MEETING REPORT

SUMMARY OF THE 15TH SYMPOSIUM ON FUSION TECHNOLOGY, UTRECHT, THE NETHERLANDS, SEPTEMBER 19-23, 1988

INTRODUCTION

The 15th Symposium on Fusion Technology (SOFT) was held in Utrecht, The Netherlands, on September 19-23, 1988. Since the first SOFT meeting in Oxford, United Kingdom, in 1960, these symposia have dealt with day-to-day improvement of actual plasma experiments as well as with problems in future fusion reactors. Because the gap between these subjects has narrowed significantly, the next endeavor of the fusion community could be the realization of an experimental reactor.

The 500 participants came from 21 countries from a variety of institutions ranging from universities and technical institutions—via national, European, and international ventures—to industrial companies working on plasmas or in nuclear technology.

The topics (number of papers) presented at the symposium were as follows: experimental systems (33); plasma heating and equilibrium (57); fuel cycle engineering (11); first-wall engineering and vacuum technology (34); materials for fusion devices (45); blanket technology (24); tritium systems engineering (23); remote operations and maintenance (13); magnet engineering and power supply technology (33); reliability, availability, and quality assurance [for the first time (6)]; data acquisition and control (16); reactor studies (18); and general questions (8). Most were included in poster sessions and could be seen during either the first or the second full half of the conference. Authors could be found at their posters at least during the one session into which their paper was grouped. Some institutions, notably Kernforschungszentrum Karlsruhe, characterized all of their contributions with a remarkable, unique, and uniform layout. However, it was still difficult to bring the diversified and detailed information of this complex field to participants with such different backgrounds.

About 20 invited speakers gave lectures to the full audience, which provided an introduction to and an overview of the many facets of fusion technology. The national fusion technology programs in Europe (R. Toschi), in Japan (T. Iijima), and in the United States (R. J. Dowling) were reviewed; unfortunately, there was no similar report from the USSR, notwithstanding the excellent cooperation in the fusion field, notably through the International Atomic Energy Agency.

The other major topics covered at SOFT included preparation for deuterium-tritium (D-T) operation at the Joint European Torus (JET) (A. C. Bell); the JET active gas-handling system (J. L. Hemmerich); experience with remote-handling equipment (T. Raimondi); NET plasma-facing components (G. Vieider); erosion and redeposition (G. M. McCracken); and materials for tritium breeding, structural components, and superconductors (E. Roth, G. J. Butterworth, and G. Paterno, respectively). Also covered were commissioning and first operation of Tore Supra (R. Aymar), an overview of plasma heating systems (R. Wilhelm), development and testing of the NET breeding blanket (J. E. Vetter and M. Chazalon), NET safety analysis and the European safety and environmental program (J. Raeder), and reliability and availability (R&A) issues in NET (R. Bünde).

The scope was broadened by works on the free electron laser (M. van der Wiel), muon-catalyzed fusion (C. Petitjean), electromagnetic compatibility (P. C. T. van der Laan), and technology transfer (R. Teenhaus).

FUTURE OUTLOOK

Steady progress in understanding plasma behavior in the accessible parameter region was reported, as well as an encouraging extension of this region. On the other hand, expectations for plasma behavior in the as yet unreached parameter regions cannot be verified or proved beyond doubt. Therefore, unanimity on the scope of the forthcoming flagship fusion reactor is still not apparent. Do we need a new JET, extended by a linear upscaling of a factor of ~2.5? Or can we save ~10 yr of research and development (R&D) by starting construction on the more ambitious technology-relevant International Thermonuclear Experimental Reactor (ITER)/NET in 1994? Its plasma parameters might still be adapted if needed. Fittingly, the invited lectures were placed between the programmatic views given by R. Toschi of the NET team and P. Rebut of the JET team.

Toschi pointed out that there is a European fusion strategy that is strongly related to the NET project. The NET project will go through defined phases of operation. The first phase will include a physics machine to demonstrate scientific feasibility. It must have the potential and capability to demonstrate technological feasibility. There must be ignition and steady-state burn. Components must be tested in reactorlike conditions in NET. Safe operation of a reactorlike device with significant availability must be demonstrated. Energy extraction must be high grade (in contrast to mere cooling). Tritium breeding is essential. Parameters must be chosen to reach these goals. A 15-MA plasma current is the reference, but alternatives are considered. Various plasma shapes, such as single null, double null, and limiter, should be possible. Pulses should be at least 200 s long. Representative blanket sectors and modules need to be tested. Therefore, neutron wall loading, burn pulses, and integral burn time must exceed demand limits. The European fusion technology program is mainly oriented toward meeting NET demands, but fusion power reactors receive a growing share of attention.

