MEETING REPORTS

SUMMARY OF THE U.S.-JAPAN WORKSHOP ON D-^{3}He FUELS IN FIELD-REVERSED CONFIGURATIONS, FUKUOKA, JAPAN, NOVEMBER 28–30, 1990

I. INTRODUCTION

The sixth in a series of workshops[1–4] on D-^{3}He–fueled field-reversed configuration (FRC) fusion reactors was held at Kyushu University. The workshop was co-chaired by H. Momota of the National Institute for Fusion Science (NIFS) and G. H. Miley of the University of Illinois; Y. Wakuta of Kyushu University served as the local host. There were 20 formal presentations by participants from Japan and the United States; in addition, there were attendees from Korea and the Soviet Union.

The original purpose of these workshops was to serve as a forum for the development of the D-^{3}He-fueled FRC reactor concept. About 2 years ago, a D-^{3}He/FRC reactor design study was initiated in Japan. The design study is a multi-institutional study with major contributions from NIFS (Nagoya University), Himeji University, Kyoto University, Niigata University, Osaka University, and the Institute of Future Technologies (Tokyo). The last three workshops [Nagoya, March 1989 (Ref. 3); Berkeley, November 1989 (Ref. 4); and the current workshop] have served to guide the evolution of the reactor design in the study. The status of the design study was reported recently at the International Conference on Plasma Physics and Controlled Nuclear Fusion Research.[5]

The current workshop included the customary updates on the progress of the design study and relevant recent progress from experiments and theory. It also added, for the first time, the results of a costing study. Also presented were several papers related to technological aspects of D-^{3}He fuels coming from institutions in Kyushu (Kyushu University and Kumamoto Institute of Technology). It was evident that the 2-year design study has reached a considerable level of maturity and has led to a clear identification of the critical issues that must be addressed.

The basic reactor scenario adopted for the design study incorporates the following elements: initial FRC formation in a theta pinch (producing a temperature of ~1 keV), translation into the burn chamber, heating and flux addition by neutral beam injection to ignition, and fusion burn (at nearly 100 keV). The principal parameters of the reactor design are summarized in Table I. These parameters clearly illustrate the attractiveness of the D-^{3}He–fueled FRC reactor concept.

1. A large fraction of the energy is released in the form of charged particles that can be directly converted to electricity at high efficiency. Consequently, the waste heat released to the environment is lower by a factor of 4 than a plant based entirely on conventional thermal conversion.

2. Neutrons arise only from reactions produced by a secondary fusion product (tritium). As a result, the neutron power is a factor of 35 below that of a comparable deuterium-tritium (D-T) fueled plant. The consequent reduction in radioactive waste makes this, by far, the nuclear reactor concept with the lowest nuclear hazard.

3. The reacting plasma volume is smaller by a factor of 6 than a comparable D-T-fueled tokamak reactor.

4. The supplied magnetic field is well within the capabilities of state-of-the-art superconducting technology (niobium-titanium).

These four factors taken together significantly enhance the reactor economics. Moreover, the substantially reduced nuclear hazard associated with low neutron power is of inestimable value. In view of these attributes, the D-^{3}He–fueled FRC holds promise of being the most attractive nuclear energy option yet conceived.

This summary is organized as follows. First, relevant recent developments in experimental and theoretical plasma physics are reviewed in Sec. II; this serves as background for the evolving reactor design study. The comprehensive reactor design is reviewed in Sec. III; and advances in specific

TABLE I

Principal Parameters of 1000-MW(net electric) Reactor

Overall plant efficiency (%)	63
Waste heat (MW)	580
Neutron power (MW)	77
Fraction of energy in charged particles (%)	74
Plasma volume (m^3)	67
Supplied magnetic field (T)	6.8

subsystems are discussed in Sec. IV. Other aspects of D-^{3}He research are examined in Sec. V. Finally, a review of critical development issues as determined at the workshop is presented in Sec. VI.

