W. Saylor (Gilbert/Commonwealth)
W. Sutton (UI)
T. Tamano (GA)
S. Walker (Phillips Petroleum)

Group B

D. Graumann (GA), Group Leader
J. Baur (GA)
B. Coppi (MIT)
B. Engholm (GA)
Y. Gohar [Argonne National Laboratory (ANL)]
W. Köppendörfer (IPP-Garching)
R. Moir [Lawrence Livermore National Laboratory (LLNL)]
J. Norem (ANL)
M. Ragheb (UI)
E. Salpietro (Joint European Torus)
W. Spears (Culham Laboratory)
R. Stevenson (INESCO)
C. Weggel (INESCO)
K. Werley (UI)

Group C

T. Yang (MIT), Group Leader
W. Becraft (ORNL)
I. Bohachevsky (LANL)
F. Bohn (IPP-Jülich)
U. Braunsberger (Hochspanaung Tech.)
C. Choi (UI)
R. Hagenson (Technology International)
P. Harbour (Culham Laboratory)
J. Hovingh (LLNL)
E. Hubbard (GA)
I. Kanter (Westinghouse)
B. McNamara (LLNL)
M. Peng (ORNL)
W. Tetley (UI)
F. Turanciol (C-E).

Also, the groups were assisted by the UI Fusion Studies Laboratory staff who served as secretaries, including: Ming-Yuan Hsiao, William Sutton, Kenneth Werley, and William Tetley.

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 does not have to breed tritium, the blanket/shield can be optimized to have a thinner inboard extent (82 versus 120 cm for STARFIRE) and increased neutron multiplication (2.02 versus 1.14).

Both a pulsed and a steady-state version of WILDCAT have been studied. The pulsed version has a considerably larger equilibrium-field/ohmic-heating system and requires thermal storage. These two systems lead to an appreciably higher cost. The steady-state version relies on current drive using Alfven waves. Capital costs are estimated to be \$3100 million for the steady-state version and \$3800 million for the pulsed version compared to \$2400 million for STARFIRE. The costs of energy are 63 and 74 mill/kWh compared to 35 mill/kWh.

The major advantage of WILDCAT over STARFIRE is the lack of tritium breeding, leading to increased safety and elimination of tritium-breeding problems. The major disadvantages are reduced reactivity and higher temperatures, leading to larger sizes, magnetic fields, and beta, as well as to reduced power and power density. The major conclusion is that one would probably not build D-D tokamaks for power production as long as tritium breeding is possible, but if necessary, D-D tokamaks could be built with reasonable extrapolations of parameters considered viable for D-T reactors.

Comparative Study of AF RFP Reactors, R. A. Krakowski, Los Alamos National Laboratory (LANL)

This paper discussed results of several comparative RFP reactor studies performed by R. A. Krakowski and R. Hagenson. Extension of "conventional" D-T-fueled reversed field pinch reactor (RFPR) designs to catalyzed D-D operation was reviewed. Attractive and economically competitive D-D/RFPR systems having power densities and plasma parameters comparable to the D-T systems were identified. These designs are compared to other fusion reactor designs in Table I. The D-D/RFPR is ohmically heated to ignition, using an initial charge of D-T. Increasing the plasma temperature by a factor of 1.8, plasma density by 3.5, and energy confinement time by 3, the D-T is converted to a D-D burn. The dominant plasma loss is bremsstrahlung, with cyclotron radiation being insignificant. The factor of ~25 reduced power density of the D-D reaction is counteracted by a factor of ~2.3 increase in plasma current and, hence, magnetic field levels. The resultant D-D system is of comparable power density with magnetic fields at the coils of only $\lesssim$4 T. Tritium inventories in the D-D system are reduced to <2% that needed in a D-T reactor. The larger fraction of charged particle/neutron power for the D-D reaction requires 2.8 times the D-T first-wall surface flux for comparable power densities.

The result that catalyzed D-D operation for an RFPR could be comparable to D-T operation has recently led to the examination of more compact, higher power density RFP reactors (CRFPRs). The RFP reactor models developed for the "conventional" approaches have been applied to the CRFPR regime, which emphasizes high neutron wall loadings ($I_w \gtrsim 15$ MW/m^2 for D-T fuel operation), high blanket power densities [$P_{TH}/V_B \gtrsim 40$ MW(thermal)/m^3], high system power densities [$P_{TH}/V_c \gtrsim 5$ to 10 MW(thermal)/m^3], and low mass utilization [$M_{NI}/P_{TH} \lesssim 1$ tonne/MW(thermal)]; P_{TH} is the total thermal power, V_B is the

