A PLAIN MAN'S GUIDE to Zeta

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"A Plain Man's Guide to Zeta"

has been written by

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I. *Fuel for ever from the sea*

A good fairy with the interest of the nation at heart might sensibly decide that Britain would benefit if the Thames were turned into an inexhaustible river of petrol. Life here would be transformed out of recognition. Prosperity of a kind the world has not yet seen might be just round the corner.

The research now being carried out to harness thermo-nuclear power will, however, outdo the good fairy. When this work is successful it may well be that the flow of water in the Thames on a single summer's day will be enough to supply Britain with energy for nearly two years. A day's flow of the river in flood would supply Britain's fuel for a decade. These figures are a consequence of the simple arithmetic of thermo-nuclear power.

A two-gallon bucketful of water contains about a fifth of a gramme of deuterium, or "heavy hydrogen." This is about enough of the gas—which chemically is indistinguishable from ordinary hydrogen—to fill a man's lungs. When it becomes possible to extract all the thermo-nuclear power from it we shall be able to win from one bucketful of water roughly as much energy as can now be got by burning two tons of coal. In other words, an ordinary family, living in a small modern house, will be able to keep warm for a whole year on the deuterium in a bucket of water. The amount of water used in a single day for washing and drinking will be enough to supply it with fuel for more than a century. The rain that falls on Britain in an average year will contain deuterium enough to supply the country with fuel at its present rate of consumption for about sixty million years.

These figures are hard to grasp. They have something in common with the figures astronomers use. This is not altogether accidental, for the way in which deuterium can be used as a thermo-nuclear fuel is similar to many of the processes which go on inside the stars. Farther back in the evolution of the universe, it is possible that matter, as we now know it, together with the great energy which keeps the stars in restless motion, was created in a thermo-nuclear mould. Scientists, however, have not yet turned their ambitions to the creation of new universes. For the moment they are content with the lesser aim of making use of an entirely new kind of fuel. For most of its history, mankind has had to make do with fuels which could only be found in certain places in limited amounts. The more complex of our economies are still based on fuels won from those parts of the earth at which, by chance, conditions were suitable for the formation of coal or oil tens of millions of years ago. Willy-nilly, the world's great industries are to-day established at sites which nature picked, apparently capriciously, a long time ago in geological history.

The coming of what may now be called "conventional" atomic energy just before the war did much to liberate us from these considerations. The fission fuels—uranium and thorium—are plentiful enough to outlast oil or coal by some hundreds of thousands of years, and they are sufficiently compact to be transported easily to any part of the world in which it might be wished to make use of them. But neither of these is as easy to come by as ordinary water, and neither is as abundant on the surface of the earth.

The oceans contain some 330 million cubic miles of water. If we were to extract all the deuterium from this mass of water, and then to burn it as a thermo-nuclear fuel, the energy we should win would be equivalent to 500,000,000,000,000,000,000,000 tons of coal. This would last the world, at its present rate of consumption of all fuels, for about a hundred million million years. This interval of time, it will be noticed, is about thirty thousand times as great as the estimated age of the solar system. Clearly, there is no conceivable way in which we could use up deuterium in a thermo-nuclear furnace in such a way that we could make a perceptible difference to the world's stock of it.

These facts point to the main significance of deuterium as a fuel. It is so abundant that we cannot conceivably have to worry about supplies of it. At the same time, there is a chance that thermo-nuclear fuels will provide a far cheaper means of producing power than any we know now. Certainly, the nuclear power stations which will use it need not produce harmful stocks of radio-active poisons of the kind which drifted over Cumberland when things went wrong at Windscale last October.

So attractive is this draft of the future that it is hard to suppress dreams of what the power stations of the future will look like. First, there will be a plant, rather like a small oil refinery, at which deuterium, or heavy hydrogen, is separated from the ordinary form of the element. Factories like this already exist, and can turn out deuterium at a cost of about 2s a gramme—the equivalent of a little less than ten tons of coal. Then there will be a complicated contraption in which the deuterium is burned to yield up its thermo-nuclear power. The experimental machine which Harwell has called "Zeta" is the only guide we have to the probable shape and structure of this part of the power station. Almost certainly it is an inaccurate guide, but already it is obvious that a working thermo-nuclear power station will be dominated by the complexity and novelty of its electrical equipment. In compensation for the difficulties this will bring, the power engineers can expect to profit, because it may prove to be possible to extract thermo-nuclear energy directly as electricity, without raising steam in boilers and using this to drive electrical turbines.

Just because it is so easy to speculate in terms like these, it is important to remember that there is a long way to go before thermo-nuclear power becomes a reality. Just now the scientists are no nearer to the building of power stations which burn deuterium than was Fermi to the building of ordinary atomic power stations in 1941, when he demonstrated for the first time that a suitable arrangement of uranium bars could produce heat spontaneously. Nobody can yet say how many years will go by before the thermo-nuclear power stations begin to go up. That depends on how quickly foreseeable problems can be solved, and on the complexity of the inevitable problems which have not been foreseen. Nevertheless, we can now, for the first time, be sure that thermo-nuclear power must one day become a reality.