II. DEVELOPMENTS IN FRC PLASMA PHYSICS

Theoretical and experimental advances provide essential background for an evolving reactor design study. There were four such presentations at the workshop, three of which emphasized stability issues.

II.A. Stability

The first detailed measurements of the tilt instability were presented by M. Tuszewski of Los Alamos National Laboratory. These experiments on FRX-C/LSM employed a Mirnov probe array. The probes, which measured the toroidal magnetic field, were mounted just outside the chamber wall at several azimuthal and axial locations. Several trends were observed. Good FRCs were typically achievable for an initial filling pressure of <5 mTorr and initial bias fields <0.8 kG. FRCs with a flux confinement anomaly of <10 compared with classical transport were classified as "good" FRCs; those with flux anomalies >100 were classified as "bad" FRCs. Exceeding these pressure and bias field values rather consistently produced bad FRCs. Moreover, a clear correlation was observed between large tilt signals and the appearance of bad FRCs. A size trend was also found by comparing these results with experience on FRX-B and FRX-C; the upper bounds on filling pressure and initial bias fields become more severe with increased device size. Good FRCs, at least on the FRX series of experiments, tended to satisfy a gyrostability criterion[6]

$$s/E < \sim\tfrac{1}{3} \ ,$$

where

s = minor radius divided by the average internal ion gyroradius

E = elongation of the separatrix.

Mirnov probe results from the NUCTE-II device were presented by Y. Nogi of Nihon University. These experiments employed a smaller number of probes but showed tentative evidence for a tilt disturbance with signal levels similar to those measured on FRX-C/LSM but with apparently stable behavior. These FRCs satisfied the aforementioned gyrostability condition. The direction of the mode rotation was determined from the data and found to be opposite the direction of ion rotation. Such a counterrotating arrangement is indicative of a "restoring" tilt force in rigid gyroscopic systems, but it is unclear whether this rule applies to the FRC tilt.

Important aspects of these and other experiments are not yet understood. Observed tilt signals were below the levels predicted by nonlinear magnetohydrodynamic (MHD) simulations by a factor of 2 to 3. A long-lived plasma entity survived the tilt disturbance. This "successor" plasma was longer than the original FRC but retained axial structure symptomatic of an intact FRC. If it were indeed an FRC, its s value was reduced by a factor or 2 or 3. Large-s FRCs (3 to 6) were observed in the triggered reconnection experiment using hydrogen and special operating modes.[7] These FRCs significantly exceeded the gyrostability condition, although their confinement times fell below empirical scaling laws found for lower s FRCs. In view of these issues, results from the recently completed LSX facility will play a crucial role in understanding the stability of large-s FRCs.

The internal current density structure was the subject of a presentation by L. C. Steinhauer of Spectra Technology. A very consistent relationship was found between the current profile parameter (current density at the field null divided by the average current density inside the separatrix) and x_s (separatrix divided by coil radius). The observed current profiles are hollow, i.e., with current profile parameter less than unity. This trend cannot be explained by transport rates associated with any known anomalous mechanism. Instead, it may be evidence of a regulatory mechanism, perhaps MHD activity, which continuously assures that the internal profile of the FRC remains at the condition of marginal stability. It is not yet understood what combination of MHD and kinetic effects might produce such a marginal stability condition. If such a regulatory mechanism does operate, then the trends cited by Tuszewski could be explained as follows. Theta pinch formation tends to produce peaked current profiles, and the larger the size, filling pressure, or bias field, the more peaked the profiles. Immediately after formation, such FRCs would relax to the requisite hollow profile, dissipating some amount of flux in the process. The apparent flux limit (or possibly an s/E limit) would then be the consequence of improper formation rather than an inescapable instability.

