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Alternate Fusion Fuels Workshop

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I. Introduction

Recent advances in high-beta theory have given further impetus to the study of the use of alternate fusion fuel cycles in future confinement devices. Their advantage as compared to the d-t cycle are lower induced radioactivity levels, significant reduction in tritium inventories, and considerable simplification in the blanket design.

The workshop was organized to focus on a specific confinement scheme: the tokamak. The workshop was divided into two parts: systems and physics. The topics discussed in the systems session were narrowly focused on systems and engineering considerations in the tokamak geometry. The workshop participants reviewed the status of system studies, trade-offs between d-t and d-d based reactors and engineering problems associated with the design of a high-temperature, high-field reactor utilizing advanced fuels.

In the physics session issues were discussed dealing with high-beta stability, synchrotron losses and transport in alternate fuel systems. The agenda for the workshop is attached.

During the workshop requests were made for a statement describing Alternate fusion fuel program. We have inserted in Section 4 a synopsis of the Applied Plasma Physics Division Alternate Fuel Program. The program was formulated during the summer of 1979 with technical contributions from the community. Recent achievements already have accomplished some of the goals described. In addition, the 1979 program does not amplify the alternate fuel development activities in the mainline approaches. This workshop is the first step of several that we expect to take in order to define alternate fuel possibilities in the principal fusion approaches.

The organizers would like to thank all of the participants for their contributions. Particular thanks are due to the chairmen, R. Conn and A. Boozer and to the scientific rapporteurs, J. Rawls and L. Hively, who had agreed to write the bulk of this document.

William F. Dove

Walter L. Sadowski

January 26 - Systems Studies, R. Conn (Chairman)

J. Rawls, Scientific Rapporteur

R. Conn, "Reactivity and Trade-Offs Between Alternate Fuels"

G. Miley, "Fusion Cycles and Their Energetics"

B. Coppi, "Alternate Fuel Systems Considerations"

D. Cohn, "Advanced Fuels Operation in High Field Tokamak Reactors"

K. Evans, "A D-D Tokamak"

F. Greenspan, "FED Considerations"

L. Hively, "Q-Values for CAT-D FED"

Discussion - R. Conn, Discussion Leader

January 27 - Physics Issues, A. Boozer (Chairman)

L. Hively, Scientific Rapporteur

D. Cohn, "Hot Ion Mode"

B. Coppi, "Second Region of Stability"

G. Navratil, "High Beta Experiments in Torus II"

S. Tamor, "Synchrotron Radiation"

A. Boozer, "Transport in Alternate Fuel Systems"

A. Boozer, "Current Drive Techniques for Steady-State Reactor"

J. Rawls, "Effect of Ripple Diffusion"

J. Dawson, "Hot Ion Systems"

Discussion - A. Boozer, Discussion Leader

II. TOPICAL REVIEW

Alternate Fuel Tokamaks

Although the use of an alternate fuel cycle involves a penalty in both the $n\tau$ and T fusion requirements in comparison to those of the d-t cycle, the manifold perceived advantages of d- or p-based fuel cycles have led to their establishment as an important long term goal for fusion. The most obvious benefit is the inexhaustible, inexpensive fuel. Of equal importance is the increased flexibility in blanket design made possible by eliminating the tritium breeding function. This can result in increased component life, a significant reduction in tritium inventory, improved ease of maintenance, a reduction of the space required inboard of the plasma, and the possibility of more efficient use of the neutron power for nonelectrical applications. Advantages may be possible in relation to induced activity level although, on closer examination, the biological hazard potential, the afterheat, and the induced radioactivity in some device designs are not significantly improved with d-d in comparison to d-t. For the d-^{3}He cycle, marked improvement is found in all these areas. The lack of availability of ^{3}He presents a problem, however.

Physics Issues

The physics issues which affect the practicality of advanced fuel burning in tokamaks include the maximum obtainable beta, the fuel reactivity, the transport, and the potential for steady state. In this section each of these issues will be discussed.

There are two reasons why beta, the ratio of plasma pressure to magnetic pressure, is important. First, there is a magnet technology limitation. The plasma must be held at high temperature and density and therefore pressure, to obtain sufficient power density from alternate fuels. The plasma pressure, through the factor of beta, determines the magnetic field which must be produced by the toroidal field coils. This consideration is thought to imply that average beta values in the 12-15% range are required to burn d-d or d-^{3}He The second limitation is synchrotron radiation. The gyromotion of the electrons in the magnetic field causes them to emit radiation. The power loss is a rapidly increasing function of the electron temperature and also increases with the magnetic field strength. The power loss is alleviated to a certain extent by reflection from the chamber walls. However, there is a maximum magnetic field and hence minimum beta at which the synchrotron losses become unacceptable. This beta limit appears to be significantly lower than that set by coil technology for d-d and d-^{3}He systems.

A beta value in the 12-15% range is about a factor of two above the commonly accepted tokamak beta limit. However, the tokamak beta limit is a rapidly evolving topic both theoretically and experimentally. Talks on the theory of the limiting beta were given by B. Coppi and D. Monticello. Experimental results were presented by G. Navratil.

Although coil technology and power density appear to give a higher beta requirement, the fundamental criterion on beta in an alternate fuel system is synchrotron emission. Calculations of synchrotron losses are made difficult by the fact that radiation, which dominates the power loss, has a mean free path comparable to the system size. A talk was given by S. Tamor on his detailed computations of synchrotron losses. The minimum value of beta due to synchrotron radiation is at present unclear but thought to be about 10% for d-d.

Traditional reactivity calculations for alternate fuels were based on Maxwellian distributions. Enhanced high energy tails of the distribution functions can substantially improve the reactivity. The enhanced tails could be due to collisional effects of the reaction products, preferential heating of high energy particles, or microinstabilities. R. Cohn discussed the approximate factor of two in reactivity which can occur due to reaction product collisions for certain plasma conditions. D. Cohn and J. Dawson discussed preferential heating or hot ion modes of operating alternate fuel systems.

It is clear that one would like the option of running an alternate fusion fuel system in steady state. The possibility of steady state current drive was briefly discussed by A. Boozer.

The transport problem with alternate fuels differs from the d-t problem due to the high $n\tau$, temperature, and density requirements. The primary transport questions are the scaling of the electron transport to high densities ($\sim 10^{15}/cm^3$) and temperatures ($\sim$ 50 keV), the effect of ripple on ion transport, and impurity transport. At present electron confinement scaling is primarily empirical. The often used $n\tau \propto n^2$ is optimistic for the high densities of advanced fuel systems. The physics of ripple transport were discussed by A. Boozer and the implications by J. Rawls. The tolerances on ripple are a factor of five or so more stringent in d-d systems than in d-t. Although little is known about the transport of impurities it is clearly an important question for both d-t and alternate fuel systems.

Research areas which are essentially peculiar to alternate fuels systems include synchrotron radiation, fission product collisional effects, and ^3H_e availability. The minimum plasma beta consistent with the synchrotron losses requires further study. A relatively simple set of physics data that must be obtained concerns realistic wall reflectivities in the appropriate frequency ranges. Although the ^3H_e abundance is apparently far too low on earth to provide natural supplies, one cannot simply rule out mining ^3H_e from Jupiter, Saturn, or their satellites. Measurements of ^3H_e abundance in the vicinity of these bodies by NASA would help determine the feasibility of extra-terrestial sources. Other areas of research which can have a large impact on both d-t and alternate fuel systems includes studies of the maximum beta obtainable in tokamaks, disruption control, and transport.

Recent Developments

Recent developments have led to a heightened interest in alternate fuel cycles. The two ways to compensate for the low reaction rates are increasing the beta and increasing the field. There is reason for optimism on both counts. Three major tokamak experiments (ISX-B, JFT-2, and T-11) have all achieved beta values well in excess of the theoretical predictions for the onset of ideal MHD instabilities. And there are now three high field tokamaks (Alcator A, Alcator C, and FT) in operation with several more planned for the near future. While wall loading limits actually preclude the simultaneous use of high beta and high field for an ignited d-t system, such a combination is ideal for d-d or d-^{3}He.

Another advance is the recognition that the $n\tau$ requirements based on Maxwellian distribution have been overestimated. It is found that large angle scattering, particularly due to elastic nuclear events, gives rise to a tail enhancement that yields an increase of up to a factor of 2 in the effective reaction rates. In addition, more fusion power is deposited in the ion channel, a fact that leads to an increase in T_i and a decrease in T_e (and hence in the radiative losses).

