The Mechanism of the German Rocket Bomb ("V2")

Informal Discussion on Friday, 12th October 1945, introduced by W. G. A. Perring*

Rockets have attracted the attention of man for a very long time, and the history of rocket development goes back for some 3,000 years. Rockets were well known to the ancients, and were used by the Chinese and others. Rockets were also used as a weapon, a piece of artillery, by this country as long ago as the end of the eighteenth century and the beginning of the nineteenth.

In Germany, modern rocket development started seriously round about 1929, and experiments were begun by a group of private individuals interested in the subject. About 1933 the work attracted the attention of the Weapons Department of the German Government, and was virtually taken over by them. In 1937, there was set up at Peenemunde a rocket experimental establishment, at a cost something of the order of 300,000,000 marks; and the work which was previously carried out in Berlin was transferred there. It was there that the "A4" rocket —the "V2", as we know it—was developed.

The A4 was not the first of the Germans' rocket developments; they worked on other schemes of a preliminary kind. The A1, for example, was quite a small rocket which, as far as was known, was never fired; the A2 was a rocket weighing about 600 lb., which was fired quite successfully and reached a height of about 6,000 feet. Work on the A2 rocket began to show the possibilities of further rocket development.

The A4 (or V2) rocket was begun about 1939–40, and the first successful launching was in October 1942. The first A4 rocket the Germans attempted to launch exploded on the ground and blew up the experimental unit concerned; the second went up a few feet and did the same; the third rose some 15,000 feet, and exploded in the air; but the fourth flew about 170 km. and demonstrated the possibilities of long-range rockets. The German authorities, on the strength of this successful shot, started at the end of 1942 the production of the A4—the V2—as a serious weapon.

Fig. 1, Plate 1, gives a general view of the V2 rocket; it is roughly 14 metres long (about 46 feet). The diameter of the body is about 5 ft. 6 in., and the diameter over the stabilizing fins at the rear end is 11 ft. 8 in. It has an initial weight, at launch, of 12·5 tons, of which more than two-thirds is fuel, and it carries a warhead of nearly a ton.

Fig. 2, Plate 1, shows how the interior of the rocket is subdivided. At the front end is a conical-shaped warhead, and immediately behind the warhead is a compartment containing the main control instruments and the radio equipment. Next come, in the centre portion, the two large fuel tanks, then a motor compartment, and finally the combustion chamber and Venturi tube.

The warhead occupies roughly the first 5 ft. 11 in. of the weapon. It is conical in shape, made of mild steel about ¼ inch thick, and is filled with Amatol. The total weight of the warhead and its case is roughly 2,150 lb.

Immediately behind the warhead is a compartment subdivided by partitioning into four quadrants (Fig. 3, Plate 1), housing the automatic pilot and control gear. It will be noticed

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that the outside skin of the rocket in the vicinity of the instrument compartment is formed in such a way that the instruments can be readily serviced; and since they had to be serviced almost up to the last minute, accessibility was important.

Behind the instrument bay are the fuel tanks (Fig. 4, Plate 2). There are two tanks, each of about 150 cu. ft. capacity; the one at the front end contains alcohol, to which a certain amount of water was added, and the second tank, at the rear, contains the liquid oxygen. This compartment forms the main central compartment and is about 20 feet in length.

Towards the rear of the rocket are the pumps which provided the means of driving the fuel into the combustion chamber, and finally there is the combustion chamber itself and the exit Venturi. Fig. 5, Plate 2, gives a general view of these components.

Around the Venturi are the stabilizing fins (Fig. 6, Plate 2). The four pad pieces carry the internal controllers, which were used for stabilizing the rocket in its flight and for controlling it during flight. In addition there are four small external controllers, one on each of the stabilizing fins.

In general, most of the structure of the rocket was built rather on the lines of aircraft construction, with stringers and formers which can be seen in Fig. 7, Plate 2. The skin itself was of mild steel, about 0·025 inch thick, and the strength throughout the rocket was proportioned by spacing and varying the thickness of the stringers supporting the skin. The main thrust of the rocket, which of course was developed in the combustion chamber, was taken back to the structure through a very heavy steel tubular framework which surrounded the motor compartment, and which also provided the general supporting structure for the turbine and pumps. At the end of the motor bay, at the ends of the fuel tanks, and at the end of the

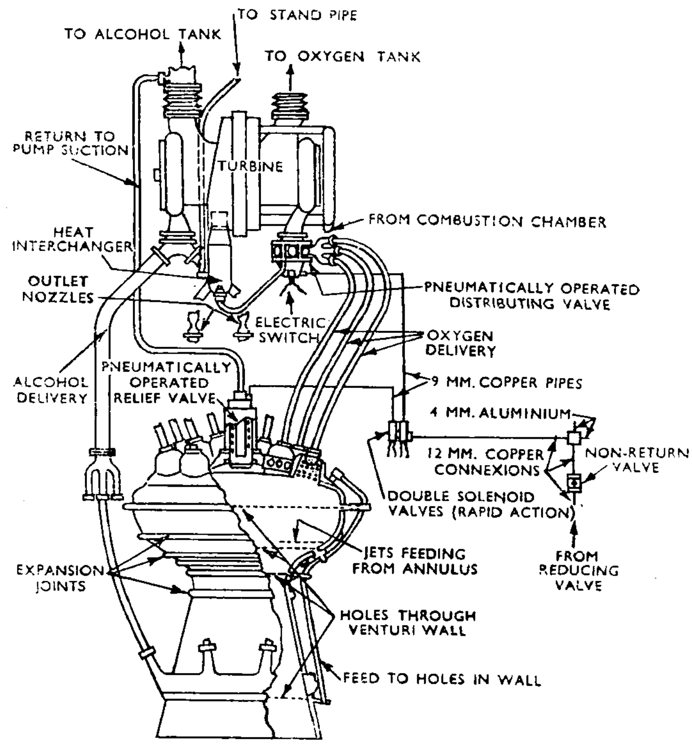

Fig. 8. Diagrammatic Arrangement of Pumps and Burners

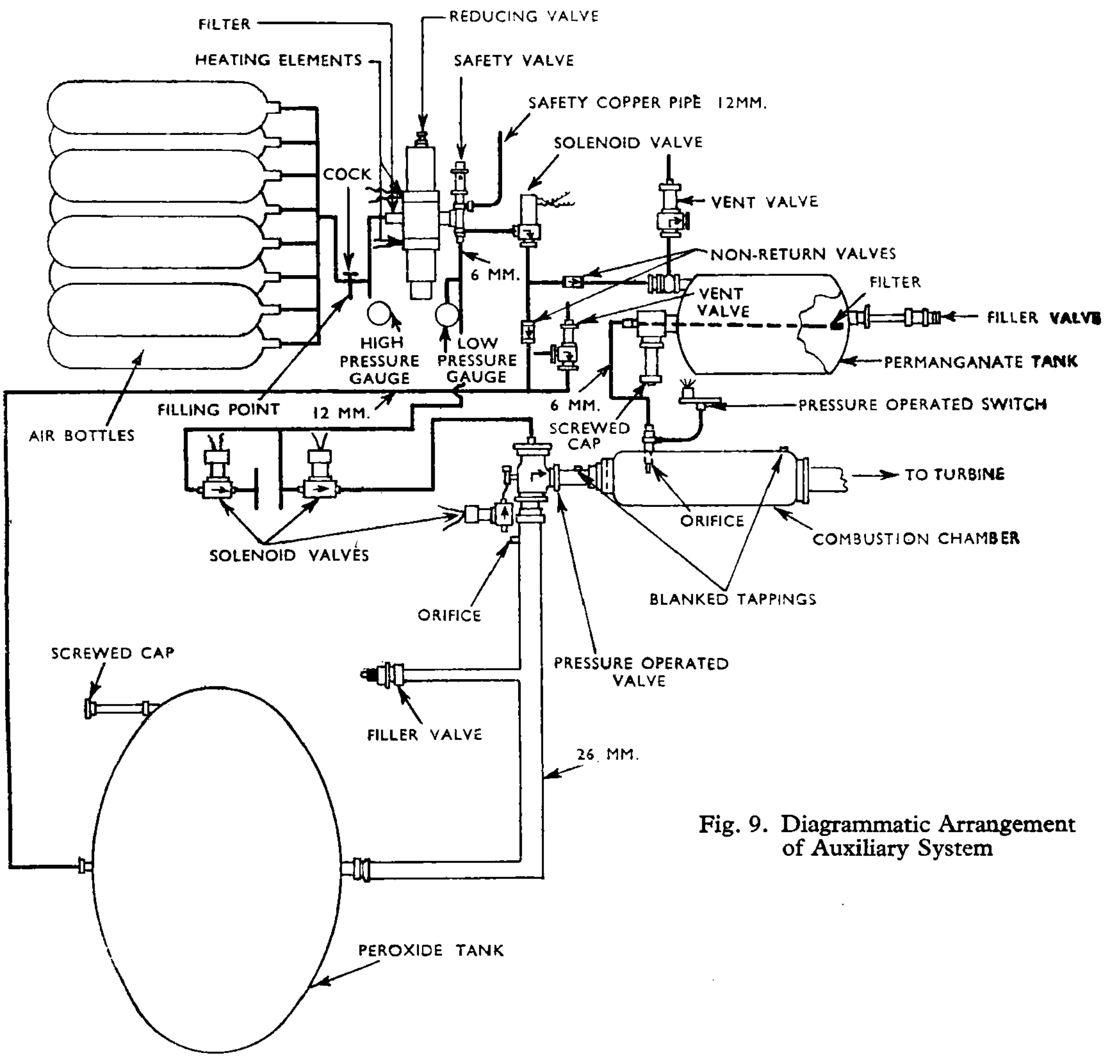

Fig. 9. Diagrammatic Arrangement of Auxiliary System

instrument compartment, very heavy angle-frames were provided, which served as transport joints and allowed the rocket to be divided into convenient short lengths for transport and handling during assembly.

