such large masses, Solomon told us, these giant clouds are gravitationally bound. Before it was realized that these clouds were so massive, it had been assumed that the clouds were held together by pressure equilibrium with more diffuse but warmer surrounding gas. It was believed that the transition from pressure equilibrium to gravitational binding was the first step in star formation, and theorists sought mechanisms for the onset of gravitational collapse. A lifetime as short as 10^6 years is excluded, because it would imply much more star formation than is actually seen. So the problem is now no longer how star formation gets started, Solomon suggests, but rather how it comes to be delayed so long. Thaddeus explained to us that evidence for turbulent motions in the clouds suggests a possible mechanism for this longevity.

Solomon points out that an age greater than 10^8 years would help to explain the astonishing variety and complexity of organic molecules and free radicals that have been seen in these clouds (see PHYSICS TODAY, June 1976, page 32). Rotational transitions observed in nearby giant clouds have revealed ethanol, cyanoacetylene, methyl mercaptan and dozens of other organic molecules in the interstellar medium, the most complex consisting of eleven atoms. Some of these species have not been seen in the laboratory; the galaxy does not suffer the limitations imposed on chemistry by vessel walls. Thaddeus notes that whatever chemistry goes on in the universe occurs almost exclusively in molecular clouds. Planets are negligible.

Charles Townes (Berkeley), who detected radio emission from interstellar ammonia and water in 1968, has recently been investigating the age of the giant molecular clouds from a different perspective. The abundance of the rarer isotopes in the clouds is a measure of stellar activity in them. Decaying stars in molecular clouds spew out isotopes of carbon, oxygen and nitrogen. Townes explained to us that the variation of isotopic abundance from cloud to cloud is a measure of the mean age of these giant clouds. Examining the world data on isotopic abundance, Townes finds evidence for a surprisingly large cloud-to-cloud variance of isotopic abundances—of the order of 10%.

So large a variance, he argues, would have taken a substantial fraction of the lifetime of the galaxy to build up. He therefore concludes that the material in the clouds must hang together between 10^8 and 10^9 years. Townes suggests that the disagreement between the two CO survey groups may be partly semantic. Although the molecular gas maintains its integrity significantly longer than 10^8 years, he expects that it experiences strong variations of density as it passes through the galactic density wave. Only while it passes through the spiral arms, he argues, is the gas sufficiently concentrated to exhibit the observational properties that one normally describes as giant molecular clouds. Scoville told us that the Stony Brook–Massachusetts cloud-lifetime estimate should be thought of as the mean lifetime of an interstellar H_2 molecule against dissociation.

Burton (now at the University of Minnesota) and Harvey Liszt of NRAO have recently studied CO emissions from the innermost 3 kiloparsecs of the galaxy. This region is also very rich in molecular hydrogen, but Burton and Liszt were surprised to find that the H_2 here does not appear to form itself into clouds. In contrast to the "clumpiness" of the H_2 distribution in the galactic regions beyond 4 kiloparsecs, they report that the central distribution of H_2 is remarkably smooth. Why this should be so is not yet understood, Burton told us.

Burton, Liszt and Gordon have also been studying the smaller molecular clouds in the region of the giant clouds. They find that the smaller clouds, typically of several hundred solar masses and 20 parsecs across, outnumber the giant clouds by two orders of magnitude. Even though the giant clouds appear to contain the bulk of the molecular hydrogen, Burton, Liszt and Gordon believe that the smaller clouds may play an important role in the dynamics of the galaxy. —BMS

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International Tokamak Reactor design

The demonstration of break-even fusion power production for brief pulses is a realistic prospect for the large deuterium–tritium tokamaks scheduled for completion in the early 1980's. But they are not likely to achieve plasma ignition. Before one can begin building practical fusion reactors, it will be necessary to build at least one significantly larger experimental tokamak—one that can achieve and control an ignited plasma for minutes at a time, with fusion neutrons bombarding the walls at power levels exceeding a megawatt per square meter.

