocity Electrothermal Accelerator for Pellet Fueling," p. 1840

- K. C. Shaing (in collaboration with B. A. Carreras, E. C. Crume, S. P. Hirshman, J. S. Tolliver, V. E. Lynch, and W. van Rij), "Bootstrap Current in Toroidal Plasmas," p. 1738
- D. A. Spong, K. C. Shaing, and J. D. Callen, "Numerical Studies of Neoclassical MHD Pressure Gradient Driven Instabilities," p. 1920
- J. D. Strachan, C. E. Bush, S. S. Medley, D. Mansfield, J. Schivell, D. Mueller, H. Park, and S. Yoshikawa, "TFTR Experiments on Detached Plasmas," p. 1742
- B. C. Stratton, P. C. Efthimion, R. J. Fonck, K. W. Hill, R. A. Hulse, A. T. Ramsey, J. Schivell, J. Timberlake, and C. E. Bush, "Impurity Transport in Ohmically-Heated TFTR Discharges," p. 1808
- G. D. Tait, A. C. England, H. W. Hendel, and J. D. Strachan, "First Results from the TFTR Multichannel Neutron Collimator," p. 1925
- J. S. Tolliver, W. A. Houlberg, and S. E. Attenberger, "Plasma Performance and Density Profiles in 1-1/2-D ETR Transport Simulations with Pellet Injection and Pinch Terms," p. 1760
- N. A. Uckan, "Tokamak Operational Boundaries -- Implications for CIT and ITER Design," p. 1923
- T. Uckan, P. K. Mioduszewski, and P. H. Edmonds, "Instrumented Graphite Rail Limiters for ATF," p. 1914
- Y. Uesugi, S. C. Chiu, M. J. Mayberry, R. Prater, F. W. Baity, D. J. Hoffman, and T. L. Owens, "Coupling Characteristics of an ICRF Compact Loop Antenna on DIII-D," p. 1901
- J. H. Whealton, R. J. Raridon, K. E. Rothe, and P. M. Ryan, "Self-Consistent Multi-Dimensional Model of the Plasma Edge Near an ICRF Antenna--A Nonlinear Limit," p. 1951
- T. L. White, D. B. Batchelor, T. S. Bigelow, M. D. Carter, R. C. Goldfinger, and H. D. Kimrey, "ECH in ATF," p. 1879
- R. M. Wieland, M. G. Bell, D. C. McCune, M. Zarnstorff, W. A. Cooper, and S. P. Hirshman, "Anisotropic Pressure Equilibrium Analysis for TFTR," p. 1927
- J. B. Wilgen, "Reducing the Multiplicity of Fringes in Microwave Interferometer Measurements of Electron Density," p. 1915
- W. R. Wing, L. R. Baylor, J. D. Bell, R. D. Burris, W. R. DeVan, D. E. Greenwood, K. L. Kannan, H. E. Ketterer, J. B. Mankin, D. R. Overbey, K. A. Stewart, J. N. Sumner, and K. G. Young, "The ATF Data System," p. 1915
- J. J. Yugo, T. L. Owens, F. W. Baity, P. Goranson, and D. W. Swain, "Development of an ICRH Launcher for the Compact Ignition Tokamak (CIT)," p. 1922
- R. M. Zubrin, F. L. Ribe, S. P. Hirshman, and D. K. Lee, "Considerations in the Design of Helical Reactors," p. 1762
- Pellet Injector Development Workshop, Anaheim, California, November 6, 1987**
- S. K. Combs, "A Three-Barrel Repeating Pneumatic Injector for Plasma Fueling of the Joint European Torus"
- P. W. Fisher, "Tritium Proof-of-Principle Experiment"
- C. A. Foster, "Electron Beam Rocket Pellet Accelerator"
- D. D. Schuresko, "High Velocity Pellet Accelerator Development at ORNL"
- Third International Workshop on Cross Sections for Fusion and Other Applications, College Station, Texas, November 6-8, 1987. Proceedings published in *Nucl. Instrum. Methods Phys. Res. B27* (1987).**
- N. Stolterfoht, C. C. Havener, R. A. Phaneuf, J. K. Swenson, S. M. Shafroth, and F. W. Meyer, "Correlated Double Electron Capture in Slow, Highly Charged Ion-Atom Collisions," pp. 584-89
- H-Mode Workshop, GA Technologies, Inc., San Diego, California, November 9-10, 1987**
- J. Sheffield, "The Connection Between Theoretical Transport Mechanisms and Ohmic, L, and H-Mode Tokamak Behavior"

Workshop on the Technology and Physics of High-Energy Neutral Beams for Tokamaks, Lawrence Berkeley Laboratory, Berkeley, California, November 9-10, 1987

J. H. Wheaton, "Motion of Transient Ions and Plasmas"

U.S.-Japan Heliotron-Stellarator Workshop, Oak Ridge, Tennessee, November 9-13, 1987. Proceedings distributed to the participants.

