MEETING REPORTS

SUMMARY OF THE WORKSHOP ON THE ENGINEERING ASPECTS OF FUSION IGNITION EXPERIMENTS, CHICAGO, ILLINOIS, OCTOBER 29-30, 1981

INTRODUCTION

A key next step for fusion development is the achievement of a "burning," i.e., ignited, fusion plasma. Not only will this signal the start of an era of fusion power experiments, but it will enable an exhaustive study of the physics of a plasma where fusion product heating dominates. Indeed, there is growing confidence in the fusion community that an ignition experiment might be carried out in a device of relatively modest size, and at a cost that would be attractive in the near future. Consequently, the present workshop was held in conjunction with the 9th Symposium on the Engineering Problems of Fusion Research [sponsored by the University of Illinois (UI) Fusion Studies Laboratory] in order to examine engineering aspects of such an experiment in some detail. Three working groups were organized. Group A was to assess the state-of-the-art in physics and technology for such experiments; group B was to consider special aspects of magnets, materials, and radiation problems involved; and group C was to provide systems aspects plus energy extraction. Summaries of discussions prepared by each group follow.

GROUP A–HEATING/IGNITION AND INJECTION/BURN CONTROL

Introduction

The goal of discussion group A was to assess the state-of-the-art in physics, engineering, and technology for near-term ignition experiment concepts. Ignition was defined as thermal runaway when $P_{aux} = 0$. This discussion was limited to small, deuterium-tritium (D-T)-fueled toroidal devices with normally conducting magnets, which could be constructed for $\approx$\$$10^8$ in a time span of $\approx$5 years. Larger devices with superconducting magnets were ruled out as they are too costly.

The questions addressed were aimed at determining whether there was an adequate basis to achieve ignition. The physics questions discussed were heating methods, needed confinement for both the plasma and the fusion products, refueling, burn control, impurity control, and plasma diagnostics. The engineering and technological difficulties that could impede a successful ignition experiment were also discussed.

The devices considered were the RIGGATRON™ tokamak, the Ignitor, the Alpha-tor, the Ohmically Heated Toroidal Experiment (OHTE), reversed field pinch (RFP), field-reversed theta pinch (FRTP), and the Spheromak. The first three of these are tokamak concepts. The OHTE and RFP are larger aspect ratio devices; they differ by the inclusion of helical windings on the OHTE. The FRTP and Spheromak represent the compact tori. For each concept, an advocate spoke for 15 to 20 minutes explaining and answering questions. A synopsis of this discussion is given in Table I. We amplify this by considering each concept sequentially.

RIGGATRON Tokamak

This program is currently funded and under way at INESCO, Inc., in La Jolla, California. The concept is to build an ignition experiment using technology that will extrapolate directly into a reactor in the shortest possible time frame. The plan is to build a number of small, high field tokamaks to explore the parameter space available to this concept. This is expected to take $\approx$5 years and to cost $\approx$\$$10^8$.

The RIGGATRON™ tokamaks will be designed to reach ignition temperatures primarily with ohmic heating (OH). Hence they will have large values of the ratio B/α where B is the toroidal field (TF) and α is the aspect ratio. Auxiliary heat will be supplied only if necessary in the form of $\approx$3 to 5 MW of ion cyclotron resonance heating and/or plasma compression. Most of the commonly cited plasma scaling laws, e.g., Alcator scaling, Coppi-Mazzucato scaling, or modest enhancements of the ion-neoclassical transport, would predict that ignition could be achieved. Alpha confinement is not expected to be a severe problem since $I_p > 6$ MA. Since $\beta \approx 2\%$ at ignition, instabilities are also not expected to pose serious problems.

These tokamaks would be refueled by gas puffing. Access is available for pellet injection if this proves desirable. There is no room for a divertor, but a first wall, which will also serve as the limiter, composed of low-Z coatings (probably beryllium or carbon) appears feasible to keep impurity concentrations to reasonable levels. Access is available for hardened conventional plasma diagnostics. Plasma neutrons will also provide a source for diagnostics. Many techniques are available to control the postignition thermal runaway. These include conventional methods such as variable TF ripple, using the beta limit, refueling and position control, and impurity injection, and other possibilities, such as variable D-T ratio and radio-frequency (rf)-induced turbulence.

The main difficulties in performing these ignition experiments lie in the technological problems of constructing the magnets and first wall. The stress and thermal-hydraulic problems in the TF and OH magnets and the first wall are severe but appear to be surmountable.

