MEETING REPORT

CONFERENCE SUMMARY ON THE 3RD IAEA TECHNICAL COMMITTEE MEETING AND WORKSHOP ON FUSION REACTOR DESIGN AND TECHNOLOGY, TOKYO, JAPAN, OCTOBER 5-16, 1981

Editor's Comment: *This conference summary was prepared by* Nuclear Technology/Fusion *editor, G. H. Miley, with the cooperation of Drs. J. Dee, Y. Iso, and K. Sako. Papers presented in the plenary session are to be published in a proceedings distributed by the International Atomic Energy Agency, Vienna International Centre, P.O. Box 100, A-1400, Vienna, Austria.* Nuclear Fusion *will publish the workshop summaries.*

This International Atomic Energy Agency (IAEA) meeting, with the Japan Atomic Energy Research Institute (JAERI) serving as host (Dr. J. Dee of the IAEA was scientific secretary, Dr. Y. Iso of the JAERI was conference chairman, and Dr. K. Sako, also of JAERI, was program chairman), consisted of two parts. During the first week approximately 45 papers were presented orally in plenary sessions while, during the second week, seven individual working groups convened for intensive discussions. Topics covered by these groups included near-term tokamak reactors, long-term tokamaks, nontokamak toroids (alternative concepts), open systems, inertial confinement fusion, and systems such as hybrids, advanced fuels, and process heat applications. Conclusions drafted in the working sessions will be published in the IAEA journal *Nuclear Fusion*. Consequently, the present comments focus on the plenary sessions.

The first meeting in this series was held in 1974 at Culham Laboratory, England[1]; the second occurred in 1977 at Madison, Wisconsin.[2] The objective of the present meeting was to review progress in experimental, demonstration, and commercial fusion reactor concepts since 1977, to identify critical issues, and to propose possible strategies for continuing development of fusion. Attendees included 48 representatives from the host country, Japan, 25 from the United States, 1 from IAEA, and 21 from the European Communities.

Papers in the plenary session were selected by the IAEA to provide a background for discussions in the working sessions.

An overriding theme of the meeting was the good progress made in the construction of the next-stage tokamak experiments, the tokamak fusion test reactor (TFTR) in the United States, the Joint European Torus (JET) in Europe, T-15 in the USSR, and JT-60 in Japan. This point was emphasized visually with a tour of the JAERI fusion laboratory and the JT-60 site. The JT-60 reactor, designed as an energy breakeven experiment, should begin operation in 1985. Some component tests have been initiated while construction of the main building to house JT-60 is well under way. One massive neutral-beam injector is already operational on a test stand. The Japanese superconducting coil for the International Energy Agency large coil task (LCT) at Oak Ridge National Laboratory (ORNL) is also in this area undergoing tests prior to shipment to the United States. A full-scale mockup of a sector of JT-60, with its distinctive tear-shaped chamber and single-null poloidal divertor could be mounted by a ladder and viewed inside by visitors. Expert craftsmanship and attention to detail were evident in all of these projects, while the funding involved (over $800 million for JT-60 exclusive of site acquisition and preparation funds) demonstrates the determination of the Japanese government to develop fusion power. Indeed, funding for fusion research and development at JAERI has grown more than 10 times in the last 10 years. Further, funding for university research from the Ministry of Education has undergone significant growth with major experimental devices at Nagoya (Hybrid Stellarator), Kyoto (Helitron-E), Osaka (Gekko IV and XII lasers), and Tsukuba (the Gamma 6 and 10 Tandem Mirrors).

International cooperation and the international tokamak reactor (INTOR) were the theme for opening talks in the plenary session. In his discussion of the European program, D. Palumbo, director of the fusion program of the European Communities, cited examples of international cooperation involving the European Communities starting from the Culham temperature measurements on T-3 and continuing through the large coil project, JET, and now INTOR. In an atmosphere of growing budgetary constraints due to inflation, he proposed that such international projects should receive budgetary priority. In his review of the Japanese program, S. Mori, director of JAERI, cited the need for an ignited deuterium-tritium (D-T) reactor to follow JT-60 and described plans for such an experiment in Japan, designated as the Fusion Experimental Reactor (FER), tentatively scheduled for a construction start in 1987 at an estimated cost of about $2 billion. Also, a driven device (R-plasma) with $Q \sim 0.3$ has been proposed by Nagoya and Kyoto Universities. This device would be built earlier and provide supporting physics data on burn dynamics, including alpha transport and heating.