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II. *The source of nuclear power in hydrogen*

Why deuterium? Why not oxygen, which is abundant in the air we breathe? Why not silicon, which is to found in rocks and sand? What has singled out such an odd and rare form of hydrogen to be the first thermo-nuclear fuel?

Deuterium has one of the indispensable qualifications of a thermo-nuclear fuel—it is a light element. The nuclei of deuterium atoms are very small compared with those of atoms like iron and sulphur—indeed only ordinary hydrogen has nuclei which are smaller. A nucleus of ordinary hydrogen consists simply of an atomic particle called a *proton*, which, in most circumstances, is indivisible and immutable. A deuterium nucleus is twice as heavy, and consists of a *proton* held tightly together with another atomic particle called a *neutron*. By contrast, the nucleus of a lead atom is roughly one hundred times as heavy as one of deuterium, and consists of more than two hundred atomic particles (protons and neutrons) held together in something like a very small ball, or water droplet. But why should light elements be important? Here the term "water droplet" is a good guide. Suppose, for example, that two small drops of water are put into contact with each other on some smooth surface. Quite quickly the drops will rupture, and a single larger drop of water will be formed. The fact that this can happen spontaneously shows that the united drop has less energy than the two of which it has been formed; so some energy must be released. That this is so can be demonstrated by a sufficiently delicate experiment, for the temperature of the fused drop will be found to be a little greater than that of the drops from which it is formed.

There is a similar release of energy if the atomic nuclei of two light elements can be persuaded to fuse together. The result of combining two deuterium nuclei should be a nucleus consisting of two protons and two neutrons (one of each from each deuterium nucleus). This nucleus is that of helium-4 (the common form of helium). Since the mid-twenties it has been known that energy would be released if deuterium could be fused into helium in this way. This is the energy we would exploit as thermo-nuclear power.

As a general rule, the lightest elements should yield the most energy when they are fused together, but there is no objection in principle to attempts to obtain fusion energy on a commercial scale by fusing carbon atoms together. There are, however, practical difficulties. Bringing atomic nuclei into contact is difficult because the nuclei carry electric charges which repel each other. These electrical barriers can only be overcome by setting two nuclei moving towards each other with sufficient speeds—which for deuterium nuclei must be measured in thousands of kilometres a second.

Not all the electrical barriers between atomic nuclei are the same—the energy needed to bring two carbon nuclei together is 36 times as great as that needed to put two deuterium nuclei in contact. Such differences stem from the differing electric charges which are carried on different atomic nuclei.

So great are these differences that for the time, if not forever, we shall have to include in the list of possible thermo-nuclear fuels only the three different forms of the element hydrogen. Deuterium is one of these and, as things turn out, the only practicable choice. For the nuclei of ordinary hydrogen are exceptions to the rule that light elements can be made to fuse together—the combination is not stable. "Super-heavy hydrogen," or tritium—the third form of hydrogen,—is theoretically attractive as a fuel, mainly because of the high yield of energy it can give. Tritium, however, has to be made artificially by a process which is so costly that the economics of thermo-nuclear power based on it would be jeopardised from the start.

It will be seen that nuclear fusion is in some ways the reverse of the process by which uranium is made to yield atomic power. That depends on the fact that very heavy nuclei tend spontaneously to split into smaller ones, mainly because of the difficulty of accommodating inside individual "water droplets" electrical charges about a hundred times as great as those in hydrogen nuclei.

There is another important difference between the processes that has added to the attractiveness of thermo-nuclear power. The fission of heavy atoms like uranium inevitably leads to the formation of atoms which are intensely radio-active, and which are capable of being serious toxic hazards for thousands of years after they are produced. Fusion, on the other hand, will not yield radio-active by-products, so that there should be no trouble in getting rid of the waste from a thermo-nuclear power station.

All this has been intelligible since 1934, when Rutherford and Oliphant at Cambridge made a thorough study of the fusion of deuterium nuclei. In their experiments deuterium nuclei were accelerated to high speeds in an electrical machine, and then fired at other deuterium atoms which were more or less at rest. In this way they were able to make some thousands of pairs of deuterium nuclei fuse together. Their work has two important implications for the research now being done to make fusion the basis of a new industry.

First, it turned out that the product of fusing two deuterium nuclei was not a nucleus of helium-4, as might have been expected. Such a nucleus, if it were ever formed in their experiments, would have had so much surplus energy that one of its four atomic particles would have been "boiled off." So Rutherford and Oliphant saw that most deuterium fusions led to a nucleus of a light form of helium called "helium-3," and a neutron which was flung off with some speed. Very much less frequently a proton appeared as the odd particle, and a nucleus of tritium was left behind. This observation means that the waste product of the thermo-nuclear power stations of the future will be helium-3, and that neutrons which may have economic uses of their own will be produced on a substantial scale.