In summary, though plasma scaling and "kitchen

TABLE I

Small Toroidal Reactor Concepts for $<\$10^8$

Topic	Reactor						
	RIGGATRON™	Ignitor	Alpha-Tor	OHTE	RFP	Spheromak	FRTP
Plasma heating	Main: ohmic Auxiliary: ICRH Compressional	Ohmic and compressional	Two-stage compression	Ohmic	Ohmic	Ohmic plus neutral beams	Neutral beams
Plasma confinement	Tokamak scaling	Tokamak scaling	Tokamak scaling	Not well known	Not well known	Electrons: Alcator Ions: 10 X neoclassical	Lower hybrid drift versus velocity space loss cone
Alpha-particle confinement	Good	Good	Poor	Good	Good	Good	Good
Refueling mode	Gas puffing (pellet)	Gas puffing (pellet)	?	Gas puffing (pellet)	Gas puffing (pellet)	Neutral beams	Pellet
Impurity control	Low-Z first wall	Gas blanket	?	Low-Z first wall Magnetic limiter	Low-Z first wall Divertor	Natural divertor	Natural divertor
Burn control	TF ripple (beta limit, refueling, rf)	Shark tooth oscillations	?	Density control Field error Beta limit	Similar to OHTE	Driven regime $Q \sim 1$ to 10	Unknown
Diagnostics	Conventional and neutron	Conventional and neutron	?	Conventional and neutron	Conventional and neutron	Strong turbulence	Conventional and neutron
Physics status	State-of-the-art common to tokamak	State-of-the-art common to tokamak	State-of-the-art common to tokamak	State-of-the-art similar to RFP	State-of-the-art similar to RFP	Presently cold, turbulent, and impure	United States cannot duplicate Soviet experiments
Technology status	TF, OH coils, and first wall are problems	Magnets are "ok"; plasma chamber is unknown	?	Straightforward modular design concept for renewable core	Straightforward except for first-wall steady-state current drive	Limits on gun and current drive	Need to solve plasma rotation problems
Backing	Funded for ignition experiment	Funding is sluggish	Funded for ignition experiment	Funded experiment	Worldwide series experiments	Slow	FRX-C work ongoing

physics" are of concern, the main problems appear to lie in the engineering design and construction of viable TF, OH, and first-wall structures.

Ignitor

This is the original ignition experiment advocated by B. Coppi that has been supported by Italian government agencies. It consists of a relatively small, high field ohmically heated device that relies on adiabatic major-radius compression to reach ignition.

The status of the physics outlook is also very good. The Ignitor was designed using Coppi-Mazzucato scaling, though other scalings would also predict success. The plasma current of 4 MA should provide good alpha confinement. The stability outlook is also very favorable.

Refueling is feasible by either gas puffing or pellets. Coppi predicts that the density will be sufficiently high so that a gas blanket will form around the plasma to shield it from the influx of impurities from the wall. He further predicts that the "shark tooth" oscillations in the $q < 1$ region will inhibit the thermal runaway and keep the temperature at a desirable level. Conventional and neutron diagnostics are planned for this experiment.

Coppi feels that the design of the adopted cryogenic magnets is adequate but that the viability of the first wall is unknown.

Alpha-Tor

This is an experiment currently under construction at the Kurchatov Institute in Russia. It is a two-stage compression experiment in which the compression is in both the minor radius and major radius. Relatively little information about this experiment was available to the workshop.

If the compressions are fast enough to be adiabatic, this device could be expected to achieve ignition temperatures. However, rapid minor radius compression appeared to present significant technological problems. Another difficulty is that the alpha-particle confinement appears poor. The final plasma current is only 1.2 MA. At this level, only $\approx$50% confinement would be predicted with classical slowing down models.

OHTE

This experiment is currently funded and under way at General Atomic Co. (GA), La Jolla, California. It is hoped that an upgrade of the present OHTE experiment could achieve ignition in six to seven years. The OHTE concept is similar to the RFP except that it utilizes an external helical coil to provide the needed transform. This obviates the need for large plasma currents near the edge of the plasma. The advantage of OHTE or RFP over a tokamak is that there is no $q_a > 1$ constraint. Thus, more plasma current may be driven through it and OH alone should be sufficient to achieve ignition.

Experimental results to date show the formation of a stable OHTE equilibrium. Experiments are under way to provide a data base of confinement time or plasma scaling, and to examine magnetohydrodynamic (MHD) stability and impurity effects.

The theoretical outlook is favorable. Stability calculations for straight cylinders predict high beta. Neoclassical losses are expected to be small. Tokamak scalings for the confinement time would be favorable.

Refueling by means of either pellets or gas puffing is planned. Impurity control with low-Z walls and magnetic limiters is feasible. For burn control, a conventional method such as density control is one option, but a better alternative may be to use field errors to enhance transport. Diagnostics using conventional and neutron detectors are planned.

The engineering of the OHTE is relatively straightforward. The modular design concept will allow quick replacement of the core. High magnetic fields are not required in OHTE.

In summary, the engineering of OHTE is simpler than for the high field tokamak concepts, but the physics data base is considerably smaller and requires greater extrapolation to ignition conditions.

RFP

The RFP is under investigation worldwide in a series of experiments. At present there is no commitment to proceed with an ignition experiment.

The prospects for a successful RFP ignition experiment are similar to that for OHTE. Most of the discussion of OHTE also applies to RFP. Differences lie in the plasma currents that create the transform. Large edge currents are required to create the reversed field equilibrium but no helical field is required. A steady-state current drive would be helpful for an ignition experiment.

The status of the RFP is likewise that the data base requires a large extrapolation to ignition regimes but that the engineering problems are relatively straightforward.

Spheromak

The principal Spheromak experiment is the S-1 at Princeton Plasma Physics Laboratory (PPPL). There is no present commitment to an ignition experiment.

Present day experiments are still cold, turbulent, and often dominated by impurities. Alcator scaling fits the electron transport but the ion losses are at least ten times neoclassical. There is, as yet, no significant data base to extrapolate to reactor conditions.

System studies of Spheromak reactors have been performed. Ohmic heating supplemented by neutral beams is proposed. These beams would also refuel the plasma. The Spheromak contains a natural divertor that should help to keep the plasma clean, though present experiments start with a very dirty plasma. Diagnostic methods to investigate the strong turbulence will need to be developed if the ions are in fact anomalously confined. Burn control would not be required in Spheromak, since no thermal excursion exists, as it would be a driven device with $Q \approx 1$ to 10.