Fig. 8 shows diagrammatically the rear end of the rocket with the combustion chamber and Venturi and part of the pumping system. The auxiliary power unit comprises a steam turbine, driving two centrifugal pumps. The pumps draw the fuel from the tanks and convey it to the combustion chamber, through a distributing system. The alcohol acts not only as the fuel but also as a coolant, and is led from the pump to an annulus at the rear of the Venturi; it then feeds back through the Venturi-skin, which is double, to a distribution valve, and then outwards to the mixing cups. The oxygen is fed down by another system of pipes to the eighteen mixing cups, and is then sprayed through a brass rose located centrally in them.

The method of delivering the fuel and driving the pumps is quite interesting (Fig. 9). The generating plant which provides the gases to drive the turbine—and therefore the pumps—comprises a container of hydrogen peroxide, and a container of permanganate. These fuels are driven under pressure supplied by nitrogen bottles, into a mixing chamber, where a mixture, mainly steam, is produced at 420 deg. C. (788 deg. F.) and 350 lb. per sq. in. pressure. The steam is then fed to the turbine —a simple single-wheel arrangement, having partial admission, which develops about 500–600 h.p. at 5,000 r.p.m.

Fig. 10, Plate 2, shows the actual turbine wheel. The gases are led into the turbine through a distributing ring through the four sets of nozzles shown. In Fig. 11, Plate 3, are shown the turbine (in the middle) and the pumps, arranged one on each side.

One of the pumps is shown in Fig. 12, Plate 3, with one of the distributors, whilst Fig. 13, Plate 3, is a view of an alcohol pump and its casing. Fig. 14, Plate 3, shows the two pump rotors. It will be noted that the rotors are different in diameter. This is to take account of the difference in density between the alcohol and the liquid oxygen, and is arranged so as to provide that both fuels are fed to the combustion chamber at roughly the same pressure.

Fig. 15, Plate 4, is a general view of the Venturi. It is interesting, because this particular Venturi came to us by accident. It was part of an experimental rocket that got off its true course; it burst in the air, not over this country, though parts of it came into our hands well before any rocket was fired against this country. The experimental rocket had all the features that the later rockets showed, though there were differences of detail. In the Venturi, for example, the end plate which carries the combustion cups, was bolted on to the rest of the Venturi, and was made of light alloy; it was a light alloy casting, whereas in later rockets this end plate was of ordinary mild steel plate and the Venturi was of all-welded construction.

Some of the features regarding the cooling can also be seen. The cooling, as already mentioned, was effected by feeding alcohol to the distributing ring and then back along a cooling jacket to a valve at the centre of the combustion face. The cooling provided in this way was augmented by internal cooling. Alcohol was taken from the jacket of the combustion face, fed by small pipes, some of which can be seen in Fig. 15, to a series of radial holes spaced out at points along the Venturi of the rocket. The alcohol led to various points on the inside face of the Venturi, thus providing a film of evaporating alcohol on the inside, which, together with the jacket-cooling, kept this general temperature of the skin within reasonable limits.

Fig. 16, Plate 4, illustrates the eighteen burner cups; the white pipe connexions are the feeds for the oxygen. The centre port houses the valve by means of which the alcohol is controlled and distributed to the eighteen cups.

A further view of the Venturi is given in Fig. 17, Plate 4; this time the end plate is taken off, so that the inside of the cups can be seen. The alcohol discharges through about a dozen brass nozzles arranged circumferentially round each cup, and mixes with the oxygen fuel which is sprayed in through the rose fitting in the base of the cup.

Coming to the combustion chamber and the Venturi, Fig. 18 shows the conditions diagrammatically, together with a throat and an exit. Those familiar with thermodynamics will at once appreciate that at the throat the velocity will correspond to the local speed of sound. The gases are passed through the throat at the local speed of sound and are expanded and become supersonic at the exit, where the static pressure conditions in the jet establish themselves as approximately atmospheric. Since the volume of gas passing any point is known, and the velocity, density, and pressures can be related by the adiabatic and Bernoulli laws, it is possible to establish the relationship

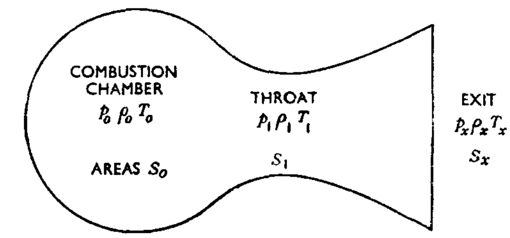

Fig. 18. Approximate Conditions in Venturi

	Combustion chamber	Throat	Exit
Diameter, feet . . .	3·11	1·32	2·41
Pressure, lb. per sq. in. abs.	294	157	14·7
Temperature, deg. C. abs. .	3,000	2,670	1,650
Temperature, deg. F. abs (approx.)	5,430	4,840	3,000
Velocity, ft. per sec. . .	0	2,000	7,000

between the pressure in the combustion chamber and pressure at every other point throughout the system. Similar relationships can also be calculated for temperature and density.

These calculations have been made for an ideal Venturi and the results are shown in Fig. 19. Curve I shows the ratio of the pressure in the combustion chamber to the pressure of exit, and curve II the temperature relationships between those two parts of the rocket. In the case of the V2 rocket the dimensions are such that the area ratio, between the exit and the throat is roughly 3·4/1, and therefore from the curve it will be seen that the pressure in the combustion chamber and the exit must be

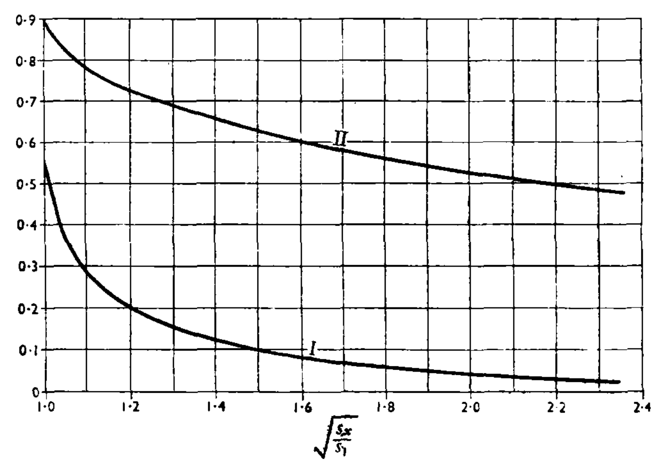

Fig. 19. Performance Characteristics of Venturi

The performance curves relate to a thermodynamically ideal Venturi when $\gamma = 1{\cdot}25$.
The abscissae show the ratio of diameter to throat diameter.

roughly in the ratio of 20/1. In the case of a rocket operating at ground level, therefore, where the exit pressures are roughly 14–15 lb. per sq. in., the pressure in the combustion chamber must be of the order of 300 lb. per sq. in. It is necessary, therefore, to feed the fuel into the combustion chamber at this pressure; and the rate at which fuel is fed in must be such that, on combustion, the products of combustion maintain this pressure.

The fuel pumps not only have to provide the 300 lb. per sq. in. pressure corresponding to the pressure of the combustion chamber, but also the pressure losses through the nozzles and the pipe system leading from the pumps. The pumps do in fact provide a sufficient fuel flow at about 350 lb. per sq. in. pressure, the amount of fuel to maintain correct conditions in the combustion chamber corresponding to a fuel delivery rate of 275 lb. per sec.

The high fuel rate introduces some interesting problems. At this rate of consumption, the fuel in the two main tanks is exhausted in a little over 1 minute; but since it is very desirable that the tanks should not collapse, provision has to be made to maintain the tanks under pressure during the combustion stage. In the case of the alcohol tank this is done by leading a pipe forward through the warhead to a point near the nose, and making use of the "ram" effects resulting from the high forward speed, which are produced at the entrance to this pipe. The ram effect "pressurizes" the alcohol tank, and provides a head which assists the pumps, and at the same time prevents the tank from collapsing. The ram pressure, however, falls off as the rocket ascends into the very rare atmosphere, and so at some height the pipe is closed, and the tank is pressurized by nitrogen supplied from three high-pressure bottles housed in the instrument bay.

The oxygen tank is treated rather differently. Because of the risk of explosion, it was considered undesirable to introduce foreign matter into the oxygen tank. The pressurizing of the oxygen tank, therefore, was achieved by fitting a relief valve and allowing the rate of evaporation to build up a pressure in the tank. During the burning stage, however, this rate of evaporation was not enough, and it was increased by passing some of the liquid oxygen through a heat exchanger located in the exhaust of the turbine, oxygen from the heat exchanger being fed back again into the oxygen tank to maintain the desired pressure.