In his overview of the U.S. program, J. Baublitz, chief of the Reactor Systems Branch of the U.S. Office of Fusion Energy, stressed the many advances made in fusion plasma experiments, technology, and reactor concepts. However, he cautioned that problems, such as $n\tau$ saturation observed on Alcator C, beta saturation on ISX-B with 1.5-MW neutral beam injection, and beta limits recently predicted for the ELMO Bumpy Torus (EBT), must be faced squarely. He stressed that the U.S. commitment to "develop fusion's highest potential" requires a continuing critical evaluation of research and development directions culimated by a decision (expected in the 1990s) about a demonstration reactor. However, his remarks concerning growing money constraints on fusion research and development were echoed by colleagues from most countries present, creating a sobering mood for all discussions of future steps.

Discussion of physics, engineering, and neutronics aspects of INTOR in talks by G. Grieger [Max-Planck Institute, Federal Republic of Germany (FRG)], F. Engelmann (FOM-Instituut voor Plasmapysica, Netherlands), W. Stacey (Georgia Institute of Technology, U.S.), T. Shannon (ORNL, U.S.), and T. Hiraoka (JAERI) clearly brought out the strong influence that this cooperative effort has played in providing a focus for identifying and tackling crucial problems for reactor development. Among the physics issues discussed were confinement scaling (a versus R dependence, beta effects), disruption characteristics (frequency, time constant, deposition profile, melt layer behavior), feedback control (reduced ripple effects on transport now limit its use for control), and plasma "edge" physics (including single-null divertor scrape-off layer). Other unresolved issues include plasma equilibrium of the poloidal field system, the operational scenario (current initiations, burn control, shut down, and dwell), and selection of maintenance procedures. The test program for INTOR was also discussed. Consisting of three phases, it would move from plasma physics experiments to blanket concept tests and finally to extended studies of component combinations and possible synergistics in radiation effects.

H. Kakihana (Institute of Plasma Physics, Nagoya University, Japan) described six "gates" that fusion development must pass: plasma confinement; burning; ignition; energy conversion; economic, safety, and environmental tests; and commercial involvement. To succeed, he cited the need to: increase power densities in reactor concepts (e.g., increase beta and wall loadings); decrease input power requirements by improving the efficiency of heating; improve output power effectiveness by, for example, moving toward steady-state operation; improve energy extraction efficiencies; and develop needed fuel cycle technology.

Considerable attention was also given to INTOR-scale devices under consideration. In the United States, there is the Fusion Energy Device (FED), and in Japan, the FER. As described in papers by R. Conn et al. (Technical Management Board for FED, Office of Fusion Energy, U.S.) and by D. Steiner et al. (Fusion Engineering Design Center, ORNL, U.S.), the 8-T version of FED would have a burn time of $\sim$100 s and produce 180 MW(thermal) with a neutron wall loading of 0.4 MW/m^2 with the goal of proving fusion engineering feasibility, thus laying the groundwork for a demonstration reactor. The design lifetime, set by fatigue limits in the magnet, is $\sim 3 \times 10^5$ pulses in ten years. Some participants questioned whether parameters such as the wall loading and subignition would be adequate for engineering tests. However, the speakers stressed that, compared to TFTR or JET, FED would represent an ambitious extension, e.g., an increase of a factor of 10 in pulse length, an increase in tritium inventory from $\sim$5 to 10^3 g, and an extension of the duty cycle from 0.01 to 0.5. Still, in contrast, goals for the FER were cited as ignited operation, 400 MW(thermal), and a 1 MW/m^2 wall loading, giving (with 100-s burns and 50% availability) a neutron wall fluence of 2 MW·yr/m^2.