Status of Systems Studies

Thought provoking recent d-d and d-^{3}He designs were presented at the workshop. Most of these studies have been carried out in considerably less detail than their d-t counterparts. In addition, they have not had the benefit of the evolutionary process that has taken place in d-t reactor design studies. Thus, there is reason to believe that the alternate fuel designs are far from optimized and, in fact, are being hampered by our preconceived notions of d-t fusion reactor design.

The early Illinois-Livermore-Brookhaven d-d tokamak study carried out under the auspices of EPRI led to both d-d and d-^{3}He designs based upon d-t match-head startup, trapped ion mode scaling, and a bundle divertor-direct collector arrangement to capture charged particle energy efficiently. More recent design studies have utilized more favorable transport scaling and have resulted in reducing the device size considerably, to $R_o \sim 8$ m (in devices with superconducting coils). While the bundle divertor idea now looks less promising, no thoroughly suitable scheme for the removal of the energy in the form of particle flow has emerged.

The use of high performance copper or aluminum magnets at cryogenic temperatures, as proposed by the Coppi team, results in much more compact designs. The Compact Ignition Test Reactor studied at the MIT Fusion Center has $R_o \sim 1.9$ m and $B_o \sim 8.8$ T. While the device was designed to demonstrate ignition in d-t, the prediction that $n\tau$ can reach values approaching 10^{15} cm^{-3}s (assuming $\langle\beta\rangle = 6\%$ can be attained) opens up the tantalizing possibility that ignition (or at least high Q) may also be achieved in cat-d or d-^{3}He.

The "Condor" compact experiment presented by Coppi was based on a design utilizing existing technology. The design is based on progress made in the theory of high beta stability in tokamaks and takes advantage of recent progress in the understanding of energy transport processes as well as improved evaluation of synchrotron losses and of the energy deposition of fusion reactor products. The proposed experiment is designed to address the feasibility of near-term ignition experiments using advanced fuels.

With the very high fields employed in Ignitor-type designs, even more compact designs can be considered. With 12 T on axis, the Condor (an MIT-European study) design is predicted to produce 100 MW of fusion power in d-^{3}He operation, with the major radius of only 1.05 m and the plasma cross section of 0.40 m x 0.55 m. Only 10 MW of ICRF power is needed to heat the initial d-t mix to ignition. While this design is based upon fairly optimistic physics, i.e. $\langle\beta\rangle$ = 13% and a modified Coppi-Mazzucato transport scaling, some relaxation of these conditions does not result in greatly increased device size.

A recent d-d design study carried out at ANL was heavily influenced by the Starfire d-t design. While such an approach imposes artificial limits on the design of an alternate fuel reactor, it does facilitate a comparative study between d-t and d-d physics and technology requirements. The general conclusions reached in this study will provide a useful compilation of the advantages and disadvantages of alternate fuel cycles.

<u>D-D vs. D-T Reactor Requirements</u>

1. D-d and d-t designs are similar. This is not surprising because half the neutrons in the d-d case are 14 MeV and most of the power comes from such particles.

2. The absence of a tritium breeding requirement allows the blanket/shield to be optimized for performance. For example, the inboard shield can be made as thin as possible to optimize the magnetic geometry while the outboard shield is designed to maximize energy multiplication. While there are two orders of magnitude less t inventory, one still needs to include the same set of safety systems.

3. The lower cross sections inevitably lead to larger size, higher field designs. As a result, the auxiliary system parasitic losses are larger and comparatively more important. There is more stored energy, giving concerns about disruptions. However, theory predicts a lower disruption probability at higher temperatures.

4. The higher operating temperature increases the importance of both cyclotron and bremmstrahlung losses and makes the achievement of ignition more difficult.

5. The smaller fraction of energy released in the form of neutrons is an advantage in wall life but is a disadvantage if the first wall is heat-flux limited. In fact 3.6 MW m^{-2} in d-t is comparable to 1.5 MW m^{-2} in cat-d.

6. The requirement on ignition is sufficiently stringent that the maximum tolerable impurity concentration in a cat-d system is an order of magnitude lower than in d-t.

A recent Illinois study has begun to map out a continuum of deuterium based modes of operation that holds promise for alternate applications of fusion as well as providing ^3He for d-^3He satellite plants. The key is to make use of the blanket to convert some of the ^3He into t through a (thermal) n-p reaction or to use some portion of the high energy neutrons to breed t. Such modes of operation give power densities considerably higher than those of CAT d-d. In fact, the energetics are dominated by d-t reactions so the reactor is similar to a d-t reactor although a breeding ratio exceeding one is not essential. Without a need for either Li or for a high utilization of the 14 MeV neutrons for breeding, such a blanket may make a far more desirable synfuel factory or fissile fuel generation factory.

Research Issues

The credibility of the d-^3He fuel cycle was cast in doubt by ANL and ORNL studies indicating great difficulty in extracting ^3He from a d-d device. This is in contrast to earlier claims that a semi-catalized d-d (all tritium produced is reintroduced into the plasma) generator reactor could supply the fuel needed for several smaller, cleaner satellite d-^3He plants sited near the users. This problem must be reexamined. It may turn out that the ignition margin depends sensitively on the fraction of helium extracted; in this case, a d-d plant with enough margin to permit significant extraction may be so large as to be unacceptably capital intensive. One possible remedy is to improve the d-d power density by using the d-t assisted approach described below.

A generic difficulty in quantifying questions on ash buildup, impurity accumulation, fueling rates, etc. is our lack of knowledge about particle transport. It would be particularly valuable to determine the dependence of transport rates on particle mass and charge. These questions take on greater importance for alternate fuel devices because of the greater multiplicity of species involved although prospects for early, clear understanding are hampered by the difficulties posed by particle transport in today's hydrogen experiments. A technological problem in this regard is that ^3He pellet injection is not feasible because there is no solid state at accessible temperatures. This problem is exacerbated by the large fueling requirements mandated by the large edge transport rates.

A credible design for a first wall is needed. The surface heating is proportionately more important in alternate fuel devices, the permitted impurity contamination is considerably less, and the disruption loads are greater because both the plasma energy and the magnetic energy are of necessity greater.

Alternate fusion fuel cycles may be particularly well suited for applications other than net electricity production. Designs should be developed that are optimized for the individual applications. In this vein, scenarios in which some tritium breeding takes place or in which some ^3He is converted into t in the blanket deserve a more thorough study.

A more general question about alternate fuel designs concerns the risks inherent in increasing B_T, Ip, a, and R to considerably greater values. These have not been analyzed in detail but it is essential that this be done to see if such risks counterbalance the advantages inherent in the fuel cycle. There are basically two technological approaches: those involving modest field superconducting magnets and those involving high field resistive magnets. In the former instance, reactor designs may be relatively large (R $\gtrsim$ 8 m) and need high current (I $\gtrsim$ 20 MA). The large energy content of the plasma and of the poloidal field make plasma disruptions a particular concern. The higher field designs naturally have higher stress levels and hence engender concerns about safety and cyclic fatigue. In addition, the large resistive and/or refrigeration power requirements introduce the risk that the device will not be a power producer.

A further general comment is that more effort should be devoted to integrating the physics and engineering. One example is the startup scenario, e.g., the effect of the d-t matchhead on the systems aspects of a d-^3He device. State-of-the-art plasma codes should be utilized for this purpose.

Programmatic Considerations

There is a concern among members of the community that the mainline (d-t central station power plant) program will not display fusion to the best advantage and that the program should be structured with a desirable alternate fuel cycle in mind. However, we have at this point no carefully thought out, fully consistent, attractive scenario to offer. Hence, the first priority of the program must be to develop one or more desirable end products and the program should be structured in a roll-back fashion. In any case, major program elements cannot be justified purely on the basis of scientific interest in those areas where their output is not directly applicable to the present confinement approaches.

With regard to the character of the near-term programs, it was strongly recommended that reactor studies be optimized with respect to the fuel cycle in contrast to minor modifications of a d-t reactor design. This will provide a much more valid basis for comparison with d-t reactor designs.

There was some sentiment for the establishment of a dedicated or at least a designated center for alternate fusion fuel research. But it seems that the primary emphasis at this stage must be to learn as much as possible from the mainline program. To a large extent, this is natural because progress in the mainline program provides a scientific base for alternate fuels.