TABLE I

Parameter Summary for Toroidal Fusion Reactor Concepts

Parameter	Modular Stellarator Fusion Reactor	EBT	Tokamak: STARFIRE D-T	Tokamak: WILDCAT D-D	RFPR: D-T	RFPR: D-D	CRFPR: D-T[a]	CRFPR: D-T[b]	CRFPR: D-D
Net power, MW(electric)	1530	1214	1200	---	750	750	750	1250	1000
Plasma radius, m	2.11	1.00	2.38	3.34	1.2	1.2	0.41	0.44	0.28
Major radius, m	20.2	35.0	7.0	8.6	12.7	12.7	7.1	11.7	9.7
Plasma volume, m^3	2050	691	781	1887	564	781	23.5	44.7	15.0
Average density, 10^{20}/m^3	1.50	0.95	0.81	2.0	2.1	7.1	3.9	3.7	27.9
Temperature, keV	8.0	29.0	22.0	31.0	10.0	18.5	20.0	20.0	20.0
Magnetic field, T	11.0	10.0	11.0	14.0	1.7	4.0	3.6[c]	3.5[c]	9.6[c]
Neutron current, MW/m^2	1.3	1.4	3.6	0.55[d]	2.7	0.86[d]	15.4	14.5	8.6[d]
Thermal power, MW(thermal)	4800	4028	4033	2522	2800	2850	2512	4158	3976
System power density, MW(thermal)/m^3	0.26	0.24	0.30	0.28	0.50	0.36	10.0	10.0	10.0
Mass utilization, tonne/MW(thermal)	9.00	10.85	3.94	---	3.8	4.00	0.65	0.63	0.72
Thermal conversion efficiency	0.35	0.35	0.35	0.35	0.30	0.30	0.35	0.35	0.35
Recirculating power fraction	0.08	0.15	0.17	---	0.17	0.13	0.15	0.14	0.28
Net plant efficiency	0.32	0.30	0.30	---	0.25	0.27	0.30	0.30	0.25

[a]Included for comparison with the "conventional" D-T/RFPR design.
[b]Included for comparison with the D-T/tokamak design.
[c]Initial toroidal bias field, reduced by ~2 after startup phase.
[d]Only 14.1-MeV neutrons. The 2.45-MeV neutron current is 4.2 MW/m^2 for the D-D/CRFPR, 0.17 MW/m^2 for the D-D/RFPR, and 0.095 for the D-D/tokamak.

blanket volume, V_c is the reactor volume enclosed by and including the coils, and M_{NI} is the combined mass of blanket, shield, and coil. These goals are met while remaining within key engineering constraints imposed by first-wall/blanket heat transfer and thermal cyclic fatigue, acceptable levels of pulsed energy transfer, and a favorable total system energy balance. Elimination of the reactor volume within the coils associated with nonproductive (i.e., near room temperature) radiation shielding is an essential element in achieving compact, high power density systems. Consequently, the use of superconducting coils is undesirable.

Interim conceptual design(s) of minimum cost 750- and 1250-MW(electric) (net) power plants are compared in Table I with more conventional designs of both RFP and tokamak reactors for both D-T and catalyzed D-D operation. The AF CRFPR designs are found to operate with power densities and costs that differ little from those projected for the D-T system. Therefore, in spite of a partially developed physics base, the interesting technological and economic merits of the high density RFPR give reason for the ongoing full parametric systems and conceptual design studies for both D-T and catalyzed D-D operation. Generally, the CRFPR proves surprisingly resilient to changes in key but relatively unresolved system parameters.

The SATYR D-D Tandem Mirror (TM) Reactor Study, R. W. Conn, University of California, Los Angeles (UCLA)

This paper described the SATYR conceptual design study for a D-D barrier TM reactor. The study shows that high central cell beta (β_c) and axisymmetry are crucial to even a moderate Q reactor. The SATYR system is large, with low power density, and $Q \sim 5$ to 6. A specialized axisymmetric configuration involving a plug-barrier cell with a levitated internal ring has been developed, though overall results are independent of the specific axisymmetric end-plug configuration. A new pressure-vessel-type blanket design with pebble beds of ferritic steel produces high blanket multiplication and has long life (exceeding plant life). A detailed comparison of economic, environmental, and safety scaling factors for D-D and D-T reactors reveals few incentives for aiming at D-D devices. The conclusion is that the linearity of TMs, their inherent modularity and potential for steady-state operation, their predicted high power density and high Q value, combined with the findings of this study, suggest that optimized D-T cycle barrier TM reactors, with axisymmetry and high β_c have the potential to be economic reactor systems and should remain the major goal of mirror fusion research.

Prospects for Higher Power Density/Lower Cost Advanced Fuel Mirror Systems, R. F. Post, Lawrence Livermore National Laboratory (LLNL)

This talk outlined some strategies for addressing the issue of power density and system cost for mirror fusion power systems that would employ AFs. The main issue to be addressed is the unfavorable cost impact of having to operate at higher plasma temperatures with AF cycles that have substantially lower reactivity than the D-T fuel cycle. The aim of the talk was to emphasize the need and the value of further physics insights and of innovative technological approaches in addressing the capital cost problem of AF mirror systems.

