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Controlled Fusion – A Review of the Sherwood Program[1])

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During the last few years, there has been an impressive and continually increasing effort throughout the world to harness the energy of the hydrogen bomb for peacetime purposes. In the United States, the effort in this field of controlled fusion—known as Project Sherwood—has been concentrated on four major approaches, with smaller efforts along several other lines. It will be attempted, in this short article, to review briefly the more important of these approaches and to point out the specific problems associated with each of them.

I.

The pinch approach, on which work began in the United States as early as 1951, is being pursued both at the Los Alamos National Laboratory in New Mexico (under the direction of J. TUCK) and at the University of California Radiation Laboratory at Livermore, California (under the direction of S. COLGATE and W. BAKER). In this approach, current induced in the plasma produces the magnetic field required for plasma confinement. The interaction of this field with the current serves to constrict, or 'pinch', the discharge to a fine filament of current at the center of the tube. The process of constriction serves to heat the plasma to a high temperature. In principle, the existence of a dense plasma filament at high temperature, isolated from the walls of the discharge tube by a concentric magnetic field, should provide a simple and effective means of producing thermonuclear reactions.

The principal difficulty, however, is that this simple configuration is unstable. There are, in fact, several modes of instability. In one of the simpler types, kinks develop in the current filament and grow rapidly,

[1]) This article is based on a lecture given at the Federal Institute of Technology in Zurich in December, 1958. A general knowledge is assumed of the principles of the controlled fusion, of the basic problems involved, and of the general features and configurations of the various approaches being explored in the USA. An elementary presentation of these matters is given in the author's book entitled 'Project Sherwood – The US. Program in Controlled Fusion' (Addison Wesley, 1958).

due to the nonsymmetrical pressure of the magnetic field, thereby shooting the plasma to the walls of the tube and quenching the discharge. Other modes of instability are more complex in their action, but result nevertheless in destruction of confinement of the hot plasma.

There are, in principle, two rather obvious methods of overcoming this difficulty. One possibility would be to constrict the plasma extremely rapidly, in the hope of shockheating it to sufficiently high temperatures and densities that appreciable nuclear burning would take place before the instabilities could develop. It may be shown, however, that a thermonuclear reactor based on this concept alone would require discharges tubes several meters in diameter, would require currents of hundreds of millions of amperes, and the energy released at each constriction would be equivalent to several tons of TNT. While not excluded from consideration (and, indeed, appreciable work was directed toward this goal), such a device could hardly be called a 'controlled' thermonuclear reactor.

The other alternative would be to find some method of stabilizing the simple pinch. A great deal of effort has been devoted to this possibility, and the results have been partially successful. It was found theoretically that it should be possible to stabilize the pinch completely by providing an appropriate axial magnetic field within the pinched discharge, together with a conducting wall external to the discharge tube itself. Experiments carried out with both straight and toroidal discharges showed indeed clear evidence of plasma stability for brief periods of time under these experimental conditions.

The trend toward pinch stabilization has proven, however, to be somewhat of a mixed blessing, for it has introduced new difficulties, some of which are quite serious. One problem is the fact that, with partial stabilization of the pinch, there is time for impurities from the walls to enter and quench the discharge. Another difficulty is that the presence of the axial stabilizing field inhibits the effectiveness of shock heating. Most important of all, however, is the recent evidence that energy is being lost to the walls of the discharge tube by unexplained processes, presumably due to an instability of a new type.

While there is hope that the various difficulties encountered in the B_z-stabilized pinch approach can be overcome, other possible methods of achieving stabilization (or quasi-stabilization) are being explored.

II.

A second approach to thermonuclear reactions is the so-called Stellarater concept, which is being pursued at Princeton University in New Jersey under the direction of L. Spitzer, Jr. Unlike the pinch effect, which would operate on a pulsed basis, this approach has the goal of maintaining a plasma *continually* at thermonuclear temperature.

