they need to add greater sophistication to their models. They must include the effects of point sources and spotty distribution, thermal impacts of the land and ocean and the dynamical interactions among particulates, the circulation patterns and precipitation rates. Most are planning to improve their models in those directions.

Points at issue. Turco, Toon, Ackerman, Pollack and Sagan have amassed an impressive amount of data from a wide range of fields and brought it to bear on one particular problem. In many instances, however, they had few data that were directly relevant to their needs, and they had to substitute either extrapolations or educated guesses. Thus, not only must the climate models be improved but input data must be refined. Already some debate is occurring over what are recognized as crucial assumptions.

One question that is being raised concerns the height distribution assumed for the soot particles from fires and firestorms. No one knows what makes some cities burn and others not: Hamburg did but Berlin did not. The conditions for firestorms to develop are even more obscure. A 1973 report by the Defense Civil Preparedness Agency concludes that, although Hiroshima burned, it should not be classified as a true firestorm. One reason is that the nuclear blast blew out many of the initial fires and lessened the intensity of the conflagration that eventually consumed the city center. George Carrier (Harvard University) has studied firestorms and told us he feels that it takes very special conditions to initiate such cyclonic motion. Even once a firestorm develops, what mechanism could drive the plume to altitudes of 19 km? More importantly, what is the real distribution of particles as a function of altitude? That question is being posed by Jerry Mahlman of NOAA's Geophysical Fluid Dynamics Lab at Princeton. He feels the issue is quite important because the higher the placement of aerosols, the longer they remain in the atmosphere and the greater is their impact upon circulation patterns.

Another point of debate is the extent to which precipitation might remove the soot and dust, and hence ameliorate their impact on the climate. A "black rain" fell just after the Hiroshima bombing, scrubbing some of the particulates from the air. Turco mentioned to us that the humidity had been quite high just preceding the bombing there. Turco further commented that the bulk of the soot particles from a fire fall in the size range where the collection efficiency by raindrops might be at a minimum. These particles are also too small to coalesce in large quantities into the ten- to hundred-micron sizes required to serve as nuclei for rain droplets.

Still another topic of discussion is the extent to which climate effects might spread even if a nuclear exchange were confined to the Northern Hemisphere. The three-dimensional models, although oversimplified, suggest that heated debris might indeed be carried across the equator. Sagan has argued that very rapid and significant transport might occur, based on observations of dust storms on Mars, where a disturbance in one locale can envelop the entire planet in seven to ten days. Sagan points out that the surface pressure on Mars is typical of the stratospheric pressure on Earth. However, Mahlman and some other scientists point out that there is no direct Earth analog to the conditions on Mars that lead to the great dust storms. They agree that some accelerated transport of aerosols towards the Southern Hemisphere should occur; what remains to be determined is how much. Clearly, truly dynamical, interactive computer models are needed to understand fully the global impact of the dust and soot generated by nuclear war.

The TTAPS group has certainly taken an important first step in focusing so many disciplines on one important problem. The next step, already underway in many places, is to narrow the ranges of uncertainty. On one point all agree: This is one theory that should never be put to experimental test.—BGL

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MIT tokamak Alcator C exceeds Lawson criterion

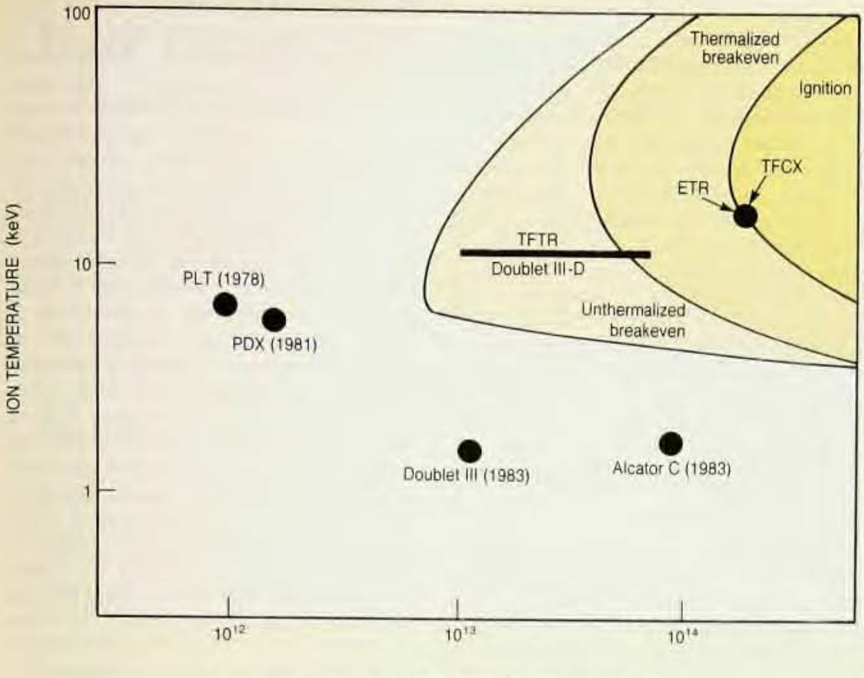
In 1957 John Lawson at Harwell pointed out a crucial minimum requirement for the achievement of net power output from a deuterium–tritium plasma in any fusion device. No matter what the temperature, Lawson showed, a thermalized D–T plasma cannot put out more fusion power than the input power required to keep it hot unless $n\tau$, the product of the ion density and the energy confinement time (often refered to as the confinement parameter or Lawson parameter), exceeds 6×10^{13} sec cm^{-3}.