Two areas for attack on this problem were discussed, the first involving physics considerations and the second, technological. Their interrelation is succinctly expressible through the relationship between fusion power density and plasma beta, the strength of the external confining magnetic field B, the fusion reaction rate parameter $\langle \sigma v \rangle$, and plasma ion temperature T; namely, $p_{\text{fusion}} \sim \beta^2 B^4 [\langle \sigma v \rangle / T^2]$. Since AFs have much lower maximum values of the quantity $[\langle \sigma v \rangle / T^2]$, one or more of the following is required to maintain an economically viable fusion power density: increased beta, increased magnetic field, lowered magnetic field cost.

Two encouraging possibilities for increasing beta are: (a) the exploitation of finite orbit and wall proximity stabilizing effects to raise the beta value toward 90% in axially symmetric TM systems and (b) the achievement of stable high beta field-reversed states for which beta values might exceed 200%. Both of these issues seemingly could be addressed through modest scale experiments.

In the area of magnet design, it was pointed out that a substantial saving in the cost of the "base" solenoidal field of an axially symmetric TM system could possibly result from the use of a "force-free" coil winding configuration. The potential gains here are twofold: (a) a force-free winding should need far less support structure than a conventional solenoid and (b) high field superconductors exhibit much increased critical currents for fields that have their primary component along B, as is the case in force-free coils. It was estimated that a factor of ~ 10 reduction in the cost of a large bore, high field solenoid might be achieved by employing a force-free design. The concept here would be to make the bore sufficiently large so that all other coils (plug magnets, etc.) could be nested well inside the main solenoid.

SESSION B: Invited Talks

(Chairman: W. F. Dove, DOE)

Prospects for Burning the Proton-Boron Fuel, T. K. Samec, TRW, Inc.

This paper summarized some of the results of an Electric Power Research Institute funded study carried out by TRW, Inc. Three issues dominated the results of this study: (a) the viability of the p-^{11}B fuel cycle, (b) the desirability of the multipole as an alternate confinement concept, and (c) the environmental consequences of proton-based fuels. With regard to item (c), the expected environmental and safety advantages of the p-^{11}B cycle do occur, but care must be taken to achieve these advantages, e.g., radiological environments are small but not negligible. Regarding item (b), the multipole is an attractive concept for use with the high temperature proton-based fuels, since synchrotron radiation losses are reduced by the use of low internal magnetic fields. However, the multipole, as with any proton-based fuel confinement concept, must operate at high beta to overcome the low reactivity of the fuel cycle and to provide for high synchrotron radiation reabsorption. Finally, regarding item (a), the conclusion was that with the physics known today, specifically the reaction physics included in the burn code, the p-^{11}B cycle does not appear to have sufficient reactivity for a commercial reactor. At the required high electron temperatures, synchrotron radiation losses are large and place increased demands on a high reactivity. It was noted that physics effects not included in the code could provide some increase in reactivity, but probably not of the magnitude (~50%) required for economical reactor operation. Thus, an "invention" is felt to be needed to efficiently drive a non-Maxwellian, hot proton tail to enhance the reactivity.

Enhanced Reactivity in Fusion Reactors, J. M. Dawson, UCLA

Enhanced reactivity produced by alpha particles and fusion reaction products kicking fuel particles to higher energy where they react more vigorously was discussed by J. M. Dawson (UCLA). The effect comes from a very large number of particles receiving very small energy boosts resulting in a substantial reactivity multiplication. The process is a kind of catalysis process in which a fast reaction particle imparts a change in energy to a fuel particle as it changes momentum due to Coulomb interactions; the increase in reactivity from particles that gain energy more than offsets the loss in reactivity by particles that lose energy. The effect was studied with a model Fokker-Planck equation and estimates of its size were presented for D-T, D-^{3}He, and p-^{11}B. The conclusion was that the enhancement is important for D-T as well as for AFs. It should add between 0.5 and 2.0 to the Q of the tokamak fusion test reactor depending on the experimental conditions achieved. The reactivity is increased by a factor of ~2 in D-^{3}He at 50 keV. The reactivity enhancement was shown to be significant to the reactivity of p-^{11}B and may lead to ignition of this fuel. If the latter were true, the conclusions of the previous paper might be changed. It was noted that there are some questions about the adequacy of the model Fokker-Planck equation, but that a proper Fokker-Planck treatment of reacting plasma should include the effect; e.g., the simple model Fokker-Planck equation predicts a reactivity enhancement for p-^{11}B of 36% at T_e = 125 keV, T_i = 200 keV for n_B/n_p = 0.2, while more detailed model Fokker-Planck calculations by G. Shuy (UCLA) predict an enhancement of 56% (~50% enhancement is required for ignition). It was recommended that the importance of the effect should be investigated for all AFs.