Rebut emphasized that JET is now midway through its experimental program. With $n_e = 2 \times 10^{19}\ \mathrm{m}^{-3}$, the T_e and T_i exceed 10 keV. Transient $N_i T_i \tau_e$ has reached $3 \times 10^{20}\ \mathrm{m}^{-3} \cdot \mathrm{keV}$ at $T > 5$ keV. Plasma currents reached up to 7 MA for 2 s. However, with increasing additional heating power (24 MW absorbed by the plasma), confinement degraded in all regimes, suggesting a scaling with $I^2 B_t R^{1/2}$. Ignition would then need a plasma current close to 30 MA at a field of 4.5 T.

The next tokamak should have a plasma similar in size and performance to an energy-producing reactor. One could then study burning plasma, test wall technology and breeding blankets, and, above all, demonstrate the potential and viability of fusion as an energy source. The features of such a device (JIT) were outlined. Basically, it is a linear upscaling of JET by a factor of 2.5. Technical goals should not burden the device; the magnets, for example, could be copper.

Dowling reviewed the U.S. fusion technology program. The superconducting toroidal coil of the International Energy Agency large coil task was successfully tested at 9 T, well above the expected 8 T. Emphasis is now on the development for the 12-T range and even 15 T for ohmic heating. The ion cyclotron resonance heating (ICRH) antennas have been delivered for the Tokamak Fusion Test Reactor and Tore Supra. The 140-GHz gyrotrons operate at 100-kW continuous wave or 650-kW pulses; power and frequency will be increased. A tritium pellet injector has been tested. Lower activation stainless steel is under development. Strategically, the United States works actively on the ITER project.

Iijima reviewed the Japanese fusion technology program. There will be just one step between the Demonstration Plant (DEMO) and the second phase of JT-60. Technology needed for the construction of this next step will receive top priority in order to begin construction in 1992. Long-term needs for the DEMO will also be pursued. Its construction is scheduled to begin in 2007.

The Japanese fusion R&D budget for 1988 was 31.3 billion yen, including 23.4 billion yen for the Japan Atomic Energy Research Institute, of which 3.2 billion yen were reserved for fusion technology. The breakdown into single technological tasks illustrates the determination to cover the entire field. One unconventional item listed is antiseismic testing. The visual presentation of the future increase in toroidal coils and in the mass of irradiated lithium oxide from at present 10 g to 100 t in 2015 was impressive.

TOKAMAKS, PLASMAS, AND HEATING

Aymar reported that Tore Supra is in operation and produces plasma. New features of future tokamaks have been introduced, notably the large superconducting magnets and the associated cryogenic systems. Active cooling of plasma-facing components is performed for long-pulse operation. Auxiliary heating systems and more diagnostics will be installed.

Bell explained the preparation for D-T operation in JET, which was designed with D-T operation in mind. This is due in 1991. Preparation for this phase includes a dialogue with the safety and regulatory authorities. Reliability will be improved further. Analyses of routine and accident conditions and of expected wastes were done. It will be shown that JET satisfies the safety targets by a large margin.

Hemmerich described the JET gas-handling system, which will cope with D-T plasmas starting in 1991. The system needs include isotope separation, detritiation, and impurity processing by cryodistillation and cryosorption and by gas chromatography. Elements of the full system have been built and test results were presented. The system will be available in 1990 for testing and in 1991 for full-scale operation.

Remote handling in JET during its D-T phase, as in all future fusion devices, requires precise handling of delicate and/or massive objects over considerable distances in rather complicated configurations. Raimondi and coworkers have made a good start; microprocessors are used for control, and forced feedback allows development of feeling. Teach-and-repeat software is applied. Training is carried out at the one spare octand. The necessary components are ready and onsite. The upcoming task to develop a single trustworthy system from all of these components must not be underestimated.