The possibility that the stable behavior might arise from ideal MHD theory with the proper equilibrium was discussed by A. Ishida of Niigata University. The discussion focused on a sufficient condition for stability (originally derived by Bernstein et al.[8]), which requires that the surface quantity $p(\oint dl/B)^{-\gamma}$ increase monotonically from the O-point to the separatrix. Equilibria satisfying this condition have previously been found.[9] However, another necessary condition for stability[10] predicts instability for essentially all FRCs and appears to be inconsistent with this sufficient condition. Evidently, the ideal MHD stability as well as gyroviscous effects require closer examination to resolve these questions.

II.B. Confinement

An MHD confinement simulation code was used by S. Ohi of Osaka University to interpret the transport behavior in several experiments. The anomaly of the inferred resistivity (compared with classical transport) was found to decrease for FRCs with higher elongation. Interestingly, it followed from these results that instances where the particle confinement time is less than twice the flux confinement time (the usual situation) have a hollow current profile. This is consistent with the inferences of hollow current profile noted earlier.

III. COMPREHENSIVE REACTOR DESIGN

III.A. Overview of the Reactor Design

An updated reactor design was presented by H. Momota (NIFS). In most cases, this design has parameters very close to those of the design presented at the previous workshop,[4] with two notable exceptions. First, the thermal power was increased to 1.6 GW(thermal) to account for more realistic direct conversion efficiencies: 65% for the first stage [thermal stream, 843 MW(thermal)], and 76% for the second stage [15-MeV proton stream, 336 MW(thermal)]. Second, refueling in the new design employs a new idea whereby a pellet is fired at relatively low speed into the region just beyond one end of the FRC. Then a control coil is activated to cause a transient "strike" of the FRC to envelop and absorb the pellet.

The two principal unresolved issues of the design were highlighted. The transport mechanism in FRCs has not yet been determined. The reactor design assumed, somewhat arbitrarily, that the transport anomaly (compared with classical) is 10 at the start of the heating phase (1 keV) and 260 in the burn phase (nearly 100 keV). The former, at least, is roughly consistent with empirical scalings in current devices. The assumed energy transport has a significant impact on one particular aspect of the design, the neutral beam power required for heating to ignition, or 150 MW in this design. Stability was assumed at all stages of the plasma evolution. Stability might be achieved by energetic neutral beam injection during the heating phase and by energetic fusion products during the burn. The most precarious stage in terms of stability may be the state just after formation and before neutral beams are injected. At that point, the value of s is ~ 13. Significantly, these two issues concern uncertainties with respect to the physics rather than the technology of the system.

III.B. Cost Estimation of a D-^{3}He FRC Power Plant

Results from a recent cost evaluation of the design were presented by Y. Kohzaki of the Institute for Future Technologies. The cost model was based on the weights of major equipment and used realistic costs in dollars per kilogram for the various system elements. The costing structure employed the standard accounting system originally developed at Pacific Northwest Laboratories, and later modified by the STARFIRE study, and the ESECOM committee. This permits a uniform comparison of economic characteristics with other kinds of fusion and fission reactors. The estimated cost of electricity (COE) is 29 mil/kW·h which is 80 to 90% of the COE of economical pressurized water reactors and 70% of the estimated cost of D-T reactors. This attractive figure springs mainly from two factors: the high efficiency of the direct energy conversion system and the compactness of the burning section and magnet system. As in other fusion reactor systems, the COE is dominated by the capital cost (which is 76%). The fuel cost, which accounts for 6% of the COE (based on \$200/g for ^{3}He), is not a dominant factor. The neutral beam injector system was identified as the most sensitive cost-driving factor. This system (the main part of which is only during the heating phase) accounts for 40% of the capital cost.

IV. REACTOR TECHNOLOGY AND PLASMA ENGINEERING FORMATION AND TRANSLATION

The reactor design relies on the well-established theta pinch formation technique. Modeling the formation and translation phase was reviewed by S. Ohi of Osaka University. The model employs a phenomenological description of reversed-flux dissipation because the actual mechanism is not understood. The associated parameter was set to conform with experience on FRX-C/LSM. The theta pinch in the design employs a 400-kV loop voltage (with four feed slots, 100 kV each), a current rise time of 35 μs, and a 33-MJ capacitor bank.

