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Chapter 5

The Supersonic Wind Tunnel Installations at Peenemünde and Kochel and Their Contributions to the Aerodynamics of Rocket-Powered Vehicles[1]

Rudolph Hermann[2]

With the goal, in 1937, to build an aerodynamic-ballistic research institute to provide all aerodynamic, stability, and heat transfer data needed for the development of rocket-powered vehicles, space vehicle research in Germany moved into a new era. This paper describes the design and construction of the resulting supersonic wind tunnel with a 40 cm x 40 cm test-section, which became operational at Peenemünde in 1939 and was moved to Kochel in 1943. Seven wind tunnel Laval nozzles, ranging in velocity up to Mach 5, were used in this facility and their theory, design, and construction, as well as their wave patterns, occupy an important part of this discussion. In addition, the results of tests in this facility for vehicles without wings, such as the A-4, and for vehicles with wings, including delta wings such as the "Glider A-9" or the "Wasserfall," provide useful case studies of the type of research conducted there. Finally, I will describe the influence of jet exhaust on drag and stability.

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Purpose, Design, and Operation of the Supersonic Wind Tunnel Facilities

Purpose and Goal

The goal in 1937 was to build an aerodynamic-ballistic research institute capable of furnishing—in a reasonable time frame—all aerodynamic, stability, aerodynamic control, and heat transfer data needed for the development of numerous projects such as supersonic projectiles (fired from guns), rocket-powered vehicles without wings, those stabilized by fins (called missiles), and rocket-powered supersonic vehicles with wings and fin-assemblies or with delta wings. This required the design and construction of supersonic wind tunnels of the highest obtainable Mach speed (at least 5 and above), which also should operate in the subsonic range, since all rocket-powered vehicles start with zero velocity.

From 1934-1937, at the Aerodynamic Institute of the University of Aachen, under the direction of Professor Carl Wieselberger, the author developed, built, and operated a supersonic wind tunnel of the blow-down type with a 10 cm x 10 cm test section up to $M = 3.3$ with a 3-component balance. Financed by the German *Luftwaffe*, some of the first models tested were anti-aircraft projectiles.

On 6 January 1936, Wernher von Braun of the German Army Ordnance organization, brought the drawing of a pointed, slender body with fins to be tested for drag and stability up to our maximum Mach speed. It was the rocket-powered missile later designated A-3. The first proposed fin assembly would have caused an unstable missile, but further experiments at the institute produced a more stable arrangement (see below, A-3 Vehicle).

For more detailed measurements, larger models and larger tunnel cross-sections were required. More power was needed because of model size and the requirement to test at higher Mach numbers. This showed the necessity of building such a facility with the aid of the Army Ordnance at the Experiment Station under construction at Peenemünde. Our work started in April 1937 with 20 people, all committed to combining available scientific basic concepts with a detailed engineering design and solid construction of all test equipment and modern measuring devices to facilitate maximum tunnel usage.

Additional assistance for the scientist was provided by a series of laboratories, especially those specializing in optics (Schlieren, Interferometer), thermodynamics of high speed gases, heat transfer, electric controls for operation of powerplant and air drying installation, electronic measurement devices, and physics (X-ray densitometer). These laboratories produced the measuring devices needed to solve the problems arising during the development of new missile projects and their counterparts in the wind tunnel.

From the start, installation planners intended that test goals could be facilitated by having a Chief Engineer, with a staff of qualified designers and with the help of ample design offices, combined with a machine shop under the direction and control of the design staff. The result was that ideas and proposals of scientists could be designed and fabricated properly and made ready for testing with a minimum of red tape.

Design and Operation

The work at Peenemünde started in April 1937 with a staff of 60 people, but not until the summer of 1939 did the tunnel first become operational. The wind tunnel continued in use until the fall of 1943, when, following a succession of Allied air raids, it was moved to Kochel—along with 200 staff members—rebuilt, and put back in operation by the spring of 1944. Step-by-step, thereafter, the Kochel staff improved the tunnel through the fall. In Peenemünde, the vacuum reservoir was 1,000 m^3 (Kochel 750 m^3); six vacuum pumps with 800 KW total (Kochel first four pumps); two test sections of 40 cm x 40 cm (Kochel one test section); one test section of 18 cm x 18 cm, capable of continuous operation through M = 3.3. During blow-down operations, Peenemünde had a running time of 20-25 seconds; while Kochel had only 15 seconds. The range of Mach numbers covered and nozzles are described in Section B.