The principal technology problem is that a limit exists on the size of the plasma gun. Thus current drive must work.

Thus, for Spheromak, there are significant questions relating to both physics and technology that must be solved for a successful near-ignition experiment.

FRTP

There is an ongoing series of experiments with FRTPs, though none is an ignition experiment nor is there a commitment to build an ignition experiment. The Field Reversal Experiment-C (FRX-C) at Los Alamos National Laboratory (LANL) is the largest U.S. experiment.

Plasma confinement in FRTPs is largely unknown. Candidate loss mechanisms are the lower hybrid drift mode and velocity space loss cone effects. These two mechanisms involve considerably different physics and affect scaling differently. Alpha-particle confinement should be good. There are experimental discrepancies between experiments in the United States and the Soviet Union.

Neutral beams would be used for heating, to build up the plasma density, and to inhibit rotational instabilities. Pellets would be used for refueling. The FRTP also has a natural divertor for impurity control. The question of burn control has not been investigated. Conventional diagnostics plus neutron detectors would be used in an ignition experiment.

The technology to develop the neutral beam injection and refueling needed to prevent rotation and to obtain/maintain ignition remains to be demonstrated. Thus again there are significant deficiencies with both the physics data base and the technology needed for an ignition experiment.

GROUP B–TOROIDAL MAGNETS, RADIATION, ACTIVATION, AND MATERIAL STRESS PROBLEMS

Overview

Fourteen workshop attendees participated in the discussions of working group B, bringing to the sessions a broad expertise, ranging from extensive knowledge in conceptual design of fusion ignition machines and reactors to actual experience in design and fabrication of high field, compact experimental fusion devices.

Because of the broad subject matter and the limited time, the approach taken by working group B was to identify issues and hold brief general discussions as one group, to divide into subgroups according to issues and participant's expertise, to discuss the issues in more detail in these subgroups, and finally, to involve all participants in postworkshop preparation of discussion summaries.

The original list of issues as identified by the group is shown in Table II. As a result of subsequent group and subgroup discussions, some of the items on this original list were subsequently defined as "non-issues" for a compact ignition device.

TABLE II

Original List of Issues Identified for Consideration by Working Group B

Electrical insulation lifetime
TF coil stresses
Remote maintenance on small devices
Shielding
Plasma chamber
Design and fabrication of components
Materials handling, recycling, activation
Decommissioning
Engineering information to be gained from an ignition experiment
Coil cooling
Diagnostic and testing systems
Blankets

Four subgroups were identified:

1. magnet design and fabrication
2. neutronics (activation, damage, shielding, etc.)
3. plasma chamber issues
4. diagnostic and testing systems.

These subgroups discussed the issues to establish the status of the particular item, to identify specific problems or needs, to define possible approaches to solving the problems or meeting the needs, and to identify the engineering information to be gained from an ignition experiment that would be beneficial for subsequent devices. A general guideline was adopted that discussions would be limited to compact ignition devices with nonsuperconducting magnets and would exclude issues relating to demonstration or commercial reactors.

The subgroup discussions and conclusions are presented in the following sections.

Magnet Design and Fabrication

Issue: Magnet Insulation–Organic Versus Inorganic

This particular subject was discussed in both the magnet design and fabrication subgroup and the neutronics subgroup, and as similar conclusions were reached in both groups, the discussions have been consolidated in this section.

This issue is concerned primarily with the lifetime of the insulators in the magnets that are close to the plasma neutron source in a compact ignition machine. The response of both classes of insulators to very high 14-MeV neutron exposures is not known. In general, organic insulators exposed to lower energy neutrons display severe mechanical degradation at $\sim 5 \times 10^9$ rad. Depending on the wall loading characteristics of the particular device, this can limit the machine operation to a few thousand shots.

Inorganic insulators, on the other hand, have an exposure limit of $\sim 10^{12}$ rad. However, in contrast to organic insulators, they are typically quite brittle materials and very little appropriate experience exists in magnet applications. An appropriate magnet design using organic insulators has to avoid shearing stresses and excessive tensile stresses in the insulation. Bending moments should be minimized therefore and overturning moments balanced by formlocking.

The consensus was that organic insulators will work in a compact ignition machine but with a relatively short lifetime. Possible approaches to successful utilization of organic insulators, should longer machine testing lifetime be necessary, include the incorporation of 5 to 10 cm of shielding to increase the number of shots by a factor of ~2 to 5, or development of a design in which the insulation could be replaced. In some ignition devices, the addition of 5 to 10 cm of shielding between the plasma and the coil may be impossible because of the relatively narrow design window, while for others it may be possible but expensive as it increases the size of the device and dictates higher fields at the coils. Moreover, this approach will make ohmic ignition more difficult and could make formidable auxiliary heating necessary. Replacing insulation would be a very difficult task, especially since it would have to be done remotely, and therefore this was seen to be an unattractive approach.

It was also the consensus that while inorganic insulators could give longer lifetimes, significant development and testing are required before they can be utilized with confidence. It was felt that such development should, however, be strongly encouraged.

Operation of an ignition device with these insulators would provide a practical demonstration of their use in a high energy neutron environment and could be the source of valuable data on irradiated mechanical and electrical properties.