IV.A. Control, Fueling, and Heating

The transitional "heating" stage, involving the addition of particles and poloidal flux as well as thermal energy, was discussed by Y. Tomita of NIFS. Particles are added by pellet injection, poloidal flux by neutral beam current drive (the Ohkawa effect), and energy by neutral beam heating. At the same time, the external magnetic field is ramped up from 0.3 to 6.4 T. An important issue is the proper programming of these various sources. If the transition is too rapid, the neutral beam power requirement is too high; if it is too slow, then the axial contraction of the FRC on a transient basis becomes too large. The selected programming represents a compromise between these limits involving a maximum of 150-MW neutral beam power and maintaining roughly constant plasma volume.

Another control issue, discussed by M. Ohnishi of Kyoto University, concerns the rotational stability that is compromised if the rotation rate of the FRC gets too large. It is undesirable to use multipoles to control the rotation instability because they break the axisymmetry of the plasma. Instead, the rotational mode can be stabilized by the inertia of energetic ion beams. A stability analysis showed that quite modest beam densities (0.002 compared with the thermal plasma) are sufficient to stabilize the mode.

IV.B. Sustainment and Burn

Sustainment of the magnetic configuration during the burn phase is achieved by neutral beam current drive near the O-point (the Ohkawa current) and by the bootstrap effect elsewhere. Penetration to the O-point region requires a 1-MeV neutral beam. Ignition is achieved by thermalization of most of the energy of the fusion products (15-MeV protons and 3.5-MeV alpha particles). M. Ohnishi presented results from a new one-dimensional model of the steady-burn phase in which the self-consistent equilibrium was determined. In these equilibria, which are far from "rigid rotor," the ion rotational velocity roughly mimics the current profile. Ohnishi estimated that 6 MW of neutral beam power would be needed to sustain the magnetic flux of a near-term experiment (a 20-cm separatrix radius).

An issue that has come up in previous workshops is what fraction of the fusion products are confined and, therefore, able to deposit their energy in the burning plasma. A conservative approach used in the past is to assume that only those fusion products with orbits wholly within the separatrix are effectively confined.[11] G. H. Miley discussed this issue and cited calculations showing that many fusion products are absolutely confined despite having orbits that extend outside the separatrix.

IV.C. Direct Conversion

Since all the primary fusion products in a D-^{3}He reactor are charged particles, direct conversion can be applied to achieve a very high plant efficiency. An overview of the direct conversion system was given by H. Momota. It is a two-stage system employing "conventional" Venetian-blind collectors for the thermal plasma stream and an innovative traveling wave (TW) system for the unthermalized 15-MeV protons. More realistic estimates of the conversion efficiency design have been made, accounting for parasitic losses to the finite size mesh, thermal spread of the plasma stream and other factors. The cooling power required in the grid has also been calculated. The engineering requirements (e.g., grid cooling) are not severe.

Details of the TW converter were described by K. Sato of

Himeji Institute of Technology. The TW converter employs a modulator to bunch the incoming stream of 15-MeV protons. Then the bunches are ponderomotively trapped in a traveling electromagnetic wave (11-MHz, ~5-cm wavelength) with a decreasing phase velocity. One-dimensional particle simulations were used to determine the conversion efficiency. The best efficiency was found when the modulator imposed a sawtooth modulation on the plasma stream. The time-dependent behavior of the converter was analyzed using a lumped circuit description. It was found to have stable operation with spontaneous startup (i.e., an external power supply for startup is unnecessary).

V. OTHER TOPICS IN D-^{3}He RESEARCH

Several other presentations on various technological aspects of D-^{3}He fusion were presented at the workshop. These activities, all representing research at institutions on the island of Kyushu, were reviewed by Y. Wakuta. As evidence of the interest in advanced fuels, Professor Wakuta cited the Committee on Advanced Fuel Fusion, which is authorized by the Japan Atomic Energy Research Institute and which meets every 2 months.