Such an engineering test facility is thought to be indispensible for solving the many remaining physics and engineering problems that stand between us and a commercial tokamak fusion reactor. But because a suitable test device would cost about a billion of today's dollars, it has been suggested that only one such tokamak facility should be built—as a joint effort of all the countries actively engaged in tokamak development.

INTOR. To this end, the International Atomic Energy Agency has initiated the INTOR (International Tokamak Reactor) project. The first phase of that project, a yearlong series of INTOR Workshop sessions in Vienna, came to an end in December, and a report of its conclusions and recommendations was delivered to the International Fusion Research Council, an advisory body of the IAEA.

Each of the four delegations participating in the INTOR Workshop (Japan, US, USSR, and the European Community) was backed up by 16 teams of physicists and engineers working in the home "country," each investigating a different problem defined by the Workshop. Weston Stacey, a nuclear engineer at Georgia Tech and head of the American delegation at Vienna, explained to us that the primary task assigned to the Workshop was to decide whether it was feasible, given the world's current fund of tokamak data and experience, to build a suitable engineering test facility by 1990. This INTOR tokamak would serve throughout the decade and into the first years of the new millenium as a test facility for the study of the plasma, the reactor materials, the blanket for heat extraction and tritium breeding, and all the other engineering components, under realistic reactor plasma conditions.

INTOR would be the next step after the generation of four large tokamaks currently under construction (see PHYSICS TODAY, January 1978, page 17). Two of them, the TFTR (Princeton) and the European Community's JET (Culham, England) will attempt to achieve break-even fusion with a deuterium–tritium fuel. The Japanese JT-60, which will simulate break-even plasma conditions without tritium, is the only one of the four to employ a magnetic divertor, a device that now appears to be crucial for maintaining the purity of an ignited plasma. The Soviet T-15 tokamak also will probably not use a deuterium–tritium plasma, but, unlike the other three, it will have superconducting magnet coils.

Consensus. After a detailed analysis of the tokamak data available in all the participating countries, the Workshop agreed that INTOR could be built by about 1990, *if* an accelerated program of research and development is undertaken (beyond current plans for the TFTR generation) on a number of engineering problems where the data are seriously inadequate. Among these problems are divertor design, pulsed operation of superconducting coils, blanket design and remote maintenance.

The Workshop was further asked to decide broadly on the nature and objectives of INTOR. Although differences remain among the four delegations on the relative emphases of various objectives, Paul Rutherford, a Princeton physicist and member of the US delegation, told us that their viewpoints on technical matters have tended to converge during the course of the Workshop. A consensus has been reached on a set of suggested parameters for the next phase of the INTOR project, the conceptual-design phase, which will run through mid-1981.

The delegations agreed that INTOR should be "the largest reasonable step beyond" the 1980's generation of large tokamaks. Its primary objective would be to provide the physics and technological information necessary for the building of a demonstration tokamak reactor at the end of the century. The INTOR device should "demonstrate a reactor-relevant mode at plasma operation," the workshop decided. Specifically, a controlled deuterium–tritium burn should be maintained for pulses longer than 100 seconds, with recovery time between pulses less than 40 seconds (a "duty cycle" of at least 70%). By contrast, TFTR will have a duty cycle below 1%. INTOR's relatively short recovery time would be made possible by the use of superconducting magnet coils.

With an intended average plasma density of $n \approx 1.4 \times 10^{14}$ particles per cm^3 and energy confinement time $\tau \approx 1.4$ seconds, the plasma is expected to achieve a confinement parameter ($n\tau$) of 2×10^{14} sec/cm^3, sufficient for plasma ignition in a deuterium–tritium plasma with an average ion temperature of 10 keV and a central temperature of 20 keV. A confinement parameter of 6×10^{13} sec/cm^3 is sufficient for break-even fusion; the fusion output power becomes equal to the external power heating the plasma. But when ignition is achieved at 2×10^{14}, the plasma literally starts to burn; the 3.5-MeV alpha particles released in the D–T fusion reaction provide sufficient heat to maintain the plasma temperature without external heating.

