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# GUIDED MISSILES*

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**Chairman.**—Dr. D. S. Kothari, Scientific Adviser to the Ministry of Defence.

The Chairman introduced the Speaker to the audience and requested him to give the talk on Guided Missiles.

Dr. Cawood said that it was a great privilege to talk on this subject to a Commonwealth gathering of Defence scientists. He had been in charge of research in guided missiles for the past few years and from his personal experience wanted to stress that the development of guided missiles was a very complex subject requiring lot of effort and many facilities. He stressed this point because it was so easy for the Services, when their orthodox weapons did not work, to say that they would like to have guided weapons. He thought that before giving up the orthodox weapons which after all had many years, even hundreds of years, of development behind them, one should be quite certain that one had reached the point of diminishing returns when it was not worthwhile developing the orthodox weapons any further. In the U.K. they had done a good deal of this sort of study. He thought it was worthwhile considering some of the reasons which had been sought to justify pushing aside the orthodox weapons and starting on some new weapons.

The first main reason was that as the science or art of warfare had progressed sometimes defence had beaten offence and at other times offence had taken the initiative. One thing had been happening most of the time and that was in direct warfare. Leaving out strategic long range warfare, in the direct battle, ranges had increased and so the probability of a hit had decreased. This was not because of the long range. In other words it was not because the fire control instruments had not the necessary power of resolution through all angles for long ranges. It was because during the time of flight of the missiles—the shells, the rocket, whatever it is,—the target could take avoiding action and this appeared to be the most powerful argument initially, at any rate, for the development of guided weapons. In other words, requirement was for weapons which could be controlled during the time of flight in which the error during the flight can be measured and rectified. From this point of view it was worthwhile remembering that although naval gunnery had improved in accuracy, that is in angular accuracy, several times since the days of Nelson, the actual number of hits on the targets had decreased by several times purely due to enemy movements during the time of flight of the missile.

The second reason was that it was necessary to replace the human brain or the human body because it had neither the high enough speed of reaction or because it was not, as a structure, sufficiently tough to take the necessary acceleration.

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* Based on a lecture given by Dr. W. Cawood during the CACDS Conference. The lecture was illustrated by lantern slides.

The third reason was to increase the range of strategic operations. When a long range bomber is developed it is meant to carry a crew and to have sufficient range to go over enemy territory, do their job and then return. If these bombers need not return they could be much smaller and if they have only got the one job to do, they could be much more highly stressed and could be much cheaper. That would produce a type of guided missile from which the human crew is taken out. It could be a bomber, one may call it what one likes, a large ballistic rocket like V2 or the pilotless bomber having completely automatic control which is used just to make a one-way journey. If one were ruthless enough one could still leave the crew in, and that was what the Japanese did in their aircraft, In the U.K. he felt that that could not be any part of their policy. Then one may have to reconsider if the pure economics of the expendable long-range missile showed to be better than that of the piloted missile. So these were some of the reasons one had to go through before one decided on starting guided weapons development.

Dr. Cawood gave a brief account of the different types of guided missiles which were being developed by a good many countries in the world today. The first set of guided missiles were the anti-aircraft missiles, launched either from the aeroplane towards the bomber or from the ground towards the bomber. He first dealt with the latter, those launched from the ground. When the enemy bombing aircraft was coming in one had missiles on the ground. There were a number of different ways of getting them upwards. The simplest way of doing so was by what was called the beam rider. In other words, there was a radar beam which could be locked on to the target. The missile was fired into the beam ; it stayed there, and eventually it hit the target or passed close to it This method had certain disadvantages. First of all, the beam was not parallel to the course ; it was diverging and therefore the accuracy did decrease with range. As a consequence of this, the range was limited. To overcome this, there was another type of guided missile which may, in fact, start by flying up the beam and had for external guidance towards the targets what was called the "homing head" in the front of the missile. In its nose, it had a small radar transmitter which transmitted signals along a narrow beam. They were reflected back from the target, picked up and again there was the normal closed loop, a very complicated one but nothing fundamentally difficult about it. Moreover, several loops cancel the error. The homing type of missile could either be fired directly from the ground, the homing head of the missile being locked on before it was launched or if it was desired to use it at long range, because the power in the homing head was quite small, one might decide to fire along a radar beam. (That gave a very long range with low angle.

The missile, either beam riding or homing, can also be fired from an aeroplane. There were difficult problems, in this case, because a rocket fired from an aeroplane must be fired along the line of its flight. If the aircraft was on a collision course towards the bomber it was probably not pointing at the bomber. If the bomber was coming along and the fighter aircraft was making an interception, the rocket being much faster could get there too soon and, in fact, the beam riding aero-launched guided missile must compute a part to get round into the beam and that was quite a complicated thing to accomplish. On the other hand, the homing aero-launched missile must have its radar locked on to the bomber before launching because it would be difficult to give it the necessary very sophisticated search facilities. This again meant quite complicated servo control.