Some Physics Issues for AF Reactors, D. R. Dobrott, SAI

This talk and the following one were intended to raise some of the more generic issues associated with AF reactor studies for discussion during the working sessions to follow. Before enumerating some of the physics issues of AF reactors, it was argued that there are different approaches that may be and have been taken in analyzing AF reactor plasma behavior. On the one hand, one may accept the current data base and project reactor behavior from models that are consistent with present knowledge. This approach often leads to reactor designs that suffer the disadvantage of being constrained by unfavorable physics, and in this sense may be regarded as a conservative approach. On the other hand, one may choose to relax selected physics and/or technology constraints so that more attractive AF reactor designs are possible. The rationale for this is that in many ways the data base is incomplete or lacking altogether. This approach tends to be more optimistic and assumes that physics or technology obstacles to favorable reactor design and performance can be overcome. It was argued that some elements to both approaches exist in all reactor studies, and it is clear that both approaches are used and needed. Care must be taken in choosing an approach so that comparisons among various reactor concepts are even-handed. A partial list of physics issues that impact reactor design was then described.

1. *Configurational issues*. These issues relate to the achievement of stable equilibria with sufficiently high beta for attractive reactor design.

2. *Confinement*. Plasma transport scaling in many cases is a weak link in reactor plasma modeling, e.g., plasma transport has generally been dominated by empirical Alcator scaling for tokamaks and is also used for RFPs.

3. *Radiation transport*. Radiation losses have a strong impact on reactor design for AFs. Synchrotron radiation not only affects the power splits but also modifies the temperature profiles, and thus impacts plasma stability and technology considerations, such as thermal wall loading.

4. *Reaction kinetics*. Important questions still remain regarding the degree of reactivity enhancement in AF cycles.

5. *Heating*. Important heating questions such as accessibility and energy deposition still remain in radio-frequency heating.

6. *Boundary conditions*. Plasma-wall interactions are still a major unknown and can have a strong influence on reactor plasma behavior.

7. *Startup and steady state*. The issues of fueling, impurity, and ash removal have not been adequately addressed in AF reactors. This is also true for D-T reactors.

Alternate Fuels Reactor Assessments—Engineering and Technology Issues, J. E. Glancy, SAI

The importance of four performance parameters in AF reactor assessments was stressed.

1. *Cost*. A list of seven parameters that impact the cost of the reactor and the cost of electricity was presented. For each parameter, a rough comparison was made between D-D and D-T tokamaks, the cost impact for D-D relative to the D-T STARFIRE was estimated, and the technology issue(s) that drives the cost was given. The information is summarized in Table II. It was concluded that it is easy to identify a 30 to 50% increase in the capital cost of a D-D tokamak over a D-T tokamak, but there are also cost issues that have been identified that should reduce the cost increase. More detailed studies are required to quantify these cost impacts.

2. *Safety and environment*. The safety issues were divided into three major categories: (a) accident risk, (b) routine release and occupational exposure, and (c) waste management. A rough comparison of these issues was made for D-D versus D-T and is summarized in Table III. The conclusion was that there appears to be a net safety advantage for D-D relative to D-T, but more work needs to be done to quantify this advantage so it can be compared with the cost disadvantage.

3. *Resource utilization*. Utilization of resources is one of the primary reasons for studying D-D fusion reactors because the fuel is abundantly available in nature, whereas tritium must be bred from lithium. However, the amount

TABLE II

Major D-D Versus D-T Cost Assessment Issues

Cost Issue	D-D Versus D-T Comparison	Potential Cost Impact	Technology Issues
Power density	D-D two to four times lower	Plus 10 to 15%	$\beta^2 B_0^4$ Thermal wall load
Magnet stored energy	D-D two times larger	Plus 10 to 15%	β^2
Recirculating power fraction	D-D two times larger	Plus 5%	Efficient current drive
Blanket mass and complexity	D-D less complex but larger mass	Even	Simple, safe, high reliability D-D blanket
Thermal cycle efficiency	D-D potentially 15% more efficient	Minus 1 to 2%	High temperature D-D blanket
First wall and blanket lifetime—availability	D-D six to eight times longer life	Large	First-wall erosion/particle to radiation power shift and creep rupture limits
Lower tritium inventory—licensing	D-D 10^{-2} times less tritium	Small to medium	Vulnerability of tritium in storage and blanket of D-T

TABLE III

Major D-D Versus D-T Safety Assessment Issues

Safety Issue	D-D Versus D-T Comparison	Impact	Technology Issues
Accident risk			
Source terms	D-D tritium inventory 10^{-2} to 10^{-3} lower	Large	Vulnerability and consequences of D-T tritium inventories
	D-D-induced short-term radioactivity two times lower	Small	Lower activation first-wall materials
Stored energy	D-D magnet stored energy two times larger	Large	β^2
	D-D plasma stored energy four times larger but wall area 1.5 times larger; net E/A 2.5 times larger	Small	---
	D-D afterheat two times lower	Large	Lower activation first wall/ blanket materials
	No lithium metal reactions	Large	Solid tritium breeders
Routine release and occupational exposure			
Source terms	D-D tritium inventory in coolant considerably lower	Large	Tritium migration
Leak paths	D-D blanket less complex	Large	Blanket leak path/failure analysis
Maintenance	D-D blanket six to eight times less maintenance	Large	First-wall erosion/particle to radiation power shift and creep rupture limits
Waste management			
Source terms	D-D long-term radionuclide inventory two to four times larger	Small	Lower activation first wall/ blanket materials

of energy that can be obtained from lithium is very large and the lack of a tritium-breeding requirement translates more into a cost and safety advantage than a resource utilization advantage.