Early in November this "Lawson criterion" was surpassed for the first time. After five years of somewhat disappointing results, the Alcator C, a compact, high-field tokamak built largely for this purpose at MIT in 1978, finally achieved an $n\tau$ of 8×10^{13} sec cm^{-3} in a deuterium plasma with a central temperature of 1.5 keV (17 million kelvin). Ronald Parker, head of the Alcator group, describes the Lawson criterion as "a kind of holy grail sought after by fusion researchers for a quarter of a century."

The temperature at which the Alcator C surpassed 6×10^{13} sec cm^{-3} is still at least a factor of five below what one would need to achieve "breakeven" fusion power in a D–T plasma. But there had been some concern, especially after the disappointing failure of the early Alcator C experiments to follow the march of its predecessor, Alcator A, to ever higher values of $n\tau$, that the attainment of the Lawson criterion might be running up against some unanticipated saturation effect that could sabotage the whole idea of a tokamak reactor. That fear appears now to have been dispelled.

The essential step that led to the ultimate success of the Alcator group's quest for the Lawson criterion was the introduction last spring of a new fueling technique. In place of the traditional method of adding fuel to the plasma in the form of puffs of deuterium gas, the group adopted a technique developed at Oak Ridge—firing small pellets of frozen deuterium into the plasma core. The physics of why pellet fueling results in a dramatic improvement of plasma confinement is still not clear. But it appears to be closely connected to the fact that the pellets produce a more favorable density profile in the toroidal plasma column than one gets with gas puffing.

In the mid-1970s Alcator A set a record for $n\tau$: 3×10^{13} sec cm^{-3}. The Alcator machines, with smaller dimensions and stronger magnetic fields than conventional tokamaks, are particularly well suited to achieve high confinement parameters because they can



Lawson diagram shows historical and anticipated progress of US tokamaks to higher values of temperature and Lawson parameter. Shaded regions indicate conditions necessary in a D–T plasma for: scientific breakeven with a non-thermal high-energy tail; breakeven in a thermalized plasma; ignition. TFTR and GACs Doublet III-D anticipate breakeven, while ignition must wait at least a decade for the Tokamak Fusion Core Demonstration or the Engineering Test Reactor.

tolerate higher plasma current densities without encountering gross instability. But for higher temperatures, one needs larger dimensions, still-higher fields or a combination of both. The Princeton Large Torus in 1978 reached a record temperature of 7 keV—seven times that of Alcator A—but at an $n\tau$ of only 10^{12} sec cm^{-3}. The much larger Tokamak Fusion Test Reactor, which has now been in operation at Princeton for a year (see PHYSICS TODAY, March, page 17) is expected to reach a temperature of about 10 keV with an $n\tau$ of about 2×10^{13} sec cm^{-3}. Although this is well below the Lawson criterion, it should nonetheless suffice for the attainment of "scientific breakeven" when a deuterium-tritium plasma is introduced in 1986. The Lawson criterion applies only to a *thermalized* plasma. Neutral-beam heating in the TFTR will provide a nonthermal tail of excess high-energy deuterons, permitting breakeven at lower values of the confinement parameter.

Until now, all tokamak confinement experiments have used only hydrogen or deuterium plasmas, because under sub-breakeven plasma conditions tritium provides no additional information that would justify dealing with the radioactivation problems it engenders. Alcator C uses deuterium rather than hydrogen because the small number of neutrons liberated in D–D fusion reactions at modest temperatures serve as a useful diagnostic handle without presenting activation difficulties.