F. W. Baity, "The ICRF Heating Program for ATF"

A. Carnevali, "Status of Heavy Ion Beam Probe for ATF"

B. A. Carreras, N. Dominguez, L. Garcia, V. E. Lynch, J. F. Lyon, J. R. Cary, J. D. Hanson, and A. P. Navarro, "Low Aspect Ratio Toratrons"

B. A. Carreras, K. C. Shaing, N. Dominguez, V. E. Lynch, and J. S. Tolliver, "Currents in ATF"

M. D. Carter, "Plasma Production"

E. C. Crume, Jr., "Transport Scaling in the Collisionless-Detrapping Regime"

R. H. Fowler, J. A. Rome, R. N. Morris, and K. Hanatani, "Benchmarks of Neutral Beam Injection Codes for Stellarators"

H. C. Howe, "Transport Analysis for ATF"

R. C. Isler, "Diagnostics for ATF"

M. Murakami, "ATF Experimental Plans"

G. H. Neilson, T. C. Jernigan, R. L. Johnson, P. H. Edmonds, R. D. Foskett, and M. J. Saltmarsh, "Status of the ATF Project"

D. A. Rasmussen, A. C. England, J. H. Harris, T. C. Jernigan, R. R. Kindsfather, M. Murakami, G. H. Neilson, J. A. Rome, M. J. Saltmarsh, C. C. Eberle, W. R. DeVan, R. B. Wyszor, R. N. Morris, O. Motojima, H. Okada, and K. Uo, "Suppression of X-rays Generated by Runaway Electrons in ATF"

1987 Winter Meeting of the American Nuclear Society, Los Angeles, November 15-19, 1987

M. L. Grossbeck and J. A. Horak, "Effect of Helium on Irradiation Creep in an Austenitic Stainless Steel"

P. T. Spampinato and D. Macdonald, "Ex-Vessel Remote Maintenance Design for the Compact Ignition Tokamak"

International Conference on ECR Ion Sources and Their Applications, East Lansing, Michigan, November 16-18, 1987. Proceedings published by the University of Michigan.

F. W. Meyer, "Application of ECR Ion Source Beams in Atomic Physics" (invited paper)

IAEA Specialists' Meeting on the International Nuclear Data Library for Fusion Reactor Technology, Vienna, November 16-18, 1987

D. C. Larson, D. M. Hetrick, and C. Y. Fu, "Description of Evaluation for ^{54,56,57,58}Fe Performed for ENDF/B-VI"

D. C. Larson, D. M. Hetrick, and C. Y. Fu, "Description of Evaluation for ^{63,65}Cu Performed for ENDF/B-VI"

D. C. Larson, D. M. Hetrick, and C. Y. Fu, "Description of Evaluation for ^{50,52,53,54}Cr Performed for ENDF/B-VI"

D. C. Larson, D. M. Hetrick, and C. Y. Fu, "Description of Evaluation for ^{58,60,61,62,64}Ni Performed for ENDF/B-VI"

U.S.-Japan Workshop on Stability and Current Drive, Kyoto, Japan, November 16-19, 1987

B. A. Carreras, N. Dominguez, K. C. Shaing, V. E. Lynch, and J. S. Tolliver, "Bootstrap Current in ATF"

B. A. Carreras, J. A. Holmes, L. A. Charlton, and V. E. Lynch, "MHD Stability of Tokamaks with Low Shear at the $q = 1$ Surface"

**ITER Project Design Meeting, Lawrence Livermore National Laboratory,
Livermore, California, November 17-18, 1987**

D. C. Lousteau, "Configuration Studies"

R. L. Reid, "Design Sensitivities and Trade Offs"

**Magnetic Fusion In Energy Policy, National Research Council, National Academy
of Sciences, Princeton, New Jersey, November 19, 1987**

