caused by different assumptions about the equation of state and by difficult numerical techniques, with the work by Melosh *et al.* probably coming closer to reality. Because vaporization does not discriminate between impactor and impactee, Melosh's prelunar disk is a roughly equal mixture of impactor and protoearth. Making the Moon out of a mixture of impactor and protoearth mantle seems to solve the siderophile problem, because the protoearth composition would also be altered by the addition of the bulk of the impactor, with the final Earth mantle being composed of as little as about 70 per cent protoearth mantle (assuming a three-tenths Earth-mass impactor striking a seven-tenths Earth-mass protoearth), a proportion closer to that of Melosh's prelunar disk.

Clearly many details remain to be investigated and other problems, such as giant impacts totally melting the Earth and producing a massive crust incompatible with the present Earth, will require explanation. If divining the origin of the Moon were a paying proposition, venture capital firms would certainly be well advised to invest in improved models of giant impacts. □

1. Benz, W. *et al. Icarus* **66**, 515 (1986).
2. Ringwood, A. E. *Nature* **322**, 323 (1986).
3. Boss, A. P. *Science* **231**, 341 (1986).
4. Hartmann, W. K. & Davis, D. R. *Icarus* **24**, 504 (1975).
5. Cameron, A. G. W. & Ward, W. R. *Lunar Science Conf. VII*, 120 (1976).
6. Wetherill, G. W. *Science* **228**, 877 (1985).
7. Cameron, A. G. W. *Icarus* **62**, 319 (1985).
8. Melosh, H. J. & Sonett, C. P. in *Origin of the Moon*, 621 (Lunar Planet. Inst 1986).
9. Kipp, M. E. & Melosh, H. J. *Lunar planet. Science Conf. XVII*, 420 (1986).

Alan P. Boss is in the Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road NW, Washington DC 20015, USA.

Fusion energy

Highest temperatures yet

R.S. Pease

DEUTERIUM gas in the Tokamak Fusion Test Reactor at Princeton was heated this summer to a temperature of 230×10^6 K (20 keV), perhaps the highest temperature yet recorded in a laboratory[1,2]. It lies close to the temperatures planned for fusion reactors, and paves the way for the planned production of megawatts of fusion power in deuterium–tritinm experiments in 1989. These promising results bring us closer to the goal of controlled nuclear fusion energy.

What does this experiment amount to, and how does it relate to other attempts? The Tokamak Fusion Test Reactor experimental assembly is a toroidal electric discharge in a strong longitudial magnetic field. Three other large tokamaks are now operating: the Joint European Torus at Culham, JT-60 at Tokai in Japan and D III-D at San Diego. In the Tokamak Fusion Test Reactor, the torus major radius is 2.4 m and its minor radius is about 1 m. The discharge current in the high-temperature experiments is about 1 MA and lasts about 5 s; this current provides the magnetic field which confines the high-temperature deuterium plasma and provides the necessary thermal insulation; it also provides a relatively small amount of heating which on its own heats the plasma to about 20×10^6 K. The higher temperatures at Princeton were obtained with considerable additional heating provided by injecting into this plasma a stream of energetic neutral deuterium atoms (pre-accelerated as ions to 95 keV and then neutralized).

The additional heating amounted to 17 MW for up to 0.5 s during the latter half of the current pulse; it raised the ion temperature at the centre of the discharge to 230 $\times 10^6$ K. This temperature was still rising at the end of the heating period (which is limited by engineering technicalities). The ion number density in the central region (within roughly 20 cm of the centre of the minor cross-section) is of the order of 5×10^{19} m^{-3}; and the thermal coupling between the electrons and the ions is relatively slow. The electron temperature is about 70×10^6 K, noticeably lower than that of the ions. The ion temperature was measured by the Doppler broadening of line radiation from nickel and iron impurities (in highly stripped, lithium- and helium-like states), and is consistent with magnetic measurements of the total energy in the plasma (roughly 2 MJ). The energy confinement time, a measure of the thermal insulation obtained by dividing the plasma energy by the input power, is between 0.1 and 0.2 s.

The experimental error of the estimated deuterium ion temperature has not been announced; it is probably of the order of 25 per cent, but until a full exposition of the estimation methods is published, some reservation must remain on the value of the temperature quoted. The temperature planned for in reactors is about the 230 $\times$ 10^6 K (or 20 keV) now claimed. No such uncertainty applies to the deuterium–deuterium fusion power in the plasma, which is unambiguously obtained by measuring the neutron flux emitted from the plasma. This fusion power is reported to be about 10 kW. A substantial but unspecified proportion of this power must be due to direct interaction of the injected 95-keV deuterons with the plasma deuterons, an enhancing effect explicitly sought in the objectives of the Tokamak Fusion Test Reactor. If a 50/50 mixture of deuterium and tritium had been used in the same conditions, then the fusion power would have exceeded 1 MW. Previously about 0.5 kW of deuterium–deuterium fusion power has been reported from Princeton[3].

The achievement of these results primarily arises from the heating power — the largest yet used on a tokamak. As reported both by Princeton and by the Joint European Torus team at a recent symposium[4], neutral injection is an effective way of heating large tokamaks to the 10 keV range, but is nonetheless accompanied by some degradation of the thermal insulation obtained without it, and a consequent two-fold reduction of the energy confinement time, depending on the power used. An encouraging feature of the Princeton result is that this degradation has not increased at the higher power used. The best heating was obtained using so-called balanced injection: that is, the angular momentum imparted to the plasma by the injected deuterium atoms (which, in the unbalanced case, causes the plasma to rotate at near-sonic speeds) is kept small.

From the point of view of scientific understanding, the key issue of the magnetic thermal insulation remains. The energy losses from the plasma exceed the unavoidable minimum values arising from ion–ion collisions and from the inevitable bremsstrahlung radiation of hot electrons. But in some conditions, and in some other experiments, these minimum values have been approached rather closely. One encouraging indication given by the Princeton result is that a qualitative characteristic of the ideal thermal insulation, the bootstrap current[5], in which the collisional outward diffusion of the plasma across the magnetic field can by itself sustain the discharge current, has been indicated in some conditions of their reactor.

Overall, the preliminary report from Princeton indicates the achievement of conditions close to those hoped for when construction of the $300-million apparatus was approved in 1976, and suggests that fusion power in the megawatt range is achievable in the planned deuterium–tritium experiments. The report gives an encouraging foretaste of the results from experiments on all the large tokamak assemblies. □

1. Zarnstorff, M.C. *et al. Bull. Am. Phys. Soc* (in the press).
2. Owens, D.K. *et al. Bull. Am. Phys. Soc.* (in the press).
3. Murakami, M. *et al. Plasma Phys. cont. Fusion* **28**, 17 (1986).
4. Pease, R.S., Rebut, P.-H. & Bickerton, R.J. *Phil. Trans. R. Soc.* (in the press).
5. Bickerton, R.J. *et al. Nature phys. Sci.* **229**, 110 (1971).

R.S. Pease is UKAEA Programme Director for Fusion at the Culham Laboratory, Abingdon, Oxfordshire OX14 3DB, UK.