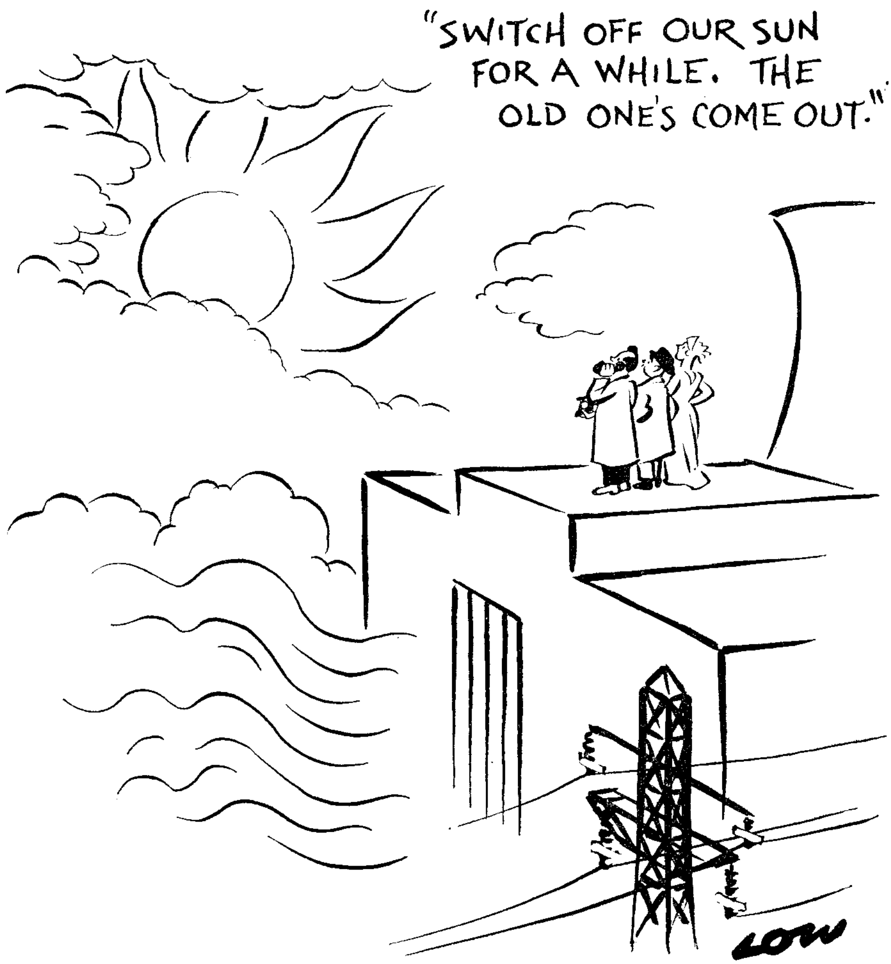
A second observation bears on the practical task of producing thermo-nuclear power. In the Cambridge experiments, only one in a million of the fast deuterium nuclei ever came within fusing distance of another nucleus. The others spent their energy in fruitless collision with other parts of the deuterium atoms at which they were shot—with the electrons, for example. This shows that no attempt to exploit the energy of nuclear fusion by firing streams of fast particles at others could hope to be successful; the process would be so inefficient that much more energy would be needed to run the accelerating machine than could possibly be recovered from fusion. To obtain a net gain of power it is necessary to create a system in which deuterium nuclei are moving with sufficient speed for a large proportion of them to have a good chance of fusing together, and in which the energy of those which escape fusion is not wasted.

It seems that the simplest way of doing this is to heat a gas of deuterium to a high temperature, for at temperatures above 100,000 degrees C. the nuclei will be detached from the electrons which make up the rest of the atom, and will move about with considerable speeds. The average speed of motion will depend on the temperature, but there will always be nuclei which move with sufficiently high speeds for fusion to be possible. The energy of less exceptional nuclei will not under these circumstances be lost to the system, for what is lost by one nucleus in a fruitless collision will merely be transferred to another.

This is the significance of the word *thermo-nuclear*. It implies that fusion energy is produced by a process which is essentially thermal.

From this point it is a relatively simple matter to work out how hot deuterium gas must be so as to contain enough exceptionally fast nuclei to produce a useful yield of fusion power. It must, nevertheless, have been a douche of cold water for those who first made these calculations to discover that something like 100 million degrees centigrade would be needed in thermo-nuclear power stations. The fact that a temperature of 30,000 degrees was the highest ever recorded in a laboratory before 1950 is a telling tribute to the courage of the men who are now running the experimental thermo-nuclear machines.

Until now, temperatures like these have been beyond human imagination. The hottest object we know is the sun, whose temperature on the outside is about six thousand degrees. Ninety million miles away from it we can lie on a beach—at least, in summer—and be burnt by it. The temperature at the centre of the sun has never been directly sensed, and its magnitude can only be inferred from what is known



about the sun's structure. It is believed to be about 15 million degrees —comparable with, but only a fraction of, the temperatures which it is hoped to create in thermo-nuclear power stations.

The temperatures at the centre of stars are the only ones which are known to be comparable with 100 million degrees, and it is now abundantly clear that the sun's heat is produced in the deep interior of the star by nuclear fusion. Indeed, the sun is nothing but a complicated system for turning light elements—principally ordinary hydrogen—into heavier ones. The fact that it has to rely mainly on light hydrogen as a fuel means that the sun's thermo-nuclear mechanism is a good deal more complicated than that proposed for the terrestrial thermo-nuclear power stations.

