ON THE HISTORY OF THE DEVELOPMENT OF THE SCHMIDTROHR

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1. INTRODUCTION

In his excellent paper of 1946, "The Pulsating Jet Engine — Its Evolution and Future Prospects" L. B. EDELMAN provided a review on the development of the pulse-jet [1]. I would like to emphasize his remarks on the work of KARAVODINE and the ideas of MARCONNET, in which it is shown that the principle of intermittent combustion had been introduced as early as 1908. KARAVODINE's turbine constructed and operated in 1908, constituted a remarkable technical achievement, and mention must be made of BARBEZAT who, 50 years ago, succeeded in measuring the pressure distribution of an intermittent combustion. In my first publication in 1948 reference was made by me to the first interesting patent of MARCONNET of 1909, and I am of the opinion that the most prescient views as expressed therein deserve our fullest appreciation [2].

When I refer in this paper exclusively to my own work, I do so because of the limited time available to me. A more detailed presentation of the history of this particular technical field would be both interesting and instructive.

When, in 1928 to 1930, I began to think about the problems of aeronautics, it was merely a sort of hobby, since at that time I was most busy as a consulting engineer in the sphere of fluid dynamics. Out of mere curiosity and interest I devoted some thought as to how small aircraft could be designed so as to be able to take off and land vertically, whilst still retaining the proven shape of conventional aircraft.

Consequently, the research was to be directed towards designing a propulsive unit of small weight which was capable of carrying the total weight of the aircraft.

Without any knowledge of earlier developments in this field, I conceived the idea that such a propulsive unit could possibly consist of a thin-walled tube with explosions being produced therein in rapid succession. With an arrangement of three such tubes, it should be possible to lift and to control an airplane.

The solution thought of is shown in Fig. 1, which accompanied my patent application of 1930 [3]. In the lower portion of the illustration three tubes can be seen, two of which are mounted in the wings and one in the fuselage. The air-gas jets are deflected towards the ground at the exit end of the tube, thus providing three supporting jets. The calculations made proved that the space

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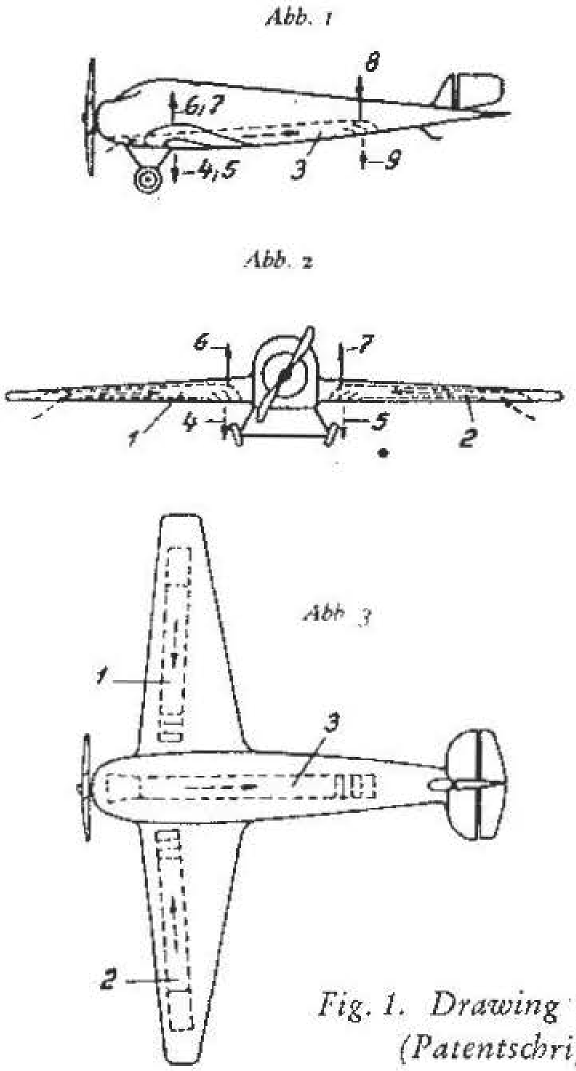

Fig. 1. Drawing from the patent application of 1930 (Patentschrift 567 042, Kl. 62 b, Gr. 37_{02})

requirements and the weight of such intermittent pulse-jet engines could be kept sufficiently low, provided the combustion process could be performed with sufficient efficiency.

2. THE INVENTION

The pressure of the explosions produced in the tube was to supply the desired thrust and the expanded high-speed explosion gases would suck into the tube a maximum quantity of fresh air. A portion of this air would be mixed with the fuel and the remainder would serve to produce additional thrust. For this purpose it was necessary to incorporate a valve in the intake.

Fig. 2, which also accompanied a patent of that time, conveys an idea of the supposed method of operation [4]. The front portion of the top tube of the illustration is filled with an air-fuel mixture (illustrated by small dots). The tube immediately below shows the left hand flaps closed. The mixture has been ignited and the explosion gases convey the total contents of the tube toward the right. This is illustrated by the arrow in the rear end of the tube. The next sketch illustrates the flow within the tube after the pressure of the explosion gas has fallen. The accelerated mass continues to flow to the right, thus producing a section of low pressure in the intake end of the tube. The negative pressure causes the valve to open and fresh air is sucked in. Prior to the termination of this sucking process, fuel is added to the air to form a certain mixture. This stage of the process is shown by the lower tube of the illustration. The

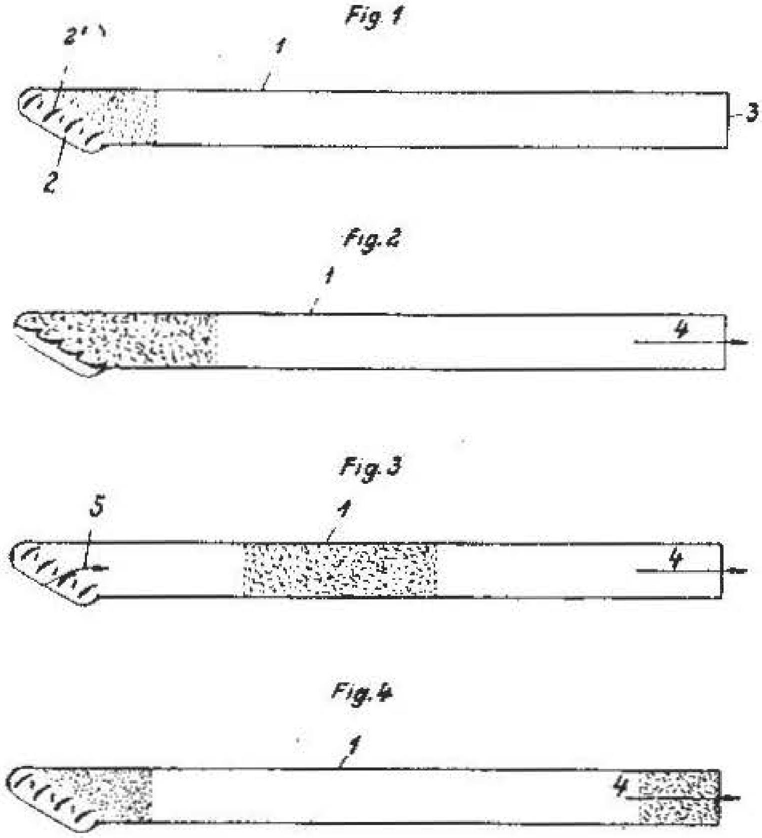

Fig. 2. Method of operation of the Schmidtrohr

subsequent closing of the valve and igniting of the mixture results in a repetition of the process.

My ideas for a powerful tubular jet engine were theoretically correct, as I was assured by a competent scientist around 1930/31. However, an apparently insignificant matter proved to constitute a major objection — it was the ignition system, for the known ignition velocities were much too slow for this process.

In order to overcome this difficulty, at the beginning of 1931 I invented a novel ignition method so as to obtain ignition at a sufficiently high rate. According to this invention, ignition was to be produced by a shock wave. If it were possible to obtain ignition, such a wave would provide an ignition velocity of several 100 m/sec, i. e. more than 10 times as fast as any known ignition velocity.

3. THE DEVELOPMENT

3.1. The Principles of the Ignition System

Papers [5] on the development of the Shock-Wave Ignition Method were published by me some years ago so that I need not discuss this extensive subject in detail. Moreover other authors have recently published reports on tests of ignition produced by shock waves. In this connection I would like to refer you to the report by SHEPHERD "Third Symposium on Combustion" [6], and also to the recently announced book by GREENE and TOENNIES "Chemical Reactions in Shock Waves" [7].

Our practical work which began in 1931, was primarily concerned with the ignition effect of a shock from a hot gas on a cold mixture. The results of the tests could not be explained by the well known laws of the dynamics of gases and, therefore, consideration was given to the relationships of molecular kinetics. In this way we finally obtained satisfactory agreement.

I began the development of the ignition system by augmenting my knowledge of the theoretical background, and the effects of shock waves, from the relevant literature, since up to that date I had no intimate knowledge of this particular subject. In a dissertation by R. WENDLANDT of 1923, I found my views on the ignition effect of shock waves confirmed in principle[8]. The shock wave — in this dissertation — was produced by exploding oxy-hydrogen gas ($2 H_2 + O_2$). Fuel-air mixture was not investigated by WENDLANDT.

In order to determine the effects of a detonation wave on such a mixture — this constituted the problem — I devised a test arrangement consisting of a tube of approximately 60 mm diameter. The first 250 mm of this tube were filled with an acetylene-oxygen mixture, and the second section of 500 mm length contained the fuel-air mixture. The final 1000 mm was provided with an air intake valve and was open at its rear end.

The test equipment is shown in Fig. 3. The acetylene-oxygen mixture and the fuel-air mixture were fed in under pressure, the feed being controlled periodically. Whilst the mixture was being fed in, the fuel-air and acetylene-oxygen compartments were separated by means of a controllable hinged flap (not shown in the diagram) immediately in front of the fuel-air valve.

The acetylene-oxygene gases burnt earlier were exhausted separately whilst the shut-off was in operation. As shown in Fig. 3, a baffle plate was suspended at a certain distance behind the exhaust end of the tube so that the pressure impulse of the gas jet which issued periodically could be measured.

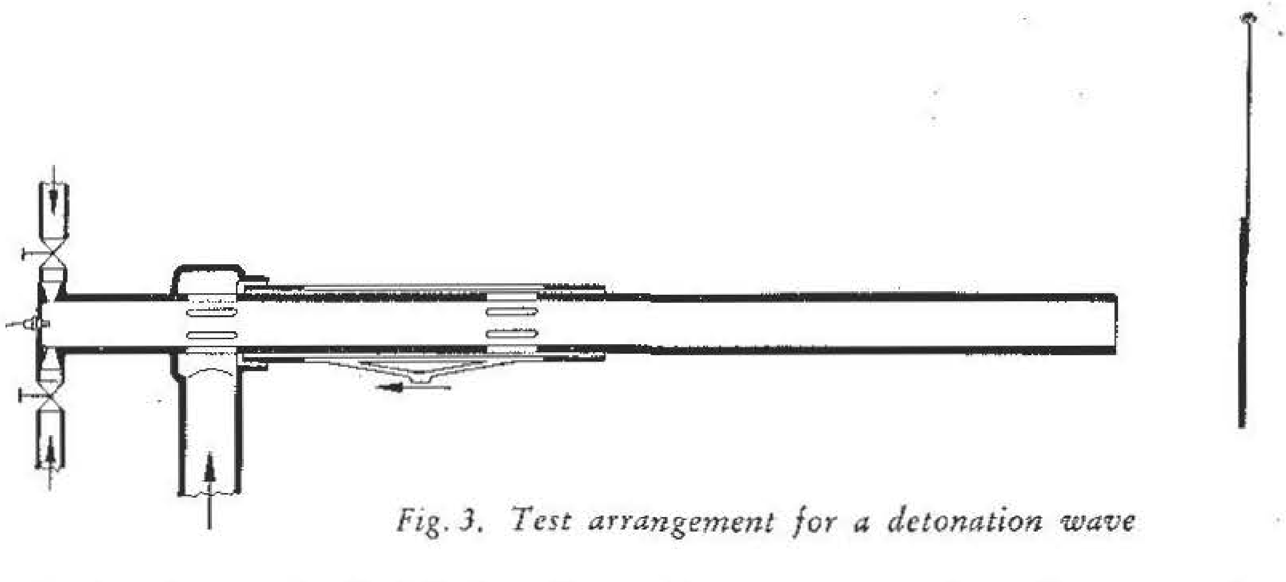

Fig. 3. Test arrangement for a detonation wave

During the test, the fuel feed to the combustion air was shut off temporarily, whilst the feed of the combustion air was maintained. The modification in the operation thus consisted only of a temporary shut-off of the fuel supply. It was ascertained that the impulse of the gas jet became considerably greater as soon as fuel was fed in. Thus it was proven that the fuel-air mixture was ignited effectively.

Based on this knowledge, a systematic research on the ignition effects of shock waves produced by the explosion of compressed fuel-air mixtures was conducted from 1931 onwards. For this purpose, a device was designed to produce a single shock wave (see Fig. 4). This device consisted of an explosion chamber *a* followed by a combustion tube *b*. The explosion chamber was

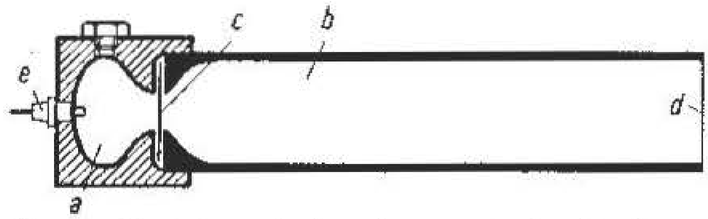

Fig. 4. Ignition device for a single shock wave
a = Explosion chamber *b = Combustion tube* *c = Diaphragm*
d = Paper diaphragm *e = Spark plug*

separated from the tube by means of a diaphragm *c*. The tube was supplied with fuel and air at atmospherical pressure and at the ambient temperature. The exhaust closed by a paper diaphragm *d*, which prevented the mixture from escaping. Some ethyl ether or gasoline was fed into the chamber *a*, followed by compressed air at approximately 5 ata, and this mixture was then ignited by the spark plug *e*. The pressure of the explosion ruptured the diaphragm *c* and the expanding gas sent a shock wave into the tube *b*. The investigation of the combustion occurring in the tube was extended to various fuels such as gasoline, ethyl ether, hydrogen and carbon disulphide. By proper control of the volume of the explosion chamber, of the excess pressure of the explosive mixture therein, and of the tube diameter, good shock-ignitions of the mixture in the tube were obtained.

The diagram in Fig. 5 shows the pressure distribution within the tube shortly after the diaphragm *c* has been torn. The shock wave moves along the tube

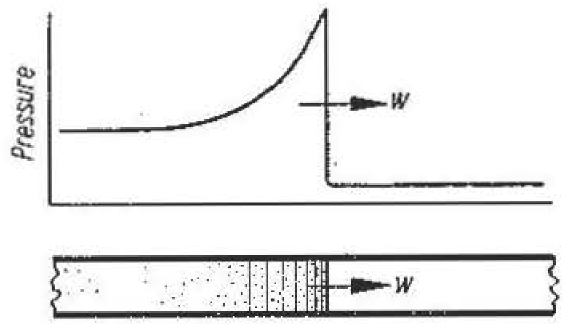

Fig. 5. Pressure distribution in tube b of Fig. 4
w = Velocity of shock wave

from left to right at the supersonic velocity *w*. The gas ahead of the wave front is not disturbed and thus is at atmospheric pressure and ambient temperature. On arrival of the shock wave, the pressure and the temperature of the gas within a narrow zone are suddenly increased. Thus combustion is initiated and the gas behind the shock wave is compressed accordingly.

The effects of a shock of cold gas were investigated in additional tests in 1932; a device as shown in Fig. 4 was used, the only modification being the absence of the spark plug. For this purpose, the chamber *a* was filled with hydrogen at ambient temperature; some nitrogen was added in order to obtain a specific weight similar to that of the combustion gases. On increasing the pressure of the hydrogen to approximately 20 ata, the diaphragm *c* was torn. Under these conditions the shock wave, acting on the mixture of carbon disulphide and air contained at atmospheric pressure and temperature in the combustion tube, produces efficient combustion. Because of the expansion, the temperature of the moving gas which produces the shock (shock gas) is lowered to approximately $-100\,^0$C. As in the case of the "hot" shock gas, the initial pressure of the "cold" shock gas must exceed a certain minimum value in order to achieve combustion. If the pressure was below this value, no combustion could be obtained.

During these tests, the question arose as to whether this "cold-ignition" might be perhaps an electric ignition, caused by friction, interrupted spark or another reason. The energy contributions of electrical processes of this kind are, however, very small. Experience shows that they should be substantially greater in order to be able to act on the contents of the tube in the way, and with the regularity, described above, despite the very low temperature of the shock gas. Furthermore, it has been established that the additional arrangement of a bronze mesh behind the diaphragm — thus eliminating electrical tensions — does not alter the ignition effect of the shock gas. If electric effects exist, the precisely defined minimum pressure of the shock gas cannot be explained. No ignition could be observed at pressures below the minimum pressure, neither with a hot nor with a cold shock gas. Since there were no other sources of ignition present (spark plug or the like), only the action of the shock wave can be considered to be the cause of ignition.

I would like to remark that such tests later were repeated with the tube contents consisting of an ethyl ether-air mixture. The same results were obtained, with the "cold" shock gas having a pressure of approximately 75 ata excess pressure.

3.2. Efficiency of Combustion

At the beginning of the tests, the efficiency of the combustion was determined by an arrangement employing a suspended baffle plate (Fig. 6). A tube *c* open at one end was attached to the combustion tube *b*. A thin paper diaphragm *d* was clamped between the combustion tube and tube *c*. The air *A* within tube *c* was accelerated by the ignition of the mixture *M* in tube *b* and flowed against the baffle plate *e*. Since the plate was attached to a swinging lever, it moves to the right due to the impact of the air and, subsequently, of part of the combustion

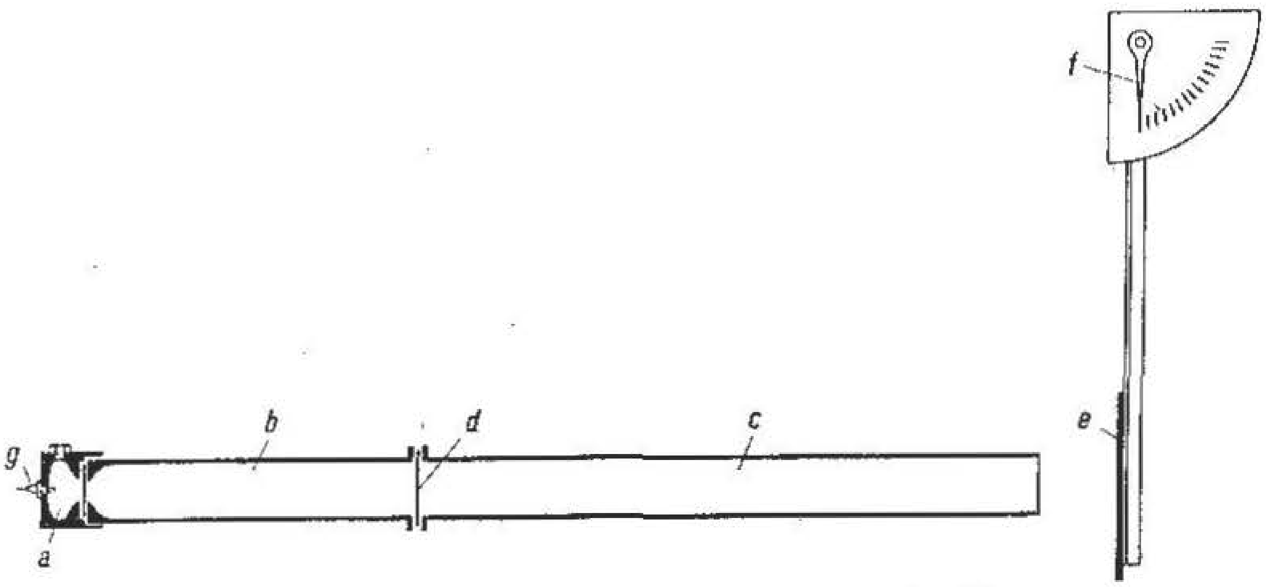

Fig. 6. Ignition device for a single shock wave with additional air
a = *Explosion chamber* *b* = *Combustion tube* *c* = *Air tube*
d = *Paper diaphragm* *e* = *Baffle plate* *f* = *Pointer*
g = *Spark plug*

gases. The maximum deflection was recorded by the pointer *f*. The shock gas contained in the explosion chamber *a* was ignited by the spark plug *g*.