While most questions are in fact the same as for d-t, several issues must be dealt with separately. One is the containment of 15 MeV protons, which determines the minimum current needed for a viable d-based system. This can be tested in a single particle framework in a high current device such as JET or it can be tested decisively via a d-^{3}He colliding beam experiment in TFTR. Two other effects are important in d-d and d-^{3}He but are masked in d-t; knock-on effects ($\langle\sigma v\rangle_{eff}$ enhancement) and synchrotron radiation. These are perhaps best tested in non-tokamak devices.

Research Problems To Be Addressed

Problems to be addressed in the area of system studies include:

- Development of a methodology of risk assessment for alternate fuel reactors.
- Development of a reasonably detailed d-based reactor design similar to the UWMAK design.
- Study of impurity and transport control.
- Study of particle confinement (especially ^{3}He) and recyling.
- Early experimental verification of high beta, large size and high field confinement of plasmas.
- Experimental verification of synchrotron radiation calculations.
- Experimental test of the effect of large-angle scattering on high-temperature reactivities.
- Experimental test of d-^{3}He operation by injection of ^{3}He into TFTR (estimated yield of $Q \sim 0.1$).
- Experiment to check the calculations of production rates of ^{3}He from decay of tritium.

The problems to be addressed in the physics area are:

- Experimental studies of beta limits for high magnetic field operation.
- Models of synchrotron radiation losses for a system size comparable to the radiation mean-free path, anomalous distribution tails and nonlinear plasma dielectric effects.
- Measurements of wall reflectivity in the quasi-optical regime for realistic surface structures, including contamination, radiation, environment and other relevant conditions.
- A study of anomalous slowing down of fusion products.
- Development of codes to calculate self-consistent plasma heating which include the effect of profile changes on reactivity and thermalization.

- Further experimental studies of energy confinement to resolve present discrepancies in various scaling laws.

- Studies of wall damage due to disruption of high-temperature, high-beta plasmas.

- Studies of feedback systems to control disruptions or when these are unavailable, keeping the hot plasma off the vessel walls.

III. PROCEEDINGS OF THE WORKSHOP

January 26 System Session - R. Conn, Chairman

R. Conn, UCLA. "Reactivity and Trade-Offs Between Alternate Fuels."

Bob Conn (UCLA) began the Monday "Systems Session" with a talk on "Reactivity and Trade-Offs Between Alternate Fuels." A d-d reactor would have stricter requirements on confinement than a d-t reactor, e.g., $n\tau \sim 10^{15}$ cm^{-3} s, β 10-20%, B $\sim$ 12-20 T, and $T_i \sim$ 40-60 keV.

The high field requirements for magnets and related technology have an important impact on reliability and safety which needs to be assessed. Advantages of d-based fuel cycles include:

- lower neutron flux with corresponding improvements in wall lifetime and induced radioactivity,
- lower tritium inventory for d-t startup and from d-d reactions implying that an intermediate heat exchange loop may not be required for tritium isolation,
- simpler blanket design since t-breeding is not required,
- prospect of direct energy conversion from the large fraction of charged fusion products.

The disadvantages arise from the higher stress (and therefore higher risk, lower-reliability) inherent in high field, high current ($I_{pl} \sim$ 30 MA) reactors. Such a risk assessment requires a reasonably detailed reactor design and a corresponding methodology for risk determination. Questions of physics include:

- analysis of burn scenarios d-t $\rightarrow$ d-d $\rightarrow$ cat-d) including impurities,
- radiation from high temperature, high-β plasmas,
- incorporation of uniquely d-based fuel physics into an optimal design, with experimental confirmation in d-d tokamak experiments,
- MHD limits on β,
- nuclear elastic scattering enhancement of fast ion thermalization, with corresponding improvements in reactivities (up to 80% at T = 140 keV and T_i = 75 keV) and in ignition requirements $n\tau \sim 10^{15} \rightarrow 2.5 \times 10^{14}$). The net impact of all this physics needs to be included in realistic, cost-conscious designs.

G. Miley, University of Illinois. "Fusion Cycles and Their Energetics."

George Miley (University of Illinois) spoke about "Fusion Cycles and Their Energetics." Since alternate fuels are an ultimate goal for neutron- and tritium-free fusion reactors, there should be a program dedicated solely to such studies. This could include a dedicated center with an advanced-fuel-dedicated experiment. A strategy for such a d-based fuel approach could procede from a d-fueled tokamak to a cat-d (or semi-catalyzed d tokamak) to produce ^3He for a d-^3He reactor. A fission-fusion hybrid is an alternate goal. Non-tokamak confinement schemes with possible applications to syn fuels and hybrid devices should not be ruled out. Cat-d tokamak reactors are larger than d-t devices due to the lower power density inherent in the former. Recent design work by UI/EPRI, ANL, MIT, UCLA/U. Wisc., and ORNL should be combined, emphasizing the unique aspects of alternate fuels. The evolution of such a cat-d reactor might include features like:

- steady-state operation, though RF current drive may not be best, rather fusion-produced current looks better;
- direct energy conversion is a good prospect possibly via bundle divertor;
- blanket design might use a radiation trapped blanket versus solid lithium breeding.

The objective is to reduce reactor cost by decreasing the major radius as has occurred in recent d-t reactor design evolution.

B. Coppi, MIT. "Alternate Fuel Systems Considerations."

Bruno Coppi (MIT) discussed "Alternate Fuels Systems Considerations" and in particular proposed a near-term, d-^3He based ignition experiment. The long lead time for design, construction and implementation of present experiments places realization of fusion reactors after 2000. This is "too late." Existing research which makes such an ignition experiment look promising includes:

- successful high-field tokamaks (Alcator C and FT)
- improvement in electron energy confinement with density,
- effects leading to the second region of high-β stability (needs experimental confirmation),
- minority ion heating by ICRH (without saturation up to densities of $10^{14}cm^{-3}$),
- no bad problems after an improved analysis of synchrotron radiation.

The proposed tokamak would have d-t startup with I_{pl} = 6 MA, using 10 MW of ICRH (using the first harmonic of ^3He and the second harmonic of t). The machine size is R_o = 1.05 m, a x b = 0.4 x 0.55 m (giving 4.6 m^3 plasma volume). The plasma parameters would be $\bar{\beta}$ = 0.13 ($\beta_o \sim 0.4$-0.45),

T_{eo} = 65 keV, $n_{eo} \sim 1.7 \times 10^{15}$ cm^{-3}, giving $\tau_E \sim 0.8$ s and $\tau_{Ee}^{cond} \sim 1$s for d-^{3}He ignition ($n_d/n_{He} \sim 1$). The TF coils would be cryogenically cooled aluminum at 30^{o}K with a 12T field of copper at liquid nitrogen temperature (77^{o}K). The power balance is:

100 MW fusion total
53 MW charged particle transport
33 MW *Bremsstrahlung (need to include photonuclear production)*
10 MW Synchrotron radiation
4 MW neutrons

(With more pessimistic physics a more "optimal" device would have R_o = 1.2 m, a x b = 0.6 x 0.75 m, I_{pl} = 9 MA). The burn time is limited by heating in the magnets; at full power this device is limited to $\sim 10^3$ shots. Such a device is relatively low in cost and quickly buildable, and could rapidly lead to a reactor which would be limited to $\sim 10^5$ shots at full power. The large variations among various scaling law predictions for τ_E strongly impact this design. An experiment is needed to resolve the question.

D. Cohn, MIT. "Advanced Fuels Operation in High-Field Tokamak Reaction."

Dan Cohn (MIT) next spoke on alternate fuel operation of high-field tokamak reactors. This design proposal was a compact d-t ignition test reactor using liquid-nitrogen-cooled magnets without shielding which would be limited to $\sim 10^4$ pulses at full field. The device would have B_o = 8.8T, $\bar{\beta}$ = 5.8%, R_o = 1.9 m, a x b = 0.85 x 1.11 m, $\bar{n} \sim 5.6 \times 10^{14}$ cm^{-3}. Its purpose would be to study α-heating to ignition, thermal stability, MHD stability, and long-pulse physics (impurity generation, refueling, ^{4}He buildup). The ignition margin according to Alcator scaling is $(n\tau)_{emp}/(n\tau)_{ign} \sim 5$ at 15 keV, with a flat-top burn time of $\tau_{flat} \sim 26$s. If cat-d or d-^{3}He are used, then $n\tau_e \sim 9 \times 10^{14}$cm^{-3} is required with $T_{io} \sim 50$-60 keV. This device is flexible in heating alternatives (20 MW of RF, neutral beams, or compression) with operation possible at higher aspect ratio, and the option of nuclear shielding. The trend in design of such compact devices is to increase the product of TF field strength and TF coil current density.