Returning now to Fig. 18, the table of figures shows roughly the working conditions of the rocket. The pressure in the combustion chamber corresponding to 15 lb. per sq. in. pressure at exit is 300 lb. per sq. in., and the pressure in the throat is about 150 lb. per sq. in. The temperature of the gases in the combustion chamber is about 3,000 deg. C. abs. (about 5,430 deg. F.) and this drops to about 1,650 deg. C. abs. (about 3,000 deg. F.) at the exit. The velocity which, of course, is initially zero in the combustion chamber, rises steadily, and at the throat is 2,000 ft. per sec., and at exit reaches about 7,000 ft. per sec.

Despite the very high temperatures in the combustion chamber, it was interesting to find that the Germans were able to use mild steel. The worst conditions might be expected near the throat area. A careful examination was made of a number of Venturi tubes, and from this evidence it was found that the skin temperature was never more than about 950 deg. C. (about 1,740 deg. F.), nor were any signs of distress found; the cooling, therefore, did its job excellently. The only sign of trouble which was noticed concerned expansion troubles. As more rockets fell into our hands modifications in details were observed, such as the introduction of loops in pipes and connexions to avoid these serious differential expansion troubles. In the early rocket special care had always been paid to expansion problems.

The rocket was stabilized by the four very large fins, and it was indicated in passing that controllers were provided to maintain the rocket on its path and keep it steady on that path. Fig. 20, Plate 4, shows one of the four graphite controllers located in the exit jet, on which the high-temperature high-velocity gases of the jet impinge. These controllers provide a very powerful control on the rocket motion.

Fig. 21 gives further details of the controllers. Pairs of internal and external controllers were coupled together to provide stabilization in roll, and maintain direction. These controllers prevented the rocket, once discharged, from rolling around its axis, and at the same time they provided a directional control of azimuth, so that once the rocket was pointed to the target it would maintain direction. The pitch control (or, in aeronautical language the elevator control) is provided by the other pairs of controllers, which are used to steer the rocket from the vertical position in which it is fired, on to a path in which the rocket axis is at approximately 45 deg. to the horizontal, corresponding approximately to the angle for maximum range.

It has always been a little puzzling why the Germans bothered to fit the external controllers. At take-off, the velocity over the external controllers is zero; the control provided by them is therefore zero. As soon as the turbine runs up to speed and the main flow of gases starts, the internal controller becomes very powerful, so the internal controllers in fact provide the main control and the external controllers exert a negligible

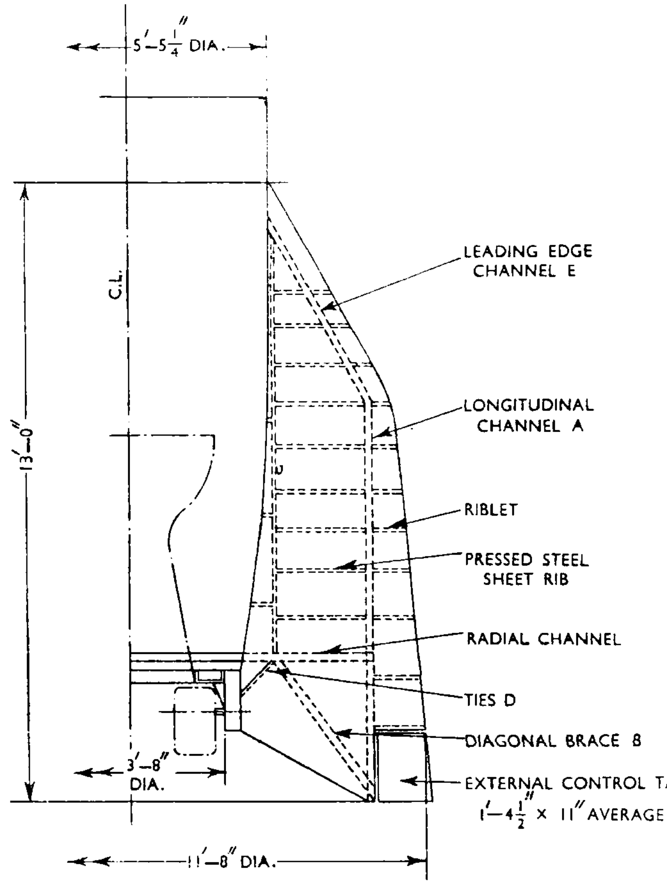

Fig. 21. Diagrammatic Layout of Stabilizing Fin and Controllers

influence. Near the end of the "all-burnt" stage, when the rocket has reached a height of 22 miles, the density of the air through which the rocket is passing is so low that again the external controller provides almost no force. At no time, in fact, during the motion are the internal controllers inadequate; it is therefore difficult to see why the Germans went to the extra complication of providing both internal and external controllers, seeing that the internal controller can provide all the control that is necessary.

