accept this, the deuteranope has his pigments mixed in a single class of cone. We cannot say in advance what is the relative efficacy of erythrolabe and chlorolabe in producing a nerve signal, but we may deduce it by noting how greatly the chlorolabe curve of Fig. 3 must be scaled up so that when added to the erythrolabe curve it will correspond to the deuteranope visibility curve; the factor is about 2. The curve of Fig. 4 gives the combined effect of erythrolabe and chlorolabe so estimated, and is seen to correspond well with Pitt's visibility curve (dots).

In work extending over twenty years, Stiles[4] has investigated colour mechanisms in normal subjects by measuring the increment thresholds of flashes of one colour upon the background of another colour—a method crudely followed in my deuteranope experiment described above.

In the red–green region of the spectrum, Stiles has found two quasi-independent colour mechanisms labelled π_4, π_5, of which π_4 has nearly the same spectral sensitivity as the protanope (Fig. 1) and π_5 as the deuteranope (Fig. 4, circles). We may say, then, that the normal red–green colour mechanisms are reduced in the dichromat as follows: protanopes have only π_4, deuteranopes only π_5. But from our analysis of the foveas of these dichromats the nature of π_4, π_5 in the normal eye may now be stated. For π_4 is the response of the green-sensitive cones which contain only chlorolabe and the sensitivity of which corresponds to the chlorolabe spectrum. π_5 is the response of the red-sensitive cones which contain mixed pigments and the sensitivity of which does not correspond to the erythrolabe spectrum. The physical proportions in which the two pigments are mixed are shown in Fig. 3, but since chlorolabe is twice as effective as erythrolabe in exciting vision, we should increase its scale proportionally in all problems where we turn our analysis from pigments to sensations.

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[4] Stiles, W. S., *Docum. Ophthal.*, **3**, 138 (1949). Coloquio Sobre Problemas Opticos de la Vision (Madrid), 1, 65 (1953). *Proc. U.S. Nat. Acad. Sci.* (in the press).

A BOREHOLE TO THE EARTH'S MANTLE?

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THE Mohorovičić discontinuity is the boundary between the mantle and the assorted surface rocks of the Earth, and it marks a very sharp change in the velocity with which earthquake waves travel—a jump from about 21,000 ft./sec. to 27,000 ft./sec. The mantle extends about half-way to the centre of the Earth, and encloses a core which earthquake seismic waves demonstrate to be fluid. At last year's meeting of the International Union of Geodesy and Geophysics at Toronto a resolution was passed urging the importance of drilling a bore-hole deep enough to penetrate the rock layer that lies below the Mohorovičić discontinuity.

The use of artificial earthquakes has been common practice for many years now in studying the Earth's crust. The seismic prospecting methods used to locate underground oil reservoirs tell the approximate depth and the shape of the surface of the underground layers of rock, but they do not give a firm indication of the type of rock. In order to draw an unambiguous picture of the sub-surface geology, it is necessary to follow particular rock layers from their surface outcrops, or from bore-holes. The layer below the Mohorovičić discontinuity does not come to the surface and therefore it is necessary to drill in order to find out what is the material—what chemical or radioactive properties it has—that forms the Earth's mantle.

It is found that the mantle lies at a depth of about 20 miles under the land, but that underneath the deep oceans it is only about 7 miles below sea-surface. The nearest the mantle comes to the surface of land is under oceanic islands, and here it is depressed below normal oceanic level to about 10 miles below surface. This is probably the best place to drill the hole to the Mohorovičić discontinuity.

The seismic measurements in the oceans enable estimates to be made of the thickness of sediment that has collected and compacted over millions of years on the sea-bed. As with oil-finding seismic work on land, the support of an outcrop or a bore-hole is needed to make an unambiguous interpretation of the measurements. In particular, there is a hard layer, lying beneath about 1,500 ft. of soft sediment, which could be a band of cemented limestone, or a continuous layer of volcanic rock. Beneath this again is a layer of rock which is probably the primeval ocean floor. The seismic measurements combined with analyses of volcanic material erupted from inside the Earth give some idea of what this rock might be, but they are only guesses because the exact origin of the molten lava of the volcano is not known, and in any event mixing will occur as the lava is forced upwards. A second recommendation was therefore made at Toronto—to drill a few thousand feet through the sediments that cover the three-mile deep oceans to see both what kind of rock lies beneath them and to collect samples all the way down in order to elucidate the depositional processes that have been going on in the past.