The Stellarater configuration is that of an endless tube with an axial magnetic confining field provided by current in external windings. It may be shown that in order to achieve adequate plasma confinement, the magnetic configuration must possess what is known as 'rotational transform': i.e., the lines of magnetic force must rotate gently as they traverse the tube. Such a rotational transform can be produced, it was found, either by using a discharge tube in the shape of a figure-eight or, more simply, by the addition of a set of gently helical conductors around a toroidal-shaped tube, just inside the confining field windings.

Plasma heating is accomplished by several successive processes: a) the application of a radio-frequency to produce a partial ionization of the gas; b) the subsequent imposition of a unidirectional voltage along the axis of the tube, which accelerates the ionized particles and (through randomizing collisions) ohmically heats the plasma to several hundred thousand degrees; and finally c) the application of a process known as magnetic pumping, in which the magnetic field strength in one region of the tube is caused to oscillate rapidly about a given value, thereby transmitting energy to the plasma and heating it to still higher temperatures.

At one phase of the effort, there was much concern over the possible development of a so-called 'interchange' instability, which was predicted theoretically. It was later shown, however, that the same helical windings which provide rotational transform in the toroidal geometry would also provide a type of 'shear field' which would tend to inhibit the growth of any interchange instability. Calculations showed, however, that stability would only be achieved for rather small value of the quantity β, defined as the ratio of the plasma pressure relative to the pressure which the magnetic field is capable of producing. While the total power output of any thermonuclear device varies with β^2, it is believed that a full-scale thermonuclear reactor based on the stellarater concept may still be of economic interest.

Recent experiments have, however, brought to light a new difficulty. During the ohmic heating process, plasma is lost to the walls in a series of sudden spurts. This serious mechanism of energy loss, to which the name 'pump-out' is given, is far from being understood at the present time. It appears, however, to be due to a new type of instability associated with the second phase of plasma heating. As a result, there is hope that, by modifying (or perhaps even bypassing) this phase of heating, this difficulty may eventually be overcome.

III.

Still a third approach to controlled fusion, being actively pursued at the University of California Radiation Laboratory under the direction of R. F. POST, is the Pyrotron concept. Here the magnetic confining field is again along the axis of the discharge tube. Unlike the Stellarater, however, the tube is straight, rather than being closed upon itself. Loss of plasma out the ends of the tube is reduced by intensification of the magnetic field strength at the tube ends, thereby producing what are known 'as magnetic mirrors' which tend to reflect the plasma particles back toward the center of the tube.

In this approach, relatively low energy deuterium ions (and sufficient electrons to create a neutralized beam) are injected into the discharge chamber while the strength of the confining field is weak but increasing. The increasing magnetic field serves both to trap the injected particles and to heat them by adiabatic compression to high temperatures.

The primary difficulty which has been encountered to date is that of injecting a sufficient intensity of neutralized beam into the chamber during the short period that is available. Intensive work has been carried out over the past several years to improve the performance of the injecters. The results have been encouraging, and sources are now available which are capable of injecting intense ion beams into the chamber at energies of several kilovolts.

In spite of early theoretical predictions that magnetic mirror confinement would be unstable, no experimental evidence of any instability has yet been found. It is reasonable to expect, however, that with increasing temperatures and densities, instability may occur, and some sort of modifications of the magnetic configuration may be required to ensure adequate stability under these conditions.

IV.

The last approach to be discussed in this brief article is the concept of Molecular Ion Ignition, being pursued at the Oak Ridge National Laboratory in Tennessee under the direction of E. D. Shipley and P. R. Bell. This concept employs much the same magnetic conficuration as the Pyrotron approach, but instead of involving pulsed operation with an increasing magnetic field, it involves continuous operation with a strong, steady magnetic confining field.

The required high plasma temperature is obtained by injection of a high energy *molecular* deuterium beam into the discharge chamber—a beam with particle energies already sufficiently high (hundreds of kilovolts) to undergo fusion reactions effectively with one another. In order to achieve adequate trapping of the deuterons, the molecular beam is passed through a special arc discharge near the axis of the chamber. This discharge partially dissociates the molecular beam, and the resulting atomic beam (having a smaller radius of curvature) is thereby trapped within the chamber. As sufficient density of particles build up, the beam particles thermalize, and a high temperature plasma is formed.