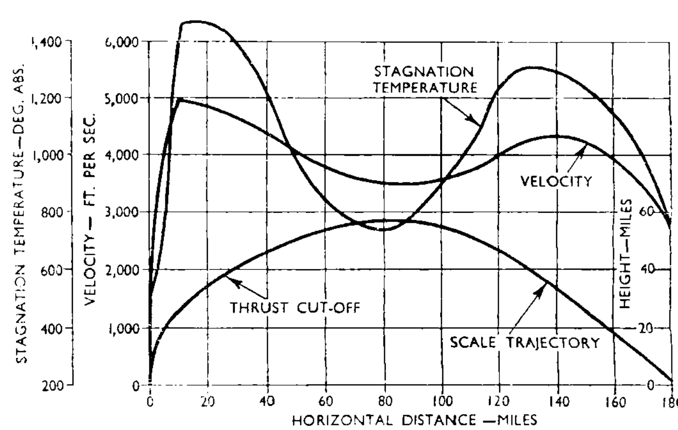

Fig. 22. Typical Trajectory

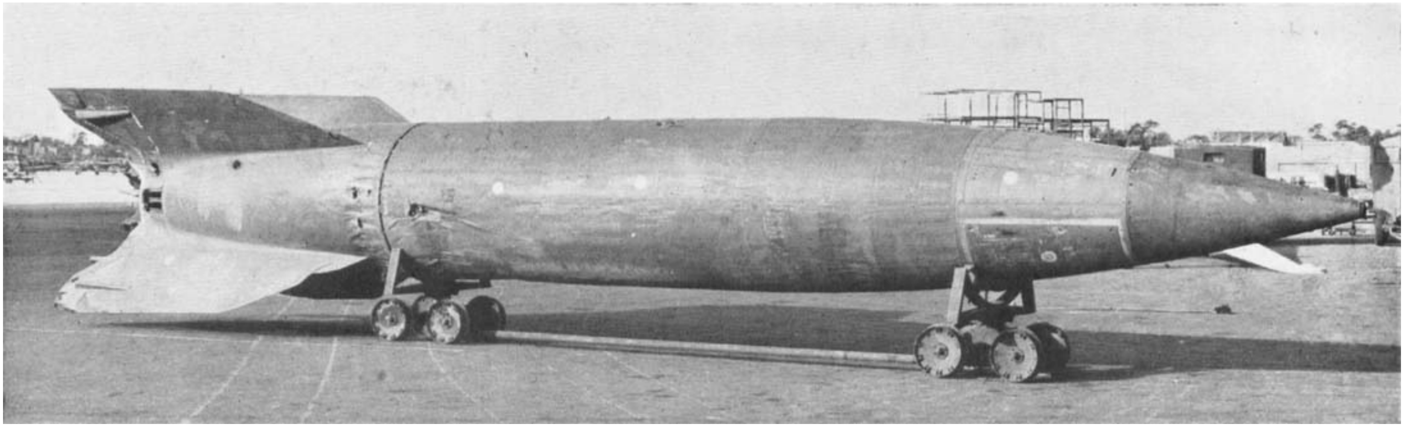

Fig. 1. The German "A4" (V2) Long-Range Rocket

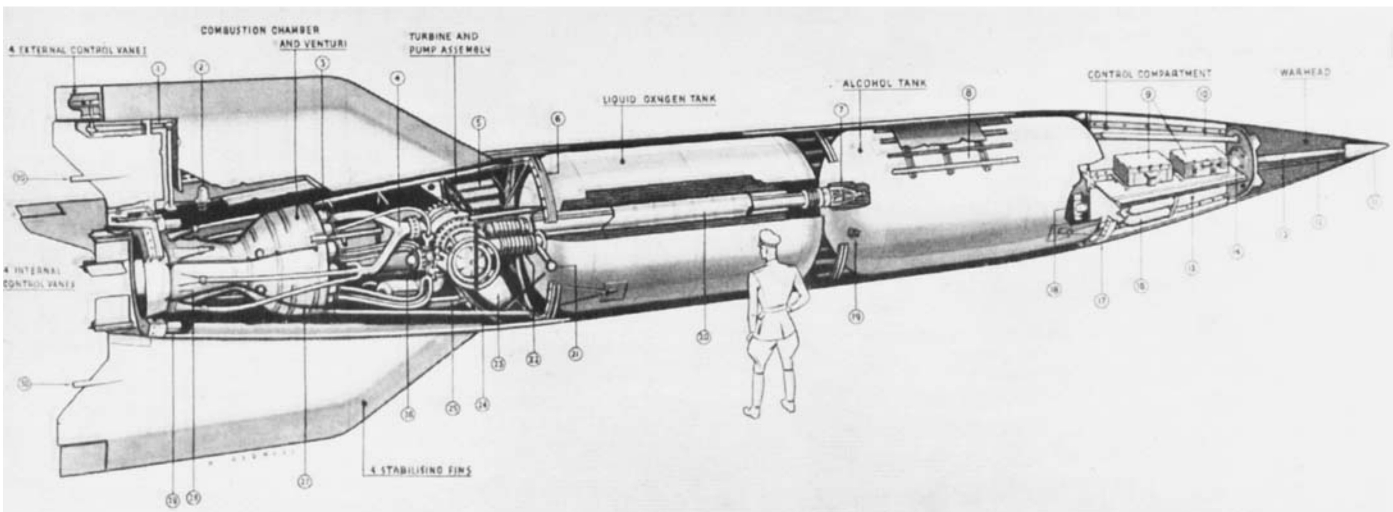

Fig. 2. Arrangement of Interior of Rocket

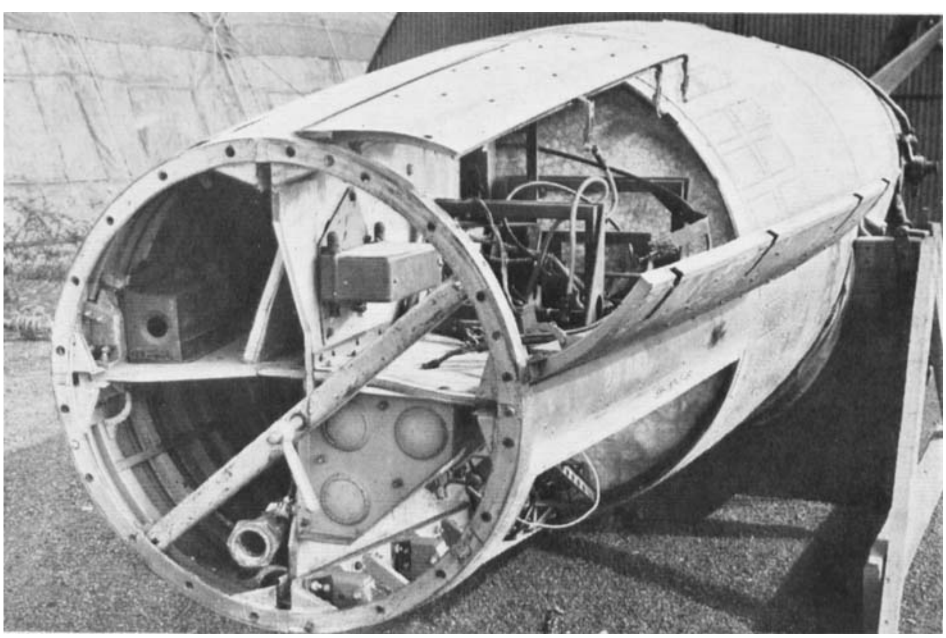

Fig. 3. Radio and Instrument Bay

[I.Mech.E., 1946]

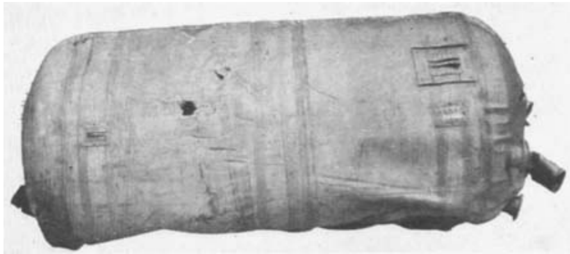

Fig. 4. Oxygen Fuel Tank

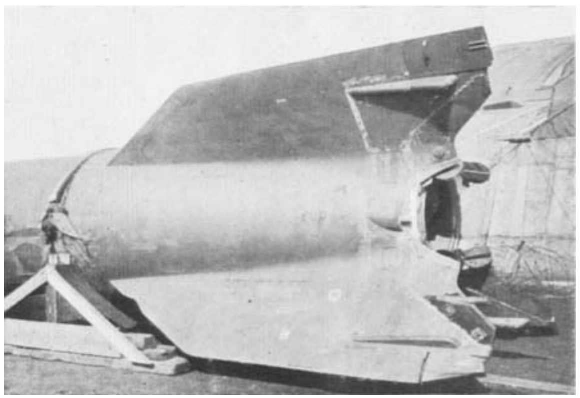

Fig. 6. Stabilizing Fins

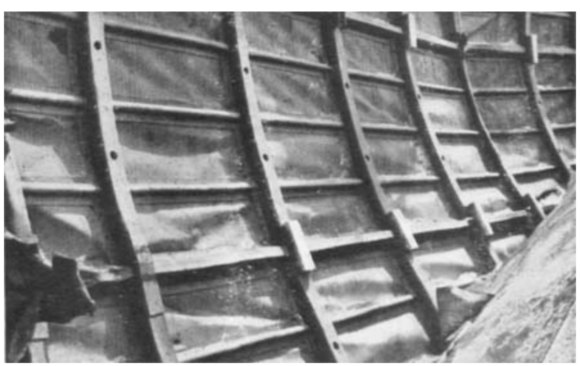

Fig. 7. Structure in Neighbourhood of Fuel Tanks

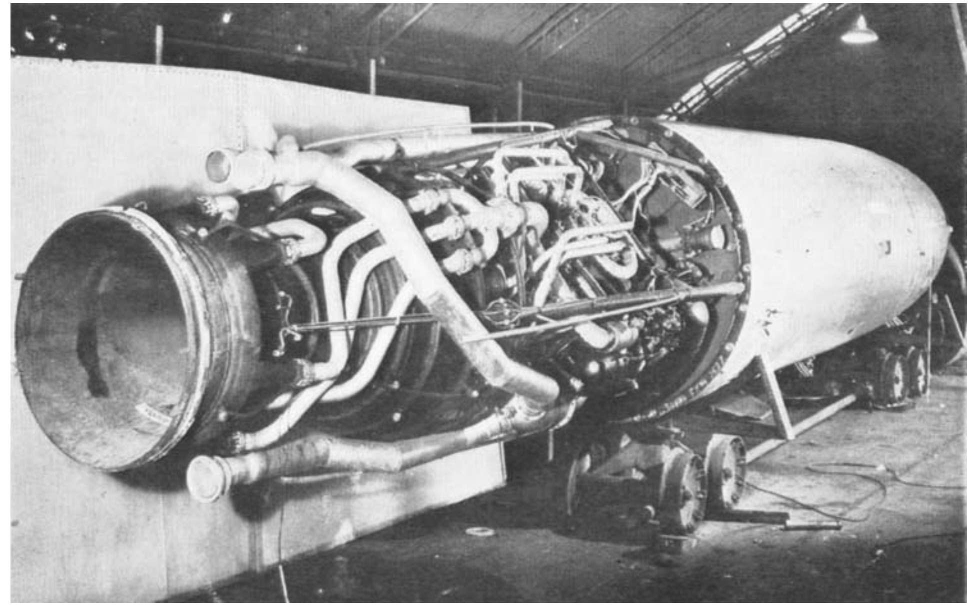

Fig. 5. Motor Compartment and Venturi

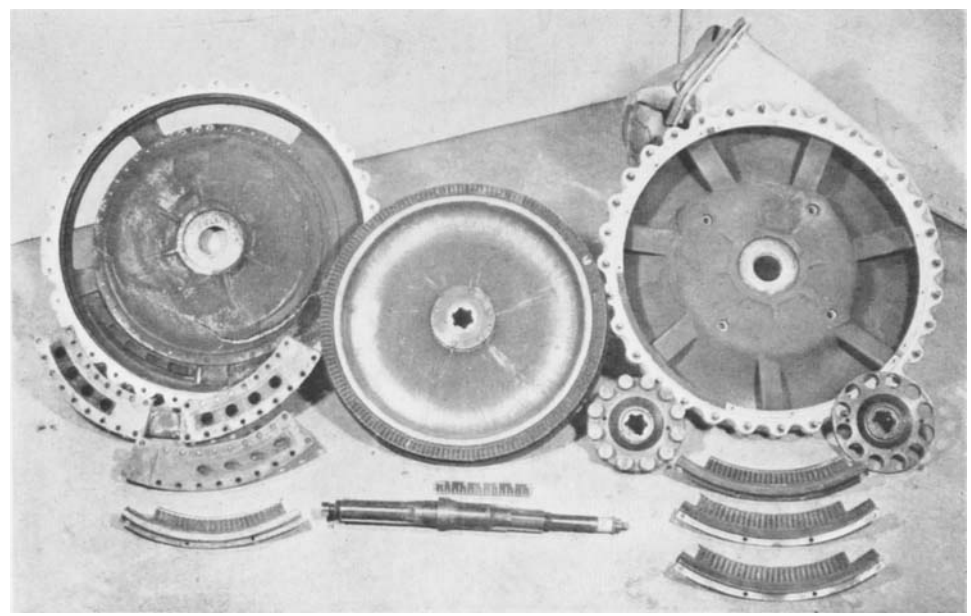

Fig. 10. Turbine Components (dismantled)