K. Evans, ANL. "A D-D Tokamak"

Ken Evans (ANL) presented "A D-D Tokamak Reactor" design based on STARFIRE. The transport model used in the design averages over assumed profiles including d,t, ^{3}He, ^{4}He, electrons, and fast d as separate species. Rose-model slowing down is included for fast t, ^{3}He and ^{4}He as well as their contribution to β. The reactivity determination accounts for thermal fusions as well as for superthermal d, t, and ^{3}He. Radiation losses included Bremsstrahlung, synchrotron radiation, line radiation and recombination. Impurities are introduced in a controlled way to prevent runaways and control heat flux to the wall. The resulting reactor has R_o = 8.6 m, a = 2.6 m, B_{max} = 14 T, $\bar{\beta}$ = 0.11, β_o = 0.4, I_{pl} = 29 MA, T_e = 30 keV, T_{eo} = 52 keV, $\bar{n}_{Be}/\bar{n}_d$ = 0.03, $\bar{n}_{Xe}/\bar{n}_d \sim 2\text{-}5 \times 10^{-5}$ and generates 2.7 GW_{th}. Unless the reflectivity for synchrotron radiation is > 40%, ignition is not possible. More than 90% ^{3}He recycling is required to maintain ignition. However, in the presence of impurities a synchrotron relectivity > 0.9 is needed to maintain ignition and > 0.95 of the ^{3}He must be recycled as well. Startup requires ohmic heating and a 9000 s (2.5 hr) burn.

Half the neutrons come from the d-t reaction ($\sim$ 1.6 MW/m^2 total), but no lithium is needed for breeding. While ignition can occur as low as T_e = 24 keV, $\bar{T}_i$ = 25 keV (3.3 GW_{th}), the higher operating point requires one-tenth the impurity level allowed by a d-t reactor, raising $(n\tau)_{ign}$ ten-fold. The combination of large synchrotron reflectivity and low d-based reactivity requires a larger reactor with larger auxiliary systems. The larger stored energy can melt the wall if a disruption occurs.

W. Houlberg, ORNL. "Ignited Tokamaks."

Wayne Houlberg (ORNL) discussed "Ignited Tokamaks" in cat-d regime with R_o = 7 m, a = 2 m, B_o = 7 T, I_{pl} = 10 MA, $\bar{\beta}$ = 0.1, β_o = 0.31, $\bar{T}_e$ = 45 keV, $\bar{T}_i$ = 51 keV, $\bar{n}_d \sim 1.2 \times 10^{14}$ cm^{-3}, $\bar{n}_e \sim 1.8 \times 10^{14}$ cm^{-3}. The WHIST calculations assumed no impurities and a synchrotron reflectivity of 0.9. Ion conductivity assumed ripple trapping and neoclassical terms. Alcator plus PLT scaling was used for the electron conductivity. Particle diffusion included the neoclassical and empirical terms. Startup requires sufficient tritium to ignite after which the tritium was burned out. Ignition requires that >0.6 of the 14.7 MeV α be contained, edge ripple below 0.9% without the magnetic axis shift, >0.82 synchrotron reflectivity and >0.9996 ^{3}He recycling fraction. The 14.7 MeV α containment seems achievable but raises questions on microinstability- and ripple-induced losses. The edge ripple limit will decrease when the magnetic axis shift is considered, but lower ripple can allow thermal runaway. The large ^{3}He recycling fraction poses severe questions on edge physics and transport coefficients. Alternately, ^{3}He reactivity could be increased by minority ICRH. Details are included in "Plasma Physics Sensitivity Analysis of Catalyzed-d Operations in Tokamaks," by S. E. Attenberger and W. A. Houlberg in the 4th ANS Topical Meeting on the Technology of Controlled Nuclear Fusion (14-17 October 1980).

E. Greenspan, U. of Illinois. "FED Considerations."

E. Greenspan (University of Illinois) described his "Search for Promising Operation Regimes," by controlling the fraction of ^3He burned. There is a shallow minimum in the ignition temperature at 0.3 of ^3He burned. Alternatively, the ^3He can be captured and used to breed tritium via neutrons: $^1n_0 + {}^3He_2 \rightarrow {}^3T_1 + {}^1H_1$ yielding an ignition temperature of 20 keV. The cross section for this scheme is large (~1000 barns!), so it pays to maximize the fraction of t per d-t neutron. Extracting the ^3He lowers the ignition temperature which has the net effect of decreased $n\tau$ requirement. This "tritium-catalyzed-deuterium" technique (tcd) permits a simpler blanket but requires better confinement than for cat-d. This has possible advantages for synfuel and fissile-fuel conversion by judicious use of a high-temperature blanket region. Thus, co-production of ^3He and synfuels can yield a ratio of synfuel energy to electrical energy of 2. Details are contained in "Promising Regimes for Deuterium Based Fusion Fuel Cycles," by E. Greenspan and G. H. Miley, submitted to ANS 1981 Meeting (June 7-12, 1981, Miami Beach, Florida).

L. Hively, ORNL & GE. "Q-Value for Cat-D FED."

Lee Hively presented his calculation of "Q-values for Cat-D FED," using a zero-dimensional, time independent model. RF feedback was assumed to compensate for electron energy losses for Alcator scaling. Both thermal and fast ion fusions were included, without radiation losses or particle recycling. The fusion power was found to be <1% of the RF input for fixed $\bar{E}$, and varies as $T^{-\alpha}$ with $\alpha \sim 2$ for $T < 30$ keV and $\alpha \sim 1$ for $T > 40$ keV. Details are documented in "Q-values for Catalyzed-D FED Plasma," by L. M. Hively, ETF-M-80-PS-126 (24 October 1980). Using the techniques described above, E. Greenspan obtained $Q \lesssim 0.5$ using various recyling techniques (details forthcoming).

Discussions. R. Conn, Discussion Leader

Bob Conn led the final Monday discussion on program needs. Questions that should be addressed include:

- an evolution of reasonably detailed d-based reactor designs (like UWMAK designs) and a corresponding methodology for risk assessment,
- experiments to resolve the large extrapolated differences among empirical electron energy confinement scaling,
- impurity transport and control,
- particle (especially ^3He) confinement and recycling,
- fast experimental tests of high-β/large size/high-field confinement,
- experimental tests of large angle scattering effects on high-temperature reactivities, as well as verification of synchrotron radiation calculations,
- an experimental test of d-^3He operation by ^3He injection into TFTR (estimated to yield $Q \sim 0.1$),
- regarding production of ^3He for d-^3He reactor, an experiment to check the calculations.

While these suggestions might point toward making alternate fuels a part of the tokamak program, it was emphasized that technologically relevant goals are more important than simple science experiments.

January 27. Physics Session. A. Boozer, Chairman.

D. Cohn, MIT. "Hot Ion Mode".

Dan Cohn (MIT) began the Tuesday "Physics Session" with a talk on "Hot Ion Mode" operation. The motivation for this work is to improve power density and the $n\tau$ requirement for ignition of cat-d and $d-^3He$ reactors. This study assumes the energy and particle confinement times are very long compared to those for electrons (Alcator scaling). Classical thermalization of charged fusion products results in a modest rethermalization between the hot ions and cooler electrons. There is a large decoupling of the ion temperature from the electrons if all the fast ion energy is anomalously given to the ions. The fusion power density for both cat-d and $d-^3He$ is poorest when $T_e = T_i$, better when $T_i > T_e$ for classical fusion product thermalization and best when $T_i > T_e$ for anomalous thermalization as shown below:

Maximum Specific Power Density $P_f/\beta^2 B^4 (MW/m^3T^4)$

Case	$d-^3He$	Cat-d
$T_e = T_i$	0.025 @ T_{io} = 60 keV	0.032 @ T_{io} = 37 keV
Classical Thermalization	0.034 @ T_{io} = 82 keV	0.035 @ T_{io} = 40 keV
Anamolous Thermalization	0.055 @ T_{io} = 98 keV	0.037 @ T_{io} = 60 keV

While hot-ion mode operation increases the fusion power density, the maximum pressure-limited fusion power densities are <1/30 of those for d-t plasmas. Assuming Alcator scaling, $n\tau_e \sim n(na^2) \sim \beta^2B^4a^2$ x (some function of temperature), it is then sufficient to consider βaB^2 versus T_{io} as an ignition requirement. There is a 20% decrease in the minimum $(n\tau)_{ign}$ requirement for cat-d, but the temperature where that minimum occurs increases by 15% for anamolous versus classical fusion product thermalization. The corresponding $n\tau$ decrease for $d-^3He$ is 35% with a 15% increase in T_i.