Two versions of the FER are under consideration: a conventional solid shield, 5.5-m radius device described by K. Tomabechi et al. (JAERI) and a unique Swimming Pool-Type Tokamak Reactor (SPTR). The SPTR is described in various papers by K. Sako et al. and Y. Seki and H. Iida (JAERI) that deal with system, neutronic, and maintenance considerations. The SPTR would use a water shield to ease problems of structural access and in this way allow smaller toroidal coils. (The elimination of void space necessary for access in devices using a solid shield permits a reduction in coil radius.) In addition, the entire reactor would be immersed in a pool for personnel shielding, the objective being to replace the need to move large shield blocks for access with the simpler procedure of pool draining.

Three presentations on possible alternatives to an FED or FER tokamak-type device were included. D. Cohn et al. (Massachusetts Institute of Technology Plasma Fusion Center, U.S.) described studies of a High Field Advanced Test Reactor (HFATR) that would employ Bitter-type resistive magnets to obtain high fields ($B_t \sim 9$ T), hence favorable $n\tau$ and power density, with relatively small size (R = 3.8 m, a = 1.1 m). A unique feature of this approach is that the high densities result in attractive operation with tritium assisted deuterium-deuterium fuel [i.e., catalyzed deuterium (Cat-D) with tritium added from blankets with an $\sim$0.7 breeding ratio]. A tandem mirror concept (TASKA) designed as an engineering test facility was described by W. Heinz et al. (Institut für Technische Physik, FRG). With a power level of 86 MW(thermal), a central cell length of 21 m (0.46-m radius), and a neutron wall loading of 1.5 MW/m^2, this device would test key technologies ranging from superconducting coils to tritium breeding and remote handling. Likewise, R. Hagenson and R. Krakowski [Los Alamos National Laboratory (LANL), U.S.] described preliminary studies of a high density reversed-field pinch reactor (RFPR) that could possibly lead to a small ($\sim$ZT-40 size) device capable of serving as an engineering "test bed" device. However, all three alternatives—HFATR, TASKA, and the RFPR—face the obstacle of a limited physics data base compared to the conventional tokamak.

A variety of commercial and/or demonstration-scale reactor studies was reviewed. M. Abdou et al. (Argonne National Laboratory, U.S.) presented results from the recent "benchmark" STARFIRE tokamak study. Unique features of STARFIRE include use of a plasma current drive to achieve steady-state operation, a mechanical limiter (versus a divertor), and a solid breeder blanket. In addition to reviewing various design decisions, these authors noted that uncertainties in plant availability and construction time introduce a large unknown into economic evaluations. A commercial reactor study (SPTR-P) based on the swimming-pool concept was described by T. Tone et al. (JAERI). The advantages of the concept, in which water replaces huge and heavy solid shield structures, make the reactor structure simple and the size as small as an INTOR-like device. It assumes steady-state operation with a pumped limiter for plasma exhaust, and has a stainless steel blanket structure with lithium oxide breeder and water cooling. This design study is the only commercial reactor study now in progress in the world. With respect to economics, R. Buende (Max-Planck Institute, FRG) considered the question of the net energy balance for such a tokamak and, in contradiction to some prior studies, found the tokamak better than a light water reactor (LWR) or a coal-fired plant. One difference between his and the previous pessimistic studies is that he included a consistent treatment of the fuel cycle.

Reactor studies for a variety of alternate confinement approaches were presented including: a modular stellarator reactor (MSR) by R. L. Miller et al. (LANL, U.S.) and the

UWTOR-M stellarator design by I. Sviatoslavsky (University of Wisconsin, U.S.); a Heliotron reactor by K. Uo (Kyoto University, Japan); an EBT reactor study by C. Bathke et al. (LANL, U.S.); separate tandem mirror reactor (TMR) studies by G. A. Carlson [Lawrence Livermore National Laboratory (LLNL), U.S.] and by G. A. Emmert et al. (University of Wisconsin, U.S.); RFPR studies by R. Hagenson and R. Krakowski (LANL, U.S.); and a compact-toroid reactor (CTOR) based on the reversed-field theta pinch, also by R. Hagenson and R. Krakowski. Due to the widely different physics base and various assumptions used in these studies, neither an intercomparison of the concepts nor a direct comparison with the tokamak studies is possible. However, some unique aspects deserve comment. All studies attempted to provide improved maintenance capability. Both the MSR and UWTOR-M employed a modular design for both blanket and coil along with periodic distorted ("twisted") coils. In contrast, the Heliotron reactor (essentially a torsatron-type stellarator) employs a continuous coil system that, it was stated, could be repaired in place. The other designs, e.g., the EBT, the RFPR, and the linear TMRs, take advantage of the natural access afforded by a large aspect ratio to incorporate maintenance procedures. The importance of maintenance considerations in reactor design was further stressed by four additional papers, explicitly devoted to the topic [by J. Mitchel (Culham Laboratory, U.K.); by Y. Sawada et al. (Toshiba Corporation, Japan); by T. Iwamoto et al. (Hitachi Limited, Japan), and by Niikura et al. (Mitsubishi Industries Group, Japan)] that considered remote operational procedures related to both single- and double-null divertor-type tokamaks and to the SPTR concept noted earlier.