The Workshop decided that the major radius of the INTOR torus should be 5.2 meters, more than twice that of TFTR. With an average minor radius of 1.6 meters, the total plasma volume of INTOR would be more than seven times that of TFTR. The consensus of the Workshop was that the minor cross section of the toroidal plasma should be D-shaped rather than circular, to achieve the highest possible β (ratio of kinetic plasma pressure to magnetic field pressure).

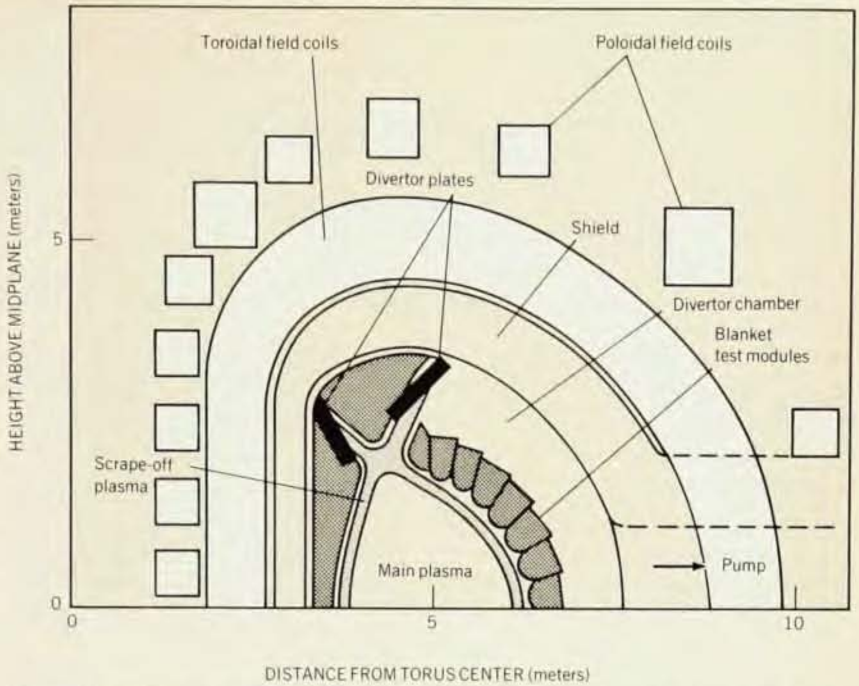
Plasma stability. INTOR calculations indicate that the plasma would ignite at a β of 4%, rising to 5 or 6% in the burning phase. The question then arises whether such a plasma would be stable. The stability limit for plasmas in a tokamak of INTOR's geometry is calculated by the standard theory to be at $\beta = 4.5\%$. But Rutherford told us there is good reason to believe that the D-shaped INTOR plasma would remain stable at somewhat higher values of β; the highest β achieved to date with a circular cross section (2.5%) exceeds the theoretical limit for circular tokamak plasmas. Pushing β to the highest possible values is a trade-off. The higher this pressure ratio can be pushed, the more fusion power one gets. But as β increases, the plasma expels more and more of the confining magnetic field and tries to squeeze out between the field lines, ultimately becoming unstable.

Rutherford told us that impurities in the plasma represent the most serious threat to the maintenance of ignition in INTOR. An unavoidable contaminant is the helium that builds up in the plasma from the α particles produced in the fusion reaction $D + T \rightarrow n\ (14\ \text{MeV}) + \alpha(3.5\ \text{MeV})$. If all this helium were retained in the plasma, the burn would quench in about half a minute. After considering various alternatives, the Workshop concluded that INTOR will require a magnetic divertor to remove the helium from the plasma and to keep out heavier ion impurities. Heavy ions (iron, tungsten, and so on) entering the plasma from the walls are a serious problem, because they do not ionize completely in the plasma. The remaining atomic electrons instigate serious heat loss from the plasma by line radiation.