Approach	Confinement	Configuration	Stable ?		Heating	Models	Problems
Pinch (LASL & UCRL)	Confining field produced by current in plasma	Toroidal	without B_z	No	Joule	Perhapsatron	Configuration is unstable
		Straight	without B_z	No	Shock	Columbus	Very large size apparently required to reach temperatures and densities of practical interest
		both toroidal and straight	with B_z	Yes (theoretically)	Joule (interdiffusion)	both	1) Shock heating inadequate due to B_z field; major heating from interdiffusion of fields 2) Impurities from walls 3) Spurious energy losses
Stellarater (Princeton)	Confining field produced by current in external coils	Endless tube: Figure 8	?		1) R.F. ionization 2) Ohmic heating 3) Magnetic pumping	A B_1, B_2, B_3 B_4	Probably unstable
		Endless tube: Toroidal with helical conducters	Yes (β-limited)		,, (pumping at cyclotron frequency)	C	1) Limitation in β for stability 2) Spurious losses (due to runaway electrons ?)
Cusped Geometry (NYU)	,,	Cusped Geometry	Yes		Shock	None built yet	Plasma leakage due to difficulty of maintaining sharp boundaries

Approach	Confinement	Configuration	Stable ?	Heating	Models	Problems
Molecular Ion Ignition (ORNL)	Confining field produced by current in external coils	Straight tube plus mirrors at each end	?	High energy ion ignition and trapping	DCX	1) Is configuration stable ? 2) High neutral background results in loss of high energy particles through charge exchange 3) Inadequate intensity of D_2 injection
Pyrotron (UCRL)	,,	,,	?	Adiabatic Compression	Table top Toy top Felix	1) Unstable (?) 2) Difficulty of obtaining initial adequate density of neutralized plasma with low background of neutrals. 3) Losses of particles through mirrors
Shock tubes (UCRL, LASL, & NRL)	,,	,,	?	Shock plus adiabatic compression	Scylla, etc.	,,
Rotating plasma	,, plus centrifugal force	,,	?	transverse electric field	Homopolar, Ixion	,,
Astron	Field produced by E-layer	Straight tube	?	Energy transfer from E-layer	Astron	Possibly unstable (?)

The primary difficulty which has been experienced to date with this approach is presence of neutral particles within the discharge tube. These low energy neutral particles exchange charge with high energy deuteron ions within the chamber, and the resulting high-energy neutral particles escape through the magnetic field and strike the walls of the discharge tube, thereby producing more low energy neutrals. This process of charge-exchange has been a serious source of energy loss from the hot plasma. Theory predicts, however, that if the initial background pressure of neutral particles can be made sufficiently low, and the intensity of the injected beam sufficiently high, a critical point (known as 'burn-out') should be reached, at which the trapped ions would ionize the neutrals as rapidly as they entered the plasma region. Beyond this point, a snow-balling process would occur, in which the density of ions would rapidly build up, their motion would randomize to produce a truly thermalized plasma at thermonuclear temperatures. While burn-out has not yet been achieved, calculations show that only moderate improvement should be required to achieve this condition.

The above sections provide only the briefest description of the major approaches underway in the U.S. Space does not permit discussing either further ramifications of these approaches or some of the other concepts which are also being pursued but which are in a less advanced stage of development. The accompanying chart, however, gives a survey of the field as a whole and lists a few of the more important experimental models associated with each approach.

Each approach has its advantages, each has its drawbacks. Each faces serious problems and none is sure of ultimate success. Much tangible progress has, however, been made during the few short years since this program's inception, and as of now there is every reason to believe that a full-scale thermonuclear reactor will eventually be built. Whether it will ever be economically competitive is anyone's guess. If, however, it is indeed of economic interest, it is clear that this new and important source of energy will not outmode other sources—from coal, oil, and uranium—but rather will supplement them in man's ever-increasing need for power.