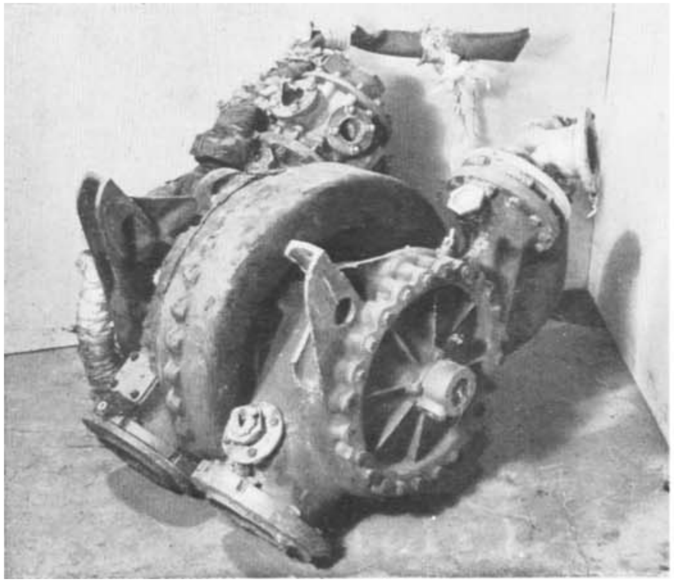

Fig. 11. Turbine and Pumps

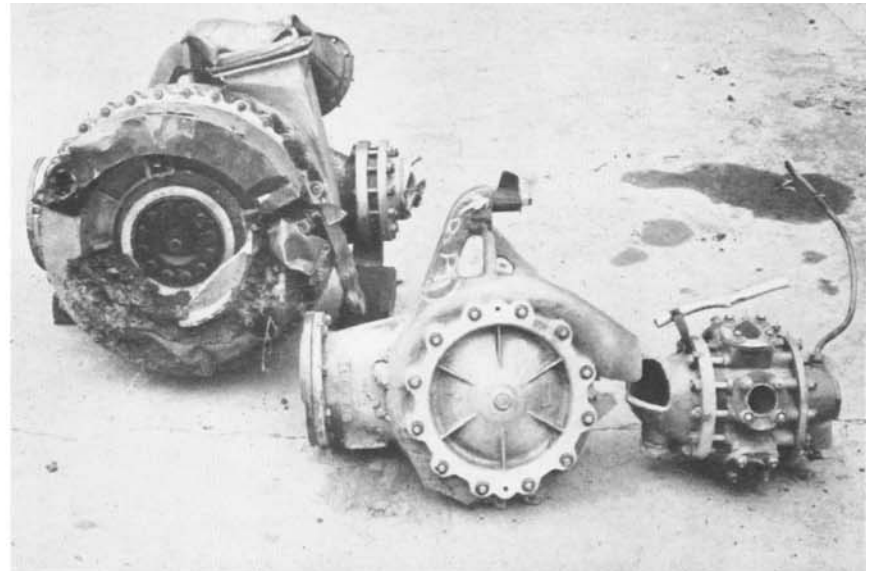

Fig. 12. Fuel Pumps

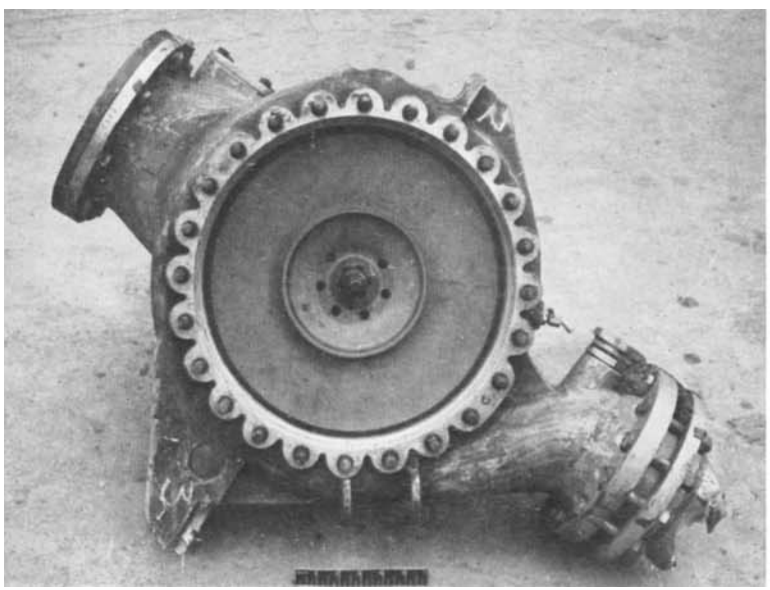

Fig. 13. Alcohol Pump and Casing

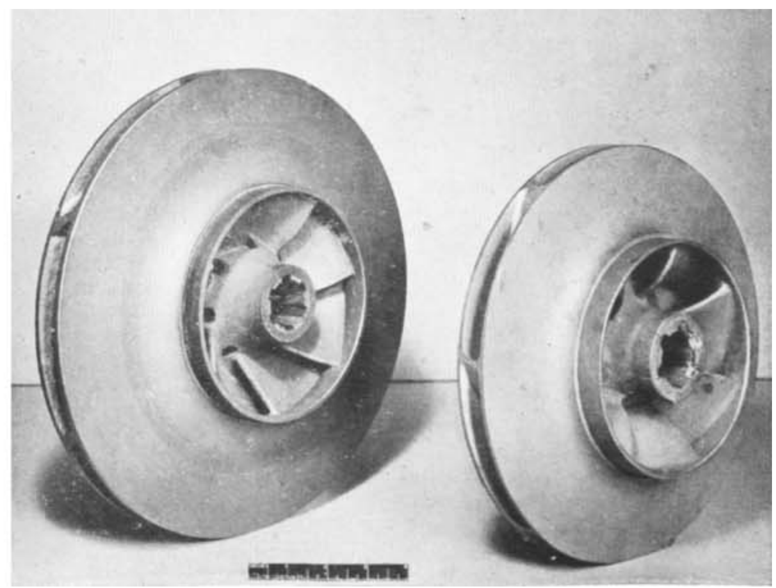

Fig. 14. Pump Rotors

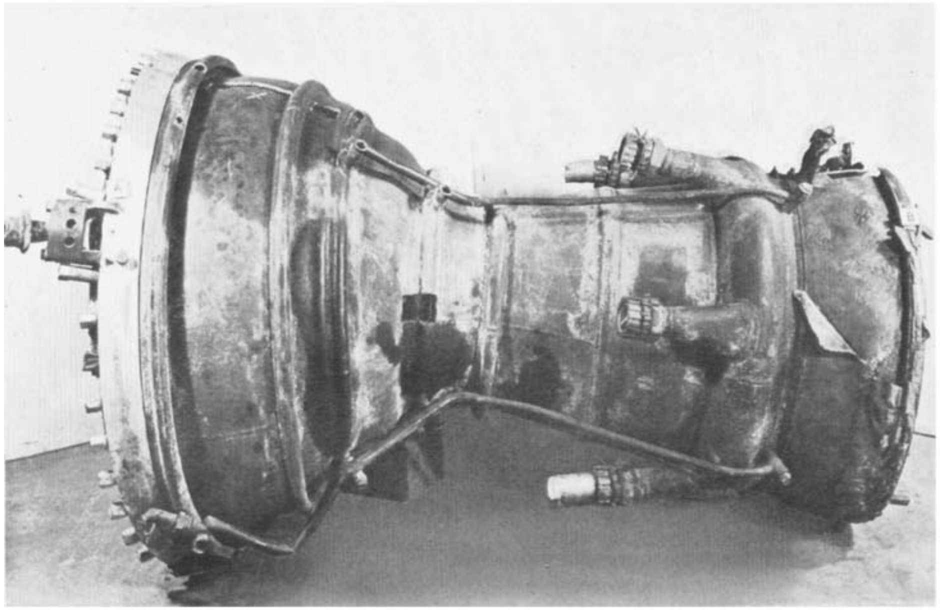

Fig. 15. General View of Venturi

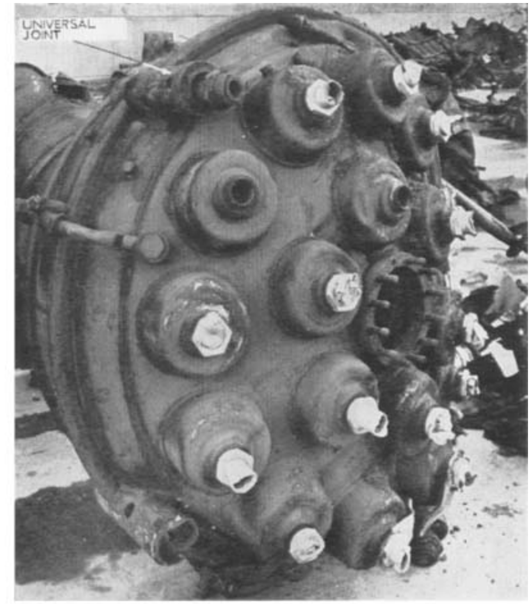

Fig. 16. Burner Cups

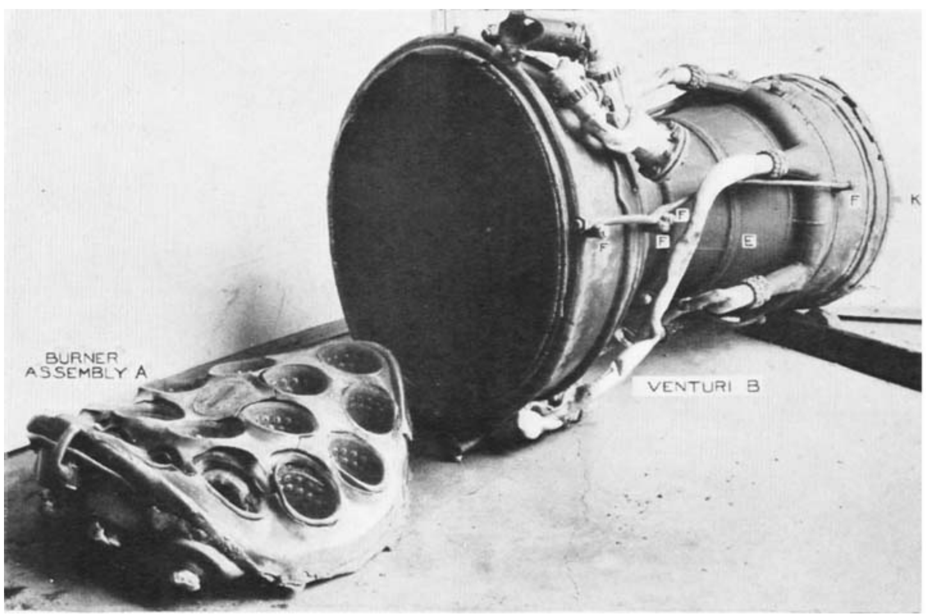

Fig. 17. Another View of Venturi

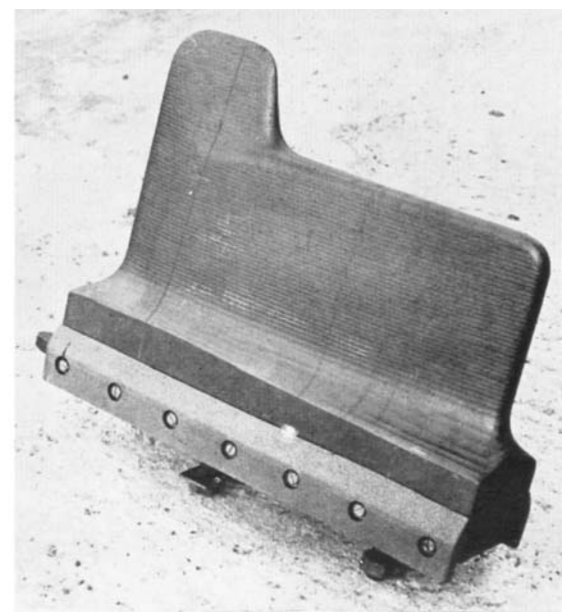

Fig. 20. Graphite Controller

The shape of the trajectory is shown in Fig. 22. The rocket is fired vertically when standing up on its end. After firing, the rocket is turned so that it moves towards the target along a path of the type shown in the figure. At some point about 22 miles above the earth's surface the fuel is either cut off or exhausted, and the rocket then proceeds along a roughly parabolic arc until it descends into the denser air and the path steepens slightly.

Over the first part of its upward course, the rocket acceleration steadily increases as the fuel is burnt, and the rocket weight decreases. Acceleration increases until the "all-burnt" stage; the velocity therefore reaches a maximum at that point and then decreases as the rocket moves up in space. After passing the top of the trajectory the velocity again increases, but as the rocket descends into the denser air the velocity again decreases. The maximum velocity at the all-burnt stage is approximately 5,000 ft. per sec., i.e. about 3,400 m.p.h. Particulars of the velocity over the trajectory are shown in Fig. 22.

As the rocket leaves the ground, the Venturi is producing about 60,000 lb. of thrust. The weight of the rocket is of the order of 12½ tons, or 28,000 lb.; the rocket therefore commences to move upwards with a net acceleration of $1g$, i.e. at the same rate as a body falling freely. As the fuel is exhausted the acceleration increases, and by the time the fuel is nearly exhausted, the weight of the rocket has fallen to about 6,000 or 7,000 lb., and the thrust has increased slightly, with the result that the acceleration has increased to about $8g$. In other words, the structure of the rocket is experiencing a force of roughly eight times its own weight. In aeronautical work, this condition would not be regarded as very serious.

Another interesting point is that at the end of the "all-burnt" stage, when the velocity has reached about 5,000 ft. per sec., the stagnation temperature is in the region of 1,400 deg. C. abs. (about 3,040 deg. F.). The skin temperature of the rocket should approach the stagnation temperature and it would therefore become very hot. A careful examination of the skin condition of a number of rockets was made, but no evidence was found to show it ever having reached a temperature of more than about 650 deg. C. (about 1,200 deg. F.). The skin temperature therefore is well removed from the stagnation temperature which might have been expected. The explanation probably lies in the fact that conduction plays an important part in keeping the temperature down; but the effect of radiation is perhaps even more important at these high temperatures. The radiation losses vary as the fourth power of the temperature, and these losses exert an important influence in keeping down the skin temperature. Nevertheless, it is obvious from the fact that the skin does reach temperatures of the order of 650 deg. C. i.e. about 1,200 deg. F. (perhaps a dull red), that at night it might have been possible to see the rocket.

The existence of this high skin temperature, coupled with the fact that the rocket contains a very considerable liquid oxygen system, emphasizes the importance of taking account of differential expansion. The oxygen tank, for example, which is certainly at a temperature of about −185 deg. C., is next door to a skin which is of the order of 600 deg. C. (about 1,110 deg. F.). Changes in length, resulting from these extremes of temperature, are provided for by floating the oxygen tank in guides, which allow an ample end movement; the weight of the fuel being taken through small strut members back to the main stabilizing ring already mentioned, and not carried directly to the skin except at the stabilizing ring.