The Alcator C torus has major and minor radii of 64 cm and 16.5 cm, respectively. Its predecessor, proposed by Bruno Coppi and Bruce Montgomery in 1967 and completed in 1972, had major and minor radii of 54 cm and 10 cm. The decision to increase the minor radius so substantially resulted from the widespread belief, based on straightforward arguments about heat diffusion and experience with a variety of tokamaks of different geometries, that the confinement time scales like the square of the minor radius, a, with very little sensitivity to the major radius, R. (The confinement time, τ, is defined as the exponential time constant with which heat would escape from the plasma in the absence of heat input.) The best τ achieved by Alcator A had been about 20 msec. Thus, with τ scaling like a^2, the designers expected Alcator C to achieve a τ of more than 50 msec. In fact, prior to the introduction of pellet fueling, τ never got much above a disappointing 35 msec in Alcator C, and with the ion density n failing to equal the highest values reached in Alcator A, the confinement parameter, $n\tau$, barely exceeded the record value of 3×10^{13}, half the Lawson criterion, set by the smaller machine.

From the classical theory of heat transport one would expect that τ deteriorates with increasing plasma density; a denser plasma should be a better heat conductor. Because of the notoriously anomalous heat transport by electrons in a tokamak plasma, however, the opposite turns out to be the case. The transport of heat out of a plasma proceeds by two basic pathways: the electrons and the ions. The former is dominant at low densities. Heat conduction by plasma electrons is much greater (worse) than one expects from classical arguments, so that τ has always been observed to be significantly shorter than the predictions of classical diffusion calculations. Because one does not understand the anomalous electron heat transport, one has had to make do with empirical scaling laws. Perhaps the most important contribution of Alcator A has been the observation of "Alcator scaling," which tells us that τ, far from falling with increasing density, is directly proportional to n.

Alcator A was uniquely suited to observe this scaling behavior because it was capable of generating a much broader range of plasma densities than were larger, conventional tokamaks. The generation of high densities depends upon high plasma current densities. Current density, however, is limited by the Kruskal–Shafranov stability condition, which states that the helical twist imparted to the toroidal magnetic field of a tokamak by the plasma current must be small enough so that the field lines traverse the torus at least once toroidally (the long way around) before they complete a poloidal twist (the short way). This gross magnetohydrodynamic instability limit on the plasma current turns out to be proportional to B/R, the ratio of the externally imposed toroidal magnetic field over the major radius. The compact dimensions of the Alcator design thus help on two counts: They make a very high magnetic field intensity feasible on engineering and power-consumption grounds, and they reduce the Kruskal–Shafranov denominator by shortening the toroidal path length.

The name Alcator comes from *altus campus*, Latin for high field. Employing sophisticated magnets developed at the MIT Francis Bitter Magnet Lab, Alcator A had a magnetic field of 10 tesla; its successor was designed to get up to 14 tesla, but it operates now at a more cautious 11 tesla. With its high field and small R, Alcator A was achieving plasma current densities an order of magnitude higher than the conventional tokamaks of the mid-1970s. High current density helps raise *both* factors of the confinement parameter independently: The ohmic power raises n, and the twist it imparts to the confining magnetic field directly improves the confinement of chargedparticle trajectories in the plasma. For confinement in a tokamak one wants the greatest possible helical twisting of the magnetic field—short of the Kruskal–Shafranov limit, where gross instability sets in.

At first we expected to get up to an $n\tau$ of 10^{14} sec cm^{-3} quite easily when we turned Alcator C on in 1978," Parker told us. But the anticipated na^2 scaling of τ was not forthcoming. At low density, τ began to grow like n, but as the group pushed to higher densities the confinement time failed to maintain its linear Alcator-scaling growth. "We were pinned at about 30 msec," Parker recalls. Dire theories of new saturation and instability effects were invoked. The confinement time was neither growing like n, nor was it exhibiting the anticipated quadratic increase with minor radius in the larger machine. Looking for hidden bugs in Alcator C, the group then stopped its minor radius down from 16.5 cm to the 10 cm of its predecessor. They found, to their surprise, that τ was varying linearly, not quadratically, with a. At this point they began varying the major radius of the plasma torus within the restrictive limits imposed by the vacuum vessel. By the end of 1982 the group reported that the geometric dependence of τ was proportional to R^2a—referred to as "neo-Alcator scaling"—rather than the previously supposed a^2. But the linear scaling with density was still not in evidence at higher densities. Despite their best efforts, the group could not exceed a τ of 35 msec nor an $n\tau$ of 4×10^{13} sec cm^{-3}.

In 1982 the Alcator group undertook a collaboration with Stanley Milora's Oak Ridge group, which had for a decade been developing the pellet fueling technique. Last spring, Martin Greenwald and his Alcator colleagues began using a pneumatic injector "much like an air rifle," designed at Oak Ridge, to inject frozen pellets of deuterium, about a millimeter long, directly into the plasma core at velocities of about a km/sec. Whereas the usual gas-puffing technique delivers fresh deuterium ions primarily to the edges of the plasma column, these solid, high-speed pellets penetrate deep into the plasma core, delivering the deuterons primarily to its central region.