The deepest hole so far drilled is just over four miles. This hole, like most deep borings, was drilled to find oil—and it is to the oil industry that we owe most of the recent developments that have taken place in drilling. The total depth drilled is now well over a million miles, and last year in the United States alone 40,000 miles of oil wells were drilled—enough to go several times right through the Earth. Since 1927 there has been a steady increase, from 8,000 ft. to 22,000 ft., in the depth of the deepest hole.

Most modern oil-well drilling is carried out by the rotary method. It is difficult to appreciate the enormous length of pipe which is used to rotate the cutting tool at the bottom of the hole. To give an idea of the scale, a 33-ft. long wire, of 7/1,000 in. diameter, has about the same length-to-diameter ratio as a 20,000 ft. length of 4-in. drill-pipe. The

* Substance of a Royal Institution Discourse entitled "Drilling Deep Holes in the Earth", delivered on June 11.

cutting tool cannot be forced into the rock by pressing on such a long flexible length of pipe because the pipe would buckle. The tool is therefore driven into the rock by about 20–30 tons of extra thick pipe at the bottom of the hole, and the main length of the drill-pipe supports and rotates this bottom section. Without the heavy rigid section the drill-pipe bends, and the friction between the drill-pipe and the bore-hole almost stops the rotation ; furthermore, the bit tends to go crooked. With a heavy section at the bottom, the thin drill-pipe is held in tension and the rock is penetrated quite readily. The motive power for the bit would be better at the bottom of the hole, and electric motors have been tried but without great success. It is difficult and perhaps dangerous to handle the large electric power needed, with cables that are subjected to the wear and tear of running in and out of a bore-hole.

Much more commonly used is a multi-stage turbine motor, which is driven by mud and water pumped down the drill-pipe and up the space between the drill-pipe and the walls of the hole. The driving motor consists of a hundred rotor elements, which give enough power to rotate the bit many times faster than the conventional rotary systems. The friction of the drill-pipe all the way down the walls of the bore-hole limits the rotary drilling speed to about 120 rev./min. High speed of rotation means correspondingly faster rock penetration ; but apart from this, light-weight drill-pipe can be used, since it only carries the weight of the turbine, and does not have to twist it around ; and, since the pipe is not rotated, there is very little wear on the sides of the bore-hole. Furthermore, if the cutting bit jams on an extra tough piece of rock, the turbine will be halted but the mud will circulate and keep the hole free. With the rotary drill, jamming of the bit often means that the drill-pipe is twisted until it breaks off.

The turbo-drill has another potential advantage which has not yet been realized. Because the drill-pipe is not rotated, the turbo-drill may be made to alter course by setting the axis of the drill at a few degrees to the drill-pipe with an elbow joint. There is no reason why this process could not be in some way controlled from the surface, so that the drill could be virtually steered in any direction. This is a desirable feature, because sometimes it is necessary to drill holes that are deviated sideways ; for example, when producing oil from strata below a town where drilling would be inconvenient. However, it may also be the means of speeding up rate of drilling. The rate of penetration of the drill is approximately proportional to the weight which is allowed to press on the bit at the bottom of the hole ; but there is a limit to the weight because in a narrow bore-hole the weight must be distributed over a length of heavy drill-pipe. Any slight bending of the pipe causes the drill to go off course, and this effect is often accentuated by the non-uniformity of the rock strata. If the drill can be steered along the true course, then we can press harder on the drill bit while still keeping straight and thus penetrate the rock correspondingly faster.