Mixtures of different fuels and of different degrees of saturation were tested in this test arrangement. At the same time, the influence of different quantities of air contained in tube *c* was investigated. For this purpose, tubes of different lengths, but of the same diameter, and also tubes of the same length, but of different diameters, were tested.

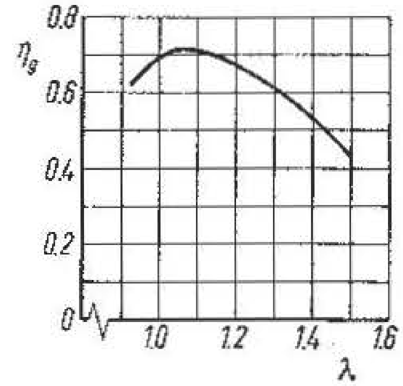

Fig. 7. Efficiency of the combustion

Fig. 7 represents the efficiency of combustion (a fraction of the energy theoretically obtainable as measured at different air-fuel ratios λ). The maximum value obtained is 0.71. In this diagram, the air column contained in tube *c* is treated as a rigid body. Thus the losses incurred in accelerating the air column, are included in the efficiency. Also losses incurred (in the air tube *c*) due to advance flow occurring during the acceleration of the air in tube *c*, are taken into account.

The efficiency of combustion was determined some years later by the Engineering Laboratory of the Technische Hochschule of Dresden where, in a similar test arrangement, the gas pressure at the bottom of the tube was recorded by means of an oscillograph. These tests were initiated by Prof. Dr. A. Nägel and performed by Dr. S. Meurer.

In these tests, the air column was varied by means of tubes of different lengths which were attached to the combustion tube. From this arrangement, the efficiency of the combustion at different conditions was obtained in terms of the ratio A/M.

In Fig. 8 the abscissa represents the time expressed in thousandths of a second. The ordinate represents the gas pressure as measured at the bottom of the tube, for the ratios $A/M = 0$, 2, and 4. According to the momentum theorem the duration of the pressure effect increases with the quantity of the air A.

In Fig. 9, the efficiency of combustion, as determined by the Dresden Engineering Laboratory, is plotted versus the ratio A/M. With $A/M = 0$, the air tube was omitted. The combustion gases thus expanded immediately into the open air, and probably part of the mixture left without having been ignited. This explains the fact that only a poor efficiency was obtained with the A/M ratio $= 0$. When an air tube is attached, the efficiency of combustion increases to a value in excess of 0.8, which confirms the previous measurements performed with a baffle plate (see Fig. 7).

The results of the determination of the efficiency of combustion by individual ignition are important in that, as will be shown later, a substantially poorer efficiency of combustion was obtained from periodic operation of the

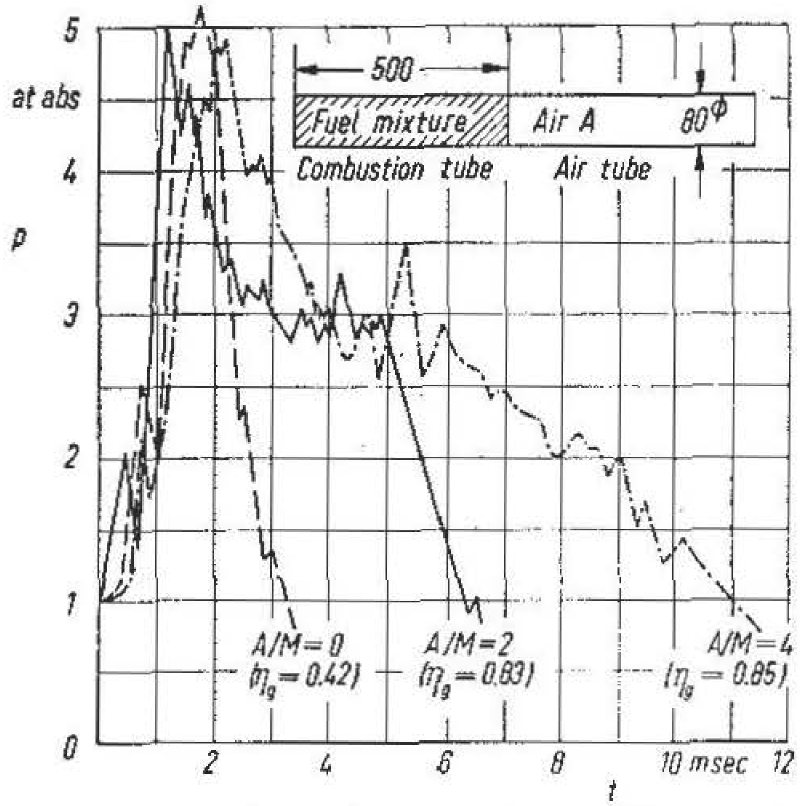

Fig. 8. Pressure in the combustion tube at different ratios A/M
A = Air M = Fuel mixture

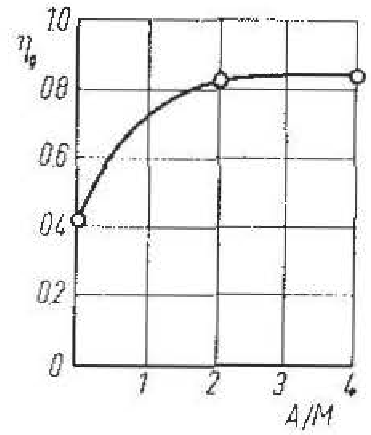

Fig. 9. Efficiency of the combustion

tube. The efficiency in stationary operation was only approximately 0.22, i. e. one fourth of the value technically obtainable. Since according to the LENOIR-Process, combustion theoretically supplies only approximately 30 per cent of the chemical energy in the form of mechanical energy, it is very important in technical applications to know whether this 30 per cent is used with an efficiency of 0.8 or of only 0.22. Furthermore, it is important that, when a tube containing air is attached, this air is accelerated without incurring greater losses. Thus these test results form a considerable part of the foundation required in the evaluation of the technical usefulness of the principle.

3.3. Operation with an Ignition Device

Towards the end of 1934, an ignition device had been developed which supplied shock waves periodically at 50 c/sec. This device is shown in Fig. 10. Check valves *d* were attached to the cylinder *a* ahead of the slots *b* and behind the slots *c*. These valves admitted the mixture into the cylinder via the slots *b*, whilst the excess mixture not utilized in combustion left the cylinder via the slot *c*. The mixture was then fed into the combustion tube *e*, the end of which is indicated (the valve is not included in the drawing). As it advanced, the free piston *f* at first pushed the mixture not used for ignition out of the cylinder via the slots *c*, and then compressed adiabatically the mixture enclosed between the slots and the bottom of the cylinder until self-ignition occured. A shock

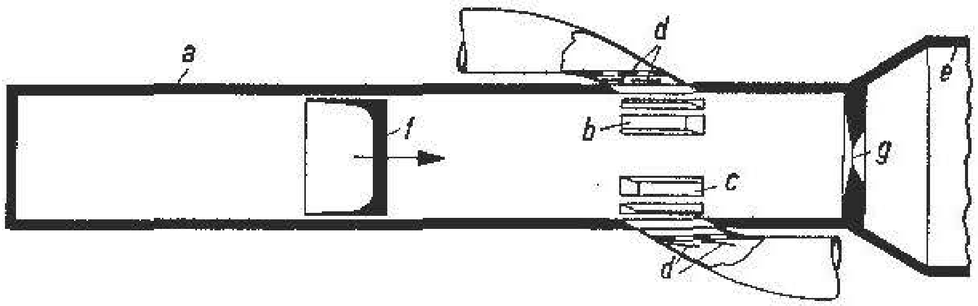

Fig. 10. Ignition device

a = *Cylinder*	*b, c* = *Slots*	*d* = *Non-return flaps*
e = *Combustion tube*	*f* = *Piston*	*g* = *Aperture*

wave left via the aperture *g* provided in the cylinder bottom and ignited the mixture contained in the combustion tube. The gas still remaining in the cylinder imparted to the piston the required backward motion of approximately 70 to 80 m/sec. On the return travel, the piston sucked in fresh mixture via the slots *b*. At the same time, the piston's velocity was reduced by the compression of the air enclosed behind the piston. The compressed air gave a forward motion to the piston and thus the cycle was repeated. In order to make sure that the rear end of the cylinder always remained filled with air only, fresh air was introduced continuously, at slight pressure, via a device not shown in the drawing.

For several years various modifications of this type of ignition device were operated successfully.

Since it was the primary object to obtain fundamental knowledge on the most suitable tube dimensions, the thrust obtainable and the fuel consumption, only short duration tests were run. Other tests performed with ignition systems extended to simple combustion tubes, and to combinations of combustion tubes and separate air-filled tubes, by means of which considerable quantities of air were accelerated by the combustion gases.

3.4. Influence of the German Air Ministry

In 1934 it had become somewhat difficult to raise the financial means required for the further development which constituted but a side-line of my normal occupation. I tried, though without decisive success, to interest and to obtain assistance from, outside circles for the idea of the vertical take-off and landing. Following the advice of a friend, I also worked out in 1934 some applications of the pulse-jet engine for defense purposes. Here I was assisted by Prof. Dr. G. MADELUNG, who worked out the aerodynamic data for a flying bomb, an interceptor fighter and a light bomber. The dimensions of the pulse-jet engines were based upon the trial results which I had obtained with individual ignition.

I submitted this worked-out project as a Memorandum to the Reich Air Ministry then in course of being established. Fig. 11 shows the proposal, from

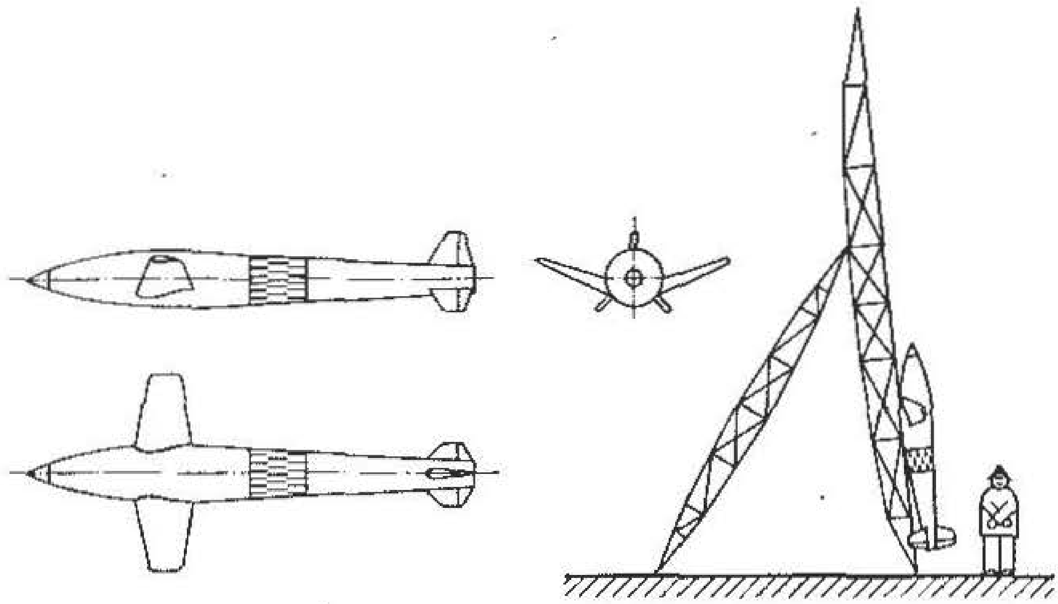

Fig. 11. Project of the flying bomb

this memorandum, for a flying bomb, which was later called the V-1. It will be seen that in this proposal the pulse-jet engine was fixed as an elongation at the rear of the fuselage. The speed of this body was calculated as 800 km/h at an altitude of 2 km. However, the proposals of this memorandum were not appreciated. At that time they were refused as being technically dubious and as uninteresting from a tactical point of view.

Nevertheless, in 1935 my being sponsored by Prof. A. Nägel, Dr. Lorenz, Prof. Busemann, Dr. Dornberger and Dr. von Braun resulted in the Reich Air Ministry and the Army Ordnance Office taking an active interest in the matter by granting financial funds which had to be paid back at a later date. I was able to re-pay these funds by the end of 1944. They amounted to somewhat less than one million Mark.

Thus, from 1935 onwards development progressed more speedily than before. Soon we had tubes operating, equipped with ignition devices and making it possible to establish data on thrust and consumption during periodic running.

3.5. Automatic Ignition

In 1937 the first oscillographic measurements were made and we found out that the ignition system operated at 50 c/sec, whilst the tube tested at that time operated at 100 c/sec. Thus every second ignition was initiated automatically. We were not too surprised about this discovery, for during the previous tests we occasionally established by aural perception that one or the other tube continued to operate 3 or 4 periods after the ignition system had been switched off. In most of the tests, approximately 1000, however, the engine stopped immediately the ignition was switched off.

We decided that the automatic ignition was due to the action of a weak shock wave travelling from the end of the tube back into the tube after the explosion took place and thus caused the second ignition. We intended to increase this shock wave in order to obtain automatic ignition. For this purpose we increased the resistance of the inlet valve at the intake end of the tube a little, and the success was striking. The engine immediately operated with automatic ignition and the ignition device previously necessary was no longer required.

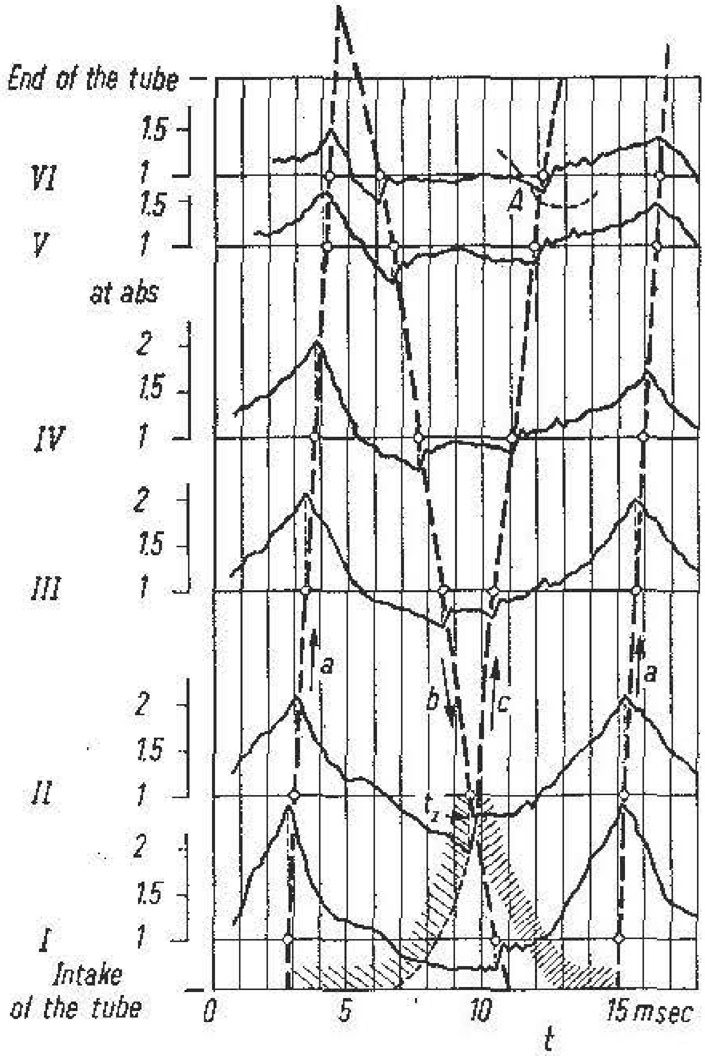

Fig. 12. Pressure oscillograms

The oscillograms of the pressure as obtained from this tube in 1938 are shown in Fig. 12. The pressure distribution curves are plotted versus time for various tube diameters. The dashed line shows the distribution of the maximum pressure and of the shock wave returning from the end of the tube. It was a cylindrical tube about 2 m long, the diameter was 120 mm, and it was provided with check valves. It was operated with an ether-air mixture, which was sucked in, by the tube, from a tank. The ignition effect of the shock wave having a pressure jump of only about 0.3 atm. is surprising. According to our tests, a minimum pressure jump of approximately 0.3 atm. is required in periodic operation for ignition of cold fuel mixture by shock waves coming from the combustion gas. The size of the pressure jump required depends on the temperature of the mixture, thus ignition of a pre-heated fuel mixture can be obtained with a still smaller pressure jump.

The evaluation of the test data shown in Fig. 12 makes — by using further measuring data and experience — a qualitative determination of the flow within the tube possible. This is shown in Fig. 13. Besides the pressure curves *a*, *b*, and *c* of Fig. 12, the flow curves are plotted versus the time between which equal proportions by weight of fuel mixture, gas or air are included. Flow curves delimiting a new charge against the gas left over from the previous combustion are referred to as *d*. The new combustion gases fill almost the whole tube, but still do not flow out.