Thus the net benefit of anamolous energy deposition into the ion appears small. The thermal runaway time is of the order of the energy confinement time ($\tau_{runaway}/\tau_E \sim 1$-$3$) and increases monotonically with temperature (including the thermalization time of the fusion products). Inclusion of density shift and enhanced ripple loss as the plasma shifts outward will stabilize the thermal runaway. The trade-offs are among high-β and low-power density versus maximum power density at a chosen temperature versus thermal wall loading limits. The resulting tokamak would have $B_o \sim 8T$ and $\beta \sim 0.12$. Details are contained in "Ignition and Thermal Stability Characteristics of Advanced-Fuel Tokamak Plasmas with Empirical Scaling," Nuclear Fusion 20 (1980) 703 by J. H. Schultz, L. Bromberg, and D. R. Cohn.

Bruno Coppi, MIT. "Second Region of Stability".

Bruno Coppi (MIT) discussed the implication of the "Second Region of Stability" on alternate fuel tokamaks. The ballooning mode limit to high-β operation arises from a combination of shear Alfvén and Rayleigh-Taylor instabilities having

$$\omega^2 \sim k_{\parallel}^2 V_A^2 - g/r_n \ , \ r_n = \frac{1}{n}\frac{dn}{dr} \ ,$$

where ω is the mode frequency, $k_{\parallel}$ is the wave number parallel to $\vec{B}$, V_A is the Alfvén speed, g is the curvature drift acceleration, and n is the plasma density as a function of radial position, r. For magnetic confinement of a hot plasma, the magnetic well is carried away with the wave, destroying containment. For a low-β, circular plasma with concentric flux surfaces,

$$\begin{aligned}
k_{\parallel} &\sim 1/qR, \text{ where } q = \text{shear parameter} \\
& \qquad\qquad\qquad\;\; R = \text{major radius} \\
g &\sim V_s^2/R, \text{ where } V_s = \text{speed of sound in the plasma} \\
r_n &\sim r_p, \text{ where } r_p^{-1} = p^{-1}\, dp/dr \\
& \qquad\qquad\qquad\;\; p = \text{plasma pressure.}
\end{aligned}$$

The resulting condition for stability is

$$\frac{g}{r_p}\,\frac{1}{k_{\parallel}^2 V_A^2} = \left(\frac{V_s^2}{V_A^2}\right)\left(\frac{R^2}{r_p R}\right) q = \frac{\beta q^2 R}{r_p} = G < 1$$

For a high-β plasma, $k_\parallel$ must be generalized to $1/qR\ (1 - a_\theta G)$, yielding a region of second stability and an enlarged first stability region (relative to the stability limits known before Varenna, 1977). In the space of $\hat{s} = (d\ \ln q/d\ \ln r)$ vs. $G = (\beta q^2 R/2p)$, there is an unstable region for large s and large G. Surface (kink) modes would seem to be stabilized by image currents in nearby walls and by finite-β effects. Typical present-day experiments operate in the stable region of small G. Proposed high-β, alternate fuel tokamaks should start up in the stable, small-G region and move into the small-$\hat{s}$, finite-G, stable region. This could be done by evolving the plasma through a sequence of flux-conserving equilibria to ignition at high temperature where finite resistivity effects are negligible. If FED could ignite a d-t plasma under this scenario, d-^{3}He would also be a feasible operating regime. Details are documented in "Search for the Beta Limit," by B. Coppi et al., M.I.T. Report PRR-80/19 (Aug. 1980).

D. Monticell, PPPL. "Beta Limits".

Don Monticello (PPPL) addressed the question of "Beta Limits" using PEST2.1 for sensitivity studies. It is possible to operate in the region of second stability for low values of $\varepsilon\beta_p$, where ε is the inverse aspect ratio and β is poloidal beta. Calculations included both large mode number $(N=\infty)^P$ and a low mode number (e.g., N = 2). Lower critical values of $\varepsilon\beta_p$ result for a large aspect ratio plasma, for broader pressure profiles to a smaller degree, and for larger values of q on axis (q_o = 1,2) to an even smaller degree. These variations can be seen from the equation for critical stability:

$$\begin{pmatrix}\text{stabilizing}\\ \text{term}\end{pmatrix} + \frac{P'}{R}\left[1 + \left(\frac{a^2}{R}\right) + \frac{a}{R}\frac{J_c}{q^2}\right] = 0$$

where P' is the pressure-gradient-driving factor, the 1/R term is the driving term due to toroidal curvature, and the quantity $aJ_cR_q^{\ 2}$ is the shear-driven part of the instability. These trends point towards domains of plasma operation optimization, though it is difficult to maintain $q_o > 1$. Low shear also allows surface kinks ($q_o \sim 1$ and $q_a \sim 1.9$) without shell stabilization which grow to large values quickly ($\sigma_{kink}/\sigma_{internal} \sim 5$-10).

G. Navratil, Columbia U. "High Beta Experiments in Torus II".

Gerry Navratil (Columbia University) spoke on "High Beta Experiments in Torus II." The objectives of this work are to produce a high-β tokamak equilibrium, investigate stability for volume-averaged betas of $.01 < \bar{\beta} < 0.2$ and study the physics of turbulent heating. In particular, a toroidal Z-pinch start-up technique is used to anomalously heat (field soak-in time is faster than classical) a small elongated plasma (R_o = 22.5 cm, a x b = 6 x 12 cm). The rapid formation time ($\sim$ 4 μs) allows generation (faster than MHD mode evolution) and study of potentially very unstable equilibria. However, the short pulse length (30-50 μs) limits the observation time. While MHD-time scale phenomena are separated from the resistive time scale, some plasma parameters (including $\bar{\beta}$) decay during the observation. Fast radiative plasma cooling also makes experimental interpretation difficult. Questions about disruptions and particle/heat losses in conventional tokamaks cannot be addressed by Torus II. The toroidal field decreases as 1/R after $\sim$ 5 μs with $\bar{\beta}$ = 8% and $q_a \sim 1.3$ at 1/4 heating power (full power: 800J over 1 μs). For this case, $n_e \sim 2 \times 10^{15} cm^{-3}$, I_p, $\sim$ 20 kA, $\varepsilon\bar{\beta}_p \sim 0.7$, $T_i \sim T_e \sim 100$ eV, B_T= 6 kG, β_o = 0.3 and $\bar{\beta} \sim 0.12$ with n_e and I_{pl} as above. These equilibria are consistent with high-β calculations but a stability analsyis has not yet been done. The peaks in both density and temperature are shifted in the outboard direction by $\sim$ 1/2 the plasma radius. During the period of maximum $\bar{\beta}$, the plasma appears stable, both globally (from streak camera data) and locally (from laser scattering data). After $\bar{\beta}$ has decayed somewhat in time, an exponentially growing instability occurs at the outboard plasma edge with a growth rate, $\gamma \sim (4\tau_A)^{-1}$, where τ_A is the Alfvén time. The observed growth rate is $\sim 10^5$ s^{-1} compared to maximum growth rates of 10^6 s^{-1} for MHD and resistive tearing modes respectively. The observed edge instability may be a resistive mode since the growth rate for such modes would increase to that observed as the plasma decays and cools. The present ability to pick a large variety of stable, high-β plasmas is a hopeful sign for high-β, advanced fuel tokamaks.

S. Tamor, SAI. "Synchrotron Radiation".

Steve Tamor (SAI) described calculations of synchrotron radiation using a 2-D "arbitrary" axisymmetric code. Plasma and magnetic profiles are included, together with boundary conditions (reflective/diffusive walls), relativistic optical properties (emission/absorption) and a consistent polarization treatment (important for diagnostics). Non-Maxwellian particle distributions are considered; the opacity calculation accounts for arbitrarily high temperatures (optical mode number approaching infinity). Profile and toroidal effects are important, leading to a net emission in the core and a net absorption in the edge plasma for a wall reflectivity near unity. However, a surprisingly simple cylindrical model can be used to speed calculations for transport codes if the reflective wall is replaced by a diffusive boundary condition. Both the total radiative loss and loss profile of this simple model are within 10-15% of the full toroidal calculation. Radiation-flattened temperature profiles will reduce fuel reactivities in the plasma center as well as affecting fast fusion product thermalization. The net effect must be determined by a self-consistent energy/particle transport calculation, and is especially important for high-β, high-temperature, advanced fuel simulations.