Polarization of the deuterium nuclei results in a 50% increase in the D-^{3}He fusion reaction rate if all the nuclei are polarized. This can have a significant impact on a marginal fusion system. O. Mitarai of the Kumamoto Institute of Technology presented the results of a study of polarization effects in a D-^{3}He tokamak reactor and found that a 33% increase in reactivity leads to a factor of 2 reduction in the required beta and a similar reduction in the radio-frequency heating power. Polarization of deuterons was demonstrated at very low temperature (1 K) using a high magnetic field (10 T). It may also be possible using microwave techniques. Once achieved, polarization is easy to maintain, requiring magnetic fields of only a few Gauss to maintain, and having a relaxation time on the order of 1 h in the absence of a field.

The issue of tritium handling in the fuel cycle of a D-^{3}He fusion reactor was discussed by M. Nishikawa of Kyushu University. The obvious advantage of D-^{3}He fusion fuels is requiring no tritium breeding (a requirement for D-T fuels that imposes severe demands on the blanket design). However, tritium handling is still necessary because of secondary D-D reactions that produce ~15 g T/day. There are two strategies. One is to remove the tritium from the unburned exhaust fuel, which requires an isotope separator (tritium from deuterium). This option leads to a statically stored tritium inventory of 80 kg of tritium after 30 yr (accounting for its normal decay). The second strategy is to leave the tritium with the deuterium and to simply burn it. This, of course, leads to increased neutron damage and shorter first-wall lifetime.

Two papers addressed aspects of D-^{3}He fuels in inertial confinement fusion (ICF) systems. Results from a burn simulation were presented by Y. Nakao of Kyushu University. Apparently, a core of D-T is needed in the center of the pellet to achieve ignition of the D-^{3}He reaction. A magnetically protected, liquid-wall ICF reactor cavity was examined by H. Nakashima of Kyushu University. Some of the reaction energy in such a system can be directly converted by means of pickup coils that respond to the plasma recoil. An instability analysis was performed to assess the effect of the Rayleigh-Taylor instability on the plasma-magnetic field interface.

VI. CRITICAL ISSUES

The final session of the workshop was devoted to identifying the critical issues that must be addressed in the D-^{3}He-fueled FRC development program. These issues will influence the direction of the next generation of FRC experiments. Some attempt was made to distinguish between critical issues and issues of lesser importance. The development issues were classified under four headings: physics, technology, concept merit, and development strategy.

VI.A. Physical Issues

The most critical issues in the development program concern the physics rather than the technology. Four issues stand out (the first two of which are perceived to be the most crucial): (a) global stability, (b) transport, (c) energetic beam-plasma interaction, and (d) fusion product-related physics. The most important global stability question concerns the tilt and related modes with higher azimuthal mode numbers. The least attractive possibility here is the case where the principal intrinsic stabilizing factor is gyrostability, which requires s/E to be less than $\sim\frac{1}{4}$. In this case, gross stability requires a combination of neutral beam injection and energetic fusion products. The current reactor design, which incorporates neutral beam injection, makes the conservative assumption that this possibility applies. There are other possibilities that may reduce or eliminate the need for neutral beam stabilization: The stability may be improved by parallel kinetic effects or by proper equilibrium. In the most attractive case of all, the plasma takes care of its own stability by means of a regulatory mechanism, some evidence for which was cited earlier. A related issue concerns a "stability bottleneck": If stability depends on an energetic beam component, then how can the postformation FRC (which has $s > 10$) be stabilized, because, at that point, neutral beam injection has not yet been initiated.

Transport is a crucial issue because it affects the size of the reactor and of important subsystems. For example, in the current design, the 150-MW neutral beam system accounts for 40% of the capital cost. The size of the neutral beam system is determined by the transport rate. There are two important aspects of the transport question: What are the dominant transport mechanisms and the associated rates, and how does the edge layer contribute to particle and energy confinement? (The edge layer may, in fact, turn out to be an asset.) A related question concerns the effect of energetic fusion products on transport, e.g., by induced turbulence. Finally, there is a question of a confinement bottleneck in the initial heating phase where the transport is poor and drives the design accordingly.