Issue: Conductor Form—Bitter Plate or Tape Wound

Two of the basic approaches proposed by designers of tokamak ignition experiments for the form of the TF coil conductor are Bitter plate and tape wound. Participants in this subgroup were generally in agreement that either approach could work and felt that the needed technological solutions for high field toroidal magnets had been found during the designs of the Alcator devices, Massachusetts Institute of Technology (MIT), the Frascati Torus, Ignitor (U.S.-Europe), and ZEPHYR (Federal Republic of Germany). The successful operation of the Alcator devices and of the Frascati Torus at 100-kG levels with no apparent difficulties has verified the soundness of the adopted design criteria.

Selection of the preferred method depends to a large extent on the experience of the particular design group and the parameters of the considered device. For this reason, the MIT and INESCO design teams have selected the Bitter plate approach for their designs while the tape wound design is the choice of the Garching group. The Frascati and Ignitor groups have adopted novel and different solutions that are more suitable for the magnetic configuration they have chosen.

Issue: Coil Cooling—Inertial Versus Steady State

Both inertial and steady-state cooling of the TF magnets have been proposed for experimental ignition devices. As an example, the ZEPHYR design as developed by IPP-Garching incorporates liquid nitrogen inertial cooling with plasma burn times of 6 s and cooldown times between shots of 50 min. The RIGGATRON design of INESCO, on the other hand, aims at utilizing steady-state water cooling for a shorter burn time of 1 to 2 s. An important factor in the selection of steady-state water cooling for RIGGATRON is the desire to use an approach that can be carried forward to subsequent longer burn time devices.

Considering only the internal heating (surface heating was considered by the first-wall subgroup), it was the consensus of the subgroup that sufficient information exists in the literature and that there is sufficient experience in both LN_2 cooling and water cooling that there are no significant data needs. Inertial cooling is thought to be adequate for reaching ignition conditions; however, when very long burn time effects in the plasma need to be studied experimentally, steady-state cooling will be necessary.

Issue: Remote Maintenance of Compact Devices

In general, it was felt by the subgroup that remote maintenance of a compact ignition device would be significantly easier than remote operations on a large ignition machine. It was, however, acknowledged that such operations would by no means be trivial and that significant work must go into developing designs that are readily maintainable. The basic reason behind the perception that compact device remote maintenance should be simpler is related to the small size. Either the small device will be replaceable entirely (an approach being considered for RIGGATRON) or made modular so that small pieces are replaced. If modular, the handling of the relatively small segments can be accomplished more readily than the manipulation of the large modules typical of superconducting tokamak designs. While it was recognized that the compactness of these devices would in some instances make certain areas less accessible and that design development work is required to assure that these machines can be maintained, no specific problems or data needs unique to small ignition devices were identified in this area.

Neutronics

Issue: Shielding

In the opinion of the neutronics subgroup, shielding design techniques, as might be required for a compact ignition device, are available; however, careful analysis and development will still be required. Since shielding of the TF coils is not envisioned, except for the possibility of a nominal amount to prolong coil insulation lifetime, the shielding needs anticipated are:

1. biological protection for operators and technicians
2. shielding for diagnostic equipment
3. biological shielding during waste handling and storage operations.

Design of shielding to meet these needs is considered design dependent.

Issue: Activation

After a relatively few number of shots (significantly fewer, for instance, than the number that might be attained before an inorganic insulator fails), hands-on access to a compact ignition device will be infeasible. Because calculational methods are available to quantify levels of activation and the times associated with such levels, no major development needs are envisaged in this area. Nevertheless, it is emphasized that because of the potential impact on machine maintenance schemes and personnel safety, the activation of compact ignition devices must be carefully considered and remote maintenance techniques and procedures must be systematically defined.

Issue: Tritium

Practical experience in the handling of tritium is very limited in fusion experimental programs. In the Tritium System Test Assembly Program currently under way at LANL, methods for the control and handling of tritium are being advanced, and confidence in tritium management and safety is developing.

In a compact ignition experiment, a complete tritium system is required for fueling, plasma exhaust recovery and purification, and storage. Because such devices will probably not include tritium-breeding blankets, the tritium-handling system will be less complex than that for a commercial machine which is tritium self-sufficient. No particularly unique problems are foreseen for the tritium-handling system for a compact ignition experiment relative to that for a larger "mainline" ignition device. Depending on the machine experimental lifetime, however, the cost of purchased tritium is significant and should be included in operations planning.

Items Defined as Non-Issues for Compact Ignition Experiments

A number of subjects initially listed as issues for compact ignition devices were subsequently found to be non-issues based on neutronics subgroup discussions. These items and the reasons they became non-issues are summarized in the following paragraphs.

The matter of breeding blankets was raised originally because of concerns that, with close TF coils covering a large fraction of the toroidal surface area, the achieving of self-sustaining tritium-breeding ratios in compact commercial or demonstration reactors would be very difficult. While this is still a long-range concern for commercial applications, based on the workshop guideline that only ignition experiments were to be considered, breeding blankets became a non-issue because ignition experiments are not expected to breed large amounts of tritium. Therefore, blankets will not be used in these devices except possibly on a very small-scale experimental basis.

Materials recycling was identified as a possible issue because in a device with little or no shielding between the neutron source and the coils and structure, frequent replacement of major portions of the device would likely be necessary. This could become expensive if the materials were stored or discarded and not reused. Again, however, this is a concern for large-scale commercial applications and not for few-of-a-kind experimental devices. Material recycle is a question that must eventually be addressed if compact devices reach commercial status, but for an ignition experiment, recycling is not contemplated and is a non-issue.