The sun can also afford to burn fuel at a much slower rate than would satisfy power engineers. In several thousands of millions of years the sun has used up less than 5 per cent of its original stock of fuel—mainly because the temperature at the centre is no greater than fifteen million degrees. Nevertheless, the parallel between the stars and the experiments now being made is, without any shading of the truth, sufficiently close for it to be said that thermo-nuclear power stations will be small artificial suns built by human beings on the earth.

III. *Making a cage for a sun*

How are we to make artificial suns on earth ? This is essentially a problem for engineers. It raises one question, however, which is novel in every way : in what can you contain a sun ?

No material can possibly contain a gas at a temperature of 100,000 degrees, let alone at 100,000,000 degrees. Quartz, porcelain, and granite are all vaporised below 5,000 degrees. At 10,000 degrees molecules start breaking up into atoms, and at 100,000 degrees atoms start losing their electrons. Above a million degrees even atomic nuclei begin to behave in strange ways—this, after all, is the principle of thermo-nuclear power. Above a million degrees matter as we know it does not exist.

Thus the first object of thermo-nuclear research has been to invent a new kind of container for hot gases. Tangible materials were ruled out from the start, and this is why all research teams in the field have been driven to what may properly be called the design of containing vessels made of nothing more substantial than magnetic forces. The important container in machines like Zeta is not the doughnut-shaped metal or glass vessel but the complicated system of magnetic forces inside it. The container problem is all important. Once it is solved the actual production of very high temperatures presents few difficulties of principle. It is not, of course, possible to heat deuterium gas to 100,000,000 degrees with a bunsen burner, or anything like that, but electrical methods of heating are well up to the task. In fact, once a column of deuterium has been contained in a "magnetic tube" of some kind, it can be heated up as if it were an element in an electric fire. All that needs to be done is to pass a sufficiently large electric current through it.

Thus most experiments in the control of thermo-nuclear reactions make great play with electrical discharges in deuterium gas. These are the electric currents which, it is hoped, will heat up the deuterium to high temperatures, where the release of energy by thermo-nuclear means will begin. Simple though this may be, the practical difficulties in reaching temperatures above a million degrees are formidable and varied. As yet, only some of them have been solved. But in one important respect, at least, nature seems to be on the side of the experimenters.

For five years it has been known that the act of passing an electrical discharge through a gas like deuterium can, at the same time, produce the magnetic forces to keep the gas together. This phenomenon is known by the unassuming name of the "*pinch effect.*" Its mechanism can be most simply understood in a straight discharge tube, which might be a simple glass cylinder, with an electrode at each end. At the beginning, before the discharge is struck, the gas inside the tube is put into a condition in which it can conduct electricity. At the beginning of the discharge a very small electrical current will flow beween the electrodes and down the tube. Simply because there is an electric current there will be magnetic forces around the tube. Their direction is circular, and perpendicular to the line of the discharge but their effect on the electrical particles of the gas is to give any one of them which happens to stray towards the walls of the tube a little push back towards the main current.

When the current is small, the magnetic forces are not powerful enough to prevent contact between the walls and the gas. As it increases, when the discharge gets under way, the magnetic forces become stronger and in the end they may be powerful enough to turn most of the electrified particles of the gas away from the walls ; and, indeed, to compress them along a comparatively narrow region down the centre of the tube. This is sometimes pictured by representing the lines along which the magnetic forces act by elastic bands. (This can be done, because the laws of electricity imply that energy is needed to stretch these lines, just as work must be done to stretch elastic.) With an increase of current in a discharge tube, it is said, there is a contraction of the elastic bands, and the gas is carried inwards. The effect of the "pinch mechanism" is to scour out the gas in a tube, and to compress it into a small region along the line of the electrical discharge. This, then, is the "magnetic bottle." It is not a rigid bottle, nor is it free from leaks, for hot gas will leak out of its magnetic container at a certain rate. It is lucky for the experimenters that their magnetic containers are not so leaky that hot deuterium cannot be contained for lengths of time great enough for fusion to have a chance to work.

But magnetic containers of this simple kind have one disconcerting property; they tend to wriggle about. In the earliest experiments on "pinched" electrical discharges the line of the electric current did not stay long where the experimenters wanted to see it. Sometimes the discharges would wriggle wildly enough to touch the walls of the tube and there spend a substantial part of their energy on vaporising metal or glass. This meant that really high temperatures could not be attained. The consequences of this wriggling in full-scale thermo-nuclear power stations would clearly be of a catastrophic kind.

So for the past two years it has been obvious that some means of stabilising electrical discharges in hot gases would have to be found. The great contribution of Zeta to thermo-nuclear research rests in a large part on the fact that it is the first machine to have shown that these instabilities can be smoothed away. Again, magnetic fields are the solution—this time because they are deployed in a way that provides a kind of "backbone" for the electrical discharge. To the extent that magnetic forces can be likened to elastic bands, this action can be understood quite simply. Before a discharge is struck in a discharge tube a field of magnetic force is laid down in the direction in which the discharge will flow. As this builds up and pinches, the magnetic forces along the axis of the current are carried inwards with the gas. If, now, the column of the discharge wriggles about, the line of the magnetic forces along its axis must be stretched. But elastic bands do not stretch spontaneously. It has been found that electric discharges which have been reinforced with magnetic fields will not do so either.