J. Sheffield, "Contribution to Panel Discussion: Potential Benefits of a Broad Magnetic Fusion
R&D Program"

December

**CIT PF Design Workshop, Princeton Plasma Physics Laboratory, Princeton, New
Jersey, December 1, 1987**

R. O. Sayer, S. C. Jardin, and D. J. Strickler, "TSC Disruption-Induced Forces on the CIT
1.75-m Vacuum Vessel and Internal Coils"

**Eighth Miami International Conference on Alternative Energy Sources, Miami
Beach, Florida, December 14-16, 1987. Proceedings to be published in *Alternative
Energy Sources--An International Compendium*.**

N. A. Uckan, "The Compact Ignition Tokamak (CIT) and the International Thermonuclear
Experimental Reactor (ITER): An Overview"

**12th International Conference on Infrared and Millimeter Waves, Lake Buena
Vista, Florida, December 14-18, 1987**

T. S. Bigelow, T. L. White, and H. D. Kimrey, "ATF ECH Waveguide Component
Development and Testing"

H. D. Kimrey, M. A. Janney, and P. F. Becher, "Techniques for Ceramic Sintering Using
Microwave Energy"

SEMINARS PRESENTED BY FUSION PROGRAM STAFF

- C. O. Beasley and C. L. Hedrick, "Stellarator and Torsatron Transport Coefficients in the $1/\nu$ Regime," Massachusetts Institute of Technology, Cambridge, December 1, 1987
- E. E. Bloom, "Materials for Fusion Reactors," Department of Metallurgical Engineering and Materials Science, Carnegie-Mellon University, Pittsburgh, November 1987
- D. N. Braski, "The Effect of Neutron Irradiation on Vanadium Alloys," Chinese Delegation, Fusion Engineering Design Center, Oak Ridge, Tennessee, December 7, 1987
- W. A. Houlberg, Physics Department, Auburn University, Auburn, Alabama, February 13, 1987
- P. J. Maziasz, "Phase Formation and Stability in Neutron-Irradiated Steels and Some Consequences for Alloy Development," Atomic Energy Research Establishment, Harwell, England, October 22, 1987; Kernforschungszentrum Karlsruhe, Karlsruhe, Federal Republic of Germany, November 2, 1987; Kernforschungsanlage Jülich, Jülich, Federal Republic of Germany, November 5, 1987
- S. L. Milora, "The Pellet Injector for JET and Its Recent Results," ENEA, Frascati, Italy, December 10, 1987
- G. H. Neilson, "Vertical Position Control in Tokamaks," Fusion Research Center, University of Texas, Austin, September 8, 1987
- J. Sheffield, "Advanced Fusion Energy," Oak Ridge Chapter, Sigma Xi, Oak Ridge, Tennessee, June 2, 1987
- D. A. Spong, "Fusion Energy: Search for a Man-Made Sun," Tennessee Technological University, Cookeville, November 10, 1987

REPORTS

ORNL Reports

- ORNL-6090 *Collisions of Carbon and Oxygen Ions with Electrons, H, H₂, and He (Vol. 5, Atomic Data for Fusion)*
R. A. Phaneuf, R. K. Janev, and M. S. Pindzola
February 1987
- ORNL-6332 *Fusion Energy Division Annual Progress Report for Period Ending December 31, 1986*
O. B. Morgan, L. A. Berry, J. Sheffield, and Fusion Energy Division Staff
October 1987
- ORNL-6335 *Implementation of a 3-D Nonlinear MHD Calculation on the Intel HyperCube*
J. B. Drake, B. F. Lawkins, B. A. Carreras, H. R. Hicks, and V. E. Lynch
August 1987
- ORNL-6430 *Microstructural Evolution in Fast-Neutron-Irradiated Austenitic Stainless Steels*
R. E. Stoller
December 1987