It was further concluded by the neutronics subgroup that the matter of decommissioning a compact ignition experiment, while an important consideration to be addressed, was not a major issue that might impact the success or failure of an ignition device. No unique critical problems relating to disassembly, removal, or packaging of activated hardware in such a device were identified. To a large extent, dismantling would be accomplished with the remote-handling equipment that would be available for reactor maintenance.

Plasma Chamber Issues

Issue: Plasma Side Protection

Plasma-structure interfaces in present-day experiments are characterized for the most part by bare metal walls and metallic or graphite limiters. Some operating experiments as well as future device designs incorporate graphite tiles as wall protection or as part of the limiter. The use of special coatings is not common except in some applications on limiters. As the fusion community has begun to think more seriously about ignition experiments and long burn devices, increased interest in wall coatings is evident and preliminary small-scale testing has begun.

Compact ignition devices are likely to require some combination of low-Z limiters and/or wall coatings or protective tiles to limit impurities, at least for extended burn times. Possible approaches that have been or are being investigated include an array of TiC-coated graphite limiter knobs in the ZEPHYR design, and, in the case of RIGGATRON, low-Z wall coatings or even possibly bare walls for short burn times. Questions that must be answered include such matters as the adherence of coatings during the burn or during disruptions, coating application methods, repair of coatings, and methods of attachment of wall tiles.

Issue: First-Wall Heat Load Effects

The heat loads on the first walls of present-day experiments are characteristically <1 MW/m^2, with occasional higher local loadings during plasma disruptions. Because of the relatively short duration plasma discharges, these devices are typically inertially cooled or not cooled at all. Depending on the particular concept, wall heat loads during the burn of a compact ignition device can range from 1 MW/m^2 to as high as 10 MW/m^2. In addition, disruptive heat loads can be very high. Wall cooling at the lower heat loads is probably not too difficult; however, cooling at the high heating rates will be a significant challenge. Approaches that have been suggested for investigation include inertial cooling for short burns, steady-state active cooling for longer burn times, or use of a thick insulating layer of a low-Z material on the surface. Actively cooled limiters may suffice for lower average wall load machines, but for the very compact ($a < 25$-cm) concepts, which exhibit higher heating rates, this approach would probably not work because of the small space available.

When a compact ignition machine becomes operational, important information on first-wall heat loading can become available if appropriate instrumentation is provided. Besides verifying designs for handling high heat loads over large surfaces, data on the uniformity of wall heat loading during steady-state burn and spatial and time-dependent characteristics of disruption heat loads may be obtained.

Issue: Mechanical Design and Stresses

The plasma chambers of fusion experiments are typically sheet- or bellows-type corrugated structures. Mechanical stresses due to vacuum loads and electromagnetic loadings during disruptions are probably the main drivers in the mechanical design. Generally, little or no cooling is needed and thermal stresses are low. A major challenge in their design and fabrication is the assurance of a high integrity vacuum boundary.

With compact ignition devices, there will be additional burdens placed on the plasma chamber. Heat loads will be high during steady-state burns and disruptions, leading to the possibility of high thermal stresses. Because of the compactness, space for coolant ducting and plenums may be restricted. With the high fields characteristic of these machines, electromagnetic loads may be high. Here again, plasma chamber characteristics and the type and magnitude of stresses will depend on the particular design concept. Most compact ignition approaches maintain the basic concept of a separate structure for the plasma chamber/vacuum vessel, located inboard of the TF coil. A variation on this, however, is an approach that utilizes the inner surface of the compact TF coil as the plasma chamber. With this approach, the vacuum boundary is located outboard of the TF coil and there is no separate vessel inboard of the coils, thereby saving space. The surface of the TF coil is the first wall and must handle the surface heating due to the plasma.

Possible approaches for designing plasma chambers for compact ignition devices include a corrugated first wall with internal coolant channels or a welded tubular first wall with coolant in the tubes. These concepts would be designed as high strength, high stiffness structures to handle the loads. In addition, efforts should be made to develop techniques of plasma control in order to prevent disruptions and the sizable loads induced by such disruptions.

Diagnostics and Testing Systems

Diagnostics and testing systems were considered an important issue in the workshop discussions because of the possibility that a compact experiment might indeed be the first device to achieve ignition. And, if so, this will be the first instance in which the unique challenges and opportunities of measuring and investigating those phenomena characteristic of ignited plasmas will be addressed.

With regard to the present status of diagnostics, a wide range of instrumentation exists for measuring plasma and engineering parameters in laboratory setups, hydrogen-atmosphere plasma experiments, and modest neutron flux fusion experiments. Historically, diagnostic instruments are designated relatively late in the design of an experimental device. It is the opinion of this working group, however, that dedicated instruments to measure the new and critical phenomena expected in ignition machines will require long development times, and planning and testing in this area should be pursued in parallel with machine design.

Since a compact ignition device will be small and relatively inexpensive and will provide unique physics and engineering results, the diagnostic and testing systems will have special requirements. Instrumentation must itself be compact and noninterfering, at least to the extent to which it must be "close in" to the plasma. It too should be inexpensive, so that the potential cost advantages of the small device approach are not significantly diminished by expensive peripherals. These systems must, of course, be capable of plasma characterization, including proof of ignition, as well as providing measurements of engineering related phenomena on the machine itself. And, finally, to take maximum advantage of the intense fusion neutron source, it should be designed to accommodate test modules and experimental packages to the extent possible.