Some of the essential parts of a thermo-nuclear power station can now be roughly described. First, there must be a discharge tube, filled with deuterium gas. In this it must be possible to strike discharges sufficiently great to provide a strong container of magnetic forces as well as to heat the gas to something like 100,000,000 degrees. So that useful yields of power may be obtained from fusion the container must not allow the hot gas to leak through it at too great a speed—it must be able to hold deuterium for about a second. Then there must be magnetic forces to stabilise the discharge by providing it with a sufficiently strong reinforcement. This, in turn, dictates the solution of some comparatively minor problems of design. Material electrodes cannot be expected to survive thermo-nuclear temperatures, so that some unconventional method of striking a discharge has to be found. In the first place this means that discharge tubes should be endless ones, closed upon themselves. Hence the doughnut shape of Zeta and its smaller competitors. Electrical currents must be produced, not by direct means but by enclosing the tube in the iron core of an electrical transformer. This has the effect of linking the electrical circuit in the discharge tube to another made of copper conductors, which is also wrapped on the transformer core. A discharge may be struck by passing a current through the ordinary electrical circuit. The energy for doing this is stored, as electricity, in a battery of electrical condensers, for much the same reason as photographers set off their flash bulbs from a condenser carried on the shoulder.

It appears that British scientists were the first to realise that a discharge of a doughnut shape (a "*torus*" it should properly be called) should, ideally, be made of a non-magnetic metal. This, it turns out, has the effect of adding another element of stability to the discharges in the deuterium. For when these currents flow, others are generated in the walls of the vessel in such a way that the bodily shifting of the discharge towards the wall of the tube is made much more difficult than it would be otherwise.

The power engineers who will one day run thermo-nuclear power stations will live in a different world from those who see to the burning of coal under steam-raising boilers. While the experiments continue they will be worrying about means of feeding in sufficient electric power to keep their discharges going. They will be worrying about how to harness the still greater amounts of energy their captive suns will release. The extent of their ignorance is still greater than that of their understanding. Indeed, all they know for certain is that one day their dreams will come true.

IV. *The great achievement of Zeta*

What has Zeta done ? For one thing, temperatures of 5,000,000deg. centigrade have been created in it, and neutrons, which almost certainly come from the thermo-nuclear fusion of deuterium, have been detected flying away from the machine. So Zeta is the first machine in the world in which artificial suns have been made.

At the same time, the experiments with Zeta have successfully proved that a magnetic field laid down along the axis of an electrical discharge can successfully anchor the line of electrical current, and stop it wriggling about. Though this is a less spectacular achievement, its consequences for the future are in some ways more important. For it is now clear what steps must be taken next in the control of thermo-nuclear fusion. Zeta points the way to bigger and better captive suns.

Many of the turning points in the history of science are experiments of this prescient kind. From Faraday's simple demonstration that electrical induction was possible has sprung the whole of our electrical industry. Cockcroft's first artificial splitting of atomic nuclei in 1932 provided physicists with tools which could be used to bring about a great variety of nuclear transformations. Within six years atomic fission had been discovered, and the foundations of our " conventional " atomic power industry had been laid. There is every reason to expect that the experiments which have been made with Zeta since the middle of August, 1957, will prove to be equally significant.

The essential part of Zeta is a gas discharge tube, of doughnut, or toroidal, shape. The tube is a metre in diameter, and makes a closed ring four metres across. Its proportions are much the same as those of the inner tube of a motor-car tyre, with dimensions six or seven times as great. The discharge tube has double walls. Outside is a stout structure of aluminium plate, an inch thick, which is sufficiently strong not to collapse when the tube is almost completely emptied of gas. An inch inside this outer wall is a similar tube, made of aluminium sheet, one-eighth of an inch thick. This is expected to take the brunt of the extreme temperatures and electrical conditions which are created when discharges are struck in the machine. It is made in several separate sections, and the design of these contributes a great deal to Zeta's freedom from electrical troubles.

At two points in the walls of the outer tube windows of stout transparent quartz have been fitted, so that electrical discharges inside can be photographed, and examined spectroscopically. The photography is a difficult business, because of the speed with which exposures have to be made if they are to be of much use. Elsewhere round the tube are arrangements for making other measurements of the electrical discharges—of X-rays, neutrons, and the reflection of radar waves from the glowing column of gas.

So much for the tube. Before a discharge is struck in it, air is pumped out, and replaced by deuterium. Experiments begin with a deuterium pressure about a ten-millionth of normal atmospheric pressure. These conditions are those of a very good vacuum. Among other things, they help to ensure that the pressure of the deuterium when it has been heated to several million degrees shall not be great enough to burst its magnetic container.