4. *Operability*. The operability of fusion reactors depends on the application, but for electricity production, there appear to be no major differences in operating a D-D or D-T fusion reactor in the electric grid.

III. WORKING GROUP SESSION SUMMARIES

The remainder of the workshop was devoted to smaller working group sessions for more detailed discussion of major issues. A plenary session was held to close the workshop during which the results of the working sessions were described by their chairmen. This section summarizes the results by individual working session.

SESSION C: Working Group on Prospects for Proton-Based Fuels

(Chairman: J. M. Dawson, UCLA)

G. Shuy (UCLA) presented his calculations of "tail pulling" and enhanced reactivity of p-^{11}B. "Tail pulling" is an expression that was used to describe the effect of increasing the energy of plasma fuel ions in Coulomb interactions with the high energy fusion products as they slow down. His results show that the high energy tail population gives significant enhancement of both the plasma reactivities and fraction of energy deposition to the ions. He pointed out that the validity of using a Fokker-Planck model, which is based on the assumption of the dominance of small energy transfer collisions, to calculate the distribution function should be carefully investigated, since some large energy transfer Coulomb collisions occur as well. It was agreed that a proper treatment of the p-^{11}B reactivity enhancement has not been carried out. The tools for this calculation are thought to exist and the calculations should be carried out, particularly in light of the results presented in papers by Samec and Dawson in session B. This is also true for other AFs and even for D-T. We note here that the University of Illinois (UI) group has calculated reactivity enhancement for D-based fuels using a Fokker-Planck code and accounting also for large energy transfer Coulomb collisions (see the summary of session H). There appear to be differences in the conclusions reached by the UI and UCLA groups regarding the importance of reactivity enhancement via Coulomb interactions.

C. Sprott [University of Wisconsin (UW)] discussed the status of multipole experiments on the Wisconsin levitated octopole. The experiment has recently been upgraded by the addition of high power ion cyclotron resonance heating (ICRH) and neutral beam injection to investigate beta limits and energy confinement scaling in more reactor-like regimes of temperature and density. Plasmas are produced with beta values as high as 44%. No evidence of instability or degraded confinement is observed. To date, 2 MW of ICRH and 400 kW of neutral beam power has been applied to the plasma resulting in ion temperatures in excess of 100 eV, electron temperatures up to 60 eV, and densities on the order of 10^{13} cm^{-3}. The energy confinement time is 1 ms. Near-term plans call for increasing the ICRH power to 4 MW and the neutral beam power to 1.8 MW. Sprott argued that even if the proton-based fuel cycles prove unworkable, the multipole will continue as a useful vehicle for studying the basic physics of beta limits, stability, transport, and heating relevant to all magnetically confined plasmas. This view was shared by D. W. Kerst (UW) who further pointed out that, for example, some of the questions of "burn dynamics" need plasmas that are hot enough and confined long enough so that the migration of impurities and alpha particles can be determined. A multipole field configuration, static for times up to 0.1 s, is a possibility for measurements.

A. Wong (UCLA) described a confinement system for a pure ion, nonneutral plasma that can be used to study AF fusion kinetics and reaction rates. He thinks a device can be built with $n \gtrsim 10^{11}$ cm^{-3}, $\tau = 10^4$ to 10^5 s for $B = 10$ T. The system is not attractive for commercial generation but would be useful as a simulated AF experiment.

Wong also described SURMAC results. The experiment has achieved $n \leqslant 6 \times 10^{13}$ cm^{-3}, $T_i = 1.2$ keV, $T_e = 30$ eV, and $\beta \leqslant 8\%$, which equals the theoretical beta limit for ballooning instabilities. Magnetic guarding appears effective and additional experiments are under way at higher fields. If magnetically guarded hoop supports are proven effective, the multipole/SURMAC confinement system could be used for neutron lean fuels such as D-^{3}He as well as for proton-based fuels.

SESSION D: Working Group on AF RFP Reactors and Other Alternate Concepts

(Chairman: W. Grossmann, New York University)

The session began with an identification of alternate confinement concepts, i.e., other than tokamak and mirrors, that qualify as possible candidates for alternate fusion fuel operation. The list includes: RFP, compact toroids, ELMO Bumpy Torus (EBT), multipoles, stellarator/torsatron/heliotron (STH). The goal was a global comparison among the devices in order to assess the apparent main attractiveness or disadvantages vis-à-vis AFs. An attempt was made to assess the present and planned activities in AF studies for these concepts, and to estimate the level of information that will be available at the end of fiscal year 1983.

Figure 1 schematically illustrates what was felt to be the degree of difficulty in going from a D-T to a D-D reactor for the various alternate concepts relative to a tokamak reactor. Multipoles did not appear to fit on this diagram. Discussion of multipole physics issues concluded with the belief that multipole reactors using the proton-based fuels do not look very promising. This is a somewhat controversial point, as we have discussed before, but the onus is on physics demonstration to the contrary. It was further concluded that, whereas multipole devices as they are presently conceived may not appear attractive as reactor candidates, they may well play an important role as physics test devices where such issues as proton-based fuel burn dynamics may be investigated (see also the summary of Session C).