The next family of longer range bombardment missiles could be divided into a number of classes. There was the V2 type or long range ballistic rockets. The V2 was not in fact a guided missile because it was not controlled during the whole of its course. An alternative to the controlled ballistic rocket was the type of an expendable bomber which he mentioned earlier. The guidance in this case could either be by means of radar over short ranges or optical with the advantage one gets with the height of the missile, or it could be by the double integration of very precise accelerometers.

There was another type of the piloted bomber and that was the controlled bomber. After the bomb was dropped it had movable controls on it and by a whole variety of ways it could be controlled down to hit the targets. He thought that that was rather important because it did appear that as the aeroplanes got faster and higher they were not very good platforms for precision bombing. Here was a perfect case of not putting commercial effort into the development of more accurate bombsights because the conditions of release were so variable and so difficult to measure precisely that it was unlikely to achieve the required accuracy. There were a good many other types of guided missiles but they were not of much importance.

Dr. Cawood next dealt with some of the technical problems which one had to look into during the development of guided missiles. First of all, there was one thing common to practically all these guided missiles and that was that it was still very important to keep the time of flight to a minimum for a whole variety of reasons and so they all had to fly at speeds above the speed of sound. In fact, they flew at speeds higher than twice the speed of sound. When this work was started in U.K. very little was known about supersonic flight and even less about controlled supersonic flights. The gunners, ballisticians, of course, knew a great deal about the effect with drag under various conditions of supersonic speed but these were not of much help because what they were concerned was, first, of having enough thrust on motors to achieve supersonic speed. That, in itself, was quite difficult, and secondly, having achieved it, to be able to control it with a great degree of precision. So the technical problems fell into three main fields ; first propulsion, second supersonic aerodynamics and third guidance.

**Propulsion**

Dealing with the problem of propulsion, he said that they found it quite difficult to achieve enough thrust to obtain supersonic speed. The ordinary aircraft engine could not give enough thrust and analysis showed that the criterion of thrust per frontal area was important. In this respect, the rocket motor had great advantage. It could give for a short time very high thrust for a very low frontal area. The rocket motor was not an air-swallowing motor but was a motor which carried its own oxygen with it. It was, therefore, a heavy motor. On the other hand, if one considered the alternatives to rocket motors such as the piston engine, jet engines, and so on they were much heavier in themselves so that by doing performance runs it was found that up to certain distances rockets did give a great advantage. But those distances were dependent upon a whole variety of things. If one were considering heights up to say fifty or sixty thousand feet then the rockets would make in fact the lightest motor up to slant ranges of something of the order of twenty thousand yards or so. If longer-distances than that were desired, the ram-jet engine would be lighter. Rocket motors are of two main types, those which use liquid fuels and oxygen and those which use solid charge such as the cordite. The general characteristics of these had to be investigated in the development of design of the rocket motors. The performance index of a rocket motor was usually given as the thrust divided by the fuel consumption and that was called the specific impulse and that was the general performance index of motor ; it was also equal to the velocity of the exhaust gases divided by heat. This was really important for rockets—it is proportional to the square root of the temperature of combustion divided by the average molecular weights of the gases in the exhaust stream. The term which was rather important was the expansion ratio—the ratio of the pressure of exhaust venturi which, of course, was generally practically atmospheric, to the pressure in the combustion chamber. If one just examined the variation of these terms, first of all there was the need to keep the molecular weight of the exhaust gases as low as possible. Theoretically, of course, the ideal rocket, one would imagine, would be of liquid hydrogen, liquid oxygen ; rockets had been built like that. They had one disadvantage because of the rather high volume of the fuel and oxygen. It is also seen that the higher the temperature the better. On plotting the temperature of combustion against the mixed ratio, that is fuel and oxygen it is found that in fact as the percentage of fuel is varied the temperature rose and then fell and there was a point where the stoichiometric ratio was ideal and that, in fact, was therefore the theoretical point to work at. In practice, this temperature may be found to be too high but it was worthwhile just to see what happened if the temperature of combustion divided by molecular weight were plotted against fuel. That showed that the engineering of the rocket motor was limited by temperature and it paid to lose on temperature, on the fuel rich side.