ORNL Technical Memoranda

- ORNL/TM-10030 *Compact Toratron Configurations*
B. A. Carreras, N. Dominguez, L. Garcia, V. E. Lynch, J. R. Cary, J. D. Hanson, A. P. Navarro, and J. F. Lyon
September 1987
- ORNL/TM-10164 *Modular Pump Limiter Systems for Large Tokamaks*
T. Uckan, C. C. Klepper, P. K. Mioduszeewski, and R. T. McGrath
September 1987
- ORNL/TM-10186 *Emittance of the ORNL Negative Ion Source*
J. J. Donaghy, W. K. Dagenhart, K. L. Kannan, P. M. Ryan, W. L. Stirling, and C. C. Tsai
November 1987
- ORNL/TM 10212 *Convective Contributions to Local Power Loss in a Bumpy Torus*
S. Hiroe, G. R. Haste, J. S. Tolliver, B. H. Quon, L. Solensten, J. R. Goyer, and K. A. Connor
April 1987
- ORNL/TM-10219 *Calculated Neutron-Induced Cross Sections for ^{58,60}Ni from 1 to 20 MeV and Comparisons with Experiments*
D. M. Hetrick, C. Y. Fu, and D. C. Larson
June 1987
- ORNL/TM-10222 *Evaluation of Magnetic Coordinates in Finite-Beta, Asymmetric Plasmas*
C. O. Beasley, J. A. Rome, S. E. Attenberger, and S. P. Hirshman
November 1987
- ORNL/TM-10223 *ICRF Heating in a Straight, Helically Symmetric Stellarator*
E. F. Jaeger, H. Weitzner, and D. B. Batchelor
July 1987
- ORNL/TM-10224 *Global Ion Cyclotron Waves in a Perpendicularly Stratified, One-Dimensional Warm Plasma*
E. F. Jaeger, D. B. Batchelor, and H. Weitzner
April 1987
- ORNL/TM-10280 *Graphite for Fusion Energy Applications*
W. P. Eatherly, R. E. Clausing, R. A. Strehlow, C. R. Kennedy, and P. K. Mioduszeewski
March 1987
- ORNL/TM-10297 *Electron-Impact Ionization Data for the Fe Isotopic Sequence*
M. S. Pindzola, D. C. Griffin, C. Bottcher, S. M. Younger, and H. T. Hunter
November 1987
- ORNL/TM-10310 *Hydrogen Recycle and Isotope Exchange from Dense Carbon Films*
R. E. Clausing and L. Heatherly
March 1987

- ORNL/TM-10331 *Stability of Ideal and Resistive Internal Kink Modes in Toroidal Geometry*
R. J. Hastie, T. C. Hender, B. A. Carreras, L. A. Charlton, and J. A. Holmes
February 1987
- ORNL/TM-10363 *Feasibility of Alpha Particle Measurement in a Magnetically Confined Plasma by CO₂ Laser Thomson Scattering*
R. K. Richards, K. L. Vander Sluis, and D. P. Hutchinson
August 1987
- ORNL/TM-10365 *Relative Merits of Size, Field, and Current on Ignited Tokamak Performance: A Comparison of "CITs" and "Super-JETs"*
N. A. Uckan
August 1987
- ORNL/TM-10374 *Studies of a Flexible Helic Configuration*
T. C. Hender, J. L. Cantrell, J. H. Harris, B. A. Carreras, V. E. Lynch, J. F. Lyon, J. A. Fabregas, J. Guasp, A. Lopez-Fraguas, and A. P. Navarro
July 1987
- ORNL/TM-10382 *Volt-Second Consumption in Tokamaks with Sawtooth Activity*
W. A. Houlberg
July 1987
- ORNL/TM-10391 *Asymmetric Double Langmuir Probe: Small Signal Application*
T. Uckan
November 1987
- ORNL/TM-10412 *Some Practical Considerations Involving Spectral Representations of 3-D Plasma Equilibria*
S. E. Attenberger, W. A. Houlberg, and S. P. Hirshman
April 1987
- ORNL/TM-10417 *Calculated Neutron-Induced Cross Sections for ⁵²Cr from 1 to 20 MeV and Comparisons with Experiments*
D. Hetrick, C. Y. Fu, and D. C. Larson
September 1987
- ORNL/TM-10436 *Asymmetric Double Langmuir Probe for Fast and Automatic Measurements of Plasma Temperature*
Taner Uckan
November 1987
- ORNL/TM-10464 *Planning for U.S. Ion Cyclotron Heating Research Relevant to the Compact Ignition Tokamak and Alcator C-Mod*
D. W. Swain and J. J. Yugo
August 1987
- ORNL/TM-10482 *Progress in Stellarator/Heliatron Research: 1981-1986, Executive Summary*
B. A. Carreras, G. Grieger, J. H. Harris, J. L. Johnson, J. F. Lyon, O. Motojima, F. Rau, H. Renner, J. A. Rome, K. Uo, M. Wakatani, and H. Wobig
September 1987
- ORNL/TM-10556 *Neutral and Plasma Shielding Model for Pellet Ablation*
W. A. Houlberg, S. L. Milora, and S. E. Attenberger
October 1987
- ORNL/TM-10560 *Design Considerations of Modular Pump Limiters for Large Tokamaks*
T. Uckan, C. C. Klepper, and P. K. Mioduszewski
November 1987
- ORNL/TM-10574 *Transport Scaling in the Collisionless-Detrapping Regime in Stellarators*
E. C. Crume, Jr., S. P. Hirshman, K. C. Shaing, and W. I. van Rij
September 1987
- ORNL/TM-10579 *ORNL Contributions to the Advanced Neutron Source (ANS) Project for October 1986-March 1987*
D. L. Selby, R. M. Harrington, F. J. Peretz, R. G. Alsmiller, Jr., Y. Y. Asmy, G. L. Copeland, F. C. Difilippo, W. R. Gambill, B. H. Montgomery, R. E. Pawel, R. T. Primm III, C. D. West, D. C. Lousteau, P. B. Thompson, and S. S. Kalsi
November 1987