For the remaining concepts, the two issues forming the basis of discussion were (a) the use of scaling laws in reactor studies and (b) what type of reactor study should be made. There was no consensus on the question of whether the use of scaling laws is useful. However, there was a consensus that if such laws are used, they should be consistently applied across confinement concept lines, and the sensitivity to variations in the assumed scalings should be assessed. The difficulty here is that the degree of physics knowledge is uneven among the alternate concepts, and this makes it very difficult to compare the various concepts according to any consistent set of criteria. Regarding the second issue, there was general agreement that an optimized parametric systems analysis should be applied to all alternate fuel cycle reactor schemes. It was reemphasized that a detailed D-T reactor design study (STARFIRE) has been extended to deuterium-based operation (WILDCAT) with a concommitant source of reference data applicable for future reactor studies. It was also noted that a promising compact version of an RFP reactor, which is vastly different from the previous RFP D-T reference reactor design of LANL, has been examined with preliminary studies having been carried out for deuterium-based fuels (see the paper by Krakowski in session A).

Table IV summarizes an attempt to estimate the level of information concerning alternate concept AF reactor configurations that might be available by the end of fiscal year 1983. The analysis is based on the assumption that the current level of funding across-the-board for these studies will be held constant.

SESSION E: Working Group on AF Tokamak Reactors

(Chairman: J. E. Glancy, SAI)

The working group identified and discussed the following issues.

1. *The value of high beta (15 to 20%) D-D tokamak reactor studies.* There was considerable feeling that reactor studies should be performed to evaluate the cost impact of operation at higher beta values, and that a vigorous theoretical and experimental program to identify beta limits is a high priority. The reactor studies should proceed along two separate paths. (a) High power density studies—D-D tokamaks operated at high beta (>11%), high B field (~14 T at the coil), and therefore power densities comparable to those of the D-T STARFIRE reactor should be evaluated. These power densities will result in thermal wall loads >1 MW/m^2 for reactors of 1000-MW(electric) capacity and, therefore, alternatives to stainless steel first walls must be evaluated. (b) Low power density studies—D-D tokamaks operated at high beta (>11%) but lower magnetic fields will have power densities comparable to current D-D tokamaks such as WILDCAT but will have much less stored magnetic field energy and thus lower costs.

2. *Evaluation of the cost of D-D relative to D-T tokamaks.* In addition to investigating the D-D to D-T cost difference at high beta, a closer examination of this difference at beta values of <11% should be performed to determine the impact of other considerations (engineering, technological, licensing, etc.).

3. *Value of high magnetic field (>14 T), compact, normal conducting magnet D-D tokamak reactor studies.* The group agreed that studies of normal conducting magnet tokamaks are of high priority for ignition experiments. They acknowledged the absence of the Massachusetts Institute of Technology (MIT) group, who performed most of the research in this area.

4. *Comparison of D-D tokamaks to liquid lithium tokamaks as well as to D-T reactors with solid lithium breeders.* The group agreed that assessments of D-D tokamaks should be made relative to low power density tokamaks (neutron wall loads of ~4 MW/m^2) that utilize liquid lithium breeders as well as solid lithium breeders such as in STARFIRE because of the uncertainties associated with solid breeding.

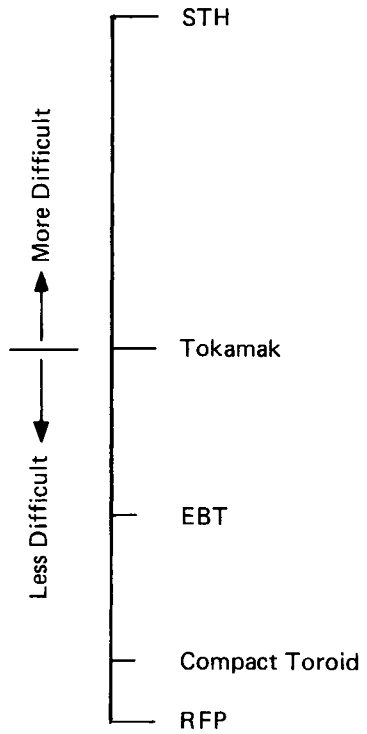

Fig. 1. Schematic comparison of alternate concept D-D reactors with D-D tokamak reactors.

TABLE IV

Projected Level of Information by the End of Fiscal Year 1983

Concept	A[a]	B[b]	C[c]	D[d]
RFP	Yes	Yes	Yes	Good
Compact toroids	Yes	No	No	Unknown
EBT	Yes	Yes	Yes	Fair
Multipoles	Yes	No	No	Poor
STH	Yes	Yes	Yes	Fair

[a]Refers to physics data base and physics assessment.
[b]Refers to reactor technology assessment.
[c]Refers to reactor performance assessment (including COE analysis).
[d]Refers to reactor prospects as they presently appear.