For determining the condition of the gas, it is assumed that minor irregularities approaching the velocity of sound *a* are present. From the oscillograms it is possible to determine the rate of travel, and thus the gas temperature can be calculated for a small tube length — at times and in sections of the tube where no combustion occurs, and where there is only negligible gas motion present. For the purpose of Fig. 13, three different gas

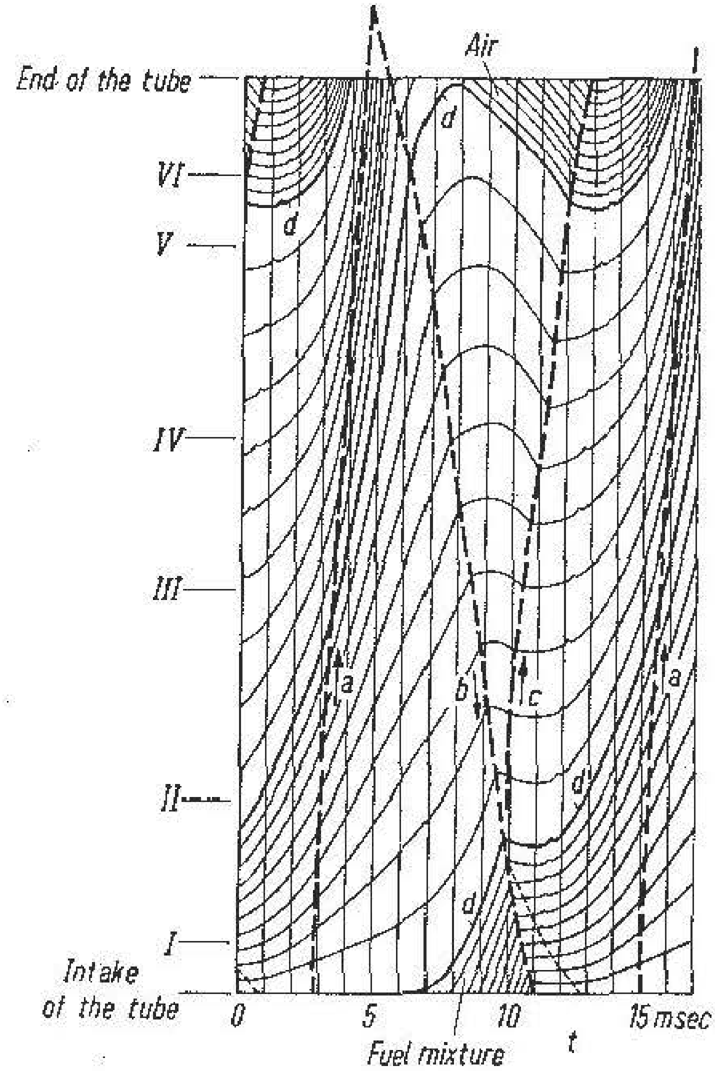

Fig. 13. Diagram of flow
a, b, c = Pressure curves of Fig. 12 *d = Flow curves delimiting new charge*

pressures were taken. They show — when reduced to the same pressure — a suitable correspondence. A further calculation was performed, in which it was assumed that the processes follow the adiabatic law sufficiently closely. Since the influence of the shock waves on the flow is relatively small, an estimate of the course of flow within the range of the waves could be obtained from the momentum theorem.

More powerful tubes which normally contain a bigger charge and which have more efficient combustion, show, in stationary operation, an expansion of the combustion gases beyond the end of the tube. The flow characteristics, however, are rather similar.

The most important technical feature found in the tests is the fact that, in the case of stationary operation, the quantity of fuel mixture that may be fed into the tube during one cycle has an upper limit. If a greater quantity of mixture is added, no automatic ignition will result. The practical solution of this problem was to provide the tube inlet with a certain minimum resistance.

3.6. Thrust Transfer

Periodic combustion involves a gradual power production resulting in power peaks, which exceed the average manifold thrust. In order to compensate the power peaks, the tube was connected to a mounting by means of a spiral spring. Thus the tube behaved as a vibrating mass, excited by the pressure pulsation of the combustion gases. With this arrangement, a power fluctuation of only about 1% of the average thrust is obtained at the point of fixture. The tube compresses the spring by about 10 to 20 mm, and in this position the tube oscillates through some tenths of a millimetre. Only the change in the travel of the spring is transferred as power fluctuation to the point of fixture of the tube.

The influence of the parameters of the spring on the levelling of the power fluctuations for a tube developing a thrust of 500 kg is shown in Fig. 14. The curve represents the maximum value of the force; the average thrust is represented by the dashed line. The abscissa represents the order of magnitude of the spring parameters *c*. The design chosen is marked by a circle.

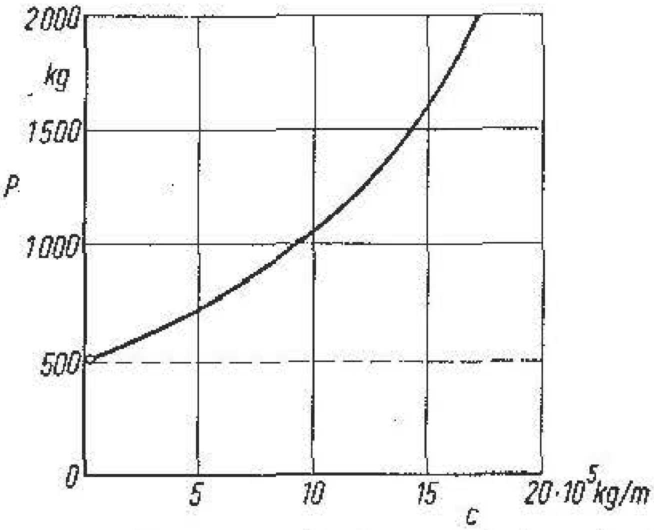

Fig. 14. Maximum force P at the point of mixture of the tube depending on spring parameter c

During operation, the amplitude of the force at the point of fixture is equal to the value by which the full curve exceeds the dashed line. When the maximum value approaches 1000 kg, the minimum value tends to zero. If a still greater spring parameter is chosen, negative power peaks will occur in addition to the positive ones. As the spring parameter increases, i. e. in the case of less resilient suspension, the vibration of the tube approaches the condition of resonance, in which powerful positive and negative forces occur.

For test purposes, in addition to a resilient suspension of the tube a hydraulic damping system was provided. The hydraulic system was composed of an oil-filled cylinder and a piston having adjustable leakage. Sudden changes in the operating conditions were thus attenuated aperiodically.

The system of resilient suspension and attenuation of the tube was applied successfully in our tests. In no instance were troublesome influences that would have been caused by the pulsating operation of the tube observed.

3.7. Tube with Additional Air

Up to 1938 we were primarily concerned with the development of the combustion tube, since this work had to provide the basis for any further development. In stationary operation, this combustion tube sucks in air at the end of the tube after every combustion. This results in additional air in stationary operation, which is eliminated, however, at higher air speeds.

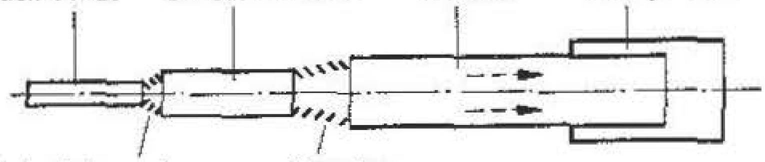

Fig. 15. Tube with additional air

In order to obtain arbitrarily a greater quantity of additional air, systems with separate air tubes were also tested up to 1938. Fig. 15 shows one of these test arrangements. The combustion tube, to which an air valve with a larger air tube was added, was attached to the 50 c/sec ignition device (left-hand-side of diagram). The end of the air tube was provided with an envelope tube, with its end closed by an annular bottom. It was intended to favourably influence the natural vibrations of the air column within the air tube through the natural vibrations in the envelope tube; however, we had to discontinue this promising project. In 1938 it was decided to stop the development of additional air (to be chosen arbitrarily) and to use all our means for the further development of the simple combustion tube.

3.8. The Development of the Valves

Therefore, from 1938 onwards, only the further development of the simple combustion tube was continued. The first effort was spent on the design of valves that could be used in practical operation. After having tested various valve forms, flaps and controlled or freely hinged valves, we selected for the purpose of further development a check valve. In the beginning of 1941 we obtained, with a certain design, a life of more than 20 hrs. of operation of the tube with a specific thrust of about 0.28 kg/cm^2. It was not our intention to retain valves with normal non-return flaps. But it was not possible to carry out further developments of this.

Substantial progress was made in the design of valve flaps, after it was realized theoretically in 1938 that the natural frequency of the flap should be chosen in a certain ratio to the frequency of the exciting force. When a non-

Fig. 16. Non-return flap

return flap (see Fig. 16) is pushed into the open position by a harmonically varying excess pressure then, due to the stiffness and mass of the flap, the displacement x of the end of the flap is given by:

$$x = \frac{x_{st}}{1-(\omega/\nu)^2}\left(\sin \omega t - \frac{\omega}{\nu}\sin \nu t\right).$$

In this equation x_{st} is the static flap displacement due to the excess pressure, ω is the frequency of the exciting force, ν is the natural frequency of the flap and t is the time. From this equation it follows that if ν/ω is odd ($\nu/\omega \geqq 3$), the flap returns to its original position with zero velocity. Thus the flap is prevented from striking too hard against its seat, which otherwise would destroy the valve in a matter of seconds.

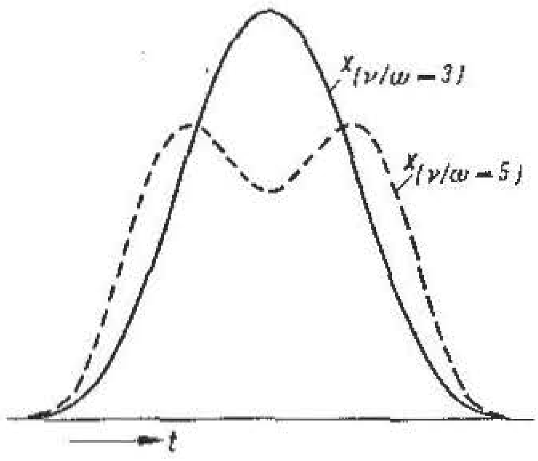

Fig. 17. Diagram of flap deflection
t = *Time*
ω = *Frequency of exciting force*
ν = *Natural frequency of flap*

The full line in Fig. 17 represents the flap deflection for $\nu/\omega = 3$, and the dashed curve represents this deflection for $\nu/\omega = 5$. Normally, these theoretical conditions are influenced by the assembly of the flaps. In particular the pressure drop of the air within the flap channel plays an important part. Moreover, the theoretical relationship provides for a pre-opening of the flap, i. e. a position of the flap free of stress, thus providing a certain opening of the valve. In periodic tube operation, a substantial increase in the quantity of air flowing through follows from such a positioning of the flap. This arrangement permits the assembly of a valve requiring only a little space.

From 1938 to 1940 larger tubes were also constructed and tested; up to 1938 we had tested only 120 mm tubes. In 1939 we increased the tube end diameter to 200 and then to 510 mm. Those tubes were approximately 3.5 metres long. The first 510 mm diameter tube operated in the beginning of 1940 and supplied a thrust of 500 kg in stationary operation.

3.9. The Preparation of the Fuel Mixture

A particularly simple kind of mixture preparation was tested in a 200 mm diameter tube. Fig. 18 shows the tube *a* with the inlet valve *b*. In the tubular inlet piece *c* there is an annular tube *d* containing some nozzles *e*. Liquid fuel is supplied continuously at a pressure of some atmospheres to the annular tube *d* via the pipe *f* so that the nozzles supply a continuous fuel spray into the tubular piece *c*. The axial velocity of the fuel spray is adapted to the periodic velocity *g*. The tubular piece c is relatively short and the periodic velocity *g* is not so great that important air oscillations occur. The air flows intermittently through the tubular piece *c* in the direction shown. At the instant of the explosion of the mixture in the combustion tube, the air in the tubular piece *c* is thus practically at rest, and during this time interval, the fuel spray from the nozzle *e* proceeds into a region whose volume corresponds to that sucked in by the tube during each period. Thus the air is provided with about half the quantity of fuel required. During the subsequent suction stroke, the pre-saturated air

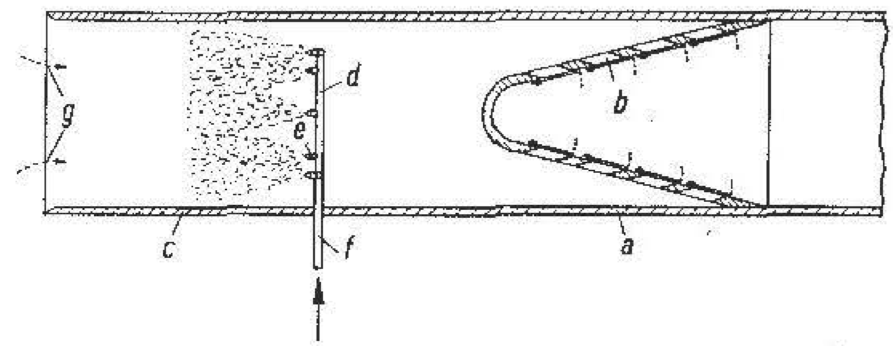

Fig. 18. Tube with mixture preparation outside the combustion tube
a = *Tube* *b* = *Inlet valve* *c* = *Inlet tube*
d = *Annular tube* *e* = *Nozzles* *f* = *Fuel pipe*
g = *Air velocity*

then passes the nozzles *e* and thus is provided with that portion of fuel it lacks for the proper preparation of the desired mixture. There will always be some prepared mixture in that portion of the tubular piece between the nozzle *e* and the valve *b*.

The mixture preparation with continuous feed of the fuel operated very well. The pressure oscillograms show very regular operation of the tube. However, this method of preparing the mixture was not continued since it took place outside the tube and thus entailed the risk of fire.

For this reason, the development of a periodic mixture preparation within the tube was started in 1939. In the spring of 1940 the so-called atomizers were developed (shown in Fig. 19). The atomizers are arranged closely behind the

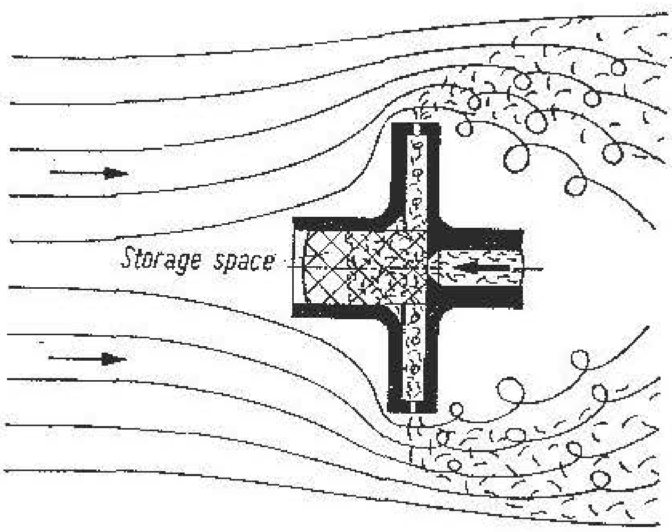

Fig. 19. Atomizer

valve, i. e. in the front portion of the combustion chamber. A steady flow of fuel enters the atomizers — in the diagram coming from the right-hand side — its flow energy is eliminated in the storage portion that is filled with a wire mesh. The storage portion is open towards the valve so that the pressure head formed by the periodic air intake can act on the surface of the fuel. Holes were machined into the rim of the hollow atomizer plate, through which an amount of fuel corresponding to the pressure head is ejected. This way we obtained an automatic and periodical admixing of fuel into the combustion air.

A 510 mm diameter tube developing a thrust of 550 kg was operated with such atomizers before the year 1940 was over. Fig. 20 represents an oscillogram of the thrust, gas pressure and fuel consumption. In terms of the maximum diameter of the tube, the specific thrust was 0.27 kg/cm². The fuel consumption per 1 kg of thrust and 1 hour was 2.8 kg.

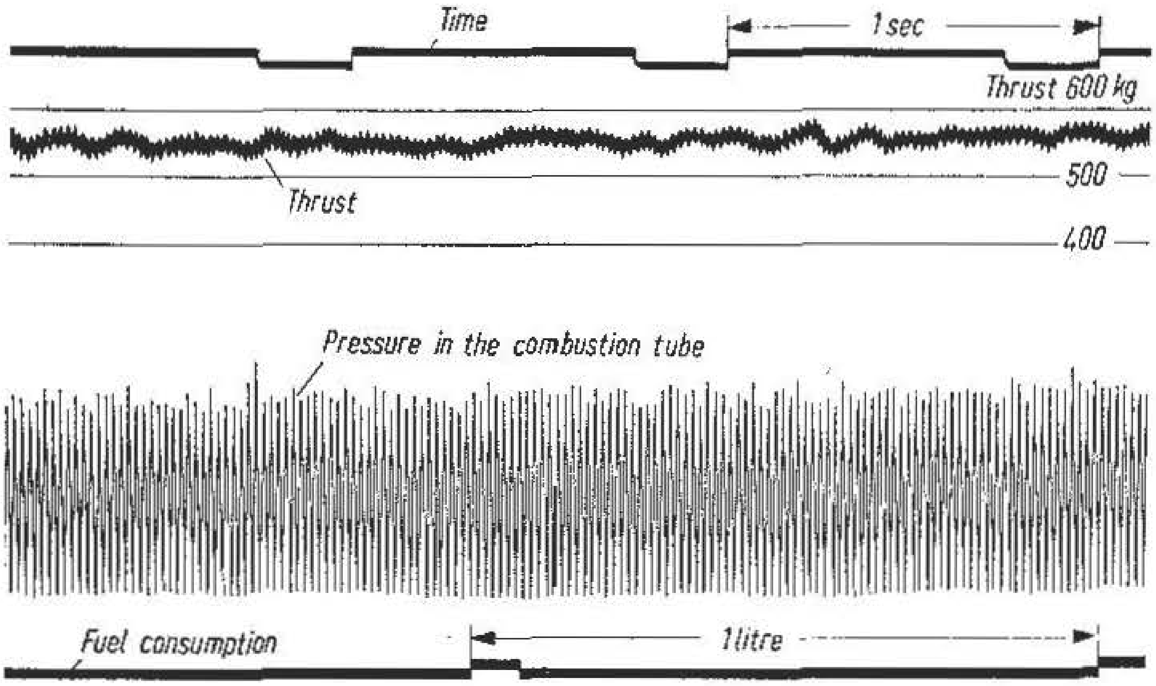

Fig. 20. Oscillogram of the 510 mm diameter Schmidtrohr

Fig. 21 shows the design of the tube. On the left-hand side there is the valve for the combustion air; the valve is composed of tapered air ducts and flaps. We also tested with equal success tubes of similar sizes which were provided with flap valves arranged normal to the tube. The diameter of the tube is reduced to 450 mm close to the valve, and the atomizers are arranged in this position. A tapered tube then connected this to the cylindrical portion of the tube of 510 mm diameter.

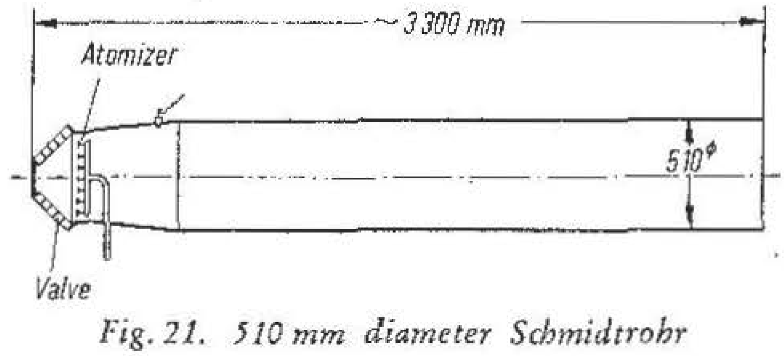

Fig. 21. 510 mm diameter Schmidtrohr

In the development of the propulsive unit, we endeavoured to satisfy the condition that the diameter should always be less than the end diameter of the tube. This demand arose because of the aerodynamic conditions prevailing when a tube is attached to a flying body. It became evident that it is necessary to feed the fuel at the frequency of the air intake in order to meet the above requirement. Otherwise an enlarged combustion chamber has to be provided, whose cross-section is approximately twice as great as that of the end of the tube. Since the size of the cross-section of the tube end is precisely proportional to the thrust produced, the extension of the diameter beyond the tube end diameter results in substantial additional resistance. It seemed important to us that this be avoided by proper design.

4. INTERDICTION OF DEVELOPMENT

At this state of development in spring 1941 I had the impression that, during 1940, about half a year had been lost in the development of the tube. My responsibility for this subject induced me to report accordingly to the Ministry.