The physics of the energetic beam-plasma interaction has several aspects about which there are important questions. How severe is the beam current requirement relative to the plasma current to assure stability? Certainly, a lower requirement means a more attractive system, and vice versa. How much does the beam degrade the confinement? What is the effectiveness of the beam-plasma interaction in terms of current drive and heat deposition profile for a self-consistent equilibrium?

There are also two important questions concerning fusion product physics. How does the effectiveness of the associated current drive and heating profile depend on the plasma size and other parameters? What is the self-consistent ash transport of thermalized fusion products relative to the transport of the main plasma? Excessive ash buildup can compromise ignition.

VI.B. Technological Issues

The most important technology issue concerns the theta pinch formation method. The theta pinch required for a reactor is considerably larger than any built to date. Since the understanding of theta pinch formation of FRCs is still empirical in several respects, it is essential to gain an understanding of the limiting factors that may constrain the design of a scaled-up device. There are two other questions of technology that are perhaps less crucial, but nonetheless, must be answered satisfactorily. How severe are the technological and/or economic barriers to a 1-MeV neutral beam system, and what are the design difficulties in the direct conversion system, including both the "conventional" and traveling wave stages?

VI.C. Concept Merit Issues

The advancement of the D-^{3}He-fueled FRC depends on the perception by fusion researchers that it is an attractive concept. The "concept merit" is a vague concept and more quantitative merit indices are needed. Certainly, economics (e.g., the cost of electricity) is one factor, but one still open to question in a development program spanning a number of years. Other merit indices need to be quantified as well, including synchrotron loss and nuclear hazard. For synchrotron loss, it must be determined how the FRC concept can be compared quantitatively with other confinement concepts. In terms of nuclear hazard, how much is the nuclear hazard reduced for D-^{3}He-based FRC fusion compared with D-T or other D-^{3}He systems. Another merit issue concerns the use of polarized fuels: Does a significant increase in the reactivity (e.g., 30%) give enough of an economic advantage to justify the trouble of making a polarized fuel?

VI.D. Development Strategy Issues

Strategy issues concern the best path to a reactor from the present status of the FRC concept. The first question relates to the sensitivity of the design. Suppose the transport rate (or some other physics index) turns out to be twice (or half) the level assumed in the design. How would this affect the design? Moreover, expecting that changes will occur in the physical understanding, what is the best strategy for accommodating such changes? For example, if the transport rate were a factor of 2 lower, is the best strategy to reduce the magnetic field, to reduce the plasma size, or some other response? The second question relates to the fuel strategy. What is the best trade-off between removing tritium, which increases the tritium inventory and requires a specialized isotope separation system, and burning the tritium, which increases the radiation damage and radioactive waste problem. The third question concerns the FRC development path and the developmental steps from the present experiments to a reactor. The intervening devices should address essential physics issues not treated in previous work, e.g., energetic beam stabilization and steady-state sustainment.

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April 19, 1991

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SUMMARY OF THE FIRST WORKSHOP ON ALPHA-PARTICLE PHYSICS IN TFTR, PRINCETON, NEW JERSEY, MARCH 28-29, 1991

I. INTRODUCTION

The First Workshop on Alpha-Particle Physics in TFTR was held March 28-29, 1991, at the Princeton University Plasma Physics Laboratory (PPPL) in Princeton, New Jersey. Approximately 35 scientists from outside PPPL attended the meeting, including representatives from major U.S. fusion laboratories and universities, as well as from Japan, Joint European Torus (JET), and the U.S. Department of Energy.

The motivation for this meeting was to clarify and strengthen the Tokamak Fusion Test Reactor (TFTR) alpha-particle physics program and to increase the involvement of the fusion community outside PPPL in the TFTR deuterium-tritium (D-T) experiments (which are currently planned for