MEETING REPORTS

COMMENTS ON THE FIFTH COURSE ON UNCONVENTIONAL APPROACHES TO FUSION, INTERNATIONAL SCHOOL OF FUSION REACTOR TECHNOLOGY, ERICE, SICILY, MARCH 16-25, 1981

The course on Unconventional Approaches to Fusion has been combined with the meeting at Erice of the International Atomic Energy Agency Technical Committee on Critical Analysis of Alternative Fusion Concepts. The two events occupied the second half of March 1981; however, the overlapping was not total, but limited to part of the second week.

The proceedings (to be available early in 1982) collect the contributions presented at the course during the first week; the contributions during the second week will be summarized in *Nuclear Fusion*.

Right from the beginning of the course, and in particular in the opening talk of R. Carruthers, it was clear that an unconventional approach was considered stimulating insofar as its conception presented advantageous aspects with respect to the tokamak. Indeed the tokamak has been recognized as an "imperfect frame of reference" (H. K. Schmitter) in the sense that, although it deserves to be considered as a frame of reference for the other devices (because it is the most advanced toward the scientific demonstration of controlled thermonuclear fusion), as a fusion reactor, the tokamak does not seem to be completely satisfactory either from an economic or from an operational point of view, if compared with that "enticing ogre," the proven fission reactor (less enticing to the public).

Comparison of a tokamak reactor with a pressurized water reactor (PWR) can be founded on considerations of such a basic nature that it becomes almost automatic to ask how far the various unconventional approaches to fusion are exempt from the tokamak's drawbacks. The reply to this interesting question was not given during the course, at least not in a systematic way.

In this summary, prepared after re-reading the various contributions, I will try to initiate a discussion on the above question, without claiming to reach a definite conclusion. Indeed, it must be recognized that this kind of analysis is difficult, if not questionable. Furthermore, an unconventional approach may presently be at an embryonic stage, either because it is inherently young, or because its financial support has been inadequate, although not necessarily for lack of merit.

An unconventional approach to fusion deserves to be considered as an alternative to the tokamak reactor if it appears to be exempt from some of the constraints that impede the tokamak from behaving more satisfactorily. I will try to review the limitations intrinsic in a tokamak in this summary, and in doing so, I find it rather convenient to borrow a bit of the language of fission people: namely, I shall use the so-called conductivity integral

$$\mathcal{J} = 4\pi \int_{T_a}^{T_0} \chi \, dT \ ,$$

where χ is the fuel [UO_2 or deuterium-tritium (D-T)][a] thermal conductivity, T_0 is the temperature on the axis of the cylinder containing the fuel, and T_a is the temperature at the wall of radius a. In a tokamak, $\mathcal{J} = 4\pi\chi T_0 = 3 \cdot 10^6$ (W/m).

It is well known that $\mathcal{J}$ measures the power produced in the unit length of the fuel element, whose average power density (transported by conduction via the charged products of the nuclear reaction) is indicated by p (W/m^3):

$$p \cdot \pi a^2 = \mathcal{J} \ .$$

The basic difference between a fission and a tokamak reactor lies in the extremely different values of p and $\mathcal{J}$. Compared with a PWR, a thermonuclear tokamak has p lower by a factor of 100 and $\mathcal{J}$ higher by the same factor (in spite of the extraordinary reduction of χ by a factor of 10^{-5}, as a consequence of the plasma magnetization). Therefore, the radius in a tokamak ($a \simeq 1$ m) is 100 times greater than that (10^{-2} m) of the PWR fuel element.

It is unnecessary to mention the international efforts in recent years expended on the tokamak program in trying to accomplish the following:

[a]The conductivity χ of the magnetized plasma of a tokamak reactor has been evaluated by extrapolating the values found in present-day experiments to thermonuclear regimes: χ is $\sim 10^{-3}$, independently of plasma parameters, provided we can assume the Alcator scaling for the energy confinement time $\tau_E = 3.5 \cdot 10^{-21} na^2$.

1. Reduce the plasma thermal conductivity (i.e., increase τ_E, since a reduction of T_0 below 20 keV is incompatible with a steady power balance).

2. Increase the power density $p = 2.3 \cdot 10^5 \beta^2 B^4$, approaching the following limits:

   a. β_c, beyond which χ may dramatically increase and even the plasma configuration could be destroyed[b]

   b. B_c, the critical magnetic field in the superconducting materials ($B \simeq \frac{1}{2} B_c$)

   c. q_c, the thermal flux due to conduction toward the wall, which is limited by the neutron wall loading $L_n = 4q_c$:

   $$q_c 2\pi a = \wp \ .$$

   This limit defines a minimum radius a_m and hence a maximum power density

   $$p_c = 4\pi \frac{q_c^2}{\wp} = \frac{(L_n/4)^2}{\chi T_0} = 3 \cdot 10^{-7} L_n^2 \ .$$

These three independent constraints are just compatible in the sense that no single one of them is dominating in a possible conventional tokamak reactor, as can be seen from the last equation, which, using the limits, can be written $\beta_c B_c^2 = 4 \cdot 10^{-6} L_n$.