The pellet fueling technique produced an immediate increase in both density and confinement time. After upgrading the Alcator C magnet coils and otherwise optimizing the machine, the group reported[1] at the annual meeting of the APS Plasma Physics Division at Los Angeles in November that they had achieved a record $n\tau$ of about 8×10^{13} sec cm^{-3}.

The frozen deuterium pellets had raised the plasma density to about 1.5×10^{15} cm^{-3}, half again the highest density achieved in Alcator A. The linear Alcator scaling of τ with density was once again operative, raising the confinement time above 50 msec. The crucial factor appears to have been the improved density profile of the plasma column, which was much more sharply peaked near the center than it had been with gas puffing. The density profile seems to have a profound effect on heat transport to the plasma edge, although the physics is not yet well understood. "The tokamak plasma has a very strong opinion about what sort of density, temperature, and current profiles it wants, and any departures from these preferred profiles enhance heat transport," explains Harold Furth (Princeton).

There appears to be a real change in the ionic heat transfer mechanism with pellet fueling, Parker told us. "It's not just the higher density." Alcator A had achieved densities high enough to put the plasma in the ion-dominated regime of heat transport. In this regime the observed ionic transport agreed very well with straightforward classical theory. But in Alcator C before pellet fueling was introduced, the ionic heat conduction was anomalously high. Now, "although we don't really understand why," Parker told us, "we've recovered classical ion conduction with pellet fueling."

Coppi regards this improved confinement as a verification of theoretical work he published with Marshall Rosenbluth and Roald Sagdeev in 1967, when all three were at the International Centre for Theoretical Physics in Trieste. They had predicted that ionic heat transport would be anomalously high in an unfavorable density profile. Alcator A and its sister machine at Frascati were, for reasons not well understood, "born with more favorable density profiles than Alcator C," Coppi told us.

Larger tokamaks. In the early days, the hope had been that tokamaks could be raised to ignition temperature simply by the ohmic heating power of the plasma current itself. The various scaling laws discovered in the Alcator program have done much to dispel this optimism: The linear growth of confinement time with density presents a problem for the attainment of high temperatures. The ratio of plasma kinetic pressure over magnetic field pressure, designated by β, is limited to about five or ten percent in a conventional tokamak. Because the plasma pressure is essentially density times temperature, the β limit imposes a tradeoff. The higher densities required by Alcator scaling for better confinement force the temperature down. (Coppi, a strong advocate of high-field, compact tokamaks as the best approach to ignition, argues that a suitably designed tokamak might not be subject to this β limit. See PHYSICS TODAY, May 1981, page 17.) The geometric dependence of neo-Alcator scaling (that is, $\tau\propto nR^2a$) poses another problem for ohmic heating. Recall that the Kruskal–Shafranov plasma-current stability limit is proportional to B/R. Thus increasing the major radius to increase τ tightens the hydrodynamic stability limit on the current density and the ohmic power it generates.

Therefore, the new generation of large tokamaks designed to achieve scientific breakeven with D–T plasmas—TFTR and the European JET at Britain's Culham Laboratory—will employ auxiliary heating techniques such as energetic neutral beams, adiabatic compression and radio-frequency heating to reach breakeven temperatures. Neo-Alcator scaling, with its R^2 dependence, comes as an unanticipated plus for these large-R machines. "It looks like TFTR and JET will do even better than we thought," Furth suggests. In its first year operation, TFTR, with a major radius almost five times that of Alcator, has already confirmed[2] neo-Alcator scaling, attaining a confinement time of 300 msec. The TFTR experimental program is headed by Dale Meade. At the January International Atomic Energy Agency meeting of the "Big Four"—the groups working on TFTR, JET and their still uncompleted Japanese and Soviet counterparts—at Princeton, the JET group was expected to announce similar results.

The extraordinary capabilities of the Alcator machines are well illustrated by the fact that Alcator C broke the Lawson barrier with a plasma current of 800 kiloamps, only slightly lower than the present plasma current of the very much larger TFTR. But it should be noted that the Alcator results are directly applicable only to the ohmic-heating regime. "Auxiliary heating makes it a new ballgame," Furth cautions. The primary difference, he argues, is not so much the higher temperatures themselves, but rather the effect of auxiliary heating on the all-important plasma profiles, which depend crucially on the nature of the auxiliary heating as well as the fueling method. Pellet fueling, Parker and Furth agree, is not just a clever trick for improving confinement in laboratory experiments. It is likely, they contend, to be a very useful method of fueling the tokamak reactors that are the goal of all this work. —BMS

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