Because of probable limitations on diagnostic access to a compact ignition device, a priority of measurements must be established and refined through discussions in the fusion community to ensure that critical measurements are made early. Integration of device mechanical design considerations with those related to diagnostic and testing system access to the plasma and structures must receive appropriate emphasis. This may require fairly detailed specification of the diagnostic and testing system early in the design process. In addition, the expected environment demands attention to hardening of the instruments against radiation, pulsed high fields, and tritium (for directly exposed components).

It is emphasized that early and appropriate attention and priority must be placed on developing the diagnostics and testing systems. Only if reliable and effective instrumentation is operational will the wide range of physics and engineering data that is potentially available in an ignited fusion device become available both for understanding the ignition machine itself as well as for developing future fusion devices.

GROUP C–SYSTEMS STUDIES AND ENERGY EXTRACTION/DIVERTOR

Introduction

The focus of group C was on the divertor system (magnetic and mechanical) in relation to ignition devices. However, after the presentation at the general session by C. Wagner on RIGGATRON, T. Tamano on OHTE, and B. Coppi on high field tokamak experiments, the majority of this group engaged in the debate of ignition systems. Therefore, the discussion was naturally divided into two sessions: the ignition system on the first day, and the divertor system on the second day.

Ignition Systems

The consensus of this group was that the small high field and resistive magnetic tokamak system may be the least expensive and fastest way to demonstrate ignition. However, it is questionable whether it is economically attractive as a pure fusion power reactor. The cost and complexity for large devices are considered too high for ignition demonstration, and the data base for advanced systems is still lacking. There was no representation or time for discussion of an intermediate resistive tokamak system. For comparison, some comments were added by taking information presented by D. Cohn of MIT at the 9th Symposium on Engineering Problems of Fusion Research. The discussions on the small, large, and advanced systems are summarized in the following sections.

Small Tokamak Ignition Devices

From the presentation given by C. Wagner, B. Coppi, and W. Köppendörfer on ZEPHYR, the viewpoints of this group are summarized as follows.

1. The confinement for small high field resistive magnetic ignition devices can be extrapolated from the experimental data of the Alcator device and the Adiabatic Toroidal Compressor (ATC). The physics base is strong. They can be ohmically heated to ignition with or without the assistance of compression. The plasma is circular and requires nominal elongation. The beta requirement is moderate. Therefore, the system is small, compact, and simple. These small devices could well be the least expensive, near term, and low risk ignition demonstration experiments.

2. Because the device is compact, the blanket will most likely be on the outside of the magnet. The tritium-breeding ratio may be too low for a reactor.

3. Shielding space is lacking; therefore, the copper will become highly radioactive and significantly resistive, and the magnet would have to be disposed of in a month's time, as proposed by Wagner. The copper becomes a form of fuel. Although the initial capital cost would be low, the operation and fuel cost would be very high. The overall unit power cost of a commercial reactor is roughly the same as for a large device, which was designed for a lifetime of 30 years in typical reactor studies.

4. It is questionable whether the electrical insulation would be damaged before the copper.

5. Waste treatment and copper reprocess technology have to be examined. The fabrication, waste storage, and copper reprocessing costs have to be carefully assessed.

6. Pure fusion net power gain is almost impossible. Hybrid is the only mode of operation for power production, or the device could only be used for synthetic fuel production.

7. It is quite possible that the copper would accidentally melt down.

8. The limiter has not been addressed. A gas blanket may be the only solution.

9. Because the device lacks accessibility, neutral beam heating appears to be impossible to achieve.

Large Tokamak Systems

There have been many studies on large devices. The advantages, disadvantages, and physics bases are well understood and documented. Because of this attention, all the problems associated with large devices appear more critical. The disadvantages and outlook outlined by M. Peng were generally accepted by the group with little debate.

Disadvantages. It is generally conceded that the disadvantages for a large tokamak are its complexity, large size, and high initial cost. The project duration from the beginning of design until operation is perceived to be much longer. Accordingly, the risk is also higher.

Advantages. A large device design study, as for the International Tokamak Reactor (INTOR) or fusion engineering device (FED), takes an alternative physics standpoint and technology projection. From the overall system down to the engineering details, the successful testing can lead to a full-scale power reactor. Particular advantages of a large ignition device follow.

1. It can study aggressive tokamak physics. The development of rf or neutral beam current drive may lead to a steady-state reactor. Disruption free operation could be possible with low q and higher beta operation.

2. It allows for component development.

3. The large superconducting coil and long pulse operation are less conservative. However, the better technology and less conservative physics constraints will permit the reduction of size. Therefore, large reduction of capital cost is quite possible.

Advanced Systems

Because of the time constraints, the discussion on advanced systems was limited to general terms. Three systems, RFP, OHTE, and Spheromak, were discussed. If the physics could be demonstrated clearly, Spheromak would be the most compact and simplest device. The OHTE may become the simplest toroidal ignition device. The general conclusions are as follows.

1. All these devices are still in a physics study situation.

2. All may have strong MHD turbulence, flux mixing, and anomalous transport problems. The OHTE has an external helical field to suppress the turbulence, but this remains to be demonstrated.