Even if we could drill very fast indeed, we should still have to spend time every now and again pulling up all the drill-pipe to renew the drilling bit when the cutting teeth became worn, or when the roller bearings which support the toothed wheels seize up. The time taken to unscrew and stack a few miles of drill-pipe is several hours. Much engineering development has gone into improving the life of drilling bits, and a recent advance has been to construct a bit which can be folded up and pulled up the inside of the pipe on a wire, so that a replacement can be lowered to carry on drilling without any need of removing the pipe itself from the hole. It is obviously much faster to wind up a wire on a drum than to unscrew all the pipe. This device is in its infancy, and a more revolutionary approach is to speed up the actual pulling out and unscrewing of the drill-pipe by means of a double hydraulic lift. The first lift raises a length of pipe, then the second lift raises the next section while the joint is being unscrewed and the first length of pipe is being stacked away. The first lift now goes down to catch hold of a third length of pipe and so a continuous hand-over-hand process goes on. These improvements in complete automation of pipe handling will not only save time and labour on the rig, but they will also give more carefully controlled operation. Automatic drillers are in fact coming into common use, and the servo system will be even better when used with smooth hydraulic feed instead of lifting by cable. The driller's job is not made less important, however ; in fact, it is becoming more skilled and technical with each new advance. One of the problems that requires expert knowledge is the behaviour of the mud that is circulated down the drill-pipe and which flows up the space between the pipe and walls of the hole, carrying with it the fragments of rock that have been cut by the bit. These chippings must be removed, and only recently have laboratory experiments shown that very rapid removal of the chippings is important. Almost as much work must be done to grind up a chip as is required to form the chip from the parent rock in the first place. For efficient drilling, then, a chip must be removed before the next cutting tooth of the bit reaches it. Special outlets are made in modern drill bits to direct a stream of mud in the right places to do this. In order to carry the rock chippings to the surface, the mud must move at a few feet per second, and in order to minimize the pump power required the viscosity of the mud must be kept down.

However, the mud has other jobs to perform, and the final mixture is usually a compromise. In the first place, the mud must not settle out into its constituent parts if left standing, because if it did, the solid material sinking to the bottom would jam the drilling tools in the ground. A mixture of ground-up shale and water separates out into its constituent parts, but the addition of a small proportion of bentonite clay maintains the shale particles in suspension and so turns the mixture into a drilling mud.

Ideally, a thin layer of dried mud cake forms over the walls of the bore-hole, and in this way preserves the mud from contamination with any soluble compounds in the rock that is being drilled. At the same time, the mud cake on the walls of the hole gives strength to resist crumbling of soft materials such as clays and shales. The weight of the mud column itself holds back the walls of the hole from caving, in much the same way as pit-props support the roofs of coal mines. A good mud has almost jelly-like properties to stop it settling and to hold up the rock chippings when drilling stops. However, it must also be easy to pump down the drill-pipe—and so must be thixotropic.

Not only does mud help to keep the walls of the bore-hole from collapsing, but it also holds back high-pressure fluids—which may be water, oil or gas—from entering the bore and causing trouble at the surface. It is unlikely that high-pressure gas will be encountered in drilling the 10-mile deep hole to the Mohorovičić discontinuity. Borings at Bikini and Eniwetok have already demonstrated that hard basaltic rock is reached at a depth of a few thousand feet, and seismic measurements have suggested that this basaltic rock continues uniformly to the 10-mile depth of the Earth's mantle. This tough basaltic rock will not need a protecting wall of mud because it is rigid enough to stand up securely on its own. The top part of the hole, which will pass through possible loose and porous coral rock, can be walled off with a strong steel casing. The main part of the hole will, however, present new problems, and in some ways these may be more akin to those met in gold prospecting than in looking for oil. Oil is not found in hard igneous rocks, and normally these are not encountered in oil-well drilling. On the other hand, bore-holes up to 6,000 ft. in length have been drilled in order to assess the potential of gold-bearing quartz strata. It is possible that water will suffice instead of mud as our circulating fluid. Some form of circulating fluid will almost certainly be needed, because although the rock may stand up without the assistance of a hydrostatic column, some cooling and lubricating of the drill bit will be required. The temperature ten miles deep is expected to be anywhere between 400° and 700° F. The pressure of the water column will prohibit boiling down the hole, but it will be necessary to cool the water when it reaches the surface. There will be no fundamental difficulty in this ; in fact, it might be possible to circulate sea-water. The most likely site for the bore-hole in order to encounter the Mohorovičić discontinuity at as shallow a depth as possible will be on the edge of a coral atoll, so that sea-water will be one commodity in ample supply.

Rock-drilling in mining is often carried out using diamond bits, and the hard basalt that will be met in a deep bore-hole will probably best be cut in this way. With the high-speed rotation of the turbo-drill it might be possible to increase the normal rate of a few feet an hour to, say, ten feet an hour. At this rate it would take more than two hundred days drilling to penetrate 50,000 ft. of rock. The time taken to pull out and renew the drilling bit may be greater than this. At present rates, the complete in-and-out round trip would take more than 30 hr. with the hole at its deepest, but it may be possible to achieve a factor of three with the new automatic hydraulic lifts that are now being developed. The life of a bit in very hard rock may be only equivalent to 50 ft. of drilling, so that there will possibly be a thousand trips in and out of the bore-hole. Even with the fast automatic pull-out, the time taken will be at least as long as that spent drilling.