5. *Alternatives to the D-T matchhead startup approach in order to reduce tritium inventory.* The group agreed that alternative startup methods should be investigated to determine (a) if they are feasible from a physics and technology point of view and (b) the reduction in the tritium inventory relative to using D-T matchhead.

6. *Assessment of the value of reduced tritium inventories and other safety advantages of D-D relative to the increased cost.* The group agreed that the cost disadvantage of WILDCAT relative to STARFIRE dominates the comparison of D-D to D-T because the cost difference is quantitative. However, there are safety advantages of D-D, such as the reduction in the tritium inventory, that are difficult to quantify and therefore receive less importance in the assessments. Further work should be done to attempt to relate the cost disadvantage of D-D to the safety advantages.

7. *Detailed modeling of energy deposition profiles for synchrotron, bremsstrahlung, and neutron radiation in D-D tokamak reactor first walls.* Most members of the group agreed that detailed modeling of the bremsstrahlung as a volumetric source made little impact on the temperature profile of the first wall or the cooling requirements.

SESSION F: Working Group on AF Mirror Reactors

(Chairman: R. F. Post, LLNL)

This session was devoted to the discussion of a variety of topics relating to mirror systems employing AFs. These topics ranged from theoretical issues affecting the Q values of such systems to innovations in their technological elements.

F. Kantrowitz (UCLA) discussed nuclear scattering effects in TM systems. He pointed out that, owing to the high ion and electron temperatures in AF TM systems, with the attendant decrease in the Coulomb scattering cross section, the role of large angle nucleon-nucleon scattering effects can become relatively more important. Their effect is to increase the predicted fraction of energy given to plasma ions. The predicted end result was to raise D-D TM Q values by as much as 40% in an example case (T_e = 60 keV).

S. Tamor (SAI) discussed synchrotron radiation effects in TM systems. The discussion concerned the effects of expected anisotropy in the electron distribution functions in the plug and/or thermal barrier regions of AF TM systems. It was pointed out that there can be important effects on the emission and absorption of microwave energy in such systems that need to be considered.

G. Miley (UI) discussed AF hybrids and other AF alternatives. He noted that there are several potentially attractive avenues for AF TM systems, some of which should not require the high Q values that pure fusion AF systems appear to require. Thus, in addition to the response of looking for improved physics and technology to raise the Q values of AF TM systems, other responses could be to look to hybrids, to synfuel production, or to ^{3}He production to power, for example, D-^{3}He field-reversed mirror systems.

K. Audenaerde (UW) spoke about electron cyclotron resonance heating (ECRH) issues in TM systems. The discussion concerned important physics differences between the problem of ECRH in tokamak systems and in TM systems. These circumstances will require careful consideration in the design of ECRH for TM systems.

G. Shuy (UCLA) described some direct converter innovations in the UCLA study of AF TM systems. These improvements include the splitting and diversion of flux bundles exiting from the end of the machine to improve the direct conversion power handling and to eliminate the bombardment of the collectors by neutrons and by energetic charged reaction products, with consequent lifetime advantages.

SESSION G: Intercomparison of Tokamak, Mirror, and RFP Deuterium-Based Reactors

(Chairman: R. W. Conn, UCLA)

A detailed intercomparison of tokamak, mirror, and RFP reactors was not favored at this time, in part because it was felt that the design bases for the studies that have been performed to date are not uniform. It was also concluded that a detailed assessment of the attractiveness of the various approaches for AFs is not yet appropriate. The working group focused its attention on the following two topics for tokamak, mirror, and RFP D-D reactors separately: (a) status of the studies, e.g., what are the key uncertainties and (b) next steps in the studies. The group expressed the strong opinion that the accent in follow-on studies generally should be on "inventiveness" and "concept design improvement," rather than simply on improvements in plasma physics models. This sentiment was particularly stressed for AF mirror studies. The concern was expressed that otherwise the danger is that D-D reactor studies are destined to make already complex D-T reactor designs more so.

It was concluded that future AF tokamak studies might benefit by emphasizing the role of high beta, i.e., will larger beta produce a big payoff? Possibilities include (a) using high beta to lower B, while retaining stainless steel walls and steady state, (b) keeping the highest superconducting B that is technologically feasible in order to maximize the power density, and concentrate on possibilities for acceptable wall designs, and (c) examining the high beta, very high B option, as suggested previously by B. Coppi (MIT), for burning D-^{3}He as an ignition test or burning physics experiment.

The emphasis in future AF mirror studies should be on improvements to increase Q (a major aim for D-D TM reactors should be to achieve $Q > 10$). Some ways in which this might be done were thought to be via (a) improved magnet designs (e.g., force-free windings) for axisymmetric systems, (b) negative barrier TM reactors, (c) high efficiency pumping schemes, e.g., drift orbit pumping, and (d) higher beta.