The German had themselves been concerned about the possible high temperatures which would be reached by the skin, and had carried out a very interesting set of experiments to explore skin conditions. Into the skin of the rocket metal plugs had been inserted which had low melting points, these plugs were coupled through electrical circuits into radio equipment which telemetered the results to ground. As the result of this work the Germans concluded that nowhere on the rocket had the temperature ever reached more than about 600 deg. C. (about 1,110 deg. F.), a result that agrees very closely with Allied examination of the surface of the rocket and the state of the paint conditions and the metallurgical conditions of the metal in the skin.

In regard to the actual forces on the rocket near the top of its trajectory, it may be remarked that the pressure of the air on a body is a function of the density of the medium through which it is passing and the square of its velocity. These air forces are conveniently referred to in terms of the indicated air speed, this being the speed at ground level that in the absence of compressibility would give rise to the same pressure reactions as those expressed by the rocket in flight. When near the all-burnt stage the rocket velocity is about 5,000 ft. per sec. and near the top of the trajectory this has fallen to something like 3,600 ft. per sec. Despite these very high true speeds, the indicated air speed (the equivalent speed at the top of the trajectory) is only about 3½ ft. per sec., so that there is very little force acting on the rocket during the upper half of the trajectory.

This fact led to speculations on the stability of the rocket in the upper atmosphere. If there are no forces acting on it, and the controls are inoperative because the gases have long since been cut off in the jet, how will the rocket behave in upper space?

Accordingly the stability was examined (Fig. 23), and this

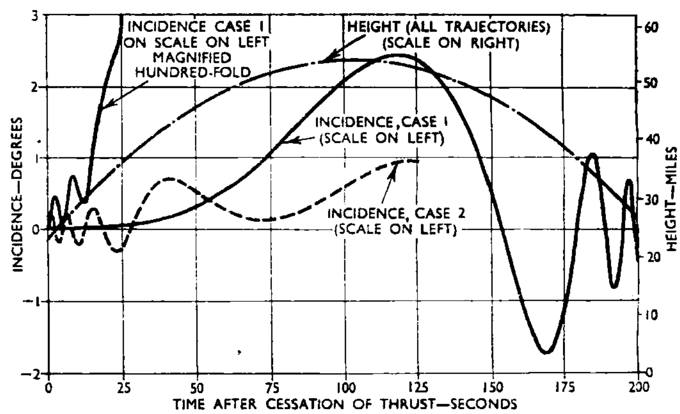

Fig. 23. Rocket Behaviour in Upper Atmosphere

The graphs show incidence and height plotted against time after cessation of thrust.
Case 1: initial rate of pitch and rate of change of path angle equal.
Case 2: initial rate of pitch zero.
Initial conditions: velocity, 4,960 ft. per sec.; height, 120,300 feet (22·78 miles); direction of motion, 0·72 radian (41·3 deg.) to horizontal; horizontal distance from starting point, 9·6 miles; incidence, zero.

figure gives some indication of the behaviour of the rocket after all-burnt stage. The origin of the curves corresponds to a height of about 22 miles; and the rocket, having reached the all-burnt stage, is travelling as a free body. Two conditions have been considered: (1) when the rocket is just allowed to proceed on its tract without any initial motion to deviate it from its tract; and (2) where the amount of pitch imposed on the rocket is the right amount to turn it on to its correct trajectory. One condition, therefore, favours the rocket continuing on its correct course—at least initially, while the other leaves it to its fate. In both cases the rocket develops an undamped oscillation of increasing amplitude until it goes " over the top". In one of the cases considered the rocket performs one oscillation relative to its main path, the maximum amplitude of which is only about 2½ deg., and in both cases as the rocket descends into the denser air the motion is damped and steadied. Never during its whole flight does the rocket experience a very serious wobble, and its motion is very well behaved, despite the fact that the stabilizing forces are small.