Regarding the other characteristics, on plotting expansion ratio against specific impulse it was found that the curve flattened at round about 500 lbs./sq. in. ; and it was quite steep upto 300 and then began to flatten. So it was clear that from an engineering point of view there was very little to be gained by going to very high combustion chamber pressures and it was normal to work at something below 500. On the other hand, if the pressure fell below 300 lbs./sq. in. then there was quite a serious loss in efficiency. That showed one of the weaknesses of the rocket motor. It was not flexible. In other words, the thrust could not be increased a great deal without the efficiency falling. This was more severe in this respect than either in jet engine or the internal combustion engine. These were the parameters which had to be investigated in the development of other liquid rockets or the solid rockets. A typical liquid rocket motor was one very much like the V2 motor in which the combustion chamber was regeneratively cooled by putting one of the liquids round a hollow jacket. The two liquids which might be, for instance, hydrogen-peroxide and kerosene or nitric acid and kerosene, alcohol and liquid oxygen and so on meet in a spray ; there might be a swell type of spray or impinging jets. By some means they are ignited. There were of course, combinations, which ignite spontaneously but they tended to be dangerous for service use so that usually other means such as pyro-technique igniters or even spark plugs were fitted to start the rocket motors. The fuel flows were very high and there were two ways of getting the fuels and the oxygen (both liquids) into the jets. One was to pressurise the tanks, the other was to have some form of fuel pump which again depended on the range. For short ranges pressurised tanks were the lightest ; for longer ranges it paid to go to the fuel pump.

The main point about solid rockets was that combustion took place on the surface of the solid so that its characteristics could be altered by altering the rate of alteration of the surface during burning. What was normally liked in rocket motors was a fairly rapid rise of thrust which later flattens and that meant that the surface should be pretty well constant. That type of characteristic could be obtained, for instance, in the cordite motor by having a star-shaped or cylindrical grain so that the burning area remained sensibly constant. There were other ways of doing it for much lower rates of burning. One could have motors burning like a cigarette end but that could not normally give the rate of thrust required for the higher performance by the missiles.

The third type of propulsion system was the ram-jet and that was possibly one of the simplest motors in conception and in Dr. Cawood's experience was very difficult to develop. It had been referred to as the flying drain pipe and in conception it was nothing more than that. The general idea was that if the flying was fast enough then the dynamic head or pitot pressure was sufficiently great to give an efficient heat engine. In the normal jet engine the flying was not fast enough and, therefore, compressors were used to compress the air. The compressor is driven by taking a certain amount of energy of the jet. In the case of the ram-jet compression was got through the shock wave at the front end of the motor. The air was slowed down ; the kinetic energy was turned into pressure ; paraffin was fed in and the whole arrangement then worked exactly like the normal jet engine. The biggest difficulty in the development was the stabilisation of the flame front. There was a great tendency for it to be blown straight out. It was more difficult than the jet engine in this respect because there was only one combustion chamber. One could not afford to lose the efficiency of that dynamic compression by splitting up into a lot of small ones as a jet engine designer can afford to do so. So that was one of the big technical problems, to stabilise flame front so that it was not blown out. In order to do that unfortunately one could not afford to build those things and just fire them into the air; that would be a waste. One had, in fact, to test them statically and it did mean large machines and large pumps in order to supply the tremendous quantities of air required.

In U.K. they use in this type of work anything upto ten to fifteen thousand horsepower merely for supplying the air. One of the disadvantages of the ram-jet as compared with the rocket or the normal jet engine was that it had no static thrust. It had to be boosted up for speed something of the order of speed of sound and preferably a good deal more before the compression process really became efficient and before it produced enough thrust to beat its drag normally required to get acceleration.

In all these missiles driven by rocket motor of ram-jet type one had to get the final answer—efficiency. It paid to use propulsion in stages; normally solid rockets were used for boosting all these rockets, from the ground or from the launches. In the case of ram jet it was, of course, essential to have the boost but in the case of others it was done in order to increase the overall efficiency.

**Supersonic aerodynamics**

As was stated earlier, very little was known about supersonic aerodynamics in the beginning and they had to investigate such things as the variation of lift and drag with Mach number as they knew that the classical linear theories were not sufficiently accurate to enable them to start engineering developments. They had, in fact, to begin investigations by a few flight tests in the very early days. They had small and simple models which were pushed up to supersonic speeds and took measurements and generally got together quite a background of data on supersonic aerodynamics. One of the early difficulties they ran into was the violent change of the centre of pressure with Mach number, specially in transonic region—that was where the velocity of the missile was round about that of the local speed of the sound. The various configurations that one could see in guided missiles, the dart-like fins and so on had generally been arrived at by the various devices necessary to defeat that change of centre of pressure and produce a missile which could be controlled quite stably over a range of Mach numbers. Dr. Cawood thought that they in the field of guided weapons had beaten the orthodox aerodynamicists who were running into quite severe troubles in the transonic region, *i.e.*, Mach number equal to unity. He thought that the best aeroplanes of the day were not much over .9 but some of their test vehicles (as they called them) were not guided weapons at that stage. Some of their test vehicles had flown stably up in the Mach number range of about 2.8 right down to .6 when, of course, they slowed down and finally fell out of the sky. They were decelerated quite slowly right through the speed of sound with no kick at all. Dr. Cawood said that they did not believe in the sound barrier as such.