A magnetic divertor is an arrangement of auxiliary magnet coils that distorts the confining field of the tokamak in such a way that ions emerging from the plasma are diverted away from nearby walls into a "divertor chamber." This prevents the particles from hitting nearby surfaces and returning to the plasma as neutral helium atoms. (The fact that neutral particles can easily penetrate the plasma, because they are not affected by the magnetic field, is also the trick behind neutral-beam heating of the plasma.) The diversion of plasma ions from the nearby walls also lessens the enormous heat load on those walls and minimizes the contamination of the plasma by metallic impurities.

As the Workshop progressed, Rutherford told us, it became clear "that there was no credible alternative to a divertor" for INTOR. It was agreed that a configuration of poloidal divertor coils external to the toroidal coils, proposed by the Japanese, was more promising than the "bundle divertor" concept originally favored by the American team. The PDX (Polodial Divertor Experiment) at Princeton and the ISX at Oak Ridge are small tokamaks that have recently begun testing various divertor designs.

To achieve ignition in INTOR, the ohmic heating provided by the 6.4-megamp circulating plasma current will not be sufficient. The Workshop looked into radio-frequency heating at the electron and ion cyclotron resonant frequencies,



A possible configuration of the INTOR tokamak, with a magnetic-divertor field produced by the poloidal field coils. Only the upper half of the minor cross section of the torus is shown; the lower half is symmetrical. The divertor field lines direct plasma from the peripheral "scrape-off region" (gray) to the divertor plates, which shield the walls from excess heat load and neutralize alpha particles produced in the fusion reaction. The resulting helium gas is pumped out by way of the divertor chamber, lest it quench the plasma burn. The array of blanket modules will test various designs for heat extraction and tritium breeding.

but they concluded that rf heating could at best serve as a subsidiary power source. The primary heat source, they agreed, should come from a 75-megawatt neutral beam of 175-keV deuterium atoms. This is going to require a considerable neutral-beam development program, Rutherford pointed out. Radio-frequency heating at the electron cyclotron frequency (130 to 140 GHz at INTOR's 5.5-tesla field) would become particularly interesting if one could develop gyrotrons capable of operating above a hundred gigahertz.

Objectives. The four delegations found themselves in reasonable accord as to the objectives of the first two stages of INTOR operation (roughly the first seven years after construction is completed). During this period one would want to achieve ignition for 100-second pulses, and learn to control a burning plasma. One would also attempt to demonstrate electricity production and tritium breeding at a modest level.

In a tokamak reactor the plasma would be surrounded by a metallic heat-exchange blanket, with water or helium coolant and some ceramic compound of lithium on its inner surface. The coolant would conduct the heat liberated in the D–T fusion reaction to an external generator of electricity. The 14-MeV fusion neutrons that provide most of the heat at the blanket would serve a second function; they would react with the lithium in the blanket to breed tritium, thus replenishing the plasma fuel. During these first seven years it is planned to test small blanket modules of various designs and materials, generating electricity at a level of about ten megawatts (compared to an input of hundreds of megawatts), and breeding some tritium.

Differences between the delegations arise when it comes to the objectives of the third stage of INTOR operation, which would begin in 1997 at the earliest. The US would like to run INTOR at the highest possible neutron-flux "wall loading" level—1.6 megawatts/cm^2, roughly half of what the walls would suffer in a practical tokamak reactor. The Americans and the Russians want to use the final stage of INTOR primarily to test candidate reactor materials—to see how they would stand up to this horrendous flux of 14-MeV neutrons.

The Japanese particularly, and also the Europeans, would prefer to use stage three to achieve substantial electricity production (100 megawatts) and tritium breeding (70% of the consumption rate). The Japanese are particularly concerned that tokamak reactors be made self-sufficient in tritium, because Japan (and similarly Germany) does not have a thermonuclear weapons industry to serve as a domestic source of tritium. To this end they would like INTOR to have a full blanket in the third stage, rather than the smaller blanket modules favored by the US and USSR, which would be more compatible with high-flux materials testing.