Figure 1 shows the complete layout. The air entered the entrance cone, in front of which was the air drying filter, not shown. Air passed through a honeycomb, entered the test chamber with two Laval nozzles, producing a parallel free jet, which was captured by the bell mouth of the variable diffuser. The diffuser had a fast moving throat to control the pressure in the chamber needed for a parallel jet. The air flowed through the quick acting valve, which opened and closed at the beginning and end of the usable running time. A fixed diffuser brought the air into the vacuum reservoir.

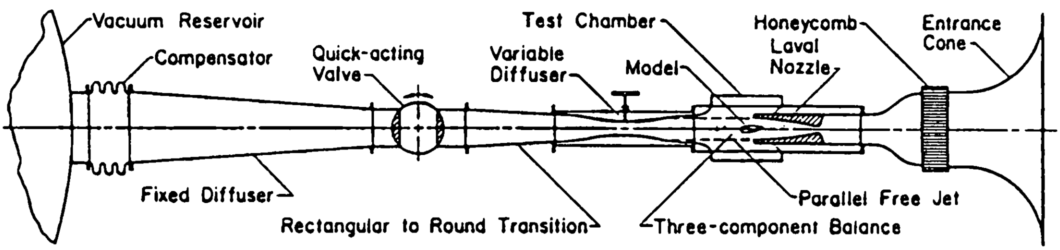

Figure 1 Supersonic wind tunnel layout (40 cm x 40 cm) at Peenemünde (1937).

A photo of the test section installed at Kochel is shown in Figure 2. A "Wasserfall" model is installed, ready for testing, supported by the mount which varies the angle of attack. This could be done from outside by push-button control without opening the test section; another feature for maximum tunnel usage.

An important piece of measuring equipment was the 3-component balance seen in Figure 3, which determined drag life and pitching moment. It was built in Peenemünde in 1939 and also used in Kochel through 1945. It was ruggedly built and installed in a pressure tight chamber, which was evacuated at each run down to the low static pressure of the respective Mach speed. The angle of attack changer can be seen here in the schematic. To determine the Center of Pressure (C.P.), the drag was measured in two components. In customary subsonic wind tunnel balances for aircraft use the lift is measured in two components. This system was needed because many of our models had no lift near zero angle of attack, but they always had drag.

The Schlieren-optical system built in 1937 had two nearly parabolic mirrors, 50 cm diameter each, with 10 m distance. It observed the flow fields around models; large glass walls on both sides of the test chamber (see Figure 2) allowed full view for Schlieren of Interferometer.

The Schlieren system was mounted on a four-wheel carriage running along the test section; and also vertically, to move the system quickly and safely for observation at any point, and also from one test section to the other. The Interferometer (since 1943) also had mirror diameters of 20 cm and a field of view 9 cm x 10 cm.

The installation of the air drying system was completed in the spring of 1940. It was based on detailed experiments on condensation shocks caused by humid air, which were done by the author in Aachen in 1935-1936. The dryness requirement increased with the Mach Number. A two stage drying system, specially developed for intermittent operations, used 600 KW of power for heating and airflow. The dryness reached was 0.2 g Water/kg air, or 0.0002 dimensionless. This was a factor of 10 smaller than that used before (at M = 3). This guaranteed shock free flow to M = 5.2 in the humid climate.