In order to investigate those things they started by field flight tests. Those tests were extremely expensive and very wasteful and the commonsense way of doing that was by building supersonic wind tunnels. Unfortunately they took a long time to build and were very expensive. Once they were built one could get the money back tenfold. There were quite a lot of supersonic tunnels operating throughout the world, in the U.K., America and so on. They were, of course, extremely expensive in horsepower, in electric power and for instance quite small tunnels with a working section of 2 ft. × 1 ft. running at Mach numbers 2.5 would consume 8000 H.P. As a comparison if one considered the normal high-speed wind tunnel used in the development of aircraft, for four to five thousand horsepower one could get a working section 11 ft. × 11 ft. That meant that one was restricted in what one could do in supersonic tunnels until a really big one was built. For instance, the control surfaces for working sections of only a foot across were extremely small in size and it might not be possible to make them of rigid enough metals so that although certain data could be obtained on such tunnels, there were other tests some of which could be better performed by free flight models.

Another research tool required in this work was the electronic simulator of the analogue type. But since the linear theory of supersonic aerodynamics was not good enough for that type of work they had, in fact, built quite a number of simulators either for tackling problems of control at supersonic speed in two dimensions, or more complicated ones in three dimensions. Even though they had not a reasonable non-linear theory what they had was extremely useful in this respect. By making models on a 1 to 1 time scale one could, in fact, take the servo motor from as it were inside the equipment as it formed part of the guided missiles and connect them up to the simulator. The simulator providing the aerodynamics which had been originally measured in free flight trials and in wind tunnel trials finally got a simulated trajectory on the ground. This was an extremely useful research tool because it meant that one could get all the characteristics of the different servo motors and so correct them before the expensive firing of the final guided missiles.

## Guidance

The main problems here were what frequency to use, what power to use for a certain range and so on. Dr. Cawood thought that the guidance side was the easiest side of this work because they had so much knowledge about radar during the war. Nevertheless the pushing of these missiles along at supersonic speeds required a lot of power and, therefore, the frontal area must be kept down. Usually with homing head missiles with transmitting and receiving aerials a radar dish was the limiting size in the total frontal area. It was not possible to get exactly the optimum value of that, as between the performance of the missile as a little aeroplane and the range of the homing head as the radar set. Other problems were of security, making circuits against counter-measures and so on.

Dr. Cawood next dealt with the ancillary effort which had to be put in; one could not fire these things during the early development stages or during any time for that matter. Anyway, a well-instrumented and very large range was necessary and he did not think that the instrumentation on the range itself was a peculiarly different one from that required in the normal ballistics range. In general, the precision that the gunner wanted was not required. What they were interested in was the measurements they could get from inside that little flying machine; they wanted to know accelerations, decelerations, pressures in the fuel tanks, the temperatures of the motors running and that type of data. Very few guided missiles had a system of instrumentation called Telemetry in which there was a small transmitting station inside the missile which transmitted various parameters down to a receiving and recording station on the ground. Quite a variety of parameters had to be measured and the type of sets could either be a continuous wave transmitter with a number of subcarriers or a pulse method, what was called the stagger pulse method of telemetry where the actual position of the pulse was received to a datum and gave a measurement of the parameters. On the range there must be some means of reducing the data quickly. Nothing was more infuriating than firing some of those expensive missiles and not getting the results back for two or three weeks. They had developed a good many automatic machines for this purpose. Brigadier Hinds would be discussing some types of such machines later on in the conference.

The guided missiles were very elegant from the tactical point of view. They had their dangers and the danger was their complete and complicated automaticity which led to very complex weapons. That again led to very large production lines and they knew that very large and complicated lines were very inflexible. There was, therefore, always a very great danger in going into the system of guided missiles. During the first few hours of a war one may find that the enemy was just a bit cleverer and that he could countermeasure the whole system. That may happen during the course of the fighting. That would be extremely serious, but even then usually nothing can be done for five or six months. At the present moment he could say that making major changes in guided missiles might even take a longer period. So he thought that all the research workers in this field were for simplifying the system rather than complicating it, developing it in such a way that one can change rapidly and so on. The lecturer concluded on the note on which he had started that he would ask the military friends to think hard before they said orthodox weapons would not do and they required guided missiles.

Dr. Cawood then showed a film on guided missiles.

The chairman thanked the lecturer for the very interesting lecture.