Wilhelm gave an overview of plasma heating applications. Tasks include electrical breakdown in neutral gas and plasma buildup, heating to fusion temperature and nuclear ignition, active plasma profile control, and steady-state noninductive current drive. Today, total heating power absorbed in the plasma with pulse times of several seconds has reached 20 MW and greater power is planned. Ignition is expected to require 50 MW; steady-state current drive could require 100 MW. The different heating systems were analyzed in detail. For the near future, Wilhelm advocates ICRH for heating, neutral beam injection for current drive, and electron cyclotron resonance heating (ECRH) for plasma start-up. For an economical reactor, the requirements are very high, so R&D is essential. It is possible that ECRH could start and heat the plasma, and slow waves might efficiently drive the current.

Erosion and deposition in tokamaks were reviewed by McCracken. Plasma pulses are becoming longer and quasi-continuous operation is nearer. Edge temperatures are also increasing. Erosion thus not only influences the plasma, but also damages the solid structural parts facing the plasma. Most of the eroded material will be redeposited on the limiter, the first wall, and the divertor, but the question remains as to the development of the spatial distribution of the material.

Erosion mechanisms considered are physical sputtering, radiation-enhanced sublimation of graphite, and chemical effects by hydrogen on graphite and by oxygen on metals. The spatial distribution of the erosion was discussed. A grazing incidence of the field lines on the limiter surface can distribute the load of incoming particles. Little is known of their distribution in the scrape-off layer, particularly data on the impurities. The probability of heavy ions sticking is close to unity. Spatial distribution of the redeposition has been simulated by a one-dimensional model. From the literature, it is known that thin films made by sputtering on hot surfaces are strong and well bound to the surface. In JET, the sputtered layers were studied in detail using scanning electron microscopy and secondary ion mass spectrometry. The thickness is up to ~100 μm. Flaking, where present, can be described by the presence of impurities in the newly formed layers. The net erosion is a factor of ~4 lower than the gross erosion. In reactors, the higher density would lead to quicker redeposition, and the ratio of net to gross erosion might then be much smaller than 1:4.

ENGINEERING, TRITIUM CYCLE, AND BLANKETS

Vetter gave a clear-cut description of breeding blanket development for NET. A blanket must convert fusion energy into heat and shield the magnets from neutrons and other radiation. Shielding blankets can be quite compact and leave much valuable space in the magnet for the plasma. But in the technology testing phase of NET, a blanket must also provide adequate tritium breeding to close the fuel cycle. Otherwise, the available tritium sources would allow only a very short operation time. The breeding blankets are also called driver blankets. A flexible strategy has been developed to provide NET with shielding and driver blankets and with DEMO-relevant test sections. Many concepts need input from ongoing experiments on critical design issues.

Chazalon reported on blanket testing facilities in NET. The NET will accommodate a range of tritium breeding blanket concepts for testing that extends from small test capsules (<1 kW) to full segments (10 MW). As far as possible, the test elements will be prototypical for DEMO. Coolants include lithium salt in water, liquid metal (LiPb), helium, and pressurized water. Wall load, total burn time, and operation scenarios can be chosen. Test equipment outside the NET device will be accessible via test loops. Solid breeders will be tested as well as liquid LiPb. Detailed design by the European laboratories must still be done. The NET will have 96 segments. Most are water-steel shields. In some, the water could be loaded with lithium salt; in others, the water could cool a lithiated ceramic. In NET, samples will be radiation tested up to 10 dpa. The operational requirements for this aim were given; in particular, long-burn pulses of several thousand seconds are desired. The blanket testing will influence NET operation. Care has been taken to keep this influence unobtrusive whenever possible.

The NET plasma-facing components were described by Vieider. The first-wall structure uses austenitic stainless steel. Electron beam welding and brazing are applied. Cooling is by double-contained water. Fatigue life under thermal stress is being tested. Carbon-based armor tiles protect against disruption damage and high-Z impurities. They require remote replacement. Their cooling therefore uses radiation; convection can be utilized when good heat contact is assured through brazing or the use of flexible graphite foil.

The R&A issues in NET were discussed by Bünde. The NET is needed as a neutron source. It must run at least 10% of its lifetime to get a 1 MW·yr/m^2 fluence. During 1 yr, an availability of 25% should be demonstrated; for 200-h periods, the aim is 80%. From the start of the NET project, R&A programs have been in effect, including failure modes, effects, and criticality analyses on the component and plant levels. Identification and improvement of critical components are then done systematically.