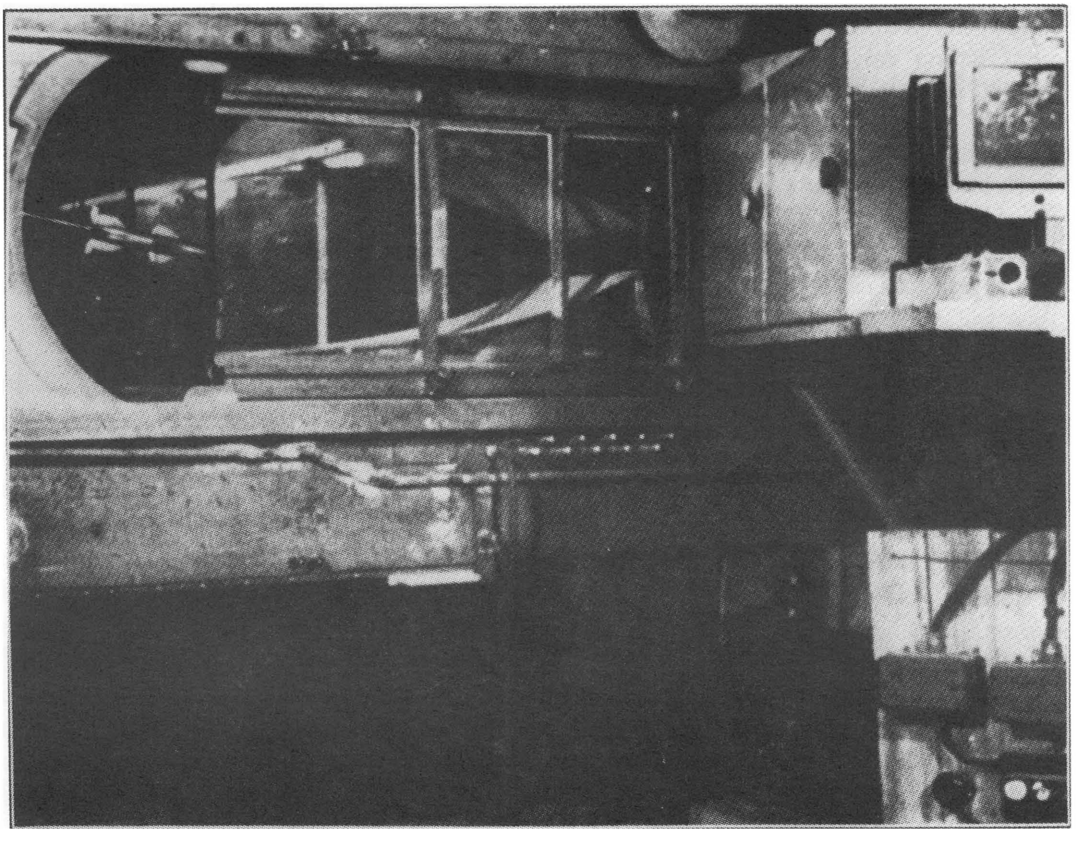

Figure 2 Test section at Kochel in 1945.

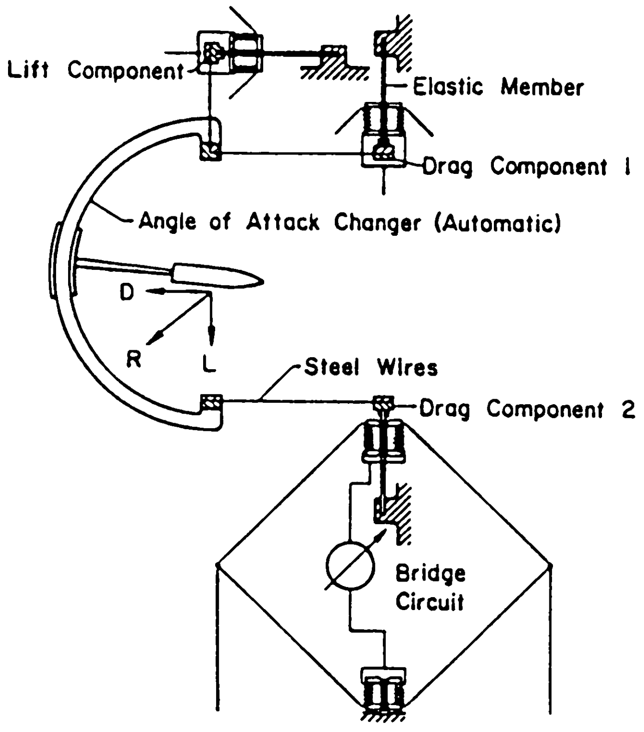

Figure 3 Schematic of the 3-component balance.