A. Boozer, PPPL. "Transport in Alternate Fuel Systems".

Alan Boozer (PPPL) discussed "Transport in Alternate Fuel System" using a general formulation which depends only on the number of symmetry directions. The types of such transport are summarized below.

Symmetry Directions	Equivalent Systems	Orbital Motion	Dominant Transport	Driving Forces
2	Slab Circular cylinder	Gyromotion	Classical	$E \sim \eta_\perp j_\perp$ (ambipolar)
1	Symmetric torus Elliptical cylinder Helix	Gyromotion Bananas	Neoclassical Pfirsch-Schluter	via $j_\parallel$ (ambipolar)
0	Rippled tokamak Stellarator Tandem mirror	Gyromotion Banana Banana drift	Ripple Super-banana	Like-particle collisions, viscous effects along $\vec{B}$ (not ambipolar)

Breaking the last symmetry direction by 10^{-3} can cause banana drift transport which overwhelms both gyromotion and banana transport. Note that an elliptical cylinder has a larger value of B near the flattened part of the ellipse. Thus, banana orbits form around the pointed part of the ellipse analogous to bananas in a tokamak. Power loss, P, from a rippled tokamak can be simply estimated using a diffusive scaling treatment:

$$P \sim 40 \text{ GW } (T_i/10 \text{ kev})^{3/2} \beta_{ei} N\delta^2,$$

where N is the number of TF coils and δ is the ripple size. This indicates that total ripple plateau losses from the ions are independent of plasma size, but are severe at high temperatures, requiring low ripple. However, even modest low-frequency MHD islands create a reasonable time averaged ripple. The analytical treatment for finding the transport for a symmetric torus uses a magnetic flux representation in which θ (polidal angle) and ϕ (toroidal angle) are periodic angles. Using ψ as the label for a flux surface (toroidal flux inside the surface), then $B^2 = |\vec{B}|^2$ can be Fourier decomposed as:

$$B^2(\psi,\theta,\phi) = \sum_{nm} a_{mn} \exp[i(n\phi - m\theta)],$$

where $\bar{B} = \nabla\psi \times \nabla\theta$
$= \nabla\chi + \beta\nabla\psi$
and $\chi^* = g(\psi)\phi + I(\psi)\theta, \ \theta = \theta_o + \iota(\psi)\phi$.

ψ is the magnetic flux inside a pressure (ψ = constant) surface; $cg(\psi)/2$ is the total poloidal current outside a ψ surface; $cI(\psi)/2$ is the total toroidal current inside a ψ surface; $\iota(\psi)$ is the rotational transform ($\iota = 1/q$).

Thus if B^2, $g(\psi)$, $I(\psi)$, $\ell(\psi)$ and the ambipolar potential are given, the particle drift can be obtained, yielding the banana and banana drift diffusive losses. Note from the above Fourier expansion that all systems with only one helicity have a known symmetry direction, and if formulated appropriately, they all have identical banana-type transport. Systems with two helicities have no symmetry direction, but if again appropriately analyzed, they all have identical banana and banana drift transport. The evaluation of transport can be done analytically for simple cases or using a Monte-Carolo code for general problems. This formulation is equivalent to saying that a 3-D description of $|\vec{B}|$ is adequate to solve for all the transport losses, and therefore applies to low-β plasmas as well as high-β, advanced fuel systems.

A. Boozer, PPPL. "Current Drive Techniques for Steady-State Reactor".

Alan Boozer (PPPL) also briefly discussed use of current drive technique to obtain a long-pulse (or steady-state) reactor. It is possible to drive ions with both ion beams and waves. To drive a significant current via beams, it is necessary to have the charge of the beam ions larger than the plasma ions; the net plasma response including electrons then drives a net current. Using scaling arguments the beam power goes like $P_o \propto nj/T$, where j is the current density. The driven power into the ions, P_I, becomes

$$P_I/P_o = \left(\frac{2^{2/3}}{3}\right)\left[\left(\frac{E_o}{E_c}\right)^{1/2} + \left(\frac{E_c}{E_i}\right)\right]$$

where E_c is the critical energy at which electron drag on the beam ions equals the ion drag ($\sim 15\ kT_e$); E_o is the injection energy of the beam corresponding to a beam injection power, P_o; and E_i is the average background ion energy ($3/2\ kT_i$). The corresponding scaling for electron current drive is

$$P_e/P_o = E_c/E_o\ ,\ \text{for } E_o \leq \frac{1}{2} m_e V^2.$$

Expressing this in terms of the nuclear power density, P_N, gives

$$P_N/P_o \doteq \beta_e \left(\frac{m_e}{m_i}\right)^{1/6} \left(\frac{a}{\rho_e}\right) \frac{\tau_{ei}}{\tau_N} \sim 100$$

without bootstrap current enhancement. Here, the scale time τ_N is defined by $\tau_N = 3/2\ p/P_N$ where p = plasma pressure, and the poloidal gyroradius is evaluated at the electron temperature.

J. Rawls, GA. "Effect of Ripple Diffusion".

John Rawls (GA) presented calculations of "Effect of Ripple Diffusion" on alternate fuel tokamak reactors by classical transport processes. Ripple losses can provide negative feedback on a thermal excursion and are therefore a means of burn control. In d-t reactors, the magnitude and spatial distribution of ripple loss is similar to the alpha power profile. Since the temperature dependence for such losses is stronger than the fusion reactivity, ripple losses can outrun a thermal excursion and stop it. This automatic burn control is enhanced by the outward radial shift (into a higher ripple region, leading to more ripple loss) which accompanies an increase in plasma pressure. However, these same features are not advantageous for advanced fuel designs because of more stringent $(n\tau)_{ign}$ requirements at higher operating temperatures. The lower reactivities of alternate fuels must also be compensated by an increased β (with a correspondingly large outward radial shift into a higher ripple) particularly for field-limited superconducting designs. Hence, ripple may be a serious problem for advanced fuel tokamaks. It is therefore important to determine the ripple constraints for various fuels and assess the prospects for meeting those restrictions. Processes included in the calculation are Bremsstrahlung, ion neoclassical and ion thermal ripple losses. The simplifications are: no anomalous electron transport, no impurities, no synchrotron radiation, and only Maxwellian ion populations. The analysis was for the INTOR reference design based on 1-1/2D code simulations including both ripple-trapping and ripple plateau losses. (Recent ISX-B experiments are in agreement with this theory, being able to explain decreased T_i, increased fast ion losses, and increased toroidal rotation drag with larger ripple). The resulting losses scale as shown below.

	$n\tau$ scaling					
Loss mechanism	T	n	ripple	size	field	origin of transport
Neoclassical	$T^{1/2}$	n^0	δ^0	a^2	B^2	banana orbit diffusion
Ripple plateau	$T^{-3/2}$	n^1	δ^{-2}	a^2	B^2	collisions at banana tip while passing through single ripple well
Ripple trapping	$T^{-7/2}$	n^2	$\delta^{-9/2}$	a^2R^2	B^2	trapping in $\vec{B}$-ripple wells

Losses are better parameterized by the ripple value δ mid way between the magnetic axis and the outboard edge, rather than edge ripple. The resulting $(n\tau)_{ign}$ requirements are enhanced by a factor of 5-20 for d-d and cat-d compared to d-t, requiring a $\beta \sim 0.2$-0.5. However, this does not include additional outward shifts of the magnetic axis at these higher-β values. All calculations were done for fixed β and variable temperature. While ripple losses become less of a concern in higher density, lower temperature designs, the larger β-values require higher magnetic fields. To achieve ignition in INTOR for $\bar{n} = 1.3 \times 10^{14}\,cm^{-3}$ the maximum ripple for D-based fuels need to be $\delta^{max}/\delta^{max} = 1/30$, 1/5, 1/5 for d-d, d^{3}He and cat-d reactors in comparison to d-t plasmas. Note that a 20% increase in magnet bore size is needed to reduce ripple by 5-fold. The corresponding constraint on a commercial reactor is $\delta(R_o + a/2) \overset{\sim}{=} 0.1\%$, which causes the edge ripple to vary with the number of TF coils as shown below.