Shortly afterwards, the authorities interdicted further research work regarding the tube to be carried out by my firm.

Regarding the loss of time, however, I continued to report to the Ministry; at the beginning of 1944 I estimated the loss of time as amounting to $2^1/_2$ years.

Some years ago I had started, on a minor scale, work on the development of a propulsive unit with high pre-compression of the mixture. The impulse for this work was given by the experience gained with the afore-mentioned ignition device. Since, with this device, the freely moving piston attained velocities up to 80 m/sec and high compression of the mixture, it seemed quite obvious to develop this construction for the combustion of all the propelling gas. With the assistance of the Air Ministry I was able to continue this work.

Furthermore, following the interdiction of development work on the simple combustion tube, my firm received an order to manufacture several tubes showing the state of development reached by us at that time. In connection with this work I occasionally found an opportunity to test minor improvements of the tube.

Thus, in 1942 I had tuned up a 500 mm diameter tube by conical enlargement to 750 kg stationary thrust, because I had heard that it was intended for taking-off acceleration. This tube had 450 mm diameter at the front end of the combustion chamber, 565 mm diameter at the end and a total length of about 3.5 m. Specific consumption in stationary operation amounted to 2.75 kg fuel per kg thrust and hour. Specific thrust in stationary operation amounted to 0.3 kg/cm^2 in relation to the maximum cross-section of the tube.

5. AUXILIARY EQUIPMENT

5.1. Starter

For starting larger tubes, a starter was developed in order to ensure starting at a specific moment. A 24 V electric motor was used for the short-time operation of an axial-flow blower unit, whose air stream was provided with fuel, and the mixture then was fed into the combustion tube from the centre of the valve. Fig. 22 shows the electric motor *a* (left-hand side) coupled to the impeller *b*. Six hinged valves *c* are arranged between the impeller and the tube front end; in Fig. 22 they are shown in axial position. When the motor is being started, they are turned automatically in this direction. When the motor is being switched off, they turned automatically for 90^0 and shut the short feed pipe *d*, thus sealing the combustion tube against the atmosphere. A fuel nozzle *e*

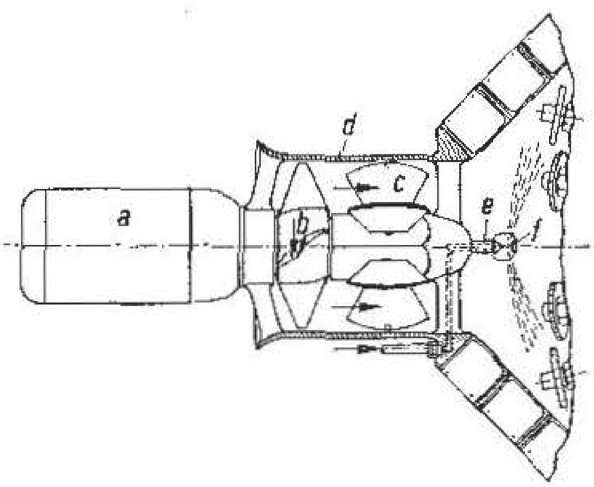

Fig. 22. Starter
a = Electric motor
b = Impeller
c = Hinged valves
d = Feed pipe
e = Fuel nozzle
f = Baffle plate

together with the fuel pipe is incorporated in the end of the short feed pipe *d*. The nozzle *e* sprays fuel against the baffle plate *f* so that the fuel is mixed into the air stream of the blower. The right-hand section of Fig. 22 shows the initial section of the valve of the combustion tube and illustrates the position of the atomizers arranged in that section of the combustion tube.

A relay is arranged beside the starter blower, which is operated by the fuel when the fuel flows into the tube from a pressure tank on opening the fuel supply main valve. The relay at first turns on the motor *a* and at the same time the supply of the starter fuel to the nozzle *e*. Subsequently, the relay operates the starter spark plug in the combustion tube and the feeding of the fuel to the atomizers of the combustion tube. Immediately after the first ignition, the relay automatically cuts off the motor and the fuel supply to the blower unit.

With this equipment starting was performed within 1.5 sec. The deviations to this period were less than 0.1 sec.

5.2. Fuel Pump

For delivering fuel from the tank, a pump was developed that was operated by the pressure pulsations of a tube of approximately 70 c/sec. The design of that pump is illustrated in Fig. 23. The fuel is fed via the short feed pipe *a*, it is conveyed by the piston *b* and it is discharged via the outlet pipe *c*. The piston *b* is designed as a suction valve. The pump is operated by the pressure pulses that arrive in the cylinder *e* from the combustion tube via the pipe *d*. The piston *f*, loaded with a pressure spring *g*, operates within the cylinder *e*. The piston *f* is connected to the piston *b* via the shaft *h*.

When, at the moment of combustion in the combustion tube, an excess pressure occurs in the pipe *d*, this pressure enters the cylinder *e* via the valve flaps *i*, and thus moves the piston *f* against the pressure spring *g*. At the same time the fuel is fed into the pipe *c* by the piston *b*. In order to obtain a uniform discharge, spring-loaded equalizer pistons *k* are provided, which allow part of the fuel to enter the cylinder sections.

If there is a negative pressure in the pipe *d*, the piston *f* will return. The flaps *i* are closed, however, so the pressure gas can escape via the holes provided in the bottom of the cylinder *e*. Non-return flaps *l* are arranged between the cylinder *e* and the pipe *d*, and provide a connection with the atmosphere in the case of a negative pressure in the pipe *d*. Thus the air enters the pipe *d* and, due to the leakiness in the bearing of the shaft *h*, the air carries the fuel with it.

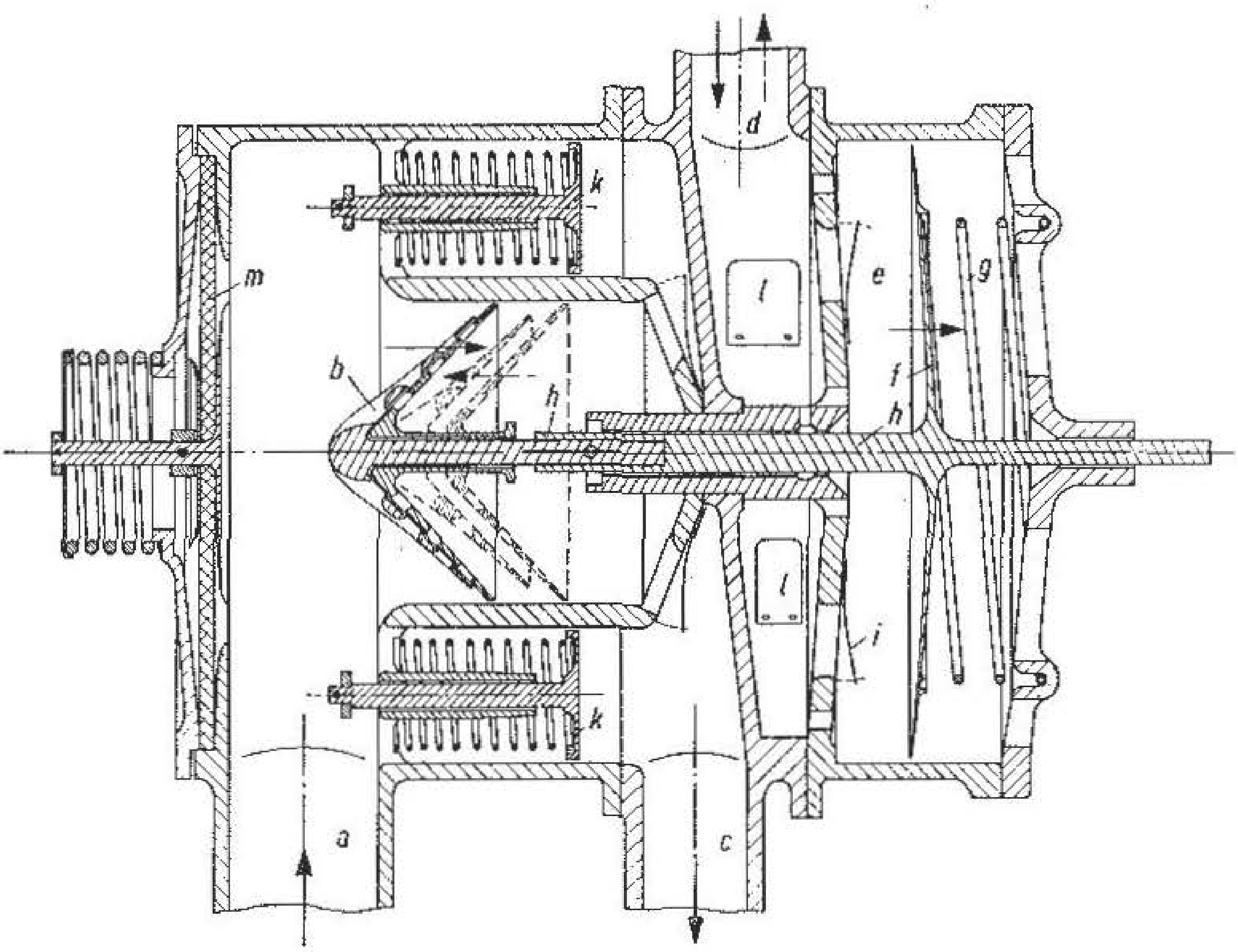

Fig. 23. Fuel pump

a = Feed pipe	*b = Piston*	*c = Outlet pipe*
d = Connecting pipe	*e = Cylinder*	*f = Piston*
g = Spring	*h = Shaft*	*i = Valve flaps*
k = Equalizer pistons	*l = Non-return flaps*	*m = Diaphragm*

Moreover, the periodic air supply provides good cooling of the equipment. When the return motion as indicated by the dashed line occurs, the piston *b* acts as a valve. The way in which a movable portion of the piston is detached from its solid seat and thus allows a flow through the piston *b*, is illustrated by means of dashed lines. In the top dead centre of the travel, the piston *b* effects sealing by the movable part resting against the supporting body. The diaphragm *m* is adjusted by means of a spring in such a way that it ensures a uniform fuel supply through the short feed pipe *a*, in spite of the periodic delivery.

The pump delivery was approximately 1 litre of fuel per second at a pressure of about 1.5 kg/cm^2.

5.3. Pilot Valve

As a rule, in our tests we used an automatic pilot valve as illustrated in Fig. 24, in order to shut off the fuel supply in the case of an unexpected interruption of the operation of the engine. When the pilot valve is open, the fuel enters the cylinder *b* via the short feed pipe *a*, and it leaves the cylinder via the outlet pipe *c*. A tubular piece *d* slides in the cylinder, the motion being imparted to it by the shaft *e*. A piston *f* is attached to the left end of the shaft *e*, with a spring *g* operating on that piston. The cylinder *h* is connected with the tubular socket *k* via a small hole *i*. The tubular socket *k* opens out into the

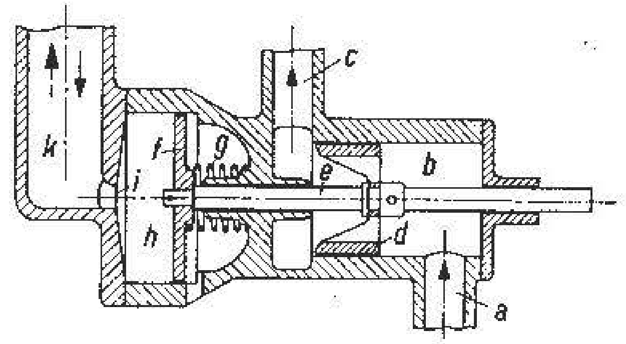

Fig. 24. Pilot valve

a = *Feed pipe*
b = *Cylinder*
c = *Outlet pipe*
d = *Tubular slide piece*
e = *Shaft*
f = *Piston*
g = *Spring*
h = *Cylinder*
i = *Connecting hole*
k = *Tubular socket*

combustion tube so that the gas pulsations operate in the tubular socket *k*. The moving masses and the spring g are balanced in such a manner that the fuel supply will not be shut off as long as combustion in the tube is regular. Should combustion fail, however, the valve is closed after 2 or 3 normal cycles so that the tube would not be flooded with fuel.

6. A TEST IN THE WIND TUNNEL

At the turn of 1942/43 the German Air Ministry asked me to send the 750 kg thrust unit for investigation in the wind tunnel at Brunswick.

In an initial test it was found out that the delivery of the fuel pump provided at Brunswick was too small for our tube. After a second fuel pump was installed, the tube began to operate on about ²/₃ of the normal fuel quantity. The engine ran rather noisily, since it operated close to the lower limit of the possible range of operation. However, the thrust could be measured, and the indicated thrust was about 375 kg at an air speed of about 350 km/h.

During this operation the building was heavily shaken and a rather excited man came to the test-stand, wanting to stop running the tube. In a side-room something seemed not to be alright; it was said that the building was in danger of collapsing.

With twice the thrust of this tube we had not experienced such shocks at our test-stand at Munich. It must be said, however, that we had fixed the tube always softly sprung, so that at the point of fixture the power fluctuation did not exceed 1 % of the thrust of 750 kg. This soft springing does not appear to have been provided for in the wind tunnel arrangement. In this case it was quite possible that shocks of several tons at 50 c/sec acted upon the building.

As far as I remember, following this incident no further trials were conducted with our tubes in the wind tunnel.

The approximate indicated thrust as determined by taking into account the resistance of the tube, was recorded correctly, as can be gathered from Fig. 25.

The top curve represents the variation of the maximum thrust with air speed, as determined by computation. It declines from 750 kg of stationary thrust to 630 kg at an air speed of 350 km/h, and later it increases again. In this operation, the tube consumes the fuel quantity indicated by the full line in the bottom of the diagram.

The point of 375 kg indicated thrust as measured is marked on the dashed thrust characteristic. The corresponding point of fuel consumption is shown on

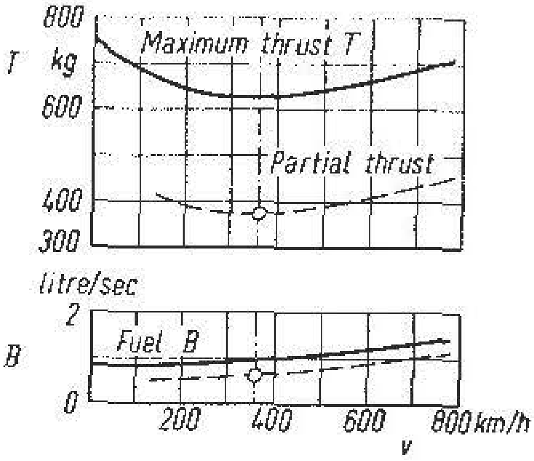

Fig. 25. Thrust and fuel consumption at different air speeds

the fuel consumption characteristic in the lower portion of the diagram. It thus becomes evident that these corresponding values are proportional to those valid for maximum thrust.

My collaborator HANS LEMBCKE established the following theoretical relationship between the thrust F in flight and the stationary thrust F_0:

$$\frac{F}{F_0} = \frac{m}{m_0} \frac{w - v}{w_0},$$

where

$$\frac{m}{m_0} = \frac{G(1 + k)}{G_0(1 + k_0)}$$

indicates the ratio of the accelerated masses and where

$$w = \sqrt{\frac{\eta_u}{1 + \zeta_w} \left[\frac{2\,Hg}{(1 + \lambda A)(1 + k)} \eta_{th} \eta_g + v^2 (1 - \zeta_v)\right]},$$

$$w_0 = \sqrt{\frac{\eta_u}{1 + \zeta_w} \frac{2\,Hg}{(1 + \lambda A)(1 + k_0)} \eta_{th}\, \eta_{g_0}}$$

are the values of the relative velocities as produced by the calorific value of the fuel. G/G_0 is the ratio of the fuel mixtures combusted. k denotes the ratio of the additional air accelerated to the quantity of mixture (corresponding to the value A/M of Figs. 8 and 9). η_u denotes the efficiency resulting from the irregularity of the flow. With reference to Fig. 26

$$\eta_u = \frac{\left[\int\limits_0^{T_0} \left(1 + a \sin \frac{2\pi}{T_0} t\right)^2 dt\right]^2}{\int\limits_0^{T_0} \left(1 + a \sin \frac{2\pi}{T_0} t\right)^3 dt \int\limits_0^{T_0} \left(1 + a \sin \frac{2\pi}{T_0} t\right) dt}$$

the integration being possible only over the outflow direction of the velocities, since the temporarily opposite speeds at the tube end are balanced according to the initial equation by an equal value of the outflow in first approximation. ζ_w and ζ_v introduce the coefficients of the resistance to the flow through the

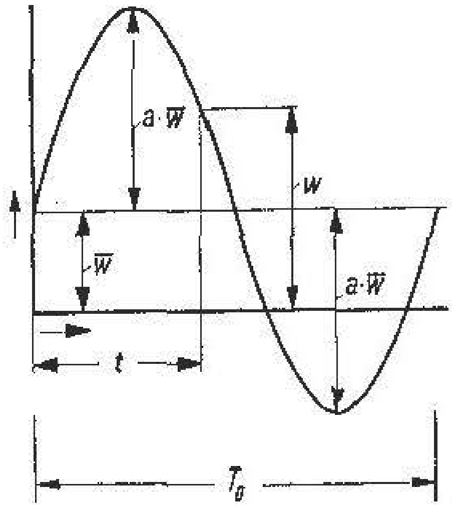

Fig. 26. Oscillation of the velocity

t = Time *w = Instantaneous velocity* *$\overline{w}$ = Mean velocity*

tube and the intake into the tube. The quantity of air theoretically required for combustion is referred to as A, i. e. the ratio of the weight of the air to the weight of the fuel; as a rule, $A = 15$. λ denotes the air, $\lambda > 1$ being a measure of the excess air. As a rule, $\lambda = 1.1$. The air speed is referred to as v, the acceleration due to gravity as g. The theoretical efficiency of the combustion, η_{th}, is the efficiency of the LENOIR-Process, which in stationary operation is 0.3. The energy decreases with the efficiency of combustion, referred to as η_g.

Besides determining the thrust in the case of air flow, the above equation assisted us in particular in establishing the efficiency of combustion. We found out early that the efficiency of combustion is only 0.22 in stationary operation. We furthermore found out that this efficiency increases in a certain proportion with the increase of the combustion air flowing in under pressure. Thus an efficiency of 0.5 is obtained at an air speed of 600 km/h.

By theoretical studies it was established that the additional air column expressed by k becomes zero at air speeds between 600 and 700 km/h due to the air return at the tube end. It declines according to the equation

$$k = k_0 \frac{G_0}{G}\left(1 - \sqrt{\frac{q}{p_0}}\right)$$

q being the ram pressure and p_0 the negative pressure as prevailing within the end section of the tube during the sucking-in cycle.

It is remarkable that theory shows that the performance of a tube can be determined at small air velocities. Thus the correctness of theoretically established relationships can be determined by tests where the velocity in blower stream, to which the tube is exposed, is relatively small. The results so obtained were confirmed later when the velocity in blower stream was great.

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DISCUSSION

Prof. Dr. QUICK (Aachen): You have spoken of the ignition and in particular of the shock-wave ignition. Is it really quite clear in which way the shock process is initiated? No doubt the shock-wave ignition offers one possibility; another possibility might be, however, that the gases remaining in the tube initiate ignition. Do you know, in more detail, which of these two processes might be the more likely one?

Dipl.-Ing. PAUL SCHMIDT: I am under the impression that there are two characteristic methods of short-time ignition of mixtures.