In regard to the distribution of the weight, it was mentioned above that the warhead accounted for 2,150 lb.; and naturally the fuel forms a very large proportion of the total weight. It is, in fact, the amount of weight that can be devoted to fuel which really governs the range of the rocket. In the case of the V2 rocket, roughly 19,000 lb., or more than two-thirds of the total weight, has been given to fuel. This is a very large proportion, and it is of interest to compare the weight distribution of the rocket with the weight distribution of, say, a high-speed bomber, and with the V1 flying bomb (Table 1).

In Table 1 the first column of figures relates to the bomber, the second to the V1, and the last to the rocket. In the aeroplane, about 29 per cent of the weight is given up to the structure, and it will be observed that the Germans have been very skilful in keeping the structure weight of the V2 down to 13 per cent. The structure weight of the V1, which is more or less an ordinary aeroplane, is 25 per cent. The power plant of a high-speed bomber of the type here considered takes up 24 per cent of the weight, whereas the power plant fitted to the V2 represents only 8 per cent, and that fitted to the V1 also represents 8 per cent. On the other hand, the fuel of the bomber is only 19 per cent of the weight, whereas that of the V2 is 69 per cent—over two-thirds—and that of the V1 19 per cent, practically the same figure as for the bomber. The equipment weight is 13 per cent in the case of the bomber, but very small —2 per cent and 1 per cent respectively—for the V2 and V1. The pay-load represents 16 per cent. in the case of the aeroplane; it is extremely low, 8 per cent, in the case of the V2, since so much of the weight has been sacrificed to fuel whereas the V1 has an excellent pay-load.

TABLE 1. COMPARATIVE DATA OF HIGH-SPEED BOMBER, FLYING BOMB (V1), AND ROCKET BOMB (V2)

Item	Fast bomber	V1	V2
Percentage weights			
Structure	29	25	13
Power plant	24	8	8
Fuel	19	19	69
Equipment	13	1	2
Pay load	16	46	8
Speeds, miles per hour			
Take-off	120	200	0
Maximum	400	350–400	3,400
Other data			
Ceiling (feet)	40,000	9,000	350,000
Range (miles)	1,600	175	220
Endurance	6·5 hours	30 minutes	5·0 minutes
Fuel consumption (lb. per sec.).	0·57	0·66	275
Fuel consumption (lb. per h.p.-hr.).	0·75	4·3	1·6 (when near "all-burnt" stage)

The next set of figures compare the speed. The take-off speed of the ordinary bomber is 120 m.p.h., and it requires a long runway. The V2, on the other hand, since it is launched vertically, requires no take-off run, and can be launched from a road or small yard. The V1 requires a high-speed catapult and quite a high launching speed. The maximum speed of the bomber is 400 m.p.h. and of the V2 3,400 m.p.h. The maximum speed of the V1 is close to that of the bomber, being 350–400 m.p.h.

A comparison of the fuel consumption figures is interesting. The fuel economy can be expressed as pounds of fuel per horse-power-hour; in the case of the bomber this is 0·75 and in the case of the V1 it is 4·3; in other words, the bomber engine uses fuel six times more economically than the V1 engine. It is interesting to note, however, that near the all-burnt, which of course is a condition favouring the rocket, the rocket fuel consumption does not compare badly with that of a conventional bomber engine, being only roughly twice as great.

A striking figure emerging from this comparison—not included in Table 1 but worth mentioning—is the horse-power that the rocket develops when near the all-burnt stage. At that altitude the thrust, which was 60,000 lb. at ground level, has increased, due to the fall of the outside pressure, to very nearly 70,000 lb.; and, since the rocket speed is 5,000 ft. per sec., the horse-power being developed is approaching three-quarters of a million—a truly amazing generation of power in such a small unit.

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Discussion

The ensuing discussion consisted entirely of questions put to Mr. Perring, and of answers given by him; an impersonal account, slightly condensed, is given below

In reply to a question as to how the V2 rocket was launched, and how it was directed at a target, it was stated that the rocket was placed vertically and (so far as was known) the main fuel valves were opened, to allow the main fuels to flow to the combustion chamber under gravity. The fuel was ignited by a black powder igniter; and an observer standing at a discreet distance away satisfied himself that the fuel was well alight. It was thought that the fuel lighted quite easily, and burnt without any disturbance. When the observer was satisfied that the fuel was alight, he completed an electric contact, which "pressurized" the hydrogen peroxide and permanganate tanks; the valve to the turbine then opened, and the turbine was run up to speed. The whole process, from starting of the operation to the attainment of full speed by the turbine, took about 7 seconds. As the turbine reached full speed, the thrust steadily built up, and soon exceeded the weight. The rocket then ascended gracefully, any tendency to wobble being prevented by the automatic pilot, which provided a very powerful control, stabilized the rocket, and maintained it on its right path. The controllers governed the roll, prevented rotation about the rocket axis, and also governed the direction, so that if the rocket was launched with its controllers correctly adjusted it should remain on the right path. The pitch control ensured that it turned at the proper rate.

It was asked why, if the weight of the fuel was so important, the Germans used alcohol, which had a low calorific value. In the reply, reference was made to a technical term used in rocket work—the "specific impulse" of a fuel, i.e. the thrust developed for every pound of fuel burnt per second. For most fuels the specific impulses under practical working conditions were not very different. In the V2 rocket, using alcohol and liquid oxygen, the specific impulse was about 220 lb. of thrust per pound of fuel. Higher specific impulses would be possible if higher working temperatures could have been tolerated. The

Germans had in fact to use a dilute fuel to keep the temperatures down. It was difficult to get more out of the fuel, because, unfortunately, when any attempt was made to increase the specific thrust of a given fuel, the pressure rose as the fifth power of the temperature. The temperature and pressure were already perhaps as high as could be tolerated; and 220 lb. per lb. of fuel was therefore a reasonable working value of the specific thrust. It was possible to do slightly better with petrol without incurring some of the difficulties mentioned, but the Germans were probably short of petrol. It would be possible to do still better by using hydrogen, since the other factor affecting the specific impulse was the molecular weight of the gases produced. Specific impulse depended on working temperature on the one hand (which usually could not be increased because of the question of materials), and low molecular weight on the other. The fuel which the Germans used gave them a reasonably low molecular weight, and was, therefore, not a bad choice.

It was stated in reply to an inquiry as to what sort of bearings were used in the liquid oxygen pump, that plain bearings, with plenty of clearance, were employed.

Information was requested on the lagging of the liquid oxygen tanks. Further, it seemed that if the tanks were made to withstand pressure and proper arrangements were made for the vaporization of the liquid oxygen, the fuel could have been fed to the burners without the use of a turbine or pumps at all, simply by evaporation of the oxygen.

The Germans, it was stated in reply, provided glass wool lagging to reduce evaporational losses. The filling of the tanks was one of the last items in the firing procedure. The rocket was made to stand on end in the empty condition and filled while in that position. The fuel was pumped into the rocket from mobile vans. Evaporation losses were small, about 4 or 5 lb. of oxygen per minute during every minute the rocket was waiting to be fired; and the Germans attempted to reduce this waiting time as much as possible. As mentioned earlier, it was necessary, in order to provide sufficient oxygen to feed the fuel forward, to use an heat exchanger. The rate of exhausting the tanks—150 cu. ft. per min.—was quite high. The more important reason, however, why pumps were used instead of relying on pressurizing the fuel tanks, is one of weight. The Germans were able to use a very light alloy tank, which they pressurized to about 1½ atmos., had they pressurized the tanks to 20 atmos. which would have been the pressure necessary to feed the fuel forward at the proper rate, the tanks would have weighed far too much, and this would have increased greatly the structure weight, and reduced the range.

It was asked whether it had been possible to check the resistance of air at the very high velocity of 5,000 ft. per sec.? The reply was in the negative, but it was pointed out that since, at the heights at which such velocities were reached, the density of the air was nearly zero, the resistance was not very large, and had little effect on the rocket motion. Estimates which had been made agreed reasonably well with the ranges that were achieved.

On the loss of resistance at or near the velocity of sound only very limited information was available, because very few results except those on bullets and shells could be consulted. There was a good deal of evidence supporting the view that at speeds above about 1·5 times the speed of sound the theoretical laws were fairly closely obeyed, and at these speeds it was possible to calculate the drag. The drag coefficient rose very steeply at speeds above 0·7 of the speed of sound, reached a maximum a little beyond it, and then fell fairly rapidly; there was a little uncertainty in the region between 0·9 and 1·1 of the speed of sound.