- ORNL/TM-10584 *Synchrotron Radiation Losses in Engineering Test Reactors (ETRs)*
N. A. Uckan
November 1987
- ORNL/TM-10585 *Nonlinear Evolution of the Internal Kink Mode in Toroidal Geometry for Shaped Tokamak Plasmas*
J. A. Holmes, B. A. Carreras, L. A. Charlton, V. E. Lynch, R. J. Hastie, and T. C. Hender
September 1987
- ORNL/TM-10611 *Physics Analysis of the TIBER-II Engineering Test Reactor*
N. A. Uckan, W. A. Houlberg, S. E. Attenberger, R. A. Dory, D. A. Spong, J. S. Tolliver, and J. Sheffield
November 1987
- ORNL/TM-10612 *Influence of Fast Alpha Diffusion and Thermal Alpha Buildup on Tokamak Reactor Performance*
N. A. Uckan, J. S. Tolliver, W. A. Houlberg, and S. E. Attenberger
November 1987
- ORNL/TM-10617 *Transport Simulations of Ohmic Ignition Experiment---IGNITEX*
N. A. Uckan and H. C. Howe
December 1987
- ORNL/TM-10644 *Design Considerations for a Negative Ion Source for DC Operation of High-Power, Multi-Megaelectron-Volt Neutral Beams*
C. C. Tsai, W. L. Stirling, M. A. Akerman, W. R. Becraft, W. K. Dagenhart, H. H. Haselton, P. M. Ryan, D. E. Schechter, and J. H. Whealton
November 1987

ORNL Engineering Design Center Reports

- ORNL/FEDC-85/10 *Liquid Nitrogen Cooling Considerations of the Compact Ignition Tokamak*
A. E. Dabiri
January 1987
- ORNL/FEDC-86/5 *System Studies of Compact Ignition Tokamaks*
J. D. Galambos, D. T. Blackfield, Y-K. M. Peng, R. L. Reid, D. J. Strickler, and E. Selcöw
August 1987
- ORNL/FEDC-86/9 *Systems Code Assessment of Innovations, Major Design Drivers, and Minimum Sizes of INTOR and ETR-Like Designs*
J. D. Galambos, Y-K. M. Peng, D. J. Strickler, and R. L. Reid
October 1987
- ORNL/FEDC-87/1 *Cooldown of the Compact Ignition Tokamak*
D. C. Keeton
August 1987
- ORNL/FEDC-87/2 *Poloidal Magnetics of a Divertor Compact Ignition Tokamak*
D. J. Strickler, Y-K. M. Peng, and S. C. Jardin
October 1987
- ORNL/FEDC-87/3 *Elastic-Plastic Analysis of the Toroidal Field Coil Inner Leg of the Compact Ignition Tokamak*
T. Horie
July 1987
- ORNL/FEDC-87/4 *Face Compression Yield Strength of the Copper-Inconel Composite Specimen*
T. Horie
May 1987

Conference Proceedings Published by ORNL

- CONF-871179 *Proceedings of U.S.-Japan Heliotron-Stellarator Workshop, Oak Ridge, Tennessee, November 9-13, 1987*
G. H. Neilson, ed.
November 1987