3. Projection of present physics still allows room to give an interesting reactor.

4. Engineering would be relatively simple if physics could be demonstrated.

Intermediate Tokamak Systems

An intermediate size tokamak system, which can demonstrate ignition and yet be extrapolated to a reactor device, has been discussed in the paper, "Near Term Tokamak Reactor Designs with High Performance Resistive Magnets," by D. Cohn. The key features of these systems are included here to complement the system study discussion. The device considered, called the Advanced Fusion Test Reactor, has a major radius of 2.5 m, which is about twice that of RIGGATRON, and half of INTOR. The use of a high performance Bitter magnet makes the overall size of the machine much smaller than that of FED or INTOR. Like a small device, high performance resistive magnets allow the possibility of near-term operation at high magnetic fields, which results in high values of $n\tau_E$ and fusion power density. There is moderate shielding space available to protect the magnet. The magnetic field intensity on axis is 7 T; therefore, the stress is moderate in comparison with RIGGATRON. The problems remaining are the machine life and the power balance for extrapolation to a reactor.

Power Extraction/Divertor

The second discussion was focused on the power extraction, divertor, and application to tokamak systems. The divertor concept was presented by P. Harbour at the general meeting. M. Peng was requested to present the mechanical divertor for FED. T. Yang gave a brief presentation on optimized bundle divertors.

As pointed out by P. Harbour, the principle functions of a divertor for an INTOR-type reactor are:

1. helium exhaust [to remove helium at the rate at which it is produced (2×10^{20} atom/s for a power of 620 MW)]

2. energy exhaust (to conduct perhaps 75 MW of power into the divertor)

3. limitation of wall sputtering

4. impurity screening.

He advocates that the divertor should be operated at collisional flow to reduce the pumping speed and to allow for recycle and high burnup rate.

M. Peng presented a single-edge pump limiter concept at the chamber bottom for FED. The leading edge shovels a stream of plasma toward a pump channel. It is a ballistic collection process of neutrals reflected from the limiter edge. The estimated particle removal efficiency is 10%, and the maximum heat flux is 20 kW/cm^2, which is peaked away from the edge. The pump limiters become active only when the plasma attains full elongation. A separate set of limiters at midplane, without pump capability, is needed during small radius startup of the plasma current. The impurity control relies on the low-Z materials.

T. Yang briefly discussed the advantages and drawbacks of a bundle divertor, and of an optimized bundle divertor configuration, which will alleviate most of the serious drawbacks. The new configuration will be feasible for medium field, large tokamak reactors.

The principal advantages of a bundle divertor are in its ease of replacement and in its potential for external particle and thermal power handling systems. Particular designs are possible such that the divertor can be decoupled from the remainder of the tokamak system. The major drawback is that the axisymmetric character of the plasma is destroyed by the bundle divertor. The perturbation on the toroidal magnetic field, called the field ripple, may cause ergodicity in the magnetic flux surfaces and enhance the diffusion loss. Also, the bundle divertor creates a separatrix with its strong TF, thus, the current required in the divertor coil is very large. The restraining of the large magnetic forces and torques is a difficult task. The need for keeping ripple low for confinement places a premium on reducing the size of the divertor coil and the distance from the plasma. This results in a very high current density and difficulty in shielding. The high current density and magnetic stress make the use of superconductors difficult, and power consumption would be extremely high if normal conductors were used. Because of these difficulties, the bundle divertor has not yet been fully accepted by the fusion community despite positive experimental results.

The ripple and the current density can be drastically reduced, the shielding space can be increased, and the confinement can be improved by suitable divertor coil configurations. The early bundle divertor was planar and had circular coils, which required very high current density (5 → 25 kA/Tesla) and produced very large ripple (>2%). The new bundle divertor is a cascâde of T-shaped coils. The current density has been reduced to ~0.7 kA/Tesla. There is 60 cm of shielding in front of the divertor for radiation protection. The maximum field on the coil is 6 T. Therefore, it can be built from a superconducting NbTi conductor with state-of-the-art technology. The divertor is a plug-in unit; it can be inserted into the tokamak and pulled out with little interference with the rest of the system.

For discussion purposes, a list was made and is shown in Table III. The subjects discussed are listed in Table IV.

In general, the particle control, energy extraction, and divertor have been neglected, or no information is available for small to intermediate devices in the ignition and reactor regimes. Serious design and study have to be carried out and evaluated in order to make a convincing case that they are reactor compatible. For large devices, innovative concepts are needed to reduce the size and complexity; however, much more information will be generated when the Large Coil Project is turned on. The physics of the poloidal divertor looks good; the complexity and maintenance remain to be solved. The bundle divertor appears to be the most attractive for maintenance and engineering because of the new development. The second Divertor and Injection Tokamak Experiment (DITE) did not confirm the first because it was operated at low density. Therefore, the physics has to be reconfirmed. The theoretical analyses in both the poloidal and the bundle divertors are progressing. There are many questions regarding pump limiters. Among these concerns are whether or not the radiating mantle can be established. There may be a need to radiate ~95% of the alpha power. The first wall may have to handle 5 to 10 MW/m^2 of power in an ignition device; radiation to the first wall increases the mechanical and energy extraction problems. Erosion and recoating have to be studied and tested. Helium and impurities removal is an open question at this time.