The magnetic forces which act as a container in Zeta, together with the current needed to keep a discharge going in the tube, are created by means of a transformer core, which is built around the doughnut. In shape, this is a slab of transformer steel (built up out of thin sheets laminated together) about a metre thick, and sufficiently wide to span the discharge tube across its diameter. There are two tunnels through the steel into which the tube fits snugly.

This arrangement provides an electrical link between the tube and a circuit of heavy electrical conductors, which is wrapped on the outer surface of the steel. If electricity is passed through the outer circuit, voltages are created in the discharge tube. Sufficiently large currents of electricity can generate voltages big enough to start a discharge, and to keep it going. Zeta, however, demands bigger currents than could conveniently be supplied from an electrical generator. So, instead, current is fed in from a bank of electrical condensers, some twenty yards away from the machine itself. The function of the condensers is to store electricity got from the mains, and to release this quickly at some chosen instant.

In fact, nearly ten seconds are needed to fill the condensers with electrical energy. In this condition they hold half a million "joules" of energy—enough to boil a cupful of water (one joule is enough to light a flash lamp bulb for half a second). The whole of this can be discharged into the transformer in four thousandths of a second, which implies that power is being fed to Zeta at a rate of 10,000-kw.—more than a tenth of the electrical output of a power station the size of Calder Hall.

The circular magnetic forces which can contain gas discharges grow up as the current discharge in the tube is struck. Those which provide the discharge with a "backbone," however, have to be supplied separately. In Zeta this is done by fitting a number of electrical coils around the walls of the tube.

The fact that Zeta is an experimental machine should not hide the fact that it is, in its own right, a remarkable piece of engineering. The transformer core is, for example, out of the ordinary both in size and shape. The power supply from the condensers has posed new problems. Their solutions have made sure that electricity can be emptied from the condensers with sufficient speed to create really powerful discharges in the doughnut.

What does Zeta look like? Outwardly it suggests in many ways some of the equipment with which Faraday made his historic experiments—though, of course, it is much bigger than anything he used. At the same time it is an exciting structure of the kind with which professional scientists like to work. Merely a sight of Zeta will persuade most people that it must be an historic apparatus.

The real justification for such an opinion rests on the results of the experiments which have been made in the past six months. The most spectacular of these is the fact that on August 30, 1957, about a million neutrons were flung out of the machine during an electrical discharge in deuterium. The temperature of the glowing gas measured at the time was nearly 5,000,000deg. centigrade. Since the end of August this kind of thing has been repeated several thousand times. Discharges lasting for some thousandths of a second can be repeated once every ten seconds—the time taken to recharge the condensers. When the current to the transformer is made great enough, a nicely pinched column of glowing gas is created down the centre of the discharge tube. Radar measurements have shown that in these circumstances virtually all the gas which originally filled the tube is drawn into the glowing column, and also that all of this is in an electrically ionised form. Depending on the current in the discharge, which may be as much as 200,000 ampères, the number of neutrons produced by Zeta can vary from nothing to 1.35 million.

It will be recalled that the energy needed to produce each electrical discharge is roughly that needed to boil a cupful of water. The neutrons that come off in the most powerful discharges represent the fusion of between two and three million atoms of deuterium, and the fusion energy produced in each discharge is hardly enough to blow a small soap bubble. So it is clear that Zeta, as it stands, is a very inefficient way of making thermo-nuclear power. Indeed, the amounts of energy produced in the discharges are so small that it has turned out to be extremely difficult to prove with the full rigour of scientific method that thermo-nuclear fusion has been brought about in Zeta. For the time being, scientists have to be content with indirect and circumstantial evidence, though this is enough to convince most of them.

One of the difficulties in this connection is that it is always possible that nuclear fusions in discharge tubes can be caused by the acceleration of a small proportion of the deuterium atoms in the gas to high speeds—as in the accelerating machines Oliphant and Rutherford used in 1934. So neutrons which may be flung off from experimental thermo-nuclear machines are not, in themselves, evidence that fusion has been brought about simply as a consequence of high temperature.

In Zeta, however, it has been shown that the yield of neutrons increases rapidly as the current in the discharge is increased, and this is what would be expected if a true thermo-nuclear process were at work. More evidence of this comes from measuring directly the temperatures in the gas discharges.

This is an interesting job, not least because the method used is one of

those that astronomers use to measure the temperature of stars. Nitrogen and oxygen are added in small quantities to the deuterium in Zeta, and the light they give out when the gas is heated is observed through narrow windows in the side of the tube. A particular study is made of certain of the intense parts of the spectra of oxygen and nitrogen—certain easily recognised "spectral lines." Temperature can be told by measuring the "fuzziness" of these lines, which increases steadily with increasing temperature. Nitrogen and oxygen have to be introduced for this purpose because deuterium itself does not yield a well-marked spectrum at the high temperatures which can be produced in Zeta.

Two conclusions have followed from this work. First, it has turned out that the numbers of neutrons given off during discharges in Zeta are roughly what would be expected from a thermo-nuclear process. Secondly, a study of the particular kind of "fuzziness" in the spectra has shown that the gas in the tube appears to be made up of atoms whose speeds fluctuate about the average in the way that would be expected of a gas at a high temperature: that is, the proportion of atoms with exceptionally high velocities appears to be appropriate to a hot gas. Before Zeta started working it was thought that it might take longer than a few thousandths of a second to bring about such a state of affairs. The fact that this is not so is perhaps another instance of nature's fondness for the experimenters.