Reports Prepared by ORNL for the U.S. Department of Energy

- DOE/ER-0313/1 *Fusion Reactor Materials: Semiannual Progress Report for Period Ending September 30, 1986*
A. F. Rowcliffe and D. G. Doran, comps. and eds.
September 1987
- DOE/ER-0313/2 *Fusion Reactor Materials: Semiannual Progress Report for Period Ending March 31, 1987*
A. F. Rowcliffe and D. G. Doran, comps. and eds.
September 1987

Reports Published by Other Institutions

- CIT-P-870615-PPL-01 *CIT Physics Report: Synchrotron Radiation Losses in CIT*
W. A. Houlberg
Princeton Plasma Physics Laboratory
March 1987
- IFSR-278 *Nonlinear Dynamics of Tearing Modes in the Reversed Field Pinch*
J. A. Holmes, B. A. Carreras, P. H. Diamond, and V. E. Lynch
Institute for Fusion Studies, University of Texas, Austin
May 1987
- LRP-299/86 *Axisymmetric MHD Equilibria with Isothermal Toroidal Mass Flow by Variational Steepest Descent Moments Method*
W. A. Cooper and S. P. Hirshman
Centre de Recherches en Physique des Plasmas,
Ecole Polytechnique Fédérale, Lausanne, Switzerland
March 1987
- PPPL-2410 *A Spectroscopic Study of Impurity Behavior in Neutral-Beam and Ohmically Heated TFTR Discharges*
B. C. Stratton, C. E. Bush, R. J. Groebner, and R. K. Richards
Princeton Plasma Physics Laboratory
February 1987
- PPPL-2417 *TFTR Plasma Regimes*
E. J. Hawryluk, V. Arunasalam, M. G. Bell, C. E. Bond, S. K. Combs, L. C. Emerson, A. C. England, S. Hiroe, C. A. Ma, S. L. Milora, and J. B. Wilgen
Princeton Plasma Physics Laboratory
February 1987
- PPPL-2435 *Coherent and Turbulent Fluctuations in TFTR*
K. McGuire, V. Arunasalam, C. E. Bush, S. K. Combs, L. C. Emerson, A. C. England, S. Hiroe, C. H. Ma, S. L. Milora, and J. B. Wilgen
Princeton Plasma Physics Laboratory
April 1987
- PPPL-2450 *MIRI: A Multichannel Far-Infrared Laser Interferometer for Electron Density Measurements on TFTR*
D. K. Mansfield, C. H. Ma, and B. J. Clifton
Princeton Plasma Physics Laboratory
July 1987
- TFTR/D-T MPG/TM-1 *Thermal Release of Implanted Hydrogen from Graphite*
R. A. Langley
Princeton Plasma Physics Laboratory
July 1987
- UCLA-PPG-1100 *The TITAN Reversed-Field Pinch Fusion Reactor Study: Scoping Phase Report*
F. Najmabadi, E. T. Cheng, R. A. Krakowski, D. Steiner, T. F. Shannon, S. L. Thomson, T. G. Brown, D. C. Keeton, A. E. Dabiri, D. C. Lousteau, and G. E. Gorker
University of California at Los Angeles, Los Angeles
January 1987

THESES AND DISSERTATIONS

- W. E. Bryan, "Design of Compact Loop Antennas for Present and Future Fusion Heating Experiments," M.S., The University of Tennessee, Knoxville, October 1987
- J. B. Miller, *Prevention of the Current Quench Phase of a Major Disruption in a Tokamak Reactor*, Ph.D., The University of Tennessee, Knoxville, March 1987
- S. L. Painter, "Optimising Performance of the Advanced Toroidal Facility's Thomson Scattering System Spectrometer Array," M.S., The University of Tennessee, Knoxville, June 1987