One method consists of the well-known ignition by heat conduction with whirling of the mixture. In this way considerably shorter ignition times are obtained than by heat conduction in an undisturbed mixture. The factor of time-gain amounts to 1 : 10 whilst the absolute value of the ignition velocity reaches 20 to 30 m/sec.

The other method is that of shock-wave ignition. The conditions prevailing here are perhaps best explained by the working of a tube the construction of which is similar to the tube shown in Fig. 21. The tube has a length of about 3.5 m. At the entry the same valve, as shown in Fig. 21, is fitted. Directly following the valve is the combustion chamber of 0.45 m diameter. From here onwards the tube increases steadily in diameter with a conical angle of 2^0, the diameter at the tube-end being 0.565 m. The air sucked in by the valve and mixed with fuel flows at about 250 m/sec through the combustion chamber the cross-section of which is completely filled. From the measured thrust of 750 kg, the fuel consumption and from the under pressure at the end of the intake cycle it can be computed that about 1.5 m of the tube length are filled by the mixture. This mixture has a volume of 250 litres. The time of one periodic cycle amounts to 20×10^{-3} sec. From the increase of pressure it follows that ignition will be terminated after about 3×10^{-3} sec. Thus an ignition velocity of about 500 m/sec for the mixture column of 1.5 m length is obtained.

Occasionally, the tube has been operated in the open air at —20 °C, and it started without lapse of time and worked through without interruption. Peak pressures of almost 5 ata were measured, so that the theoretical value can be assumed to be about 9 ata. Thus this process is to a large extent a constant-volume combustion. With a tube diameter of 0.5 m and with the forcibly axial flow of the mixture which fills out the total cross-section, wall-influences and remaining gases may be left out of consideration. For the periodical operation of this tube there seems to me to be no feasible explanation other than ignition by shock-wave. According to Figs. 12 and 13 the shock-wave originates at the tube end when the combustion gases flow out, and from there runs backwards into the tube towards the mixture.

The same ignition velocity of about 500 m/sec is obtained also from tests with individual ignitions of an undisturbed mixture according to Fig. 8. Here the mixture column of 0.5 m length is ignited by a suddenly generated shock of hot combustion gases. These gases enter through an opening of about 10 mm diameter which is situated in the middle of the bottom of the combustion chamber of 80 mm diameter. The shock gas is generated by a device similar to the one shown in Fig. 10, though only one gas shock is generated. It appears from Fig. 8 that the maximum pressure of 5 ata is being obtained in a little over 1×10^{-3} sec. Thus, combustion will be practically terminated within this period. The ignition must therefore pass through the mixture at about 500 m/sec. This appears to me to be feasible only by shock-wave ignition.

In this case, the ignition effect cannot be theoretically explained by the well-known gas-dynamical laws. According to these laws the rather weak waves, which effect ignition, result in too small a temperature increase, which is much below the ignition temperature of the mixture. The shock-wave ignition may be explained, however, when the processes within the shock-front are considered from a molecular-kinetic point of view. I may refer to the British patent Nr. 737,555, where at a later date I have laid down some details on this subject.

DEVELOPMENT OF THE V-1 PULSE JET

FRITZ GOSSLAU *

1. TASK

In 1939 the German Air Ministry decided to have jet engines developed. Each of the German aero-engine factories was asked to work on different technical solutions of this task. The ARGUS MOTOREN GESELLSCHAFT, Berlin, were asked to develop a pulse jet. Curiously enough, this task was formulated as follows:

"Take a test tube, put in some drops of gasoline, shake the tube and ignite its open end. The mixture will not burn continuously, but in rhythmic pulses."

As an oscillation process of the working gases had evidently to take place, we opposed two oscillation chambers in our first model (Fig. 1).

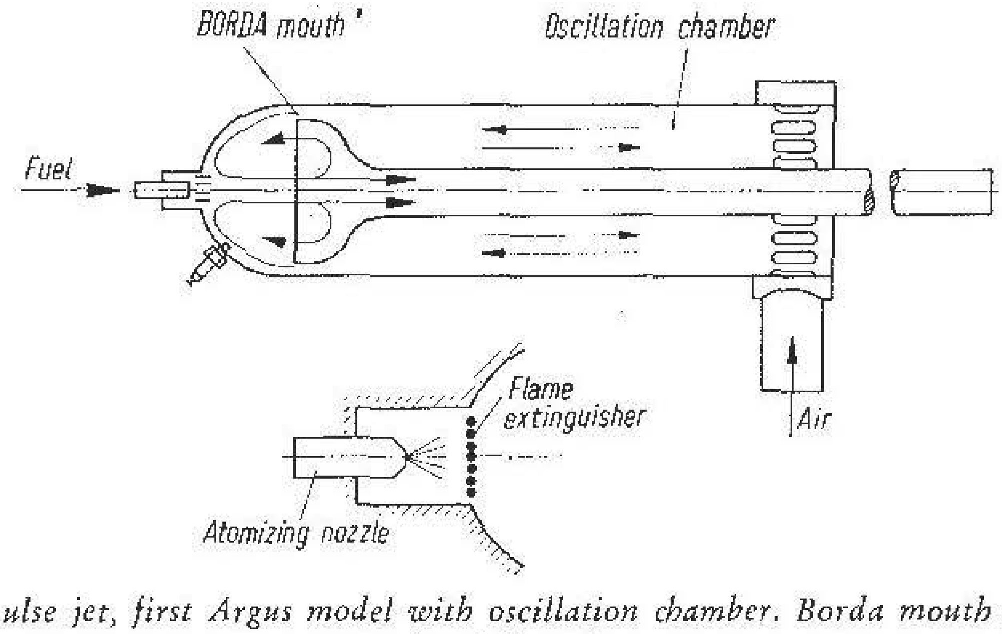

Fig. 1. Pulse jet, first Argus model with oscillation chamber, Borda mouth and flame extinguishing sieve

The pulse jet was intended for flying speeds of at least 700 km/h. We therefore thought that we could supply the air at the corresponding dynamic pressure. We told ourselves: If one of the two components needed for the explosion, i. e. the air, enters intermittently, the other component, i. e. the fuel, can be supplied continuously to the combustion chamber. This analysis facilitated the development of our pulse jet and its control system considerably, and later on contributed to the simplification of the power plant of the flying bomb.

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When pulsation took place, two things had to be prevented:

(i) A return flow of the combustion gases. We had therefore provided a flow-technical valve in the form of a BORDA mouth.

(ii) A continuous burning of the fuel. For this purpose the atomizing nozzle was sunk into a small secondary chamber, and this chamber was screened from the combustion chamber by a flame extinction strainer (based on the principle of the well-known miners' lamp).

The apparatus (Fig. 2) was first operated on November 13th, 1939, and immediately we were surprised to observe an intermittent operation with pulsations of high frequency.

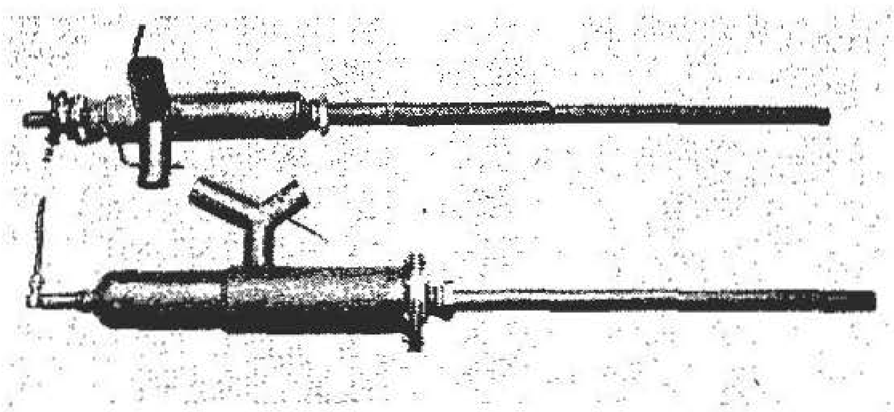


Fig. 2. Models corresponding to Fig. 1

On a second model (Fig. 3), the air entered from the front, under the ram-pressure, and was deflected into the combustion chamber via an annular vortex. We also aimed at achieving an annular vortex in this ball-shaped combustion chamber. The combustion of this model was excellent, and its pulsating operation was steady. We were surprised, however, by the fact that the apparatus continued working satisfactorily after we had switched off the ignition.

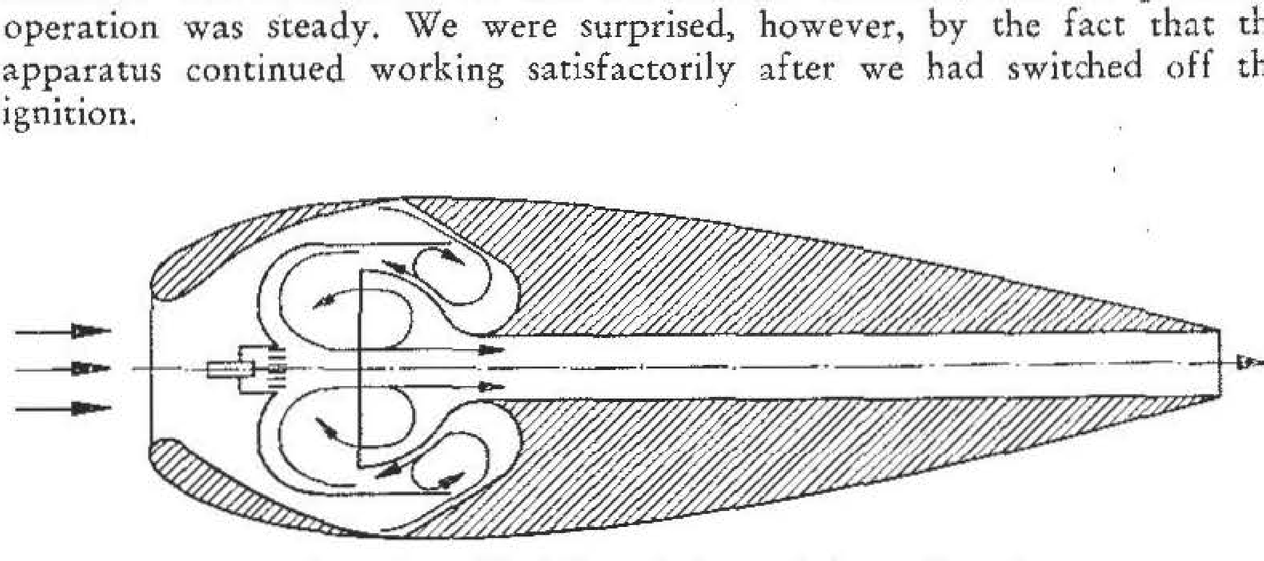


Fig. 3. Second model of the pulse jet with air intake at front

Our third model was equipped with a leaf-spring valve which could be bought as a standard product, i. e. a compressor valve. This pulse jet (Fig. 4) was designed as follows: Fuel and air enter the mixing chamber together, without deflection and in the same direction. The effect of the flame extinction strainer was now achieved by means of a necked portion. The velocity of the mixture became so high, and the pressure in the secondary chamber was balanced in such a way, that a flash back of the flame and a continuous burning

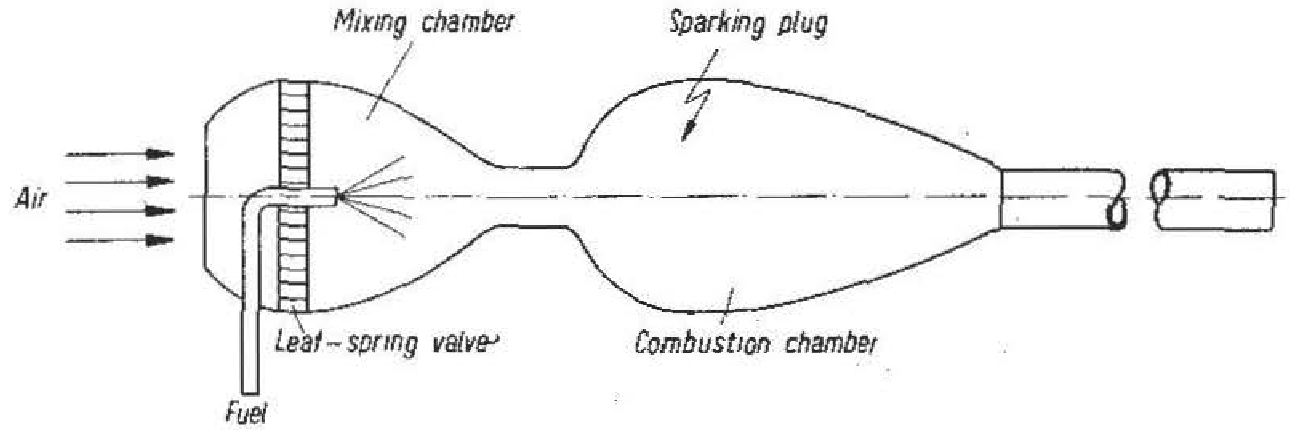


Fig 4. Third Argus pulse jet model. The neck-down in the combustion chamber prevents continuous burning of the fuel at the injection nozzle

of the mixture were prevented under all circumstances. Moreover, this device protected the sensitive valve from being directly touched by the burning gases.

Hence this apparatus already contained all the elements of our nozzle-diaphragm — mixture-formation — process, which will be dealt with later on.

After reaching this state of our experiments, three and a half months after starting them, we were informed by the Ministry that the pulse jet had already been the subject of investigations of another group in Germany for several years. It was the first time that we heard the name of PAUL SCHMIDT, and we were asked to inspect his work at Munich. Herr SCHMIDT demonstrated his big pulse jet (Fig. 5) in March 1940. A big paper bag filled with air and propane gas was suspended in front of the valve apparatus and the pulse-jet unit operated some seconds until the gas was consumed.

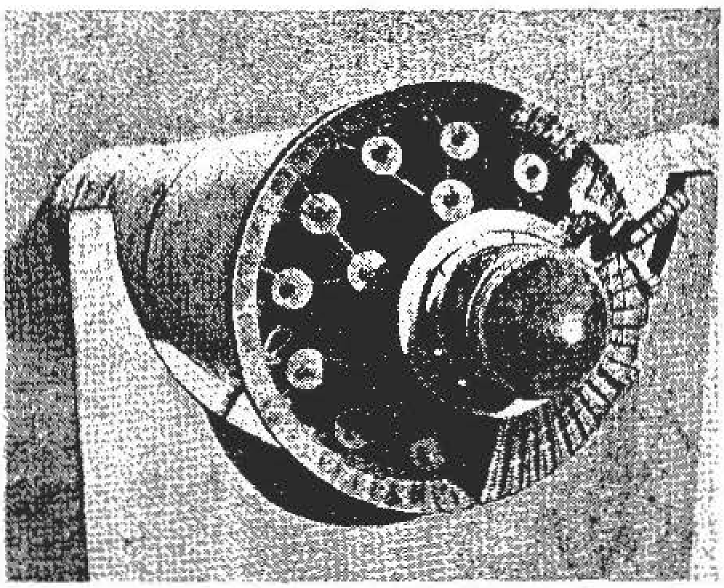


Fig. 5. Conical valve apparatus (see also Fig. 2) of the pulse jet SR 500 built by Paul Schmidt. Destroyed after 13 minutes running time with 450 kg thrust

Herr SCHMIDT had planned to use a small pulse jet for the operation with liquid fuel, but the liquid-fuel system was then obviously in its early state of development.

2. LOW-SPEED FLIGHT TESTS

Up to that time Herr SCHMIDT had only achieved short-time operation on test stands. Nobody knew what thrust could be achieved by means of these pulse jets during flight, or if the further development for the propulsion of high-speed aeroplanes was worth while.

Therefore, ARGUS was asked to develop a pulse jet with a static thrust of some 120 kg for investigations during flight. This was to be done in the shortest possible time, and on April 30th, 1941, this pulse jet made its first flight suspended beneath a training plane (Fig. 6).

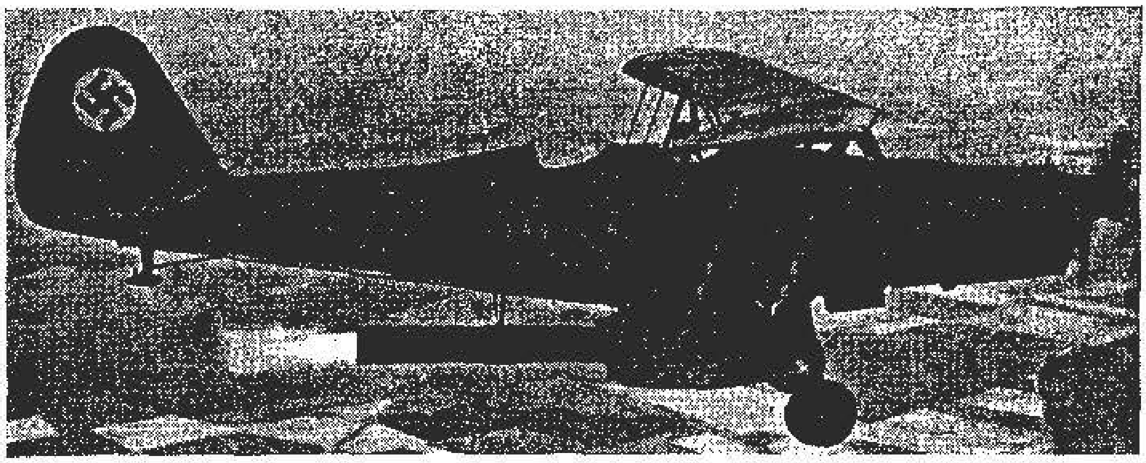
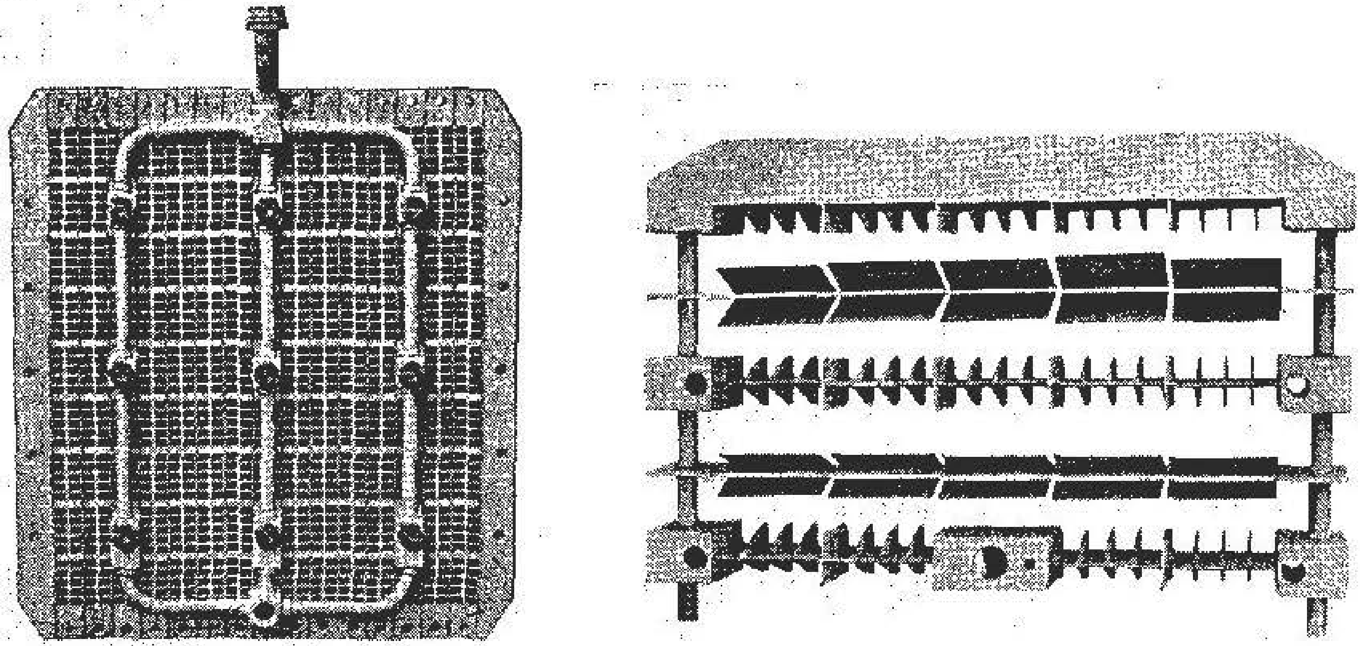


Fig. 6. 30th April 1941: First flight of a pulse jet (Argus design)

The whole valve system, however, was arranged level (Fig. 7), for simplified manufacture, and we adopted from Herr SCHMIDT the element of the preliminarily bent valve spring flap (Fig. 8). As to the mixture formation we adhered to the method developed by ourselves.