N	magnet bore(m)	plasma-to-magnet dist.(m)	edge ripple(%)	comment
12	22	10	0.4	huge bore, high cost
16	17	6.0	0.7	
20	15	3.8	1.3	
24	14	2.2	2.3	hot ions poorly confined at edge - wall problems

Ripple is therefore an important problem in alternate fuel tokamak reactors.

J. Dawson, UCLA. "Hot Ion Systems".

John Dawson (UCLA) spoke on "Hot Ion Systems" as the most desirable operating mode for alternate fuels, with reactivity peaks above $T_i > 150$ keV for d-based cycles. To reduce Bremsstrahlung and synchrotron radiation it is necessary to keep the electron temperature low, but not so low that electron-ion rethermalization becomes large. In such an operating regime, it is important to include both the electron and ion Coulomb logarithms since

$$E_c \cong 20\,kT_e\,(m_H/m_i)\,(m_i/m_e)^{1/3}(\ln\Lambda_i/\ln\Lambda_e),$$

where E_c is the critical energy at which the electron and ion drag are equal. This yields $E_c \sim 2$ MeV for fast alphas slowing down in a 50 keV plasma. Turning to the question of ^{3}He for d-^{3}He reactors, there are a number of sources including:

- sufficient amounts for experiments from the weapons program (decay of t to ^3He costing $90/liter at standard temperature and pressure);
- the possibility of exploding a thermonuclear weapon underground and allowing the trapped tritium to decay to ^3He;
- if uranium and lithium deposits coexist, spontaneous fission neutrons could convert ^6Li to tritium which would then decay to ^3He;
- significant natural ratios of ^3He to ^4He amounting to 10^{-6} in the atmosphere, 10^{-7} in most helium gas wells, and 10^{-5} from volcanos and hot springs (similar fractions are expected to exist on Jupiter, Saturn and Uranus but would cost too much to return to earth);
- generation in a semi-catalyzed-d reactor (per G. Miley).

To run a d-^3He reactor, one might consider a d-lean, hot-^3He core so that neutrons from the d-d reaction are minimized. The hot ^3He could be generated by minority ICRF heating. It is also necessary to account for fusions involving the MeV fusion products as they thermalize with the background plasma. Heating such a high-temperature plasma with multiply charged ions offers a number of advantages:

- efficiency, since neutralization is not needed,
- easy beam bending of the charged beam, eliminating neutron exposure of the beam source,
- charged beam easily focused through a small port through the blanket,
- ready penetration of the beam into the plasma center for trapping by charge-exchange ionization,
- requirement for few fast ions limiting impurity radiation to low values (S. Tamor: line radiation on a 0.1-1 μs time scale would seem to be a problem during the (∿100 μs) charge exchange time),
- use of ^3He, Li, Be or B would lead to additional fusion heating,
- gross instabilities will probably not occur due to low beam density and large spreading in pitch angle and energy,
- the majority of the momentum transfer will be to electrons, providing a means of steady-state current drive.

MeV negative-ion heating is also feasible, with the above advantages, which could be adapted to existing neutral beam ports after the neutral stripping cell. Possible candidates are Li^-, C^-, O^-; even $^3He^-$ may work, having three electrons with parallel spins and therefore in different energy levels. The resulting plasma current, I_{tot}, scales like:

$$I_{tot} = (Z_{beam} - Z_{eff}) \times (\tau_{slowing}/\tau_{bounce})\, I_{beam}$$
$$\sim 6 \times 10^7\, I_{beam} \text{ for Li into d,}$$

where Z_{beam} is the final ionization state of the beam ions, $\tau_{slowing}$ is the slowing-down time of the beam, τ_{bounce} is the banana bounce time for the fast ions, and I_{beam} is the beam current. Thus, for this example, 0.16 amps of 6 MeV Li beam are needed to drive 10^7A of plasma current, yielding 0.7 watts of beam power per amp of plasma current. This scaling is in good qualitative agreement with neutral injection experiments on DITE.

Discussion

Alan Boozer (PPPL) led a discussion on physics issues that need to be addressed for alternate fuel tokamaks including:

1) MHD/β limits for high-field coils, so

- existing codes can be immediately used to study stability for a sequence of flux-conserving-tokamak equilibria which could move into the second region of stability (consistent with ignition and burn). These calculations could combine ballooning, PEST, kink modes (internal and external) and transport simulations. PEST runs could include finite resistivity and thickness of the wall together with plasma rotation to account for mode stabilization as it diffuses through the wall. High-β high-temperature plasmas seem best for eliminating resistive modes, but high thermal wall loading must be considered along with the expense of large, complex auxiliary systems;

- in addition to near-term high-β experiments on ISX-B and PDX, TFTR might attempt such studies.

2) Models of synchrotron radiation losses

- require complex codes when the system size is comparable to the mean free radiation path, need to account for anomalous distribution tails in a self-consistent transport model and should look for non-linear effects from the plasma dielectric;

- Should be coupled to parametric measurements of wall reflectivity in the quasi-optical regime as a function of realistic surface structure/contamination, radiation environment, etc.

3) Regarding the problem of plasma transport the following questions should be addressed:

- Anomalous slowing down of fusion products, e.g., for the "thermonuclear" instability, self-consistent plasma heating should be calculated, including profile changes which influence reactivities and thermalization. A new experiment on ISX-B (and Doublet-III) should be done at higher injection power to exceed the critical density for instability onset (may need another injector);

- experiments on energy confinement with T_e to resolve the 10-50 fold discrepancy among various scaling extrapolations;

- ripple transport - theory and experiment;

- multispecies transport and the possibility of microinstabilities due to ion mass differences.

4) Hot-ion mode physics could place a higher priority on He experiments in TFTR;

5) Wall damage due to disruption of high-temperature, high-β plasmas, with an eye toward control/feedback as seems to have been recently demonstrated on ASDEX (keeping the hot plasma off the walls during a disruption by TF coil feedback).

AGENDA
Alternate Fuels Workshop
Germantown, Md., January 26-27, 1981

JANUARY 26, 1981	Systems Session
Discussion Leader: R. Conn, UCLA Start of Session: 9:00 AM	
R. Conn:	Reactivity and Trade-Offs Between Alternate Fuels
G. Miley:	Fusion Cycles and Their Energetics
B. Coppi:	Alternate Fuels Systems Considerations
K. Evans:	A D-D Tokamak
W. Houlberg:	Ignited Tokamaks
A. Greenspan:	FED Considerations
R. Conn and Participants	Discussion
JANUARY 27, 1981	Physics Session
Discussion Leader: A. Boozer, PPPL Start of Session: 9:00 AM	
B. Coppi:	Second Region of Stability
D. Monticello:	Beta Limits
G. Navratil:	High Beta Experiments in Torus II
S. Iamor:	Synchrotron Radiation
A. Boozer:	Transport in Alternate Fuels Systems
J. Rawls:	Effects of Ripple Diffusion
J. Dawson:	Hot Ion Systems
D. Cohn:	Hot Ion Mode
A. Boozer and Participants	Discussions

Alternate Fusion Fuel Workshop
January 26-27, 1981

List of Participants

R. Hawryluk, PPPL

W. Houlberg, ORNL

J. Rawls, GA

B. Coppi, MIT

D. Cohn, MIT

Boozer, PPPL

D. Monticello, PPPL

G. Miley, Un. of Illinois

W. Grossmann, NYU

G. Navratil, Columbia Un.

J. Dawson, UCLA

R. Conn, UCLA

S. Tamor, SAI, La Jolla

K. Evans, ANL

L. Hively, ORNL

A. Greenspan, Un. of Illinois

A. Trivelpiece, SAI, La Jolla

S. Dean, Fusion Power Associates

R. Blanken, DOE

C. Head, DOE

W. Dove, DOE

W. Sadowski, DOE

IV. Alternate Fuel Fusion

During the summer of 1979 the Applied Plasma Physics Division/ Advanced Fusion Concepts Branch convened a panel of fusion experts to assist in formulating technical objectives for its near term development program. An excerpt of the report concerning Alternate Fusion Fuel Cycle Systems is presented here. The experimental portion did not address d-d cycles in the mainline approaches. Recent evolution of high beta theory and synchrotron loss calculations have provided the justification for an effort in the study of d-d cycles in the mainline approaches.