If $B_c = 12$ (T), $L_n = 2 \cdot 10^6$ (W/m^2), it follows that $\beta_c =$ 6%, which, luckily enough, is quite conceivable.

In regard to the minimum radius mentioned above, it is remarkable that, with the usual $L_n = 2 \cdot 10^6$ (W/m^2), $a_m \simeq 1$ (m), i.e., of the same order (as is desirable) of the blanket shield thickness necessary to absorb the neutrons.

Moreover, it must be noted that the natural aspect ratio $A = 4$ of a tokamak defines a length ($l = 2\pi R = 2\pi a A$) of the toroidal fuel element, just suitable for producing a thermal power P of the desirable order of magnitude:

$$P = l \cdot 5 \wp = 10\pi a A \wp \simeq 10^9 \text{ (W)} \ .$$

Considering all these signs of nature, i.e., all these fortunate coincidences, it would be a dirty trick of nature if a tokamak could not result in a satisfactory reactor.

The main reason for doubt is that the engineered volume V_c, which determines the cost of the tokamak reactor is not at all the volume of the burning fuel, but rather the much larger volume of the stumpy cylinder circumscribing the magnetic doughnut.[c] The value of V_c is larger than the plasma volume by a factor of $4A$, i.e., ~16. This value and the type of technology needed for the construction of the items contained in it are the basic data for the evaluation of the economic and operational aspects of the tokamak reactor. Of course, it must also be considered that the cost of the reactor block is a fraction of the total plant cost. Unfortunately it seems (see lectures of K. H. Schmitter and N. Krall in the proceedings) that, as distinct from the fission case, for most of the fusion alternatives to the tokamak and almost certainly also for the tokamak itself, the cost of the nuclear island is dominant, i.e., it is larger than the cost of the balance of plant. However, in comparison with a fission reactor, one must consider how far the major cost of the fusion reactor is compensated for by the undeniable social advantages it has with respect to fission. In his lecture, K. H. Schmitter demonstrated that it is impossible in a tokamak to raise p_c to values typical of a PWR, maintaining the field and geometry pattern pointed out previously in this summary.

For a more optimistic scenario, it is necessary to abandon the strong condition on plasma radius made in that lecture and consider the less stringent condition imposed by alpha confinement: $a \approx 3/B$. For instance, with $a = 0.5$ (m), we find that $p = 4 \cdot 10^6$ (W/m^3), $L_n = 4 \cdot 10^6$ (W/m^2), and $\beta B^2 = 4$ (T^2). Assuming $V_c = 300$ (m^3) we find a volume-averaged electric power density of $0.4 \cdot 10^6$ (W/m^3); the corresponding payback time (derived from Fig. 13 of K. H. Schmitter's lecture) ranges from 5.5 to 8 years. Thus, in this case the payback time turns out to be about one-third of that evaluated for the NUWMAK-type reactor considered in Schmitter's lecture, which, in contrast, excluded from economic attractiveness any fusion approach except, possibly, the inertial one.

At this point, an unconventional approach to fusion deserves attention if, besides the feasibility, it has at least one of the following advantages with respect to the D-T tokamak:

1. V_c smaller

2. p_c larger

3. the fuel is without neutrons and/or does not need to be bred.

During the first week of the course, all the different devices were presented in 1-h lectures, followed by discussion. Some of the authors, recalling the different atmosphere of the big international conferences, were pleased to have plenty of time for presentations with a very attentive audience.

For the presentation, the devices were grouped as follows, according to their magnetic topology:

1. compact toroids

2. linear systems

3. multipoles (surface field).

Here I will mention one example for each configuration, if only to trigger the interest of the reader and to induce him to peruse the proceedings.

The Spheromak was presented by M. Okabayashi. The toroidal plasma has an aspect ratio not much larger than one; the complex device proposed for the production of the plasma configuration is hardly compatible with the neutronics associated with the burning phase. Thus it has been proposed to extrude the plasma toroid from the place of formation and guide it magnetically to the place of burning.

This separation of roles does not necessarily imply an increase of the volume of the nuclear island: V_c remains presumably lower than that of a tokamak, while the reactor operation, maintenance, and disassembly may become more simplified. The Spheromak, in addition to these advantages related to point 1 above, has intrinsically a high power density essentially related to the high magnetic field: its

[b]There are theories and experimental hints suggesting that another domain of stability could possibly be reached at higher values of beta (see the lecture of B. Coppi in the proceedings).

[c]This doughnut has the hole stuffed with expensive items such as a transformer, superconducting coils and a lithium blanket; on the exterior it has the startup injectors. An expression for V_c (empirically derived from many tokamak conceptual designs, e.g., from those considered in Schmitter's lecture) is

$$V_c = \pi(2R)^2 \cdot 10a = 4A(10\pi A a^3) \ .$$

intensity may reach values higher than the critical values of the superconducting coils, because the magnetic field configuration of the Spheromak is typically a force-free one.