Certainly, it is only fair to admit that a little good luck has contributed to the success of the machine. For one example, it seems that when Zeta was designed in 1954 no attempt was made to provide for a magnetic field to stop the discharges wriggling about. Instead, the diameter of the tube was made a metre across in the hope that instabilities of the current would only rarely come into contact with the walls. After construction had started, however, large electrical coils were wrapped around the tube. At the time there was no accurate way of telling how strong the magnetic forces would have to be, and so no guarantee that the electrical coils would prove sufficient for their task. By good luck, as it turned out, comparatively weak magnetic forces produced stability of the discharges, so that hats could be thrown in the air a little earlier than would otherwise have been possible.

Nobody will begrudge the men at Harwell this modest good fortune. Instead there will be admiration for their courage in having built a machine costing £300,000 without at first knowing exactly how it was going to work. For though this is in the best traditions of experimental science, few fields of research demand such complex and expensive equipment.

V. *The work that led to Zeta*

Zeta is by far the largest, and the most successful, of all experimental thermo-nuclear machines. That it should be a British achievement is probably a fair reflection of the fact that British scientists were the first to be fired with ambition to control thermo-nuclear fusion so as to get power.

The story starts in 1946. Then, Dr P. C. Thonemann, at the Clarendon Laboratory, Oxford, and Dr A. A. Ware, at Imperial College, London, embarked on modest research programmes, mainly intended to study the properties of powerful electrical discharges. By the end of the decade, the Atomic Energy Authority was convinced that thermo-nuclear fusion had a future and, at the same time, that this might have a military bearing. It was feared that thermo-nuclear machines might be used as cheap neutron sources for the production of explosives like plutonium. So thermo-nuclear research was declared secret in 1951. The Oxford team was transferred to Harwell, and the team from Imperial College to the laboratories of A.E.I., Limited, at Aldermaston.

To tell from published papers, Russian work started at about that time. In the United States, the Atomic Energy Commission was rather slower off the mark, for it now appears that serious research on the control of thermo-nuclear fusion did not begin at Los Alamos, California, and Princeton until 1954.

The early British experiments appear to have been studies of powerful electrical discharges, and of the property of the hot gas in discharge tubes. Little was known on the second point at the end of the war, and some of the things that have since been discovered about hot electrically ionised gases—"plasmas" as they are called—have prompted some scientists to describe them as a "fourth state of matter."

In the experiments before 1951, gas discharges were seen to "pinch," and it was recognised that this phenomenon might prove of great value in the ultimate control of thermo-nuclear power. But a great deal of work remained to be carried out in the development of suitable instruments for following powerful gas discharges, and it was obvious that their instability was a serious problem which would have to be dealt with.

After 1951, it appears that the technical difficulties of producing discharges of more than 10,000 ampères were successfully surmounted by the two British teams. At the same time it was recognised that toroidal discharge tubes were likely to be the most suitable, and the usefulness of metallic rather than glass or ceramic walls was appreciated. This last step appears to be a contribution of the A.E.I. laboratories, whose director, Dr T. E. Allibone, before the war, had developed high-voltage X-ray tubes on the same lines.

This period also saw the design at Harwell of toroidal discharge tubes of increasing size. Two of these, each roughly a third of the size of Zeta, are now at work in the laboratories there, accumulating information about the properties of gas discharges, and the materials of which containers are made.

The realisation that magnetic fields might provide a means of stabilising gas discharges appears to have come in 1956. Their stabilising influence was demonstrated in some of the smaller discharge tubes, though these were incapable of yielding the very high temperatures at which thermo-nuclear reactions proceed apace.

Information about Russian work is not plentiful. The first details of it were given by academician I. V. Kurchatov in a lecture at Harwell in the early summer of 1956. Though Kurchatov described an unsuccessful thermo-nuclear experiment—neutrons were produced by extremely unstable discharges in a straight tube, but were shown not to be of thermo-nuclear origin—this was a memorable occasion. For one thing, it was striking evidence of Russian seriousness, and of their substantial progress. It also came as a shock that the Russians were prepared to talk publicly about a subject that was closely guarded as a military secret in the West.

American thermo-nuclear research has followed a somewhat complicated pattern. After a late start, the object of much of the work appears to have been guided by intellectual curiosity about the behaviour of electrical discharges. Straight tubes were used for making these until quite recently.

During 1957 it appears that several studies of the stabilising influence of magnetic forces were made in the United States, and towards the end of the year suitably stabilised discharges were produced in deuterium for periods of some millionths of a second. The most successful of these experiments was made with a machine called the "Perhapsotron" at Los Alamos. This is a glass tube of two-inch bore, which forms a ring two feet across. Stable discharges have been maintained in it for up to 60 millionths of a second (roughly 1 per cent of the duration of the discharges in Zeta). On December 17, 1957, temperatures of 5,000,000deg. were attained in this apparatus, and neutrons were produced at the same time. Doubts about the thermo-nuclear origin of these are necessarily greater than about Zeta's neutrons, mainly because of the short length of time for which the deuterium is heated. It is clear, however, that "Perhapsotron" must work very near, if not above, the point at which thermo-nuclear fusion should begin.