It is possible, of course, that a modern version of the old cable-tool type of percussion drilling with its rapid method of pulling the tools out on a wire rope may be more suited to the hard basalt rock. Pneumatic chippers have been very effective in the Sahara recently in drilling tough siliceous limestone.

It is not unreasonable to consider even more fanciful means of cutting rock when standard methods are only capable of penetrating a few feet an hour. One such method is that of burning a hole by means of a flame torch. This is used for the 50-ft. type of hole that is drilled for shot-firing in mining. Suggestions have also been made that hard tough rock might be successfully broken up by letting off explosive charges at the bottom of the hole. The loosened debris could be removed afterwards by conventional drilling methods. A small charge of an ounce or so should shatter about 6 in. of rock, and if a technique could be devised to fire a shot every few minutes a drilling rate of 10 ft. or so an hour could be achieved.

It is quite clear that considerable research work is needed to produce a workable method of drilling the 50,000 ft. hole down to the Mohorovičić discontinuity, but the type of research work required is, in fact, already proceeding as part of the normal progress of oil-well drilling and rock mining. For example, the correct operation of the diamond cutter has been shown to depend on careful control of mud circulation and weight, and a factor of ten in distance of rock penetrated before the bit wears out may soon be possible. After all, diamond is tougher than the rock it cuts, and theoretically need not wear at all. In the opinion of most of those engaged in the industry, the problem of drilling to the Mohorovičić discontinuity could be successfully tackled now if the money for the project is forthcoming. The most promising method seems to be a combination of diamond bit with turbo-drill and fully automatic lifting mechanism, using sea-water circulation. The research effort to make the necessary improvements in the various components of this scheme would undoubtedly be repaid by speeding up normal oil-well drilling, just as motor racing has helped to produce better vehicles for everyday use.

The second deep drilling problem—that of drilling a few thousand feet through the sediments of the ocean bed—could be solved at once by using the techniques developed for underwater rock sampling off the California coast. Since 1953 a programme of geological investigation of this territory has called for many borings five or six thousand feet deep to determine the rock structures that exist beneath the sea-bed. In order to make these borings, a new technique was designed which permitted drilling from a floating vessel.

The motion of the vessel is taken up by gimbal systems and by sliding sections in the drill-pipe, so that drilling can proceed except in very rough weather. The barge is anchored to six mooring buoys and drilling is commenced through a string of casing suspended from the ship and clear of the ocean floor. After a few hundred feet have been drilled, the casing is cemented to the sea-bed, together with an assembly of valves and with guide-wires connecting to the ship, so that when the drill-pipe is pulled out it can be run back into the hole again.

In one trial a 300-ft. hole was drilled in a depth of 600 ft. of water without the complication of guide wires and well-head assembly at the sea-bed. The hole was drilled until the drilling bit wore out ; then, since there were no guide wires it was impossible to find the hole again after pulling out to change the bit. However, it was possible to obtain samples of the rock that was drilled by cutting cores and pulling them to the surface in a cylinder lowered inside the drill-pipe on a wire line.

It is probable that this simple 'one-shot' technique would be adequate to drill through the soft sediments of the sea-bed to determine what is the underlying hard rock layer. There is very little wear on a coring bit when drilling clay, and the one bit should be able to penetrate all the soft material and at least a few feet of any hard layer. It may not be possible to anchor the drilling barge in 20,000 ft. of water, but it is possible to anchor a marker buoy, and the barge could be kept continually in position relative to the buoy with the aid of tugs. It will be most important, of course, both to choose a place where good weather is probable, and to have good weather forecasts, because the main hazard of the operation will be the possibility of losing 20,000 ft. of drill-pipe.

There is no reason why this technique of drilling in deep water should not be extended by the use of the folding up, retractable drilling bit. If the bit can be changed without pulling the pipe from the hole, there is no limit to the depth. Experience may even show that the full Californian off-shore method is practicable, using casing cemented into the rock of the sea-bed and guide wires to the surface, in which case a very interesting possibility presents itself. The Earth's mantle is only about 10,000 ft. below the floor of the ocean, and if it is possible to drill continuously in deep water the task of reaching the Mohorovičić discontinuity would be much easier than even from a coral atoll. In the first place, it is only about 30,000 ft. below sea-level in the deep oceans, and in the second, the top 20,000 ft. is water which does not have to be drilled. The technical difficulties do not appear to be insurmountable, especially if the turbo-drill rather than rotary is used. It is probably largely a matter of gaining experience with the easier project of the two discussed, and selecting a site for the experiment where there is the essential good weather and negligible currents.