Linus is a device particularly suited to reach extremely high power densities. By means of Linus, an inertial confinement of the plasma is obtained by imploding a mechanically driven liquid liner (see A. E. Robson's lecture). Among the imploding liner systems (see lectures of J. C. Linhart), the Linus concept provides an example of slow implosion that confines the plasma for a time, which is long enough for a good burn, but too short for a significant loss of energy by diffusion.[d] These happy circumstances deteriorate if Linus is scaled down to a smaller size for testing the concept: Linus cannot be a research toy, but only a reactor, and this fact probably embarrasses the decision makers.

The plasma is produced, together with the confining field, by two rotating electron beams launched in opposite directions in the gaseous fuel. This method, *per se* interesting, is being investigated at the Naval Research Laboratory. In general, electron rings appear to be important ingredients in many devices (see lecture of R. N. Sudan).

The imploding liner is a thick cylindrical rotating shell of lithium, with a multipurpose function (besides tamping): near-megagauss magnet, renewable first wall, neutron shield, tritium breeder and coolant. Consequently the engineered volume is relatively compact and not costly. This is probably too good to be true!

According to the Linus scheme presented during the course, the fusion power density in the plasma results in being of the order of 1 GW/m^3 during burn. The tremendous wall loading of the order of 1 GW/m^2 (time average: 20 MW/m^2) is withstood by the liquid lithium wall; the fusion alpha particles push back the liquid liner, which is heated by neutrons and transfused in order to extract and use the thermal energy and tritium produced.

In regard to advanced fuels without neutrons and/or not needing to be bred, G. H. Miley has classified them according to proton- and deuterium-based reactions, and has presented some possible interesting strategies for both classes of fuel. In light of the considerations presented, present-day fusion research could be considered a necessary exercise toward the use of advanced fuels, which should satisfy the most exigent ecologist. Recent studies on the various reactivities (F. F. Chen has also reported unpublished results at the University of California at Los Angeles) have shown the enhancement of $\langle \sigma v \rangle$ due to the beneficial distortion on the Maxwellian tail induced by the fast reaction products before completion of their slowing down, and have revived the hope for p-^{11}B ideal ignition.

A plasma ignited by proton-based reactions has losses dominated by radiation and consequently the considerations previously made with regard to the conduction regime are not applicable in this case.

The space distribution of the magnetic field produced by multipoles has good confining properties and keeps low the level of cyclotron radiation.

The frightening problem of maintaining at low temperature the levitated superconducting hoops strongly irradiated by the plasma has been faced recently. F. F. Chen has reported encouraging results of shielding design studies of a floating ring for a D-^{3}He tandem mirror: the superconducting state is preserved for about five days and, in a neutronless case, for about one month.

The other worrying problem of cooling a wall under heavy x-ray bombardment has stimulated and produced interesting ideas such as that of depositing the radiation in a high-Z gas flowing behind a thin first wall.

Among the deuterium-based fuels, particular attention has been given to the D-^{3}He reaction, considering conceptual reactors based either on multipoles or on tokamak magnetic configurations. For the latter case, B. Coppi has presented a proposal of a high field tokamak with a strongly diamagnetic plasma: more precisely, a low-beta D-T plasma brings to ignition the D-^{3}He fuel and evolves towards a second stability region at high beta ($\sim$15%).

At a vivacious round-table discussion, chaired by F. F. Chen, the main issues that emerged during the first week of the course were discussed.

The final three days were spent reviewing conventional or almost conventional fusion machines: stellarators, mirrors, reversed field pinches, Elmo Bumpy Torus, compact tori.

The focus was not only on the parameters achieved, but more on the meaning of the most recent physics studies and what they implied about the future for these approaches.

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Editor's Comment: *This report, prepared by Prof. Brunelli, is taken, with permission by Plenum Publishing Co., Ltd., from the Foreword to the forthcoming proceedings of the course on Unconventional Approaches to Fusion held at the Center for Scientific Culture. Prof. Brunelli served as organizer and director of the course. Due to its interest for readers of* Nuclear Technology/Fusion, *this summary of the technical discussions at this international course is presented here. The full proceedings should be available through Plenum early in 1982.*

REPORT FROM THE TENTH EUROPEAN CONFERENCE ON CONTROLLED FUSION AND PLASMA PHYSICS, MOSCOW, USSR, SEPTEMBER 16-19, 1981

This international conference contained a variety of review and contributed papers on topics ranging from basic plasma physics phenomena to recent results in both magnetic and inertial confinement experiments and physics. Details of the papers can be obtained in the two-volume proceedings (Vol. I: 204 contributed papers, and Vol. II: invited plus 25 post-deadline papers) published through I. R. Gekker, Scientific Secretary, Lebedev Physical Institute, Academy of Sciences, Leninskiy Prospekt 53, Moscow, USSR. While a number of areas covered in the meeting are of potential interest to readers of *Nuclear Technology/Fusion*, space restrictions force us to concentrate on the highlights of the session on "Reactor Problems."

[d]Hence the considerations made for a diffusive stationary plasma are not applicable here.