In future D-D RFP studies, it was felt that there needs to be greater experimental input, particularly on confinement scaling, before conceptually new and improved reactor designs can be identified and justified, e.g., the promising compact design described by Krakowski in session A. Also, improved first-wall designs for high surface heat flux should be sought and current drive options for steady-state operation should be studied.

SESSION H: Working Group on Miscellaneous Reactor Plasma Physics Topics

(Chairman: S. Tamor, SAI)

This session was intended for discussion of miscellaneous physics topics that were not obviously suited to the other device-oriented working sessions, but that are important to the study of AFs for fusion.

J. Gilligan and S. Ho (UI) described their work on synchrotron-radiation-driven currents for a steady-state tokamak reactor similar to WILDCAT. Their conclusions were that the scheme does not appear very advantageous for catalyzed D-D tokamaks. However, for a D-^{3}He reactor that would normally operate at ~60 keV the scheme appears reasonably attractive. J. Dawson pointed out that because of the strong electron temperature dependence, use of the average T_e in these calculations may be misleading. He noted that using an appropriately weighted electron temperature, the results are considerably more optimistic for catalyzed D-D.

D. Baxter (SAI) reported on the present capabilities of the DDMAK, one-dimensional, D-D tokamak burn code, and described several applications of the code. One important set of results was that showing the pronounced effect that a proper treatment of synchrotron radiation transport has on the plasma temperature profiles in D-D tokamak reactors. These calculations used the CYTRAN subroutine developed by S. Tamor (SAI).

J. Gilligan (UI) summarized recent results of the UI group on the energetics of fast ion slowing down and its effect on reactivity. He concluded that reactivity enhancement due to nuclear elastic scattering is a small effect for deuterium-based fuel cycles. The study also compared various ion slowing down models and the importance of "tail pulling." It was found that all models predicted nearly the same reactivities (to within ~3%) and that a simple slowing down model is quite adequate for D-D reactors. The "tail pulling" effect was found to provide very little reactivity enhancement. They also found that large energy transfer Coulomb collisions had little effect on the reactivity for deuterium-based fuels.

The chairman noted that there remain disagreements between the UI and UCLA groups concerning reactivity enhancement. Since these effects appear to be crucial to the viability of proton-based reactor concepts, it is essential that this be straightened out before a definitive evaluation of proton-based fuel cycles can be made. A suggestion was made that a model problem be formulated that has the following characteristics: (a) each group agrees that it can be properly treated by its codes and (b) the problem will exhibit reactivity enhancement effects if they exist. An attempt to make detailed comparisons of results may illuminate the underlying difficulty.

IV. CONCLUDING REMARKS

We conclude with the following general comments and personal observations on the workshop based on the foregoing summaries.

1. Substantial progress has been made in AF research since the DOE workshop in January 1981.

2. A very large amount of work remains to be done before an adequate assessment of AFs for fusion will be possible; i.e., which fuel cycles and confinement concepts have true merit for commercial power production.

3. Some strong sentiment was expressed that innovation and concept improvements should be stressed in future AF reactor studies, as opposed to emphasizing improved physics modeling.

4. Some strong sentiment was expressed for modest scale experiments for physics tests of AFs. A suggestion was made that a topical workshop on what constitutes meaningful test experiments be held.

5. There should be more effort spent in the future in evaluating the less tangible, but positive, elements of AF reactors that are difficult to quantify, such as potential safety advantages, to determine if quantitative disadvantages, such as possible higher capital cost, are actually offset by them.

6. Evenhandedness in evaluating the various confinement concepts should be striven for, but the unevenness in the physics data base from concept to concept makes this difficult in practice.

7. Detailed intercomparisons of the various confinement concepts for AFs would be premature at this time.

8. There appear to be important differences of opinion on the magnitude of reactivity enhancement, particularly in Fokker-Planck calculations involving small energy transfer Coulomb interactions between high energy fusion products and plasma ions. It is vital that this issue be resolved, especially for the proton-based fuels, to determine, e.g., whether ignition and high Q operation is theoretically possible for p-^{11}B fuel in multipoles.

9. Apart from the issue of whether multipole reactors using proton-based fuels are feasible, there was considerable opinion that they may play an important role as physics test devices for AFs.

10. The LANL results of the compact D-D RFP are very encouraging, and an example of the potential payoff of an innovative "concept development" approach to reactor design. However, the present lack of a physics data base for RFPs makes it difficult to draw definitive conclusions. This is true of most confinement concepts and for D-T as well as AFs.

John B. McBride

Science Applications, Inc.
P.O. Box 2351
La Jolla, California 92038

February 3, 1982

Editor's Comment: *John B. McBride (SAI), author of this summary, also served as organizer of the workshop. The proceedings from the earlier (January 1981) DOE workshop on AFs was published as CONF-810141 by the Office of Energy Research, Division of Applied Plasma Physics, U.S. DOE, Washington, DC 20585. Also, overview articles on AFs by J. Rand McNally, Jr. and by J. Reece Roth are contained in* Nuclear Technology/Fusion, *2, pp. 9 and 29, respectively.*