HIGH-SPEED FLIGHT

At a time when the problems of the high-speed flight of aircraft, rockets and satellites are engaging the attention of scientists and engineers, it was very appropriate that Sections *A* and *G* of the British Association meeting in Glasgow on August 28 should devote one morning to lectures and discussion on this subject.

The subject was introduced by Prof. W. J. Duncan (Mechan professor of aeronautics and fluid mechanics, University of Glasgow), who underlined some of the vital principles behind these problems, showing that with the speeds that can now be attained the sharp distinction between the flight of aircraft and that of missiles has largely disappeared. The main engineering problems of high-speed flight can be grouped under four headings: (i) aerodynamic, (ii) kinetic heating, (iii) propulsion and (iv) guidance and control.

At supersonic speeds the shock-wave system around an aircraft causes an additional resistance (wave drag). One of the most important aims of the aircraft designer is to make this drag as small as possible. The problem of kinetic heating has given rise to the misnomer, 'the heat barrier'. The air in contact with the surface of the aircraft becomes heated, the effect being greatest at the most forward parts of the surface. Thus, when the speed of flight is 700 m.p.h., the temperature rise is 49° C., and this increases as the square of the speed.

The problem of propulsion depends upon the availability, or not, of atmospheric air. At extreme altitudes where the air density is very low, jet engines (for example, turbo-jets) can no longer be used and rocket propulsion has to be resorted to. Both jets and rockets have limited operational endurance (depending on the total fuel available); but whereas a turbo-jet gives a moderate thrust for a long time, a rocket gives a very large thrust for a comparatively short time.

Conventional controls are useless at altitudes where the air density is negligible. This can be overcome by using small jets to provide the moments required. The guidance of an unmanned missile may be provided by radar or by inertia navigation.

The subject was discussed in more detail in the two following lectures, the first of which, given by Mr. L. F. Nicholson (head of the Aerodynamics Department, Royal Aircraft Establishment, Farnborough), was on "Aerodynamic Aspects of High-speed Flight".

Mr. Nicholson defined the scope of the lecture as covering speeds "upwards from that of sound", the aim being to show the extent to which supersonic flight is becoming possible. For aircraft, one of the dominating factors in favour of high speed arises from the characteristics of jet engines, the thermodynamic efficiency of which increases considerably with speeds up to about five times that of sound. This increase in efficiency will be lost unless an efficient air inlet is used, which should also give low drag and avoid unstable pulsating flows; indeed, the air intake design can be one of the most exacting tasks of the design of a high-speed aircraft.

The aerodynamic efficiency was next considered. A measure of the efficiency of an aerodynamic shape for cruising flight is the ratio of the weight of the aircraft to the engine thrust required. Thus normal well-designed subsonic transport aircraft reach aerodynamic efficiencies of about 20. If such an aircraft were made to fly at supersonic speed by merely increasing the thrust, the efficiency would drop to about a tenth of its subsonic value (due to the unsuitable shape of the wings and fuselage for flight at supersonic speeds). This can be partially remedied by designing all parts of the aircraft to achieve full efficiency when operating in the flow field induced by the remaining parts of the aircraft; this has led to swept-back cambered wings and waisted fuselages. At speeds of the order of twice that of sound, a drop in aerodynamic efficiency is best avoided by using thin wing and tail surfaces and by drawing out the fuselage into a very slender shape. The wings themselves should be of large chord and of short span, with highly swept leading edges (having a plan form similar to that of a delta wing). The flow over such wings is highly complex, with separated flows springing from the leading edges at all incidences apart from that of cruising flight.

The kinetic heating problem mentioned above is mitigated to a certain extent by the effect of radiation, which increases rapidly with increase of temperature. By flying high, temperatures can be kept down to 600° C. at speeds five times that of sound.

Looking ahead to still higher speeds, a typical flight would consist of an accelerated climb (to a speed of the order of 10,000 ft. per sec.), followed by a long decelerating glide (for ranges of 2,000–3,000 miles), the aircraft being rocket powered. Sharp points and edges on the wings would have to be avoided as they would tend to become 'hot spots'. The energy of the fuel in such flights would be almost entirely used in building up the kinetic energy of the