Appendix 2

ABBREVIATIONS AND ACRONYMS

ABBREVIATIONS AND ACRONYMS

ADLP	asymmetric double Langmuir probe
AEDC	Arnold Engineering Development Center
ALT-II	Advanced Limiter Test II
appm	atomic parts per million
ATF	Advanced Toroidal Facility
BBC	Brown Boveri et Cie
B/O	budget outlay
CCD	charge-coupled device
CEA	Commissariat à l'Energie Atomique
CFADC	Controlled Fusion Atomic Data Center
CHS	Compact Helical System
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales, y Tecnológicas
CIT	Compact Ignition Tokamak
CMA	cylindrical mirror analyzer
cpu	central processing unit
CT	compact toroid
CW	cold-worked
cw	continuous wave
DBTT	ductile-to-brittle transition temperature
DOE	U.S. Department of Energy
dpa	displacements per atom
DPI	deuterium pellet injector
D-T	deuterium-tritium
DIII-D	Doublet III-D
ECE	electron cyclotron emission
ECH	electron cyclotron heating
ECR	electron cyclotron resonance
ECR-DC	ECR discharge cleaning
ECRH	electron cyclotron resonance heating
ETR	Engineering Test Reactor
EURATOM	European Atomic Energy Community
FEDC	Fusion Engineering Design Center
FER	Fusion Engineering Reactor
FFTF	Fast Flux Test Facility
FIR	far-infrared
FLR	finite Larmor radius
FMIT	Fusion Materials Irradiation Test facility
FNS	Fusion Neutron Source
FSAR	Final Safety Analysis Report
FY	fiscal year

GD	General Dynamics
G-DC	glow discharge cleaning
GE	General Electric Company
HF	helical field
HFIR	High-Flux Isotope Reactor
HIFI	HFIR Irradiation Facilities Improvement
IAEA	International Atomic Energy Agency
IBW	ion Bernstein wave
ICRF	ion cyclotron range of frequencies
ICRH	ion cyclotron resonance heating
IF	intermediate frequency
IFSMTF	International Fusion Superconducting Magnet Test Facility
INTOR	International Tokamak Reactor
IR	infrared
IRO	Information Resources Organization
ISX	Impurity Study Experiment
ISX-B	upgrade of ISX
ITER	International Thermonuclear Experimental Reactor
JAERI	Japan Atomic Energy Research Institute
JET	Joint European Torus
JPCA	Japanese prime candidate alloy
JPI	JET pellet injector
KFA	Kernforschungsanlage
KfK	Kernforschungszentrum Karlsruhe
LCT	Large Coil Task
LEBT	low-energy beam transport
LHS	Large Helical System
LLNL	Lawrence Livermore National Laboratory
MFE	magnetic fusion energy
MHD	magnetohydrodynamic
NBI	neutral beam injection
NET	Next European Torus
OH	ohmic heating
OMA	optical multichannel analyzer
ORNL	Oak Ridge National Laboratory
ORO	Oak Ridge Operations Office
ORR	Oak Ridge Research Reactor, operational readiness review
OSR	Operating Safety Requirements
PBX	Princeton Beta Experiment
PC	personal computer
PCA	prime candidate alloy
PDX	Poloidal Divertor Experiment
PF	poloidal field

PHA	pulse height analyzer
PIG	Penning ion gage
PIP	Performance Improvement Process
PLC	programmable logic controller
PLT	Princeton Large Torus
POP	proof-of-principle
PPPL	Princeton Plasma Physics Laboratory
QA	quality assurance
QAA/P	QA Assessment/Plan
RB	removable beryllium
RDL	resonant double loop
REDA	resonant-excitation double Auger
rf	radio frequency
RFP	reversed-field pinch
RFQ	radio-frequency quadrupole
RFTF	Radio-Frequency Test Facility
RGa	residual gas analyzer
RICS	Recycle, Impurity, and Conditioning Simulator
RPI	repeating pellet injector; Rensselaer Polytechnic Institute
RSIC	Radiation Shielding Information Center
SA	solution-annealed
SAMS	Synchronizing and Monitoring System
SFT	stacking fault tetrahedron
SNLA	Sandia National Laboratories, Albuquerque, N.M.
SOL	scrape-off layer
STX	Spherical Torus Experiment
TEA	transferred-electron amplifier
TEXT	Texas Experimental Tokamak
TEXTOR	Torus Experiment for Technology Oriented Research
TF	toroidal field
TFR	Tokamak Fontenay-aux-Roses
TFTR	Tokamak Fusion Test Reactor
TIBER	Tokamak Ignition/Burn Experimental Reactor
TMP	turbomolecular pump
TPI	tritium pellet injector
TPOP	tritium proof-of-principle
TSC	Tokamak Systems Code
UHV	ultrahigh vacuum
VF	vertical field
VITEX	volume ionization by transverse extraction
VSWR	voltage standing-wave ratio
WBS	Work Breakdown Schedule
YAG	yttrium-aluminum-garnet

1-D	one-dimensional
1½-D	one-and-one-half-dimensional
2-D	two-dimensional
3-D	three-dimensional

Appendix 3
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