The design parameters suggested by the INTOR Workshop represent a compromise between these positions, with both options left open for the time being. The US has agreed to a more modest wall loading than it would have liked, and Japan has retreated from its advocacy of a full blanket. The size (and hence the projected cost) of the compromise INTOR is closer to the original American recommendation ($1 billion) than to the somewhat larger device previously favored by the Japanese and Europeans.

At the end of the conceptual-design phase (mid-1981) the participating countries will have to decide whether to proceed to the next phase—detailed design and construction. Even if, as some have suggested, the participating countries eventually decide not to follow through to the actual realization of an international tokamak, it is generally agreed that the INTOR project will have been enormously useful—generating, collecting and assessing world tokamak data at a level not at present possible for any one country.

The Engineering Test Facility currently under study at Oak Ridge is a parallel national effort with roughly the same objectives as INTOR. In addition to its tokamak design studies, the ETF group is also looking at alternative magnetic-confinement schemes. According to Rutherford, the international fusion-research community takes it for granted that the first magnetic-confinement reactors will be tokamaks. In America however, doubts have been expressed on this score. The Ad Hoc Experts Group on Fusion, headed by John Foster of TRW, has warned against excessive reliance on the tokamak concept. (See PHYSICS TODAY, September 1978, page 85.) The Foster group pointed out that among its many physics and engineering complexities may lurk an obstacle that would make it impossible to realize a practical tokamak reactor in the foreseeable future. The $94-million Mirror Fusion Test Facility now under construction at Livermore, and scheduled for completion in 1982, will be the world's largest experimental mirror-fusion facility. Last year DOE chose the Elmo Bumpy Torus from among several magnetic-confinement alternatives to tokamaks and mirrors to be supported for a proof-of-principle test (PHYSICS TODAY, October 1979, page 18). —BMS

Texas tokamak is ready for proposals

The Texas Experimental Tokamak is expected to begin operating on the University of Texas campus at Austin this spring. By next January, it is expected to be available for experiments by off-site visitors. The tokamak is suitable for experiments in atomic processes, impurity transport, rf heating, plasma/surface interaction, plasma formation studies, plasma edge effects, disruptive instabilities and diagnostic development.

The machine has a major radius of 100 cm, minor radius of 28 cm, centerline magnetic field of 3 T, plasma current (nominal) of 400 kA and flat-top pulse length of 0.3 sec.

Proposals for machine time to do experiments on the Texas tokamak will be considered by an advisory committee. Inquiries should be directed to: Kenneth W. Gentle, Director, TEXT, Fusion Research Center, Department of Physics, University of Texas, Austin, Texas 78712.

in brief

General Electric has received a three-year, $1.7-million contract from EPRI to study fluidized-bed combustion, an advanced coal-burning process that may provide cleaner, more efficient energy from power plants. In this process, a stream of air is blown up through a bed of hot coal and limestone, giving the bed some characteristics of a fluid. Boiler tubes run directly through the fluidized bed, promising more efficient heat transfer. Operating about 1500 F degrees cooler than conventional coal burners, the new system would produce less pollution from oxides of nitrogen.

The installation of a second Cray-1 computer at Los Alamos recently began. The $10-million computer, manufactured by Cray Research, is described as the world's fastest, with a vector-computing capacity that makes it about four times as fast as LASL's CDC 7600. It has a million-word memory, but miniaturization makes it physically smaller than the 7600. The new system will increase LASL's computing capacity by about 35 percent.

McDonnell Douglas Corp. has added $1.85 million to the over $5.6 million in gifts it has donated to Washington University since 1974 in support of the McDonnell Center for Space Sciences. This most recent gift will fund the continuation of ten graduate fellowships, a distinguished visitors and postdoctoral associates program and the Earth and Planetary Science Department, as well as the purchase of new equipment.

The Fleischmann Foundation has donated $1.55 million for construction of a Geosciences Research Center at the Quissett Campus of the Woods Hole Oceanographic Institution. The building will house deep-sea samples and laboratories for their analysis. □