Figs. 7 and 8. The flat valve apparatus of the Argus pulse jet and constructive arrangement with fuel atomizer nozzles and starting air duct

In the summer of 1941 we were asked to motorise cargo gliders. In this connection we arrived at the first aeroplane driven solely by pulse jets.

Towards the end of 1941 the pulse jet had proved to be satisfactory for low-speed aeroplanes, but it was not at all clear if the unit was suitable for higher flying speeds. Doubts were raised in this connection which had to be taken seriously.

At that time my collaborator, Dr. DIETRICH, who had earned great merit in initiating the development, separated from ARGUS, after he had proved, as he thought, in a memorandum, that no useful thrust could be expected from jets at speeds exceeding 600 km/h *.

3. THE V-1 IS ORDERED

Aerial warfare became more and more difficult, and the argument of insufficient accuracy, which had been the reason for the refusal of the long-distance flying bomb at the beginning of the war, became invalid. We therefore decided to submit the project once more and to suggest the pulse jet as its engine.

In view of the fact that, at that time, the performance of the pulse jet at high speeds was completely unknown, it was a bold decision of the German Air Ministry to order a long-distance missile on June 19th, 1942.

The decision to equip an unmanned flying bomb with a pulse-jet engine raised additional problems for ARGUS. These were:

a) Determination of the thrust of this unit at high flying speeds;

b) Design and construction of a fully automatic fuel-control system;

c) Development of a suitable starting system in order to allow the launching of the projectile by pressing a button.

4. POWER PLANT OF THE V-1

While ARGUS worked at these tasks, considerable progress was achieved with the design of the airframe. The lay-out of the power plant is shown in Fig. 9.

* In order to set right numerous misunderstandings found in technical literature, I herewith wish to clarify the following points:

1. The pulse jets of Messrs. Argus were not constructed under licence but were an independent development.
2. Argus pulse jets, i. e. including "V-1" propulsion, did not employ the Schmidt patent 523 655 (of 25th April 1931) which was, erroneously, frequently mentioned in this connection.
3. This patent 523 655 does not at all deal with the original idea of the invention of the pulse jet itself, which had been known since 1906, but concerns an additional idea in saying that in "known, approximately pipe-shaped reaction spaces, the one end of which is open" (Karavodine, Marconnet), "a quantity of air, the weight of which is from 10 to 50 times greater than the weight of the inflammable mixture, is immediately accelerated by the force of the excessive pressure of the exploding mixture . . .".
4. The realization of this idea was succesful only in individual explosions, however, never, in repeated continuous operation. After years of fruitless test work the inventor (Schmidt) gave up his efforts to achieve continuous explosion, as early as 1938.
5. Laboratory pulse jets, as Herr Schmidt had since operated and demonstrated in March 1940, function in principle in accordance with the ideas, patents, tests and publications by Karavodine, Marconnet and Barbezat (French patents 374 124 and 412 478) which had been known since the beginning of this century. (Literature: "Die Turbine", publishing year 1909, page 305 and subsequent pages, and "Stahl und Eisen", published 1911, No. 42, page 115 and subsequent pages.)
6. Marconnet had even laid down the plate spring valve in his patent specification (French No. 412 478) as the inlet device for the pulse jets:
"The mixture enters the combustion chamber through a very light valve . . . This valve consists of a metal plate spring which opens and closes similar to the voice of a clarinet . . . ".
7. However, whilst Marconnet's plate valve was flat when in a closed state, and curved when opened, Herr Schmidt had recommended the reverse. His valves were curved when in a closed state and flat when the valve was open. This "precurved" plate valve was the only device which Argus really took over from Schmidt, whilst the valve apparatus as a whole was completely and basically remodelled by Argus, and with progressing development was more and more simplified to facilitate production.

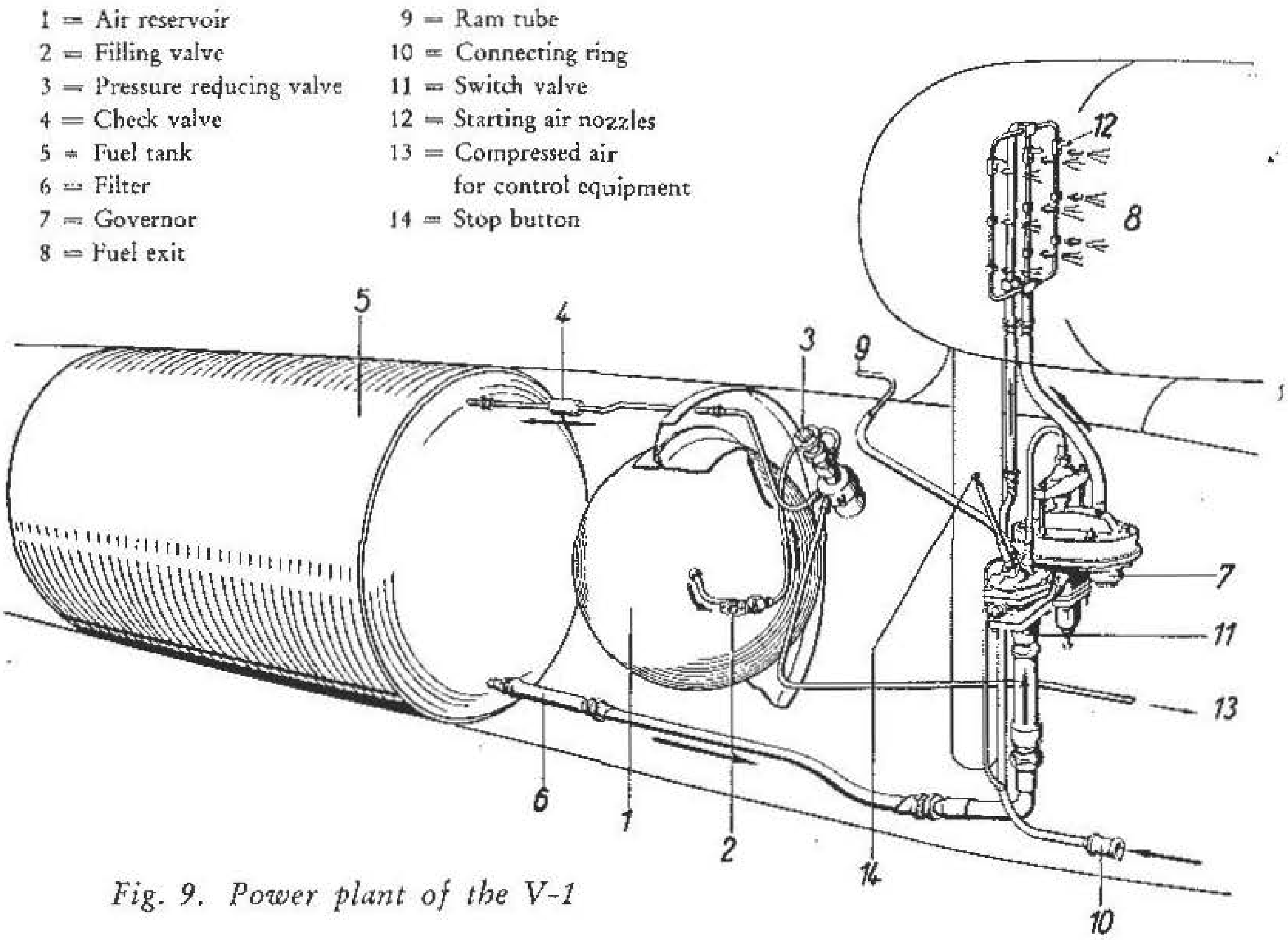


Fig. 9. Power plant of the V-1

4.1. Fuel Supply

The fuel in the tank was put under pressure by means of the compressed air which in any case was needed for the control system. The fuel flowed through the filter and control system, was atomized by the injection nozzles, and was continuously supplied to the combustion chamber.

4.2. The Fuel-Control System

With this unmanned flying body the fuel-control system had to perform complicated tasks, which can be judged from a consideration of the time histories of the fuel tank, and a point just ahead of the injector nozzles (Fig. 10).

Before the take-off the pressure in the fuel tank was 7 atm but for starting the injection pressure at the nozzles had to be reduced to 1.2 atm. Immediately after starting, the injection pressure had to rise to 2.2 atm for static operation, while the pressure in the tank simultaneously decreased to 6.8 atm.

Owing to the inertia effect of the fuel columns, a pressure peak of 9 atm arises when launching, and this pressure peak has to be removed by the control system.

During the launching operation the pressure at the nozzles had to rise simultaneously to 2.6 atm, corresponding to the take-off speed.

The injection pressure then had to drop during climb and rise again with increasing flying speed after changing to horizontal flight. During flight the pressure acting on the fuel tank slowly dropped from 7 to 6 atm.

Fig. 11 shows the design of the fuel-control system. When the stop valve was opened, the fuel flowed to the constant-pressure valve which had to maintain a constant pressure of 4 atm in front of the throttle valve. The throttle valve

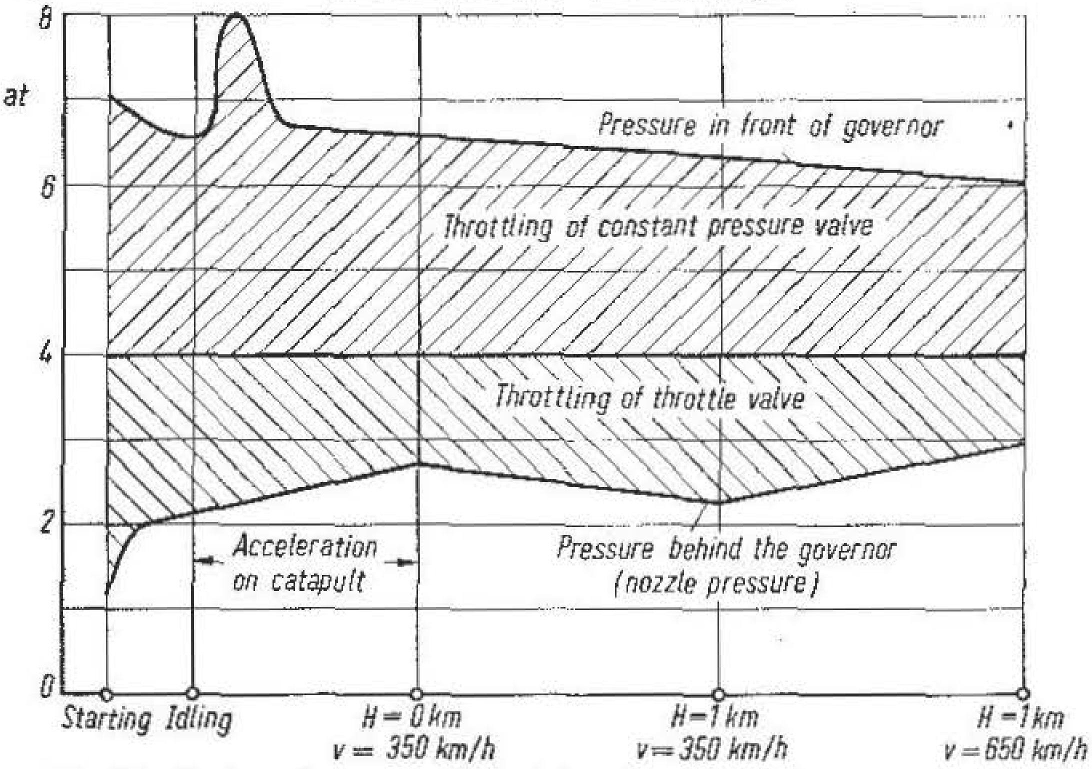


Fig. 10. Task to be accomplished by the engine fuel-control system

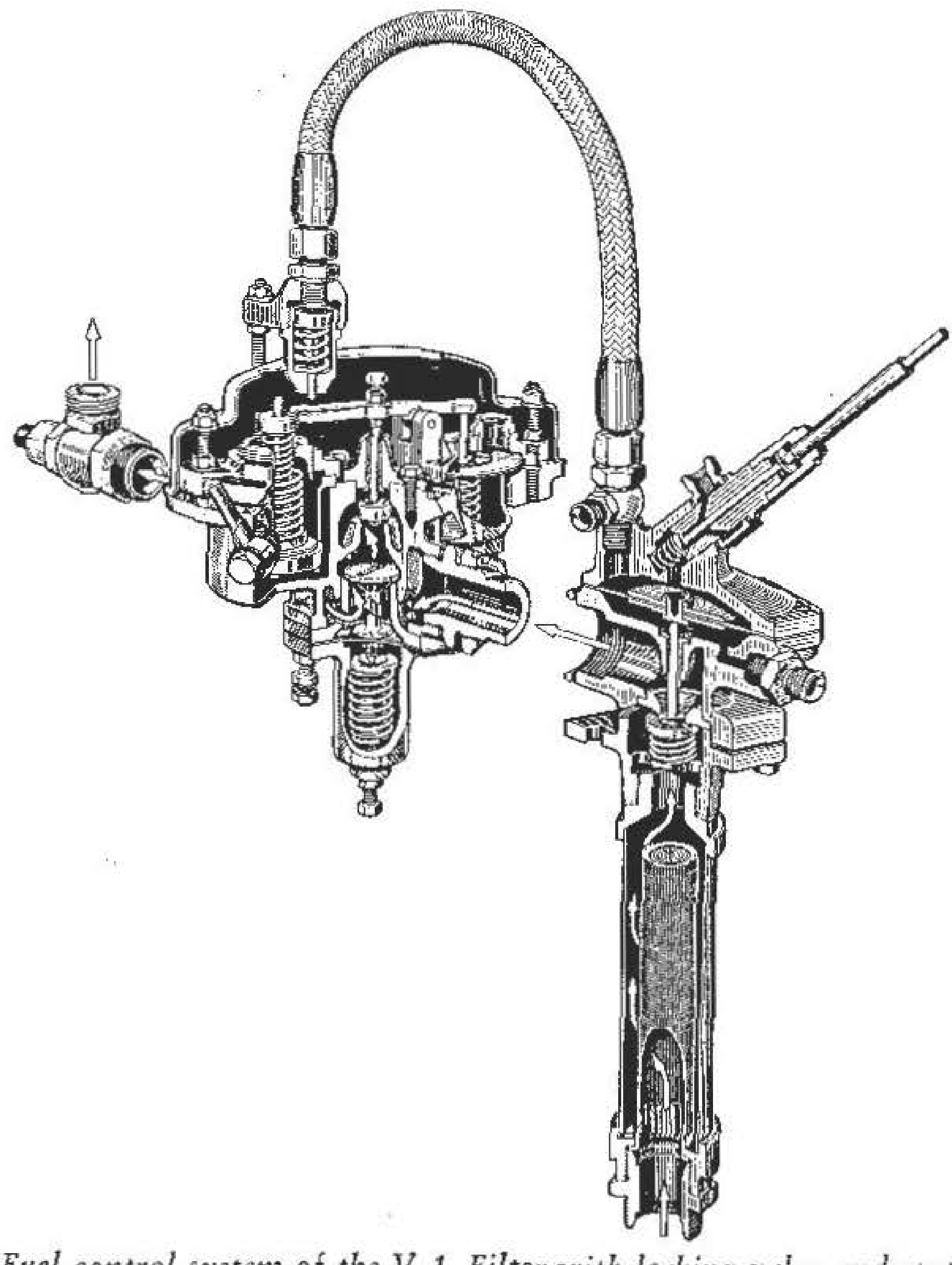


Fig. 11. Fuel-control system of the V-1. Filter with locking valve and stop mechanism, balanced-pressure valve and throttle valve, ram-pressure piston and barometer capsule

was subject to the influence of the ram-pressure on the one hand and of the altitude capsule on the other hand, both of them acting against each other on a balance beam. The altitude capsule was a chamber which was closed by a plastic diaphragm. With increasing altitude, the fuel flow was throttled and with increasing ram-pressure the throttle valve was opened wider.

4.3. The Push-Button Starter

The starter system of the power plant was connected with the fuel-control system. We had found out in preliminary tests that, for safe starting of the pulse jet, it was important to bring a certain fuel quantity with a corresponding quantity of compressed air simultaneously and suddenly into the combustion chamber, so that no burning, but rather a violent explosion, should take place.

When compressed air was let onto the diaphragm of the stop valve for starting, it opened suddenly. At the same time the compressed air on the balance beam of the fuel-control system acted in such a way that the injection pressure was reduced to 1.2 atm. This starting method was very reliable and enabled us to use the push-button starter.

5. FLIGHT-TESTING OF THE V-1

5.1. The First Test Shot

Work on completing the first test V-1 had made extraordinarily quick progress, and the first test shot was fired on December 24th, 1942 — six months after the initial order. At this time no results of the flight measurements on the pulse jet, which would have rendered possible an optimum design of the governing system, were available.

During the flight tests the pulse jet proved to be rather a troublesome power unit. The sensitive carriers could not stand the high pressure fluctuations of the pulsating jet, and long repair work on the frames had to be carried out after each test flight *.

When the fuel-control system had to be supplied in the winter of 1942 we only knew that the pulse jet extinguished easily with too high a rate of fuel flow. In order not to endanger the initial tests of the V-1 the rate of fuel flow was controlled with the greatest precaution, and the flying speed was not at all satisfactory in the first shots. But progress was achieved, and speeds of some 600 km/h were soon reached.

5.2. Speed Crisis

It was just at the time of the invasion when a serious reaction set in. Peenemünde announced that the flying speed of the test equipment suddenly

* Practical flight tests carried out by the Argus Flight Department were of decisive importance for the airworthiness development of jet propulsion, and I wish to express in this place my special thanks to our Flugbaumeister Staege and Schenk for their valuable co-operation. In the evaluation of the results, Dr. Zammert and Dr. Flössel, and in the constructive development of the various fuel-control systems which were based on these evaluations, Messrs. Weiche, Belitz and Kreuziger earned special merit.

dropped to 450 km/h. As you can imagine, we were thoroughly upset. We were thinking of the cause day and night and finally found out: the altitude capsule of our fuel-control system had been covered by a plastic diaphragm. Without our being informed, this plastic material had been changed to another material which allowed the fuel to diffuse. Gasoline sometimes flowed over this diaphragm when testing the governing system, and this gradually diffused into the capsule. The altitude cell thus worked incorrectly and hence too much fuel and power were throttled at low altitudes.