It was asked why the V2 rockets gave rise to two distinct explosions, in some cases the warhead landing some distance from the body and the explosion taking place in the air. In answer, members were told that a number of the rockets which reached this country, and of those fired during the experimental stage in Germany, burst in the air. The exact cause had never been explained, though a number of reasons could be advanced. For example, the method which the Germans adopted for pressurizing the alcohol tank seemed to invite trouble. To have the alcohol tank pressurized by "ram" effect was likely to introduce ram conditions into that tank, with the ensuing high temperatures associated with the adiabatic compression of air at the entrance to the tube. Temperatures approaching 1,000 deg. C. (about 1,830 deg. F.) or higher might be reached at the mouth of this tube; and if air at that temperature was introduced into an alcohol tank, the risk of an explosion was quite high. It was usually the alcohol tank which exploded and blew off the warhead. The rear end of the rocket usually landed in one piece, and the warhead went on and detonated on impact with the ground.

Reference was made to the fuse mechanism, and it was asked whether there was any truth in the rumour that the fuse worked on a special capacity-inductance system which detonated the charge before the rocked reached the ground, to prevent it burying itself too far in the earth. It was stated that there was a small extension, perhaps about 1 foot long, projecting from the front end of the rocket, and it detonated the charge on impact.

It was contended that in many cases the warhead exploded in the air, and made a puff of smoke, like that of an enormous shell.

In reply, the opinion was expressed that not many warheads exploded in the air, although the rockets certainly did. With regard to the two explosions, and the hearing of two reports, it would be appreciated that the rocket set up a powerful shell wave, making an angle to the nose of the rocket. This wave travelled downwards at the speed of sound, and, depending where an observer was standing when the rocket exploded, it was possible to hear the shell wave, or the rocket explosion in either order, or both together. That was a partial explanation of why two explosions were reported; a roar, which may be quite a crack, coming from the shell wave at the speed of sound, and the second explosion (i.e. that of the warhead) which would travel from the point of explosion at the same speed.

Information was requested on the quantities and quality or standard strength of the hydrogen peroxide and the permanganate, in answer to which it was stated that the amount of hydrogen peroxide carried was 370 lb., and that substance, together with 27 lb. of calcium permanganate (in aqueous solution), provided about 3 lb. of steam a second at 350 lb. pressure to drive the turbine. The peroxide was about 80 per cent concentration, and at that concentration it appeared to be quite stable.

In reply to an inquiry as to the type of engine used in the V1, it was explained that it comprised an impulse duct—a tube with a grid over the entrance. The grid in turn comprised a large number of valve openings of simple form, and the tube length was such that resonance was set up in it, with a frequency of about 47 a second, each "pulse" of the resonance creating a suction behind the grid plate. Air was drawn into the tube through the grid. The suction was followed by a pressure resulting from the combustion of the fuel which mixed with the incoming air; and so the pulsation was maintained.

Some further information was given on the fuel system. The liquid oxygen tank was of ordinary light alloy, the pump was of steel, and the general piping throughout was again of light alloy. In spite of the very high acceleration, no trouble would be experienced with cavitation in the fuel system once the rocket had started, because the fuel system itself would be subject to an acceleration of $2g$ at starting, rising to $8g$ near the end of the "all-burnt" stage; the acceleration assisted the fuel feed to the pump. Provided that priming was properly carried out (and this was checked by observing the combustion), there was no likelihood of cavitation.

In regard to the height reached by a V2 rocket, in comparison with the height to which it would be necessary to fire a rocket to overcome the gravitation of the earth, the answer was given that it was a simple matter to determine the height reached by a V2 rocket; since its path was practically parabolic, its height must be roughly one-quarter of its range. The determination of the other height was not so easy, because height did not matter so much as speed. If one could travel at about 24,000 m.p.h., it would be possible to steer oneself to any height, and to overcome the earth's gravitation. That was not outside the realms of possibility. Imagine a very big rocket in which the warhead was replaced by a smaller rocket, and the warhead of the smaller rocket replaced by the V2 rocket described above.

Such a three-stage rocket would reach the speed necessary to pass outside the earth's gravitational field.

The maximum efficiency of the V2 rocket could only be assessed in terms of the figures cited in discussing the fuel consumption. At altitude the fuel consumption compared not unfavourably with the ordinary reciprocating engine. The reciprocating engine could not operate at that altitude at all. The rocket had to carry its oxygen with it because there is nothing to burn at such altitudes, but the rocket burnt its fuel very economically when it travels at such a high speed.

In regard to testing, it was considered that the Germans carried out a great deal of check testing before firing—e.g. testing the characteristics of the pumps, etc., but they could not fire the rocket motor to judge its performance. If a rocket failed, due to any reason unknown, it was believed that it was their practice to return it to store and never try it a second time.

If, as was stated, no specially prepared launching sites were needed, it was difficult to see why the Germans built such vast concrete structures on the "rocket coast" of France. In reply, the opinion was given that in setting out to bombard this country the Germans knew they would be inviting trouble, and since numbers of troops were needed, they wanted to provide their crews with reasonable conditions of protection, so the thick concrete structures were built.

The question was raised as to whether the existing rocket was in any way an accurate weapon. For instance, did the Germans definitely aim at certain parts of London?

In reply, the difficulty in answering the question was acknowledged. The Germans began the production of the V2 rocket three or four months after the first successful shot. But in all experimental work, many difficulties must still be faced after the first successful shot. Fragments of rockets collected in this country clearly showed signs of development and evidences of change. The designer of the rocket was fully aware of its shortcomings, but also very optimistic about its possibilities, so that it would be unfair to attempt to answer the question, because the rocket designer would simply state that the rocket was a very undeveloped article, but the best that could be produced in the time. It was certainly possible to control the rocket by wireless means, but details of the actual control could not be released.

The method of launching the rocket was again referred to, and it was asked whether it was first launched vertically upwards and then diverted at an angle of 45 deg., and whether that was the most economical way to get the longest range or the maximum pay-load? Would it have been more economical to adopt a flatter trajectory, so as not to devote so much energy into pushing it into the air, only to come down again? In answer, it was stated that, clearly, it paid to send the rocket up to regions where the air had little density as quickly as possible. It paid, therefore, to send it up vertically.

Reference was made to the design of the motor attached to the fins—first a shunt motor, and later a compound-wound motor, the first being made of cast iron, which one would not expect on aircraft. No definite reason could be given in reply, but a possible explanation was that several groups of German technicians were working on the control system; it was, in fact, a feature of the rocket that underwent more change than anything else. Different firms might have developed different methods. It was clear that, in regard to the control system, many firms were making contributions.

It was asked whether it was speed or acceleration that affected the possibility of overcoming the earth's gravitational field. The opinion given in reply suggested that ultimately it was a question of speed. It was necessary to reach a definite speed; how that speed was reached depended on how long the acceleration was maintained. The V2 rocket accelerated from $2g$ up to $8g$. Had it carried more fuel it would, of course, have accelerated up to much higher values than $8g$, and would have continued to increase in speed. The acceleration affected the time necessary to reach a given speed; but the speed determined whether the rocket could move out of the earth's field. Whether or not it would be possible to find material to withstand the necessary temperatures associated with such speeds was very doubtful; for these would be enormous, even though they were greatly reduced by radiation.

It was further pointed out that the velocity of the V2 rocket was a mile a second. The speed necessary for a projectile to leave the earth was 7 miles a second. After some interval the velocity of the V2 rocket dropped from 5,000 to 3,500 ft. per sec., which was of the same order as that of a high-speed shell. These speeds were far from velocities suitable for a projectile to leave the earth—only one-seventh of the figure in fact. Rockets had not nearly attained the speeds necessary for leaving the earth's gravitational field. The power generated by the V2 rocket, was, as already mentioned, some three-quarters of a million horse-power. One must not be appalled at this figure, because the rate of generation of power of a shell in its explosion was much greater; but with the V2 rocket it was a very high rate of generation of power *under control of some sort*. That was the importance of that seemingly high figure.

Reference was made to a statement which had appeared in a technical magazine that the Germans could get an approximate idea of where a rocket landed by means of seismographs, and it was asked whether there was any truth in this. In reply, the opinion was given that the Germans did employ seismographic methods to try to detect the fall of rockets. Whether they obtained any results was not known. It would be difficult to do so without knowing a great deal more about the substratum of the earth than they presumably did; but it was fairly certain that they called in all their experts, and considered the possibilities of such a method.

It was asked whether the V1 flying bomb, as it was so simple, had any future. In answer it was stated that it was a very cheap engine to make, but it was very noisy and subject to great vibration. Except, therefore, for applications where the power unit was intended to be thrown away, it was not considered that it had a future.

Finally, a reason was sought for the difference in the type of explosion produced by the V1 and V2. (The V2 seemed much sharper and more of a detonation, and the V1 usually a thud.) In reply it was stated that the fuze on the V2 rocket was set very lightly; it exploded very close to the surface, and in any case was not intended to penetrate deeply, while the V1 was a definite blast weapon. Moreover, the explosive used in the V2 was less violent and active than that used in the V1. The difference in the audible result was possibly due to the fact that while the V1 flying bomb exploded above the surface, and was a first-rate blast weapon, very often the V2 rocket buried itself and detonated. Apart from that, people very often mistook the crack of the shock wave for the explosion itself.