Aerodynamic Data for the Supersonic Tunnels and Some Basic Research Conducted

Laval Nozzles, Theory and Design

The nozzle within a supersonic wind tunnel is of paramount importance for conducting correct and meaningful experiments. Essentially, it has two tasks. The first is to produce the desired supersonic velocity in the test chamber. To accomplish this, a Laval type nozzle is applied, which produces subsonic velocity in the converging section, M = 1 at the throat, and supersonic velocity in the divergent section. The ratio of exit area to throat area determines the Mach number. For non-movable nozzles, this requires a set of nozzles with decreasing throat area for increasing the Mach speed, since the exit cross section is kept about equal to accommodate the models.

The second involves the flow of the so-called measuring rhombus, a parallel construction of constant Mach speed and free of shocks. This can be achieved by forming the walls of the nozzle according to the method of characteristics first given by Prandtl and Busemann, applicable to two dimensional flow. Hence, the nozzles are two dimensional, with two equal portions symmetric to the axis. The method is basically graphical, but was improved by the staff of the wind tunnel by substituting calculations.

The early nozzles used at Peenemünde and Kochel had two distinctions. First, they were modeled on the Busemann method, and represented the shortest length of nozzle which could be achieved by any means for a given throat size and shape. Second, their mechanical design and construction was novel, accurate, and effective when boundary layer corrections were needed.

The shortest possible length was important for high Mach—4, 5, 10 (for future projects)—for reasons of weight, handling, and for minimizing boundary layer thickness. Each nozzle had a particular radius of curvature at the throat, producing expansion up to the point of inflection, where the angle, made by the profile with nozzle axis, was denoted by Φ_β. If υ is the Prandtl-Meyer angle which provides the desired Mach number at the exit, then, theory shows, the condition: $\Phi = 1/2\upsilon$ causes the minimum length of the supersonic portion. This condition was satisfied in all our nozzles. Figure 4 illustrates the discussion and shows wave patterns for the nozzle M = 4.4. This high Mach speed was selected to show the complexity of the design (completed in 1938). From a large original drawing it is reduced twice by photographic means. Lower Mach speeds were much simpler, for instance M = 1.56 had only eight wavelets.

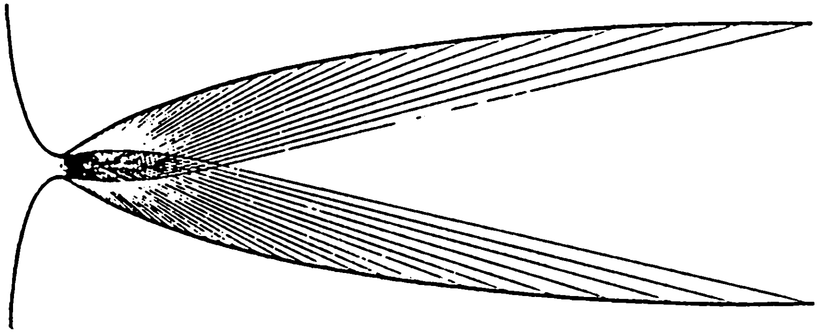

Figure 4 Wave pattern for nozzle M = 4.4.

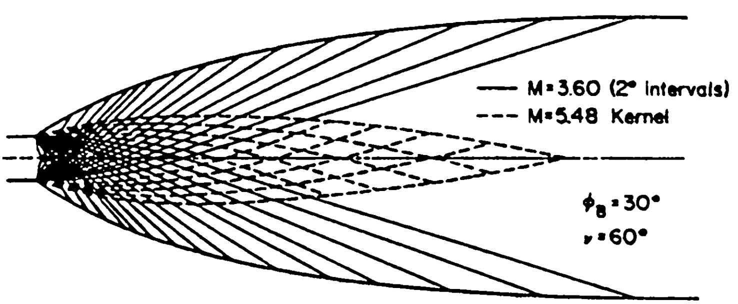

Figure 5 Wave pattern for sharp throat nozzle.