The success of this machine is in some ways comparable with that of "Sceptre III" at the A.E.I. laboratories. This is a larger discharge tube, with an internal diameter of a foot, formed into a doughnut four feet across. Towards the end of 1957 stable discharges lasting for nearly half a thousandth of a second, yielding temperatures of between 3,000,000deg. and 4,000,000deg., and pulses of neutrons which may well be of thermo-nuclear origin were produced in it.

These comparisons are not invidious. Indeed, it is clear from the record of research over the past five years that a comparison of the performance of different machines is going to be of great value in pointing the way forward. Engineers will make new and better designs, with more confidence, now that the effect of size in the behaviour of these machines has been publicly demonstrated. Progress should be faster now that some of the secrecy about thermo-nuclear fusion has been abandoned.

VI. *Into the new age of power*

Although Zeta's immediate claim to fame is that, in it, thermo-nuclear fusion was first controlled, and that its discharges are stable for appreciable lengths of time, its important significance lies in the future. For Zeta has made it plain to scientists what must be done next.

The goal has been obvious for some time. Simply, means must be found of creating temperatures in the region of a hundred million degrees, and of maintaining them for periods of about a second. Zeta itself will take us some distance along this road, and already the machine is being modified—a larger tube is being fitted, for one thing. Later this year, more condensers will be added, and the power supply circuits will be suitably rearranged. It will be no surprise if by the end of the year, Zeta is producing temperatures greater than 15 million degrees, and maintaining them for more than a hundredth of a second.

To go much beyond this a new machine will be needed. The American "Stellerator," which will be completed in three or four years, will, perhaps, yield temperatures of 50 million degrees. Thoughts at Harwell have turned to the construction of a machine which will produce as much energy from thermo-nuclear fusion as it will use up in striking the discharges. This will have to run at temperatures greater than 100 million degrees. Its design has now begun, so that at some time in the early 'sixties we can expect that the power engineers will be called in and presented with the rudiments of power stations which, in some figurative sense, can burn water.

One can guess what some of their problems will be. They will have to invent means of handling electrical energy in enormous quantities. They will have to find ways of carrying away heat from captive suns, at such a rate that these can be allowed to produce power with the speed of which they are capable. On paper, there is no limit to the capacity of a thermo-nuclear power station—one of them alone might provide all Britain's needs of power if only some means of extracting it quickly enough can be found. It may be that the engineers will decide that it will be simplest to convert the energy of fusion directly into electricity.

Whatever they do, one thing is certain—thermo-nuclear power stations will not resemble any kind of industrial plant which has yet been built. How soon we shall be able to use thermo-nuclear electricity remains to be seen. How much it will cost depends on how expensive it will be to build the power stations, but the chances are that this new power will be cheap. What its consequences for industrial society will be is a question of still greater difficulty. We, or our children, shall have to wait and see.

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THE MEN WHO MADE ZETA

" Zeta " is the code name, or pet name, that the scientists at Harwell chose for their project for a thermo-nuclear machine when they began working on it. The origin of the name is one of the less penetrable of Zeta's mysteries. Some say that it was just a convenient label from the Greek alphabet, others that Zeta really stands for the initial letters of " Zero Energy Thermo-nuclear Assembly." The words certainly fit the initials, but they may, of course, have been selected specially to fit them after Zeta had been named. One may take one's choice, and no doubt the obscurity of Zeta's name will provide material for some pleasantly speculative footnotes in later scientific histories. Zeta was announced to the world in a group of articles in " Nature " on January 25, 1958. The authors, who are among the men whose work produced Zeta, include Dr P. C. Thonemann, E. P. Butt, R. Carruthers, Dr A. N. Ellis, D. W. Fry, Dr A. Gibson, G. N. Harding, D. J. Lees, R. W. P. McWhirter, R. S. Pease, Dr S. A. Ramsden, and S. Ward. Mr. Fry is head of the Physics Division at Harwell, and Dr Thonemann leads the gas discharge group there. The average age of members of this team is 33. Five of them are still in their twenties, and the youngest—Dr Gibson—is 24. Nine of them started their scientific careers by taking degrees at universities. The others were trained at technical colleges and by engineering apprenticeships. The names of the A.E.I. team at Aldermaston, which has also been much concerned with Zeta, are given as Dr N. L. Allen, Dr T. E. Allibone, D. R. Chick, R. F. Hemmings, T. P. Hughes, Dr S. Jaufman, B. S. Liley, J. G. Mack, Dr H. T. Miles, Dr R. M. Payne, J. E. Read, Dr A. A. Ware, J. A. Wesson, and R. V. Williams. Dr Allibone is the director of the laboratories, Mr. Chick is head of physical research there, and Dr Ware is in immediate charge of thermo-nuclear research.

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