A great number of low-speed V-1's were actually launched.

5.3. Increase of the Speed from 600 to 765 km/h.

We, the engineers, did of course not agree with this decision and we were finally permitted to substitute new altitude capsules. The speed was in this way increased to 645 km/h.

The results of our flight department had meanwhile shown that the rate of fuel flow would allow another increase of speed.

That was why, in August 1944, the ram piston in the fuel-control system was enlarged. The speed of the V-1 increased by another 50 km/h, but still higher rates of fuel flow led us to expect further improvements. We now modified the constant-pressure valve so that a higher injection pressure became available at the fuel nozzles. The result of this measure was another 75 km/h increase of the flying speed.

In order to achieve an optimum (Fig. 12), a new very simple fuel-control system was designed in which the constant-pressure valve was omitted and the

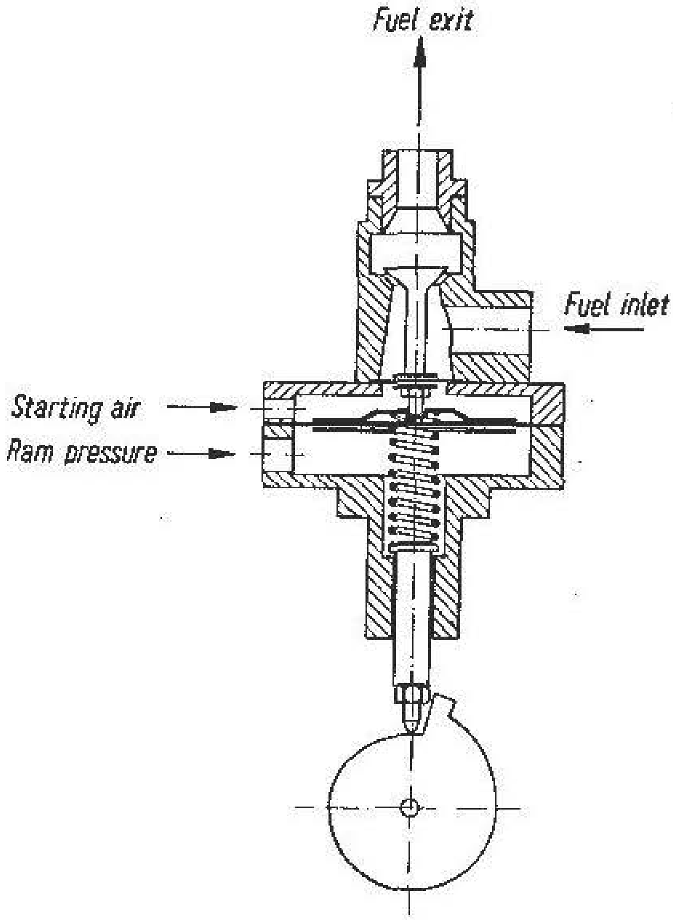


Fig. 12. Essentially simplified fuel-control system (end of 1944); adjustment of flight attitude by a cam

work of this valve was carried out by the throttle valve. Owing to the omission of the corresponding throttle losses we succeeded in using the full pressure of the fuel in the tank at the nozzles. Another 25 km/h of speed increase was thus obtained.

Fig. 13 shows the results. The upper curve shows the limit of the highest thrust obtained without superfattening. This limit was found by flight-testing.

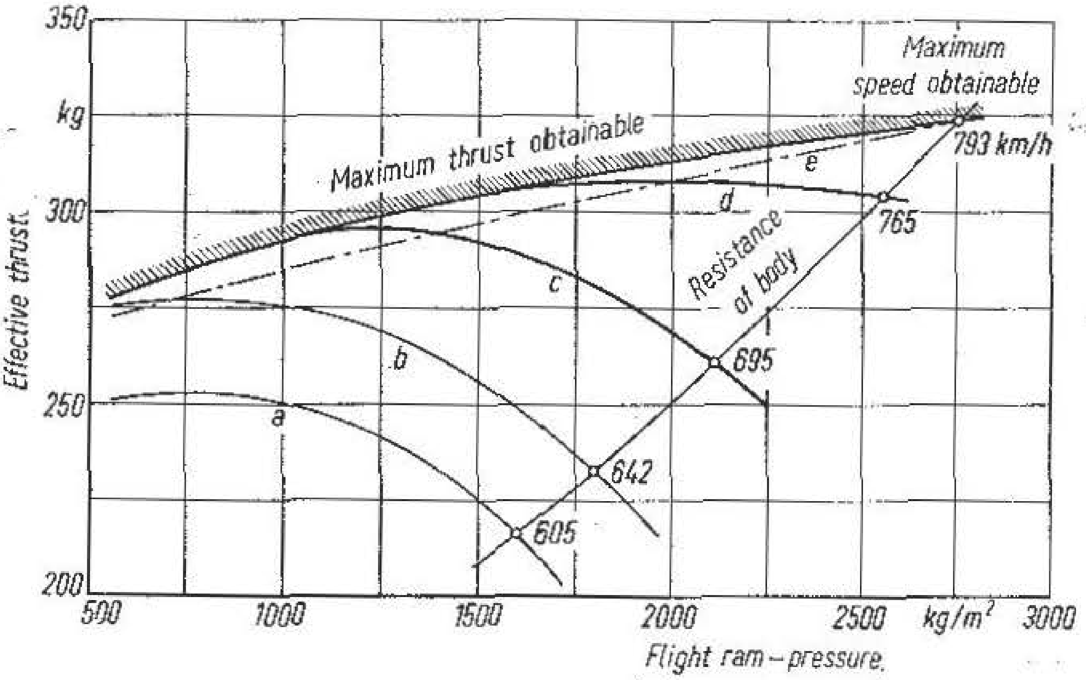


Fig. 13. Increase in flying speed of the V-1 from 650 to almost 800 km/h by adjusting the fuel-control characteristics to the possible fuel flow of the pulse jet As-014 which had been determined in flight tests

Other curves show the drag of the airframe and the thrusts achieved by means of the various types of fuel-control systems.

Only a few test types of the fuel-control system corresponding to curve *d* were constructed. The flying speed reached with them was 765 km/h.

We constructed only a few specimens of the single-valve fuel-control system (curve *e*). The results of measurement were reported in the last session of the V-1 Working Staff on February 2nd, 1945. The speed of the V-1 had been increased to 800 km/h!

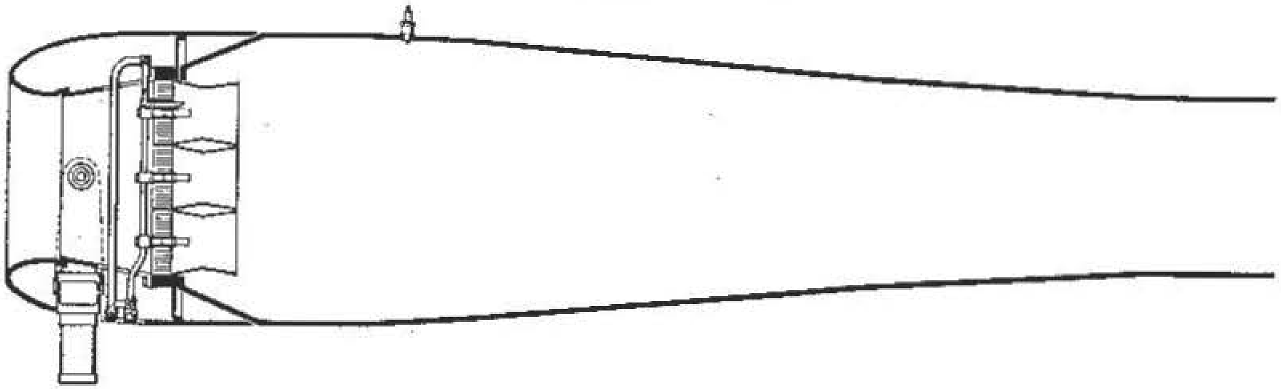
However, the war came to an end before these improvements had reached the front. They had been achieved by improving the fuel-control system only, but the pulse jet itself had not been modified.

6. THE LAST TYPE OF THE ARGUS PULSE JET (1945)

6.1. Design

Fig. 14 shows that type of the pulse jet which was finally used for the V-1. The 3 m long pipe with the combustion chamber and the spark plug, the jet diaphragm, the valve box, the fuel nozzles with the fuel line and the intake cowling with the fork suspension, can be seen at bottom left.

The upper part of the photograph shows a sectional view of the head of the pulse jet. The line of the compressed starting air and the small tubes supplying



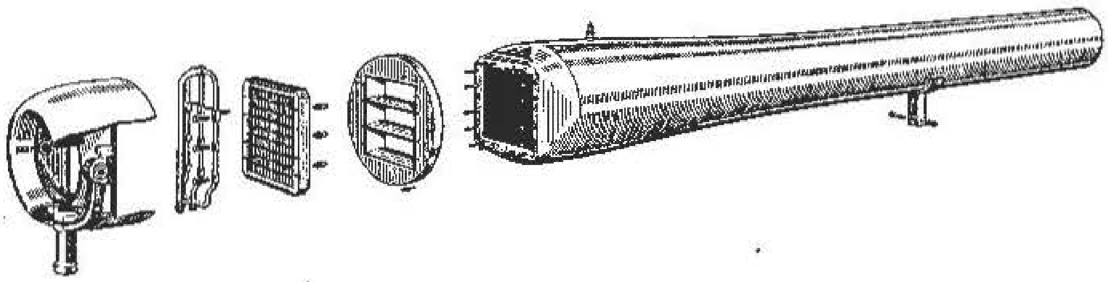


Fig. 14. The Argus pulse jet as constructed for the V-1 (1944/45)

the starting air under the upper three fuel nozzles can be seen. The fuel nozzles were constructed as swirl atomizers. At maximum speed they worked at a pressure of some 3 atm; good atomization was, however, also achieved at only 1 atm. These swirl atomizing nozzles contributed considerably to the good controllability and to the reliable starting of the pulse jet.

It was proved that the pulse jet could be controlled in such a way that it gave only 10 % of its full thrust without any irregular operation occurring.

The mixture formation plant was similar to that of our first model pulse jets. The fuel nozzle was also housed in a secondary chamber. The flame extinction was achieved by the increased mixture speed at the necked-down portion. It was proved that the nozzle diaphragm protected the sensitive valve spring flaps and the die-cast light-alloy nozzle webs from thermal overstresses, as the flame obviously did not reach the valve system.

6.2. Dimensions and Weights

This type of pulse jet gave a static thrust at sea level of 350 kg. Its weight was 138 kg for a length of 3.6 m. We achieved a thrust on the ground of 350 kg for a consumption of 0.8 g/kg.

6.3. Thrust and Consumption Curves

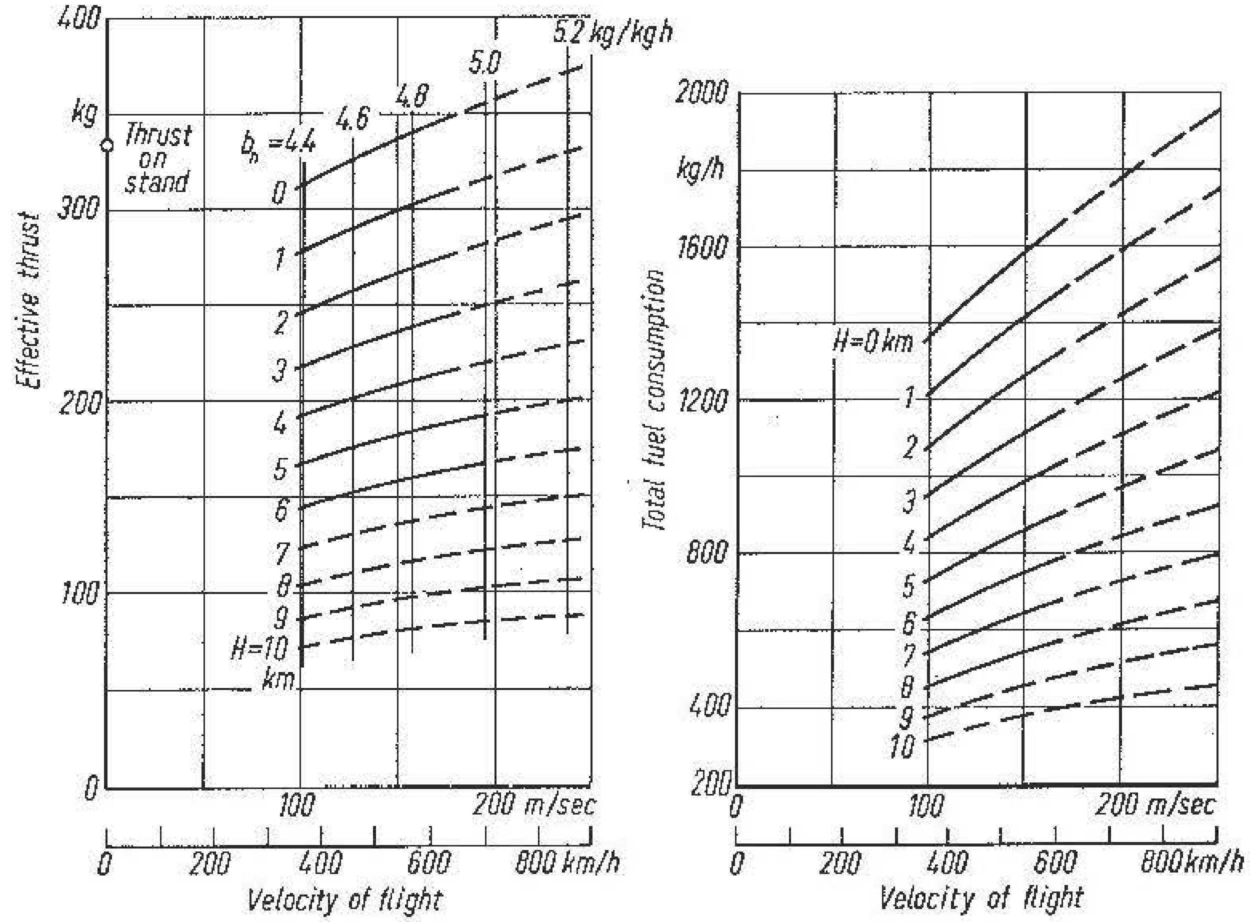
In June 1944 our flight-testing department had completed all the measurements which enabled us to draw the thrust and consumption curves.

Fig. 15 shows the thrust as a function of altitude and speed. The thrust continued rising with the speed in the measured range. Below 350 km/h the thrust was less than the static thrust at sea-level. We found later on that a diffuser at the end of the pipe was useful in this lower speed range, while it was disadvantageous above 400 km/h.

The absolute fuel supply increased according to the higher rate of air flow with rising speed (Fig. 16).

Our measurements had proved that the specific fuel consumption depended only on the flying speed (Fig. 17).

These were our last systematic flight measurements.



Figs. 15 and 16. Thrust and consumption of the pulse jet As-014

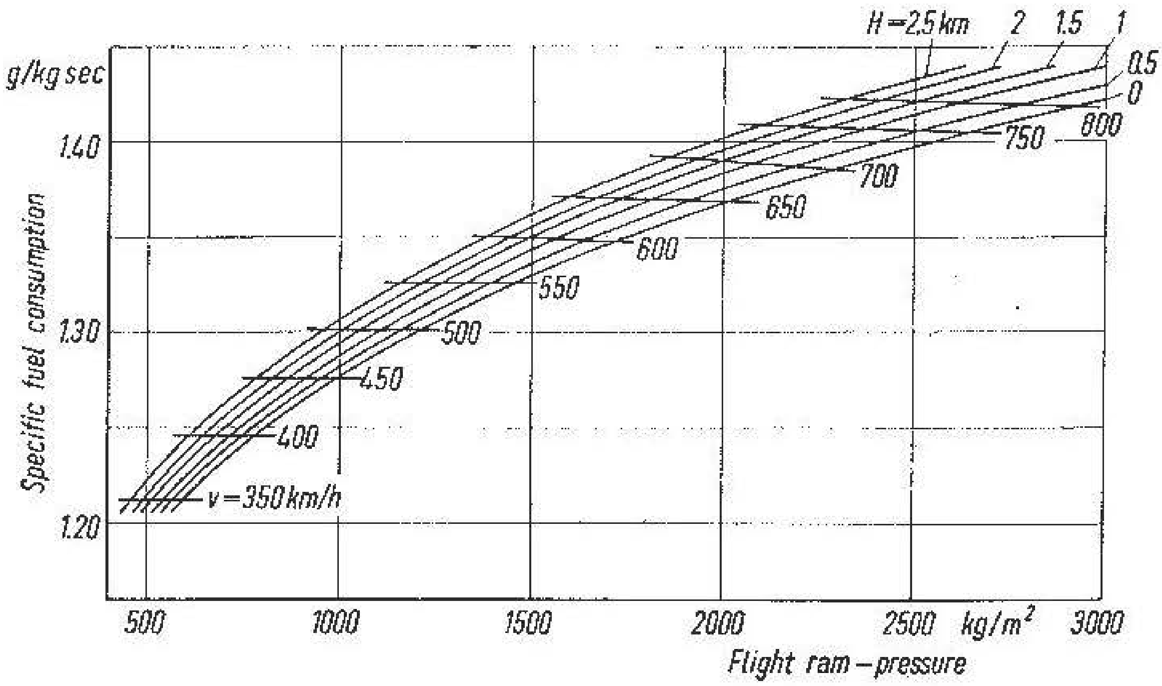


Fig. 17. Specific fuel consumption of the pulse jet As-014 at maximum thrust

7. THE FUNDAMENTAL WORKING PROCESS OF THE PULSE JETS

7.1. Ignition

The pulse jet was known to continue working after switching off the ignition. The phenomenon of self-ignition had already been observed by BARBEZAT. The following remark on this subject was published in the periodical "Die Turbine" in 1909:

"The new charge spontaneously enters the explosion chamber without any control and this process repeats automatically within a very short time. The upper part of the chamber and the nozzle pipe soon began to glow and the ignition could be stopped . . ."

This reference was interpreted in such a way that one could think the gas had ignited at the red-glowing wall.

A portion of our V-1 pulse jet began to glow, too, and we therefore had to ask whether the ignition were also started by the glowing wall in our case. Water-cooling was provided for the endurance tests of our pulse jet on the ground (Fig. 18). Under these conditions, however, the wall certainly did not glow.