Table 1 shows characteristic dimensions of six of our nozzles (M = 1.22 to 4.38) in use for many years, and for the last (M = 5.18), which was completed in January 1945 but was never thoroughly tested. The full length of the measuring rhombus gave the allowable maximum model length. The last column is the slope of profile at exit (no dimensions). It is equal to the angle of divergence in radians. The divergence is the consequence of making allowance for the displacement thickness of the boundary layer. The particular value of this angle was obtained by experiments.

Table 1

CHARACTERISTIC DIMENSIONS OF WIND TUNNEL NOZZLES

(40 cm x 40 cm)

Design Mach No.	$\Phi_{\beta max}$ degree	Throat width mm.	Exit width mm.	Length of supersonic part mm.	Length of measuring rhombus mm.	Slope of profile at exit radians.
1.22	2	386.16	399.76	271.0	?	0
1.56	~ 6	325.82	403.76	495.8	480	0.008
1.86	~11	259.20	401.84	593.7	602	0.012
2.48	~20	152.10	404.76	787.4	904	0
3.24	~27	71.52	408.74	920.0	1204	0.004
4.38	35	25.94	400.0	1080.3	1704	0.010
5.18	?	14.30	422.56	1224	?	0.010

With the higher Mach speeds, the distance between the throat and the inflection point became physically smaller and smaller, and hence harder to manufacture (and measure) according to design specifications. This led to the idea of a throat with a sharp edge, immediately followed by an expansion around the corner up to $\Phi_{\beta max} = 1/2\upsilon$. The inflection point moved up to the throat, reducing the length, *l*, to an absolute minimum. For M = 5, $l/h = 2.56$; for M = 10, $l/h = 4.98$ (*h* is height of the exit cross section.)

Nozzles with sharp throats can be designed with advantage, since all wavelets originate at the sharp edge. Figure 5 illustrates where a nozzle for M = 3.60 is designed from given wavelet field, called Kernel, corresponding to M = 5.48.

Nozzle Construction

The nozzle had a composite construction consisting of a steel base, brass sides or formers, and a cement profile. The cement's name was "monolith." The main structure was nothing more than a mold for the cement. The formers, fixed to the sides of the nozzle structure, were of brass, 5mm thick. They were shaped to the calculated nozzle profile with an accuracy of about 0.01 mm, final shaping being done by hand. Figure 2 shows part of those details. The cement was poured into the nozzle structure and shaped with the aid of a straight edge. The depth of the monolith layer ranged from 10 to 20 mm. Monolith had several advantages over wood or steel: flexibility to changes in the profile, no special machinery required such as for steel, and no deformation or cracking of wood. A complete pair of nozzle biocks required a total of about 2,000 work-hours to construct.

Experimental Investigation of Nozzle Flow

Once the nozzle blocks were completed, the flow field was carefully investigated. The procedure varied somewhat with the Mach speed, but consisted of Schlieren photography, static tube, and/or pitot tube measurement. For $M < 3.3$, pressure distribution along the axis was measured with a long static tube, which stretched from upstream of the throat to downstream of the measuring section. The tube had nine static holes, and the tube was moved lengthwise to cover all spots. Mach No. distribution, measured from Schlieren, was good up to $M = 3.3$, above that the definition of the wavelets was poor, even when ruled scratches in the nozzle surface were used. Then the static pressure and Mach number were calculated from a pitot pressure reading alone. The various variables were converted into each other, using isentropic flow, an assumption that was carefully proven previously.

In Figure 6, the first three show both pressure tube and Schlieren determinations separately. The last two nozzles show the mean of pressure tube and Schlieren. The agreement, on the whole, between pressure and Schlieren measurement was surprisingly good. It follows from the figures that the maximum deviations of Mach speed from the mean were about ± 2.5% in the worst case ($M = 1.22$; not shown here) and about ± 0.5% in the best case ($M = 4.38$).