MATERIALS FOR BLANKETS, STRUCTURE, AND SUPERCONDUCTORS

Roth evaluated ceramic tritium breeder materials, which may potentially be used for DEMO. Many ceramics properties can be tailored to facilitate blanket designs, which might also incorporate several varieties of ceramics in order to use their specific advantages. Tritium residence time in Li_2ZrO_3 is lower than in any other ceramic and seems to be adaptable to all proposed designs. Without a neutron multiplier, it could provide a tritium breeding ratio close to unity. Still, $LiAlO_2$ offers better thermal conductivity and lower activation, $LiSiO_4$ has even lower activation, and LiO_2 offers the best breeding ratio. Studies on beryllium and tritium extraction and recovery systems need to be intensified.

Butterworth stressed that low-activation materials play an important part in the development of fusion into a safe and environmentally benign energy source. In the neutron flux, with its energy range up to 20 MeV, an original construction material nucleus can change its proton number Z by 0, −1, or −2, and its neutron number by 0, +1, −1, or −2. The new nucleus may be a source of radiation, depending on its identity. This dependence can be traced back to the original composition. The log of the activity in becquerels per kilogram after 2.5 yr of service at 5 MW/m^2 varies from 4 for vanadium or chromium up to ~13 for silver and 12 for nickel and molybdenum, for instance. This means a ratio of 100 million! Unfavorable alloy components and impurities can therefore determine radiation behavior. This is true on very short time scales, as for operation and accidents, and on all intermediate time scales up to millenia, as for waste disposal. This leaves much room for adjustment. The steel industry has found no need so far to produce very specific pure materials, but the methods are available and have been proved in the electronics and space industries. (Apparently, isotopically clean materials are not considered.)

Paterno spoke of the new superconductors cooled by liquid nitrogen. They will attract much research, although it is highly improbable that they could be applied in fusion technology in the next 20 yr.

RADIOACTIVITY

Raeder gave an invited talk on the European safety and environmental program and NET. Fusion reactors will be nuclear reactors; they could be a permanent solution to the energy question. Their nuclear problems will approach reactor levels for the first time in NET. Low energies present at any moment and large volumes and surfaces lead to benign accident scenarios.

Radioactivity in operation, during maintenance, and after shutdown has two primary sources: tritium and the numerous and energetic fusion neutrons. Proficiency to handle both on the necessary scale has yet to be demonstrated. A European study program covers components, plants, safety guidance and assessment, and long-term safety and environmental aspects.

The tritium content may be in the range of 5 × 10^6 Ci per shielding blanket cooling circuit. The induced activity is mainly in the solid construction, but the mobile erosion dust from the first wall needs special attention. Even for an estimate of the induced activity, one needs to look into the detailed composition of the structural materials down to the elements used in the steel. A blanket row module might have 5×10^4 Bq/cm^3 with a conversion factor of 3×10^{-7} Sv/Bq.

Accidents are being analyzed by investigating loss of coolant flow and all coolant, loss of plasma confinement and vacuum, and loss of magnet function. The consequences of one or more loss on ~15 reactor subsystems will be considered.

Control of tritium containment benefits from the experience from Canada deuterium uranium fission reactors with heavy water moderators. Loss by operation and maintenance will be <10 mg/day. In a hypothetical accident, a maximum of 200 g of tritium could be released. The resulting dose rates depend strongly on the chemical form, D-T or DTO, and on geometric and meteorological conditions. Detailed investigations are continuing. One kilogram of highly activated structural material, if evaporated and converted into an aerosol, might possibly lead to a dose similar to the DTO release.

Fission products and transuranium elements are absent, of course. Still, the neutron-induced radioactivity leads to formidable new problems in the management of waste material. The problem exists even after only one full-power pulse. The mass and size of contaminated structural materials are very large. The configurations and compositions are complex. The tritium content complicates matters further. Detailed strategies involving remote handling of large parts are being developed. Licensing laws and regulations are still pending, which results in problems for international projects. Swedish rules have been applied in the studies, as they are the most developed.

CLOSING REMARKS

A book of abstracts is available for $50 from the SOFT secretariat, FOM-Instituut voor Plasmafysica, Rijnhuizen, P.O. Box 1207 SOFT, 3430 BE Nieuwegein, The Netherlands. The complete proceedings will be published by North Holland-Elsevier, Amsterdam.

The international and the local organizing committees, both chaired by Ad van Ingen, helped make the 15th SOFT a success. The next SOFT meeting will be held in 1990 in London.

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