Other reactor studies described included WITAMIR-I (G. Emmert et al., University of Wisconsin, U.S.), a tandem mirror power reactor that employed an HT-9 alloy steel blanket structure with $Pb_{83}Li_{17}$ for the coolant/breeding fluid in order to provide good breeding and energy multiplication while simultaneously minimizing the tritium inventory. The "compact" RFPR, described by Hagenson and Krakowski and noted earlier, utilized a high density, high current design to achieve a higher power density. This interesting concept rests, however, on several crucial assumptions including an empirical scaling of the energy confinement with plasma current and a plasma current maintenance scheme that employs an oscillating external field. The CTOR design, based on the reversed-field theta pinch, differs from the other approaches by using a moving plasmoid approach where the plasma rings travel at ~20 m/s through a linear burn chamber. A crucial problem, namely, the tilting mode observed in such plasmoids, is stabilized in this design by use of a thin (~1-mm) metallic first-wall "shell" that is permeable to magnetic flux penetration. The TMR discussion by Carlson concluded that, of three possible approaches to thermal barriers (a cusp arrangement, an A-cell type barrier, and an axi-cell), the axi-cell arrangement which uses a simple mirror cell with circular coils, followed by a transition coil and a Yin-Yang pair, appears to best combine performance and a less-demanding coil structure.

Other reactor studies included two inertial confinement designs. The SENRI-I described by C. Yamanaka et al. employs laser drivers and a unique magnetic field to guide the flow of a protective lithium curtain in the chamber. The HIBALL design presented by R. Bock et al. (GSI, Darmstadt, FRG) and G. Kulcinski et al. (University of Wisconsin, U.S.) is the result of an extensive cooperative study of a heavy ion beam driver reactor by groups in both the United States and Europe. This 8000-MW(thermal) plant employs four reactor chambers, each operating at 5 Hz with a 4.8-MJ input-pulse of Bi^{+2} ions from the accelerator driver. A unique feature is the use of an array of porous SiC tubes (called "INPORT" tubes) to contain flowing $Pb_{83}Li_{17}$ for first-wall protection. The $Pb_{83}Li_{17}$ that seeps through the tube wall is vaporized on each shot and then recondenses on the tubes. With this approach, the steel chamber is expected to last the life of the plant.

Other presentations were concerned with progress in hybrid reactor concepts and in advanced fuel fusion. T. C. Varljen and R. P. Rose (Westinghouse Electric Corporation, U.S.) reviewed results from two recent hybrid studies, a Demonstration Tokamak Hybrid Reactor (DTHR) and a Commercial Tokamak Hybrid Reactor (CTHR). The DTHR is, in many respects, similar to FED/ETF/INTOR concepts but is intended to study hybrid engineering. The CTHR would be a scaled-up version (6.0- versus 5.3-m major radius) designed to produce 2500 kg/yr fissile fuel (uranium-plutonium cycle) and a net power of 1335 MW(electric). Approximately seven 1-GW(electric) LWRs could be supported. Carefully optimized fuel management strategies appear necessary to insure competitive economics, however. The tandem mirror hybrid study described by R. Moir (LLNL, U.S.) and E. Cheng and K. Schultz (General Atomic Company, U.S.) features a fission-suppressed blanket design intended to support ~20 LWRs with ^{233}U. In addition to maximizing the ratio of fuel produced per unit thermal power, this blanket results in a very low radioactive inventory and a low afterheat level. Good economics are reported despite the relatively modest plasma gain of the tandem mirror driver ($Q \sim 2$ to 3).