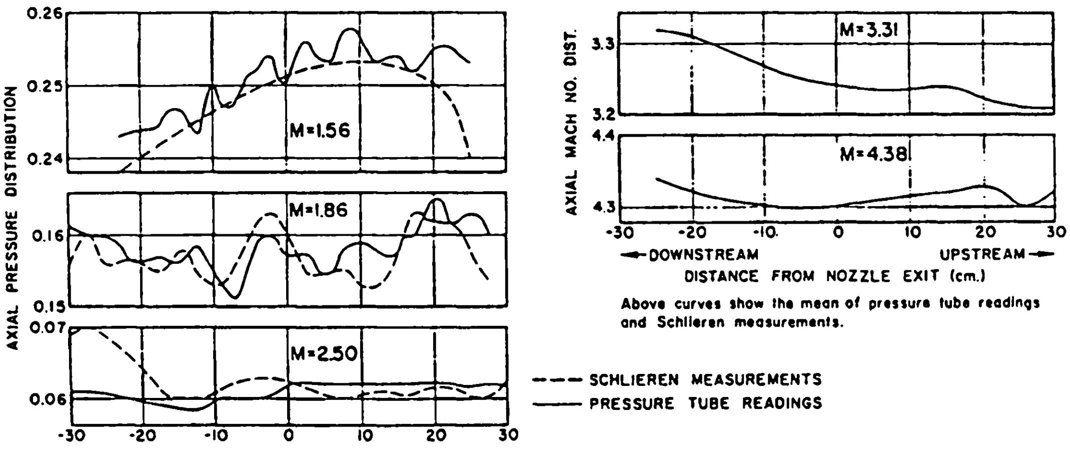

Figure 6 Measured axial distribution for pressure and/or Mach number for 5 nozzles.

Some Basic Research Conducted

When the reader assesses the amount of scientific and engineering accomplishment presented in this paper, it is obvious that this could be accomplished only by a great amount of basic research, conducted simultaneously by the staff of our supersonic wind tunnel installation and by outside consultants, mostly professors, who worked on contract with us. The author, in the summer of 1945, had prepared a summary of basic research in gasdynamics, aerodynamics, thermodynamics, and ballistics, a fraction of which is now used.

Theoretical Gasdynamics

1. Flow in the Laval nozzle and the application of the Prandtl-Busemann method, with corrections to include the boundary layer for the purpose of producing a homogeneous parallel flow.
2. Theoretical work to investigate the stationary, normal shock in the Laval nozzle, including the role of entropy, also the "normal condensation shock."
3. Professor Tollmien of Dresden developed a method of calculating supersonic flow with rotational symmetry. Pressure distribution along the A-4 body was calculated and, together with another method developed by Professor Sauer of Aachen, compared to experiment.
4. The Source-Sink method, first developed by von Kármán and Moore, was used to calculate the pressure distribution for axisymmetric, slender bodies and compared with experiment.
5. The theory for supersonic flow around an infinite wedge and cone was evaluated with the help of special diagrams and nomograms. The shock waves around cones were examined in a series of Schlieren pictures and compared with the theory.

Aerodynamic Performance of Rocket-Powered Vehicles Obtained in the Supersonic Tunnels

Requirements for Rocket-Powered Vehicles

Some requirements for rocket-powered vehicles when under development appear below:

1. Optimum aerodynamic shapes for minimum drag.
2. Lift forces required for certain missions. They are different for a ballistic trajectory, a gliding trajectory or an anti-aircraft missile trajectory.
3. Aerodynamic stability in both subsonic and supersonic ranges. Vehicle is required to be definitely stable, but stability must not be too large since, otherwise, the control requirement of movable rudders with their hinge moments will be excessive.
4. Aerodynamic pressure distribution loading and aerodynamic heating on bodies, fins, wings, rudders—needed for the stress analysis in structural design.
5. Hinge moments for rudders in the air stream or in the exhaust jet, required for control purposes, for pitch, yaw and roll motion.

Two basic groups of vehicles may be distinguished:

1. Rocket-powered vehicles without wings stabilized by aerodynamic fins; typical: A-4, with its forerunners A-3 and A-5.

2. Rocket-powered vehicles with wings, stabilized by a portion of the wing or by extra fins; typical: "Glider A-9" with lift required to stretch the ranges or "Wasserfall" with lift required for maneuverability as