I. Program Description & Motivation

The current Office of Fusion Energy program emphasizes d-t fuel cycle reactors, because d-t is by far the most easily burned fuel, and the one closest to realization. Notwithstanding these considerable assets, it carries difficulties associated with the need to breed tritium and radioactivity caused by copious fluxes of energetic neutrons. While the radiological hazards from d-t reactors are greatly reduced compared with those from nuclear fission plants, it is prudent to have a vigorous alternate fuel program which offers the possibility of reducing or even eliminating radiological and environmental problems. At a minimum such a program would establish the potential of alternate fuels on a time scale that makes the knowledge available if the environmental, safety and licensing aspects of d-t reactors turn out to be serious.

Potentially, alternate fuels offer real economic advantages over d-t in addition to environmental acceptability. These advantages include the elimination of tritium breeding, removal of a large quantity of highly reactive lithium, reduced tritium handling, lower induced radioactivity, improved maintenance potential, high efficiency energy conversion, etc. Fusion research should strive toward quantifying these advantages.

Alternate fuel (AF) cycles can be divided into two categories: deuterium-based cycles (e.g., d-d, d - ^3H_e, d-^{6}Li) and proton-based cycles (e.g., p-^{11}B p-^{6}Li). The deuterium cycles are simpler and more easily attained. They require moderate ion temperatures and produce significantly lower neutron fluxes and tritium recovery than does d-t. Most importantly, no tritium breeding is required. The proton cycles are the most promising but have the most stringent technological and physics requirements. They require high ion temperature (200-300 keV) and large $n\tau \approx 10^{15}$cm^{-3}-sec, but offer the enormous potential of being almost neutron and tritium free. The potential of both cycles should be investigated from four points of view.

- Theoretical studies of reaction kinetics, burn dynamics and plasma transport
- Experimental confinement physics
- Engineering studies to quantify alternate fuel advantages
- Long lead time technology developments

2. Goals

The goals of the AF program for the next five years are to quantitatively assess the potential of alternate fuel systems relative to d-t systems, and to implement an experimental program, which investigates the most promising AF confinement devices, in order to be prepared, if warranted, to initiate a POP level experiment design.

3. Achievements in the Last Five Years

Although research on alternate fuel cycles has been supported on a rather modest level during the last five years, significant achievements have been attained. Many calculations have been carried out for d-d and d-^{3}He in advanced tokamaks that show viability if beta values of 20-30 percent can be achieved. Preliminary studies also indicate that a tandem mirror device may be well suited to alternate deuterium fuel cycle application.

If tokamak and open (mirror based) systems prove to be suitable for confinement of deuterium-based alternate fuel cycles, then the present extensive experimental programs in each would greatly reduce the development time for these options. The status of these programs is not presented herein.

One of the potentially cleanest and most attractive reactions, p-^{11}B, has been examined in detail. Earlier results have found the reaction marginal ($Q \simeq 1$), but more recent studies hold open the promise that this fuel cycle may yet prove to be useful. The fully catalyzed p-^{6}Li chain reaction cycle has been re evaluated and is now the leading candidate for a neutronless fuel. A theoretical study of this extremely complicated cycle (over 40 reactions) is currently in progress at the University of Wisconsin, TRW, ORNL and the University of Illinois. Preliminary burn studies have shown that the hot ion mode of operation, either ignited or driven, is the most attractive for operating alternate fuel reactors.

Synchrotron radiation from the high temperature electrons which will be present in alternate fuel reactors has received preliminary examination as noted above. It appears that the energy balance for d-d or d-^{3}He tokamaks or mirrors may be favorable if beta values of 20-30 percent can be achieved. However, for the more advanced fusion reactors using proton burning fuels and for the advantageous, deuterium lean, d-^{3}He reactor, the only magnetic configuration which at present can clearly cope with the synchrotron radiation problem is the multipole.

The experimental alternate fuel program for proton based fuel cycles has been centered on the study of multipole configurations. Multipoles, due to the large volume in which the magnetic field is small, have been considered as the most promising devices for minimizing the synchrotron losses at the high temperatures required by the proton cycles. Experiments on multipoles have been extended to higher temperatures and significant betas. Ion temperatures of over 250 eV have been obtained using gun injected plasmas at UCLA and of 600 eV using rf heating at the University of Wisconsin. Experimental programs are in progress at both institutions to extend these temperatures substantially within FY 1980. Values of beta at the bridge of 5 percent have been reported at UCLA and as high as 16 percent at Wisconsin. Particle confinement has been very good for multipoles of low temperature and density, and 2 msec is being obtained at UCLA for 200 eV and 3×10^{13} cm^{-3}. The Wisconsin experiments indicated that convective vortex diffusion is the dominant loss mechanism ($\tau_B \geq 20$ msec) for gun injected plasmas and this loss can be greatly reduced by introducing a small toroidal magnetic field. There is minimal experimental evidence concerning energy confinement; energy confinement times in past and current experimental devices have been limited by charge exchange losses. This is an area in which experimental results may be greatly extended with fabrication of appropriate new devices.

Engineering studies have indicated that passive methods for stable superconducting floating rings can be found, with the optional possibility of feedback stabilization. Calculations with respect to shielding rings from heat and neutron fluxes indicate that the rings can be built so that they will remain superconducting for times of one day in the environment of a $d\text{-}^3He$ reactor. A study to determine if alternate fuels are a realistic alternative to d-t and to ensure that a confinement device is available or in an advanced planning stage when breakeven is achieved, is presently in progress at TRW under EPRI sponsorship.

4. Needs for the Next Five Years

Classification of needs is shown in Table I. The following discussion amplifies the table.

TABLE I
Classification of Needs for the Alternate Fuel Program

	Classification	
Need	Value	Timeliness
<u>Experimental</u>		
Energy and particle scaling in multipoles	1	A
β limits at the bridge for multipoles	1	A
Heating of multipoles	1	A
Alternate fuel exp. in existing devices	1	B
Effect of guarded ring supports on confinement	1	B
<u>Theoretical</u>		
Burn kinetic code for AF cycles	1	A
Synchrotron rad. code for AF conf. devices	1	A
Reactor assessment potential of AF	1	B
Technology		
Develop technology for levitating multipole superconducting rings	1	C

1) Analysis of alternate fuel burn dynamics with a set of burn and fusion dynamics codes. Subtasks include:

a) Formulate a burn kinetics code for fuel cycles of interest including sufficient numbers of side reactions to calculate

the neutron flux, energy density, ash production, and start-up and heating requirements
b) Formulate a synchrotron radiation code capable of determining radiation confinement times for all major candidate alternate fuel confinement devices.
c) Formulate theories of energy and particle transport for the candidate devices and appropriate confinement time scaling laws which bridge the gap from current experiments to the reactor regime.
d) Integrate the above results and perform reactor assessment and technology development requirement studies such as power density vs neutron production, tradeoff studies for various fuels, start up scenarios, and ash buildup.

2) Perform a quantitative assessment of the potential engineering and environmental advantages of alternate fuel power plants.

3) Since the multipole appears to be currently the most promising proton based fuel burner, the momentum of the current experimental program should be supported at a level sufficient to meet the objectives cited below within the two year time frame. Major objectives should be:

a) Determination of the energy and particle confinement scaling required to extend plasmas to the d-t regime $n = 10^{12}$-$10^{13}cm^{-3}$, $T_i \sim 1$ keV. This effort should be closely coordinated with the theoretical effort (above) which should adequately treat neutral and impurity transport to support the experimental activity. (This activity probably would not represent an alternate fuel POP experiment. The anticipated alternate fuel requirements suggest the need for 10 keV temperature and $n\tau$ values of 10^{13}-$10^{14}cm^{-3}$sec.)

b) Compare rf and neutral beam heating with particular emphasis on the former because of the difficulty of developing MeV neutral beams to heat a several hundred keV plasma. Consider pulsed, intense ion sources for MeV beam heaters.

c) Determine β limits at improved values of collisionality, connection lengths, etc.

d) Determine the effects of guarded internal ring supports on confinement.

e) Perform alternate fuel relevant experiments on other existing devices: e.g., d-^{3}He burning in PLT, reaction rate measurements with energetic ion rings in plasmas, etc.

4) Technology development should also be continued in the next five years. In particular, because of the long lead times involved, levitated superconducting ring development would be the pacing item in the fabrication of a POP multipole. Small funding expenditures may result in large schedule advantages.