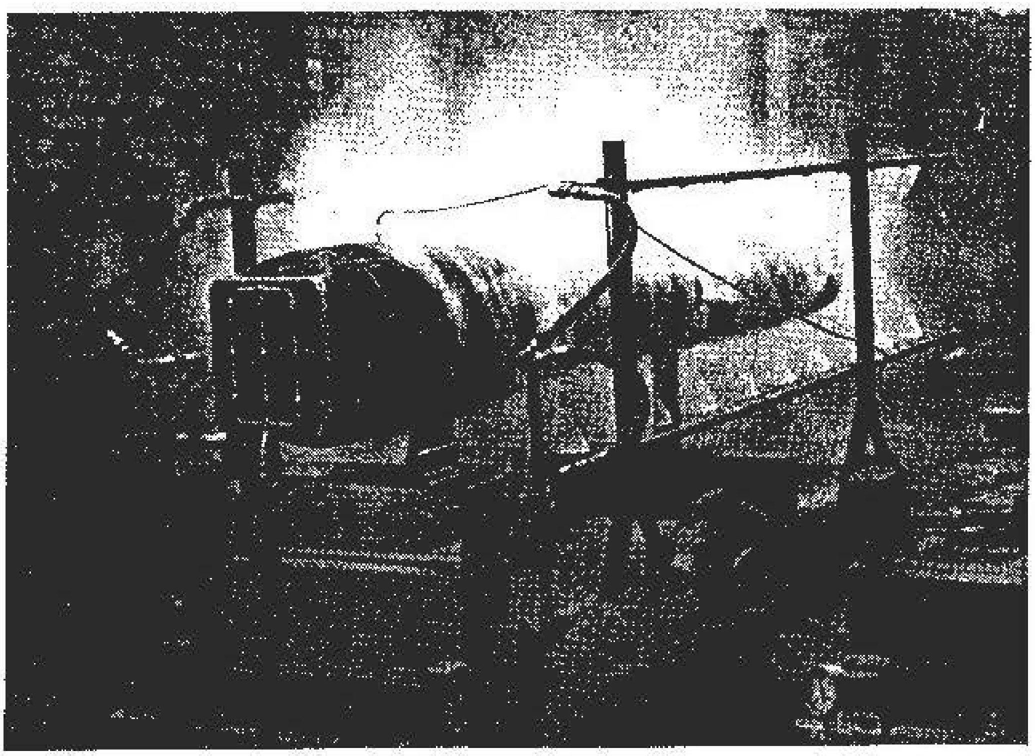


Fig. 18. Endurance test of the Argus pulse jet on the ground with water cooling

The periodically switched-off or switched-on water-cooling showed that there was no difference in operation of the jet pulse with a glowing or with a cold wall. We therefore assumed that the wall temperature did not influence the ignition.

7.2. Gas-Exchange Process

It remained to be investigated how this simple apparatus could periodically suck in a new charge without needing any mechanical devices (as e. g. pistons, etc.). This subject had also been discussed in technical journals as early as 1909.

Then it was asked whether or not the cooling down of the combustion chamber played a part.

It was explained later on that the burning gases left the pipe like a piston and sucked in the fresh charge behind them. Still later on it was clear that the pulse jet worked in resonance. But this is a summarising explanation only.

We made it our task in the ARGUS Company to find out in detail the physical processes inside the pulse jet and we first succeeded in doing so in May 1941. We calculated the processes and showed them in an animated film *.

8. APPRECIATION OF THE PIONEER WORK

If we estimate the whole importance of these processes for the principle of the plant, we shall find that the long pipe is the essential part of the pulse-jet unit. The physical processes which are necessary for the working principle take place in this pipe and the ingenious thought of such a pulse jet is obvious. A very long pipe which is shut off by a valve on one side and which is acoustically excited by pulsations can suck in and discharge gases without the aid of any movable parts and can thus carry out a thermal cycle without any ignition device.

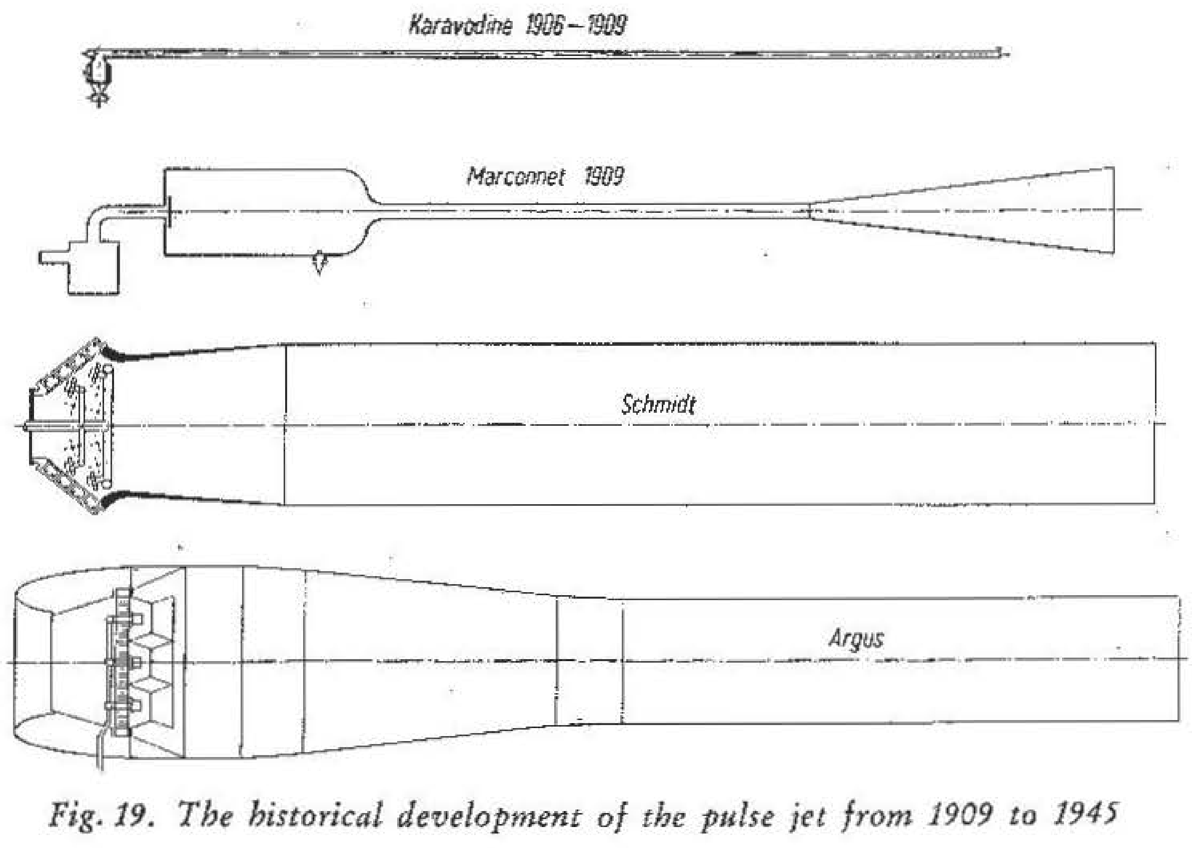


Fig. 19. The historical development of the pulse jet from 1909 to 1945

The realization of flying speeds of more than 750 km/h by means of so simple an apparatus is the success of an idea, and I think that we should remember the inventors and the pioneers of this peculiar engine, who are (Fig. 19):

* This strip demonstrates the movement of the waves in the pipe; it shows in particular how the pressure wave arriving from the combustion chamber turns at the open end of the jet, moves back as an expansion wave, opens the valves, and sucks in the fresh air load.

KARAVODINE, who talked about his idea in 1906 and who made endurance tests of many hours with a turbine;

BARBEZAT, who discovered and published in 1909 the principle of self-ignition;

MARCONNET, who suggested the use of the pulse jet as an aero-engine in 1909 and who was thus far ahead of his time;

PAUL SCHMIDT, whose merit and struggle for this unit which had gone on for many years will not be forgotten in the history of engineering.

The ARGUS Company was given the opportunity to develop this unique engine until it reached the stage where it could be used in a flying body. Thus ARGUS contributed to the realization of the long-distance missile in aeroplane form which had been suggested by the author in the first days of World War II.

DISCUSSION

Dipl.-Ing. PAUL SCHMIDT (Munich): The "tedious repairs to the bodies", which Dr. GOSSLAU quoted in his lecture as having been necessary after each test flight, were probably originated by insufficient elasticity between engine and body. This was, at any rate, the case with the V-1.

The Supreme Command of the LUFTWAFFE informed me in January 1945 of tests which were run during 1944 and which had shown strong oscillations of the bodies. It stated: "Moreover, it showed that the amplitudes decreased with increasing temperature of the pulse jet, but by then the navigation system had already been destroyed."

Several months before, I had received three or four pulse jets with their supports for testing purposes and I had found that the stiffness of the connection system between pulse jet and body was far too hard, and this resulted in a dangerous oscillation condition. Impulses with the period of the pulse jet could act on the body with a force of several thousand kilograms.

In 1942/43 the REICHSLUFTFAHRTMINISTERIUM had ordered an investigation on the previous works of MARCONNET and KARAVODINE quoted in the lecture, to find out if the power system of the V-1 was to be considered as a new type of engine. The results of this investigation led the ministry to call the engine of the V-1 the "ARGUS-SCHMIDTROHR".

Dr.-Ing. F. GOSSLAU: Based upon my remarks regarding the tedious repairs to the bodies, Herr SCHMIDT claims that the propulsion unit of the V-1 was not sprung softly enough against the body. In this connection he refers to an information obtained from the Supreme Command of the LUFTWAFFE in January 1945 concerning relevant tests in 1944.

I am under the impression that there errors in fact and in time are apparent.

Referring to the memoranda and notices which are still today in my possession, I want to reply as follows:

The propulsion unit was sprung against the body by voluminous rubber bumpers, the stiffness of which was altered in joint tests of the firms of ASKANIA and ARGUS so long until detrimental effects upon the control system were eliminated. These tests were performed on the test-stands of ARGUS at

Berlin from 22nd till 29th May 1943 for the compass. The main task of the "Working Committee V-1", which was strictly guided by the Air Ministry, was the permanent supervision of the operational safety and the permanent improvement of new weapons. If a fundamental constructional fault regarding the elasticity of the propulsion unit would have existed, quick and severe action would have been taken and an alteration would have been performed.

In fact, however, the damages to the bodies mentioned in my paper did not refer at all to the V-1, but to the manned test-carriers of our flight-test department (i. e. DORNIER and JUNKERS aircraft), and besides the damages occurring there had nothing to do with the transmission of thrust.

With those damages as mentioned by me we met for the first time in connection with transport gliders. Here the covering of the body consisting of woven material was often torn away in rags by the considerable variations of pressure caused by the rhythmic exhaust-bang of the operating pulse jet mainly near its outlet. Thus it was not the variation of thrust, but the accoustics (due to the working-principle of the pulse jet) the true cause of the damages.

Like the transport gliders, also the metal sheeting of the bodies of our test carriers (Do 17, Ju 88) was affected, and these repairs delayed so frequently the continuation of the flight tests.

The often misunderstood and criticized arrangement of the propulsion unit of the V-1 at the end of the body above the side control, and the duct which protruded far beyond of the end of the body were important factors for avoiding such damages with the V-1.

In brief, I would like to say to this subject that it was not the transmission of thrust which took so much of our time, but the enormous acoustics of this unit which damaged not only the lightly built aircraft, but even the brickwork of wind tunnels.

Prof. Dr. H. BLENK (Brunswick): I would like to add a couple of words to Dr. GOSSLAU's lecture. It must have been in 1942, when the LUFTFAHRTFORSCHUNGSANSTALT in Braunschweig-Völkenrode got an urgent inquiry from Peenemünde as to whether the ARGUS pulse jet could be tested in one of our wind tunnels. What had happened in Peenemünde was that the firing tests at high velocity showed that there was no longer a propulsive force. Obviously thrust and resistance compensated one another, so that the resultant force became zero. In Braunschweig we had a high-speed wind tunnel going up to MACH number 0.9, with a test diameter of 2.80 m, so that a full-size test pulse jet could be installed. Tests at those speeds actually revealed that the propulsion was nil, which means that the thrust equalled the resistance. In collaboration with the firm of ARGUS we then altered the pulse jet, especially the intake, from day to day and performed new tests. The firm of ARGUS based the alterations mainly on the proposals of Dr. ZOBEL — as far as I remember — with such haste that alterations were done within the day, and the new tests were done the same night. The wind tunnel tests led to a form which provided the necessary thrust for the V-1 at speeds of up to 700 km/h.

Prof. Dr. ERNST SCHMIDT (Munich): In his remarks dealing with the difference between the measurements of the effective thrust of the pulse jet placed on an aircraft and in the Völkenrode high-speed wind tunnel, Prof.

BLENK did not tell the whole story. I remember it in more detail. A careful investigation of the discrepancies of the measurements showed that the aircraft measurements which Dr. GOSSLAU mentioned in his report were actually wrong for the following reasons: the pulse jet was fixed above the carrier aircraft with the help of a frame and the thrust was measured electrically and integrated at the same time.

However, the integrating device worked quadratically and in this way the negative values of the thrust which really existed during part of each period of the pulsations were converted into positive ones. Thus, in contrast to the measurements, the effective thrust at the intended velocity of flight went down almost to zero and the whole V-1 would have been a complete failure if TH. ZOBEL had not succeeded in aerodynamically improving the air intake by adding an entrance diffuser with a well rounded mouth. Only this favourable chance made it possible for the design flight speed to be reached.

Dipl.-Ing. PAUL SCHMIDT: The remark made by Prof. Dr. ERNST SCHMIDT regarding an error in the measurement of thrust due to the periodical occurrence of a negative thrust points to too hard a springing between tube and body. It emerges from the curve in Fig. 14 of my paper (see page 387) that in the case of a too hard springing there will occur with the periodically generated positive thrust of 2000 kg a periodically occurring negative thrust of 1500 kg. However, with adequately soft springing no negative thrust is observed.

Dr. GOSSLAU: I would like to combine my replies to the remarks brought forward by Prof. BLENK and by Prof. E. SCHMIDT in this discussion. As I have mentioned before, work on the V-1 was speeded up with utmost energy and by all means available after the order was placed on June 19, 1942. In this connection the LUFTFAHRTFORSCHUNGSANSTALT in Braunschweig was asked in October 1942 to test the ARGUS pulse jet in the high-speed wind tunnel. A fast test plane equipped with an electronic device for thrust measurements was assigned to the ARGUS flight test department.

From this point there began a series of tragic errors which almost resulted in failure of the whole V-1 project. Braunschweig reported a disastrous decrease of thrust down to zero at 600 km/h. The thrust measurements of the ARGUS flight test department were wholly incomprehensible. The more we tried to reduce the resistance of the pulse jet, the worse became the effective thrust.

In this rather dangerous situation the German Air Ministry summoned, in the autumn of 1942, a committee of some 20 experts on research and production, the "Working Committee on Jet Propulsion Units". Here the results obtained by the LUFTFAHRTFORSCHUNGSANSTALT in Braunschweig and by the flight test department of ARGUS were discussed. The most important problem was: why does the pulse jet stop operating at high speeds of flight (in the Braunschweig wind tunnel)? — The general opinion was that at high speeds the flame was blown out of the pulse jet at its rear end which would terminate the working process. This statement was contradicted by our flying tests; yet the thrust measurements during the flying tests remained inexplicable. A pulse jet which was fitted with numerous collars on its outside to increase its rigidity, and which thus should have shown a high resistance, showed better effective thrusts than the same pulse jet without such collars. In view of this really senseless result, towards the end of November 1942 I sent Dr. VOLLAND, our expert on measurements, to the flight test department with the order to check critically the measuring equipment. He found out on the same day that the measuring device recorded the negative thrusts, which necessarily occur in any working cycle, erroneously as positive values. This information was passed on by me on December 1, 1942 to the Working Committee on Jet Propulsion Units to which, as far as I remember, Prof. E. SCHMIDT also belonged, and his here remark probably refers to this fact. The measuring error was the fault of ARGUS, it was, however, also discovered by ARGUS.

Following the adjustment of the measuring device, the discrepancies in the results obtained in the Braunschweig wind tunnel became larger than ever before. Braunschweig insisted that the thrust would decrease to zero at 620 km/h; flight tests carried out by ARGUS revealed an effective thrust of about 300 kg at this speed. This was the state of affairs when, on December 24, 1942, the first test shot was fired which, apart from the unsatisfactory speed, was successful.

ARGUS then decided to use its own so-called blower test stand, i. e. a sort of wind tunnel generally used for testing air-cooled engines, for testing the pulse jet. A surprising result was obtained on the very first day of test. The relevant entry in the diary read as follows: "With a blowing velocity of 300 km/h the first test runs showed a thrust of 170 kg only. Running without blowing resulted in a thrust of 200 kg only. On the open-air test stand the same pulse jet showed the normal thrust of 320 kg."

The weekly report for the period January 6 to 13, 1943 stated: "The pulse jet measurements on the blower test stand were stopped due to the lack of coincidence with the measurements in the open, and following heavy damage caused by the tests to the brickwork."

In Peenemünde a wooden hut had been erected where the V-1 performed short test runs prior to being launched. After only a few such test runs there nothing but the timber frame existed. The walling had fallen off completely due to the effects of the operating duct.

I hope have shown by these remarks that in closed rooms a pulse jet can not be correctly tested as to its thrust. Any wind-tunnel measurement is bound to lead to faulty results, and this applies also to the measurements in Braunschweig quoted by Prof. Dr. BLENK. Of course, these critical remarks refer only to the pulse jet in operation. The cold resistance may be determined satisfactorily in a wind tunnel.

When, in May 1943, various intake-diffusers were suggested by Prof. Dr. BETZ, Dr. ZOBEL, Prof. Dr. RUDEN and by ARGUS, the diffuser proposed by Prof. Dr. RUDEN showed the best results with a gain of thrust of about 60 kg at 650 km/h. There can be no doubt that the effective thrust of the ARGUS pulse jet in the V-1 amounted from the very beginning to about 215 kg at 600 km/h (Fig. 13). The further increase of the effective thrust, resulting in the speed of the V-1 increasing to 790 km/h, has to be attributed to the knowledge that the pulse jet would stand a much higher rate of fuel flow than could be assumed in view of the initial lay-out of the governor. We owe this perception to the flight test department of ARGUS, to the Flugbaumeister STAEGE and SCHENK, to the evaluation of the results obtained by their flights by my collaborators Dr. ZAMMERT and Dr. FLÖSSEL, and finally to the constructional and experimental work on the adaption of the fuel governor for which Messrs. WEICHE, BELITZ, KREUZIGER and GEILER were responsible.

Admiral FAHRNEY (Philadelphia): The V-1 missile resembles, in most of its characteristics, the "Flying Bomb" project in America in World War I and the "Assault Drone" project in World War II. It was planned to use radio control in the earlier project and it was used successfully in the latter project. Since you were able to get good triangulation stations along the coast, why did you not use radio control in the V-1 for greater accuracy of directed flight?

Dr. GOSSLAU: Owing to tragic impressions received at the front towards the end of the first World War, the idea of an unmanned, teleguided aircraft has haunted me ever since. In April 1937, in agreement with the ARGUS factory, I submitted to the DEUTSCHE FORSCHUNGSANSTALT FÜR SEGELFLUG (DFS) and to the C. LORENZ AG, a scheme for collaboration on the subject of radio-controlled flying bodies which were not to carry persons, but only technical equipment.

The teleguided anti-aircraft target model, whose teleguiding equipment has been described by Dr. KLOEPFER was the first outcome. This model performed quite a successful teleguided flight on May 14, 1939 and may be regarded as the first teleguided flying body in Germany for military use between the two World Wars.

When, on November 9, 1939, I submitted to the Reich Air Ministry my first memorandum regarding a power-driven winged bomb having a range of about 600 km, I had of course visualized radio control. But it was just this proposal which delayed for so long the realization of the flying bomb. Electronics was one of the decisive bottlenecks of that period. Furthermore, interference and possible tracking by the enemy were feared.

Only when the Channel-coast was under German occupation and when compass guidance alone promised satisfactory hitting accuracy on large target areas, was the realization of this idea decided upon. Later on, as the V-1 actually flew, the idea of its teleguiding was taken up again, as Prof. FISCHEL has told this assembly.