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TABLE III

Energy Extraction/Divertor

(Major experiments and required data basis)

Divertor Type	Present Experiments	Future Experiments	Physics Data Basis	Engineering Problems	Experiment Diagnostics
Poloidal	DIVA T-12 ASDEX PDX D-III	ASDEX upgrade D-III upgrade	Power density Heat current First-wall heat	Ash removal Impurity scrape-off layer Δn	n, T, n^0 $n^0(E)$ $\Delta n, Q, T$
Bundle	DITE upgrade ISX-B	TEXTOR INTOR	Mechanicals erosion heat	ΔQ ΔT Materials	He, H_2, H impurities
Pump limiter	Microtor Alcator	TEXTOR ISX-B INTOR	System Extrapolation to reactor	Stability Neutral particle pumping	Radiation Divertor chamber

TABLE IV

Summary of Discussion on Energy Extraction/Divertor

A. Present Status

Type	Impurity Reduction	Ash Removal	Scrape-Off Layer Δn, ΔT, ΔQ
Poloidal	Produces low Z_{eff} except 0^{+}.	Good at low heat flux to area ratio (Q/A), needs demonstration at high Q/A.	Preliminary measurements agree with predictions.
Bundle	Experiment was done at low density; result is not clear; needs demonstration at high density and large device.	Needs demonstration.	Data agree with predictions, but require reconfirmation experiment.
Pumped limiter	Requires demonstration.	Requires demonstration.	Needs demonstration.

B. Systems

Type	Mechanical	Material Maintenance	Compact High Field Devices[a]	Extrapolation to Intermediate and Large Devices
Poloidal	Can be built, but complex.	Complex	Group C knows of no work on such divertors. Because of accessibility and high field, such a divertor system may not be feasible; scoping study is needed.	May all be reactor relevant.
Bundle	Can be built, but complex.	Simpler	Same as above	
Pumped limiter	Somewhat simpler	Simple, but erosion problem needs to be solved.	Energy may have to be radiated to the wall; impurity generation at limiter and radiation may have to be limited to limiter region; the ratio of limiter area to wall area probably must increase; more physics and engineering design studies are needed.	

[a] Some kind of particle control and energy extraction system is required.

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ALTERNATE FUELS FUSION REACTOR WORKSHOP SUMMARY, LA JOLLA, CALIFORNIA, DECEMBER 7-8, 1981

I. INTRODUCTION

This workshop was held at Science Applications, Inc. (SAI) in La Jolla, California, on December 7-8, 1981. Hosted by SAI, it was a sequel to the Alternate Fusion Fuels Workshop held at Department of Energy (DOE) headquarters in Germantown, Maryland, on January 26-27, 1981. The workshop was attended by about 40 participants from various parts of the United States, representing universities, national laboratories, and private industry.

The purpose of the workshop was to: (a) review progress, particularly during the period since the Germantown, Maryland, workshop in January 1981, to determine where the alternate fuels (AFs) community stands in relation to its goal of adequately assessing the potential of AFs for fusion applications and (b) set technical directions and priorities for future work. Thus, the scope of the workshop was intentionally broad including discussion of numerous magnetic confinement concepts for AFs [tokamak, mirror, reversed field pinch (RFP), multipoles, etc.] and both deuterium-based and proton-based fuel cycles so that all the major elements of the U.S. program in AFs could be considered in a single forum.

The first morning of the workshop was devoted to a series of invited talks, which included some of the more substantial reactor studies performed to date. The purpose of these talks was to provide background for the smaller working group sessions that were held on the first afternoon and the second morning of the workshop. There were six such informal working sessions, each of which considered a particular topical area germaine to the workshop. The final afternoon was devoted to a plenary session that contained oral summaries of the working sessions presented by the chairman of the working groups.

We review the technical program of the workshop by first summarizing the invited talks (Sec. II) and then summarize the results of the individual working sessions (Sec. III). These summaries reflect the highlights of written synopses of the invited talks provided by the authors, and written comments summarizing the working sessions provided by the session chairmen. We conclude with some general comments and observations in Sec. IV. A more detailed account of the workshop is contained in "Proceedings of the Alternate Fuels Fusion Reactor Workshop," Science Applications, Inc. Report No. SAI-023-82-008LJ.

II. INVITED TALK SUMMARIES

The workshop began with a series of invited talks intended to orient the workshop. The first four talks (Session A) addressed reactor operation using deuterium-based fuels in tokamak, RFP, and mirror magnetic confinement geometries, respectively. Session B contained talks on the prospects for proton-based fuels and two talks that discussed some of the generic physics and technology issues of AF reactors to provide focus for later discussion. We now summarize these talks in the order they were given.

SESSION A: Invited Talks

(Chairman: J. B. McBride, SAI)

WILDCAT: A Catalyzed Deuterium-Deuterium (D-D) Tokamak Reactor, K. Evans, Jr., Argonne National Laboratory

This paper described the WILDCAT conceptual design of a commercial tokamak reactor, which is the D-D analog of the STARFIRE deuterium-tritium (D-T) reactor design. To overcome the reduced reactivity of the D-D fuel cycle, it has been necessary to make WILDCAT have a larger size (8.6 versus 7.0 m), higher toroidal field (14.4 versus 11.1 T), and higher beta (11 versus 7%) than STARFIRE. In addition, the power produced is less [2915 versus 4000 MW(thermal) and 810 versus 1200 MW(electric)]. The WILDCAT design has a higher electron temperature (30 keV) and requires an order of magnitude better confinement, although the confinement is still commensurate with empirical scaling laws. The first wall has a net heat load of 1.0 MW/m^2 as does STARFIRE. This leads to a reduced neutron flux and a correspondingly longer first-wall/blanket/shield lifetime of 20 years. Since WILDCAT