H. Momota et al. (Nagoya University, Japan) presented a comprehensive overview of various advanced fuel fusion cycles that placed stress on Cat-D and D-^{3}He cycles due to their favorable energy balance compared to proton-based cycles. Indeed, R. Conn (University of California-Los Angeles, U.S.) reported that recent results place doubt on the ability to ignite p-^{11}B. He also described results from a TMR study employing Cat-D fuel. While features related to removal of the tritium-breeding blanket appear quite attractive, the combination of the high magnetic fields required for the end plugs plus the relatively low plasma gain with Cat-D in the tandem result in excessive energy recirculation requirements. Consequently, it was concluded that a high-Q concept (either an advanced TMR or other high beta alternative approach) would be necessary. G. H. Miley (University of Illinois, U.S.) discussed a possible strategy for development of deuterium-based advanced fuels. One scenario involves evolution of Semi-Catalyzed-Deuterium (SCD) hybrid reactors using tritium assistance (blanket tritium-breeding ratio <1.0) in early hybrid reactors so that plasma requirements are not drastically different from D-T. The SCD reactor is a desirable goal for hybrids because the combination of a good neutron yield, low thermal power, and avoidance of tritium breeding offers an optimum support ratio per unit of thermal power, i.e., an optimum "fuel factory." In addition, ^{3}He extracted from the exhaust of the SCD plasma would support D-^{3}He satellite reactors. A longer range goal would be to introduce synfuel plants using SCD fuel while expanding the D-^{3}He satellite network.

Technology areas receiving attention included superconducting magnets, materials, blanket neutronics test programs, and tritium systems. S. Shimamoto et al. (JAERI) discussed design considerations for the magnet system for the proposed FER reactor. Sixteen 12-T maximum toroidal field coils would use a pool-cooled Nb_3Sn and NbTi conductor while a 9-T pool-cooled NbTi conductor is envisioned for 15 poloidal field coils. These coils would rely heavily on experience gained from the Cluster Test Program and the LCT.

In a comprehensive review of magnet status and development, P. Komarek et al. (Institut für Technische Physik, FRG) stressed some unsolved problems for FER- or INTOR-like superconducting magnets that include: poloidal field coil designs require experimental verification; optimization of conductor and cooling technology for fields >8 T is needed; intercoil structure for high fatigue load but minimum eddy-current losses must be studied; and optimization for minimum cost is essential.

Discussions of tritium systems by H. Watanabe and H. Kudo (JAERI) focused on experimental studies of Li_2O pellets for blanket applications including measurements of thermal conductivity, expansion coefficients, compatability with container materials and tritium diffusion as well as tritium handling (i.e., fuel reprocessing), safety, and environmental protection. In connection with the latter, R. Krakowski (representing J. Anderson, LANL, U.S.) described the Tritium Systems Test Assembly now under construction, which should develop essential handling technology.

In an extensive review of materials for fusion, G. Kulcinski (University of Wisconsin, U.S.) pinpointed some significant changes in the field since 1977. They included: increased consideration of ferritic alloys as a way to reduce swelling and avoid the severe helium embrittlement at high temperatures encountered in austenitic steels and the introduction of $Pb_{83}Li_{17}$ coolant/breeder to achieve a reduced hazard index while maximizing energy multiplication. Areas where progress has been slow were also delineated. For example, high fluence damage data (still <0.01 dpa) and data on pulsed irradiations. Another aspect of the materials problem, brought out in a presentation by K. Schultz et al. (General Atomic Company, U.S.), is the importance of maximum utilization of low activation materials like aluminum, beryllium, silica, and carbon. This aspect was emphasized by their study which showed that, compared to the original design, if such materials were incorporated into STARFIRE, activation, dose rates, and the quantities of radioactive materials to be disposed of could be reduced by up to six orders of magnitude! This improvement, however, involves a trade-off with thermal and lifetime performance characteristics of the plant and hence needs careful study. Relative to future materials programs, S. Ishino and S. Iwata (University of Tokyo, Japan) described an extensive computer-based materials data file now under development in Japan. This file will contain an extensive experimental theoretical data base that can be interrogated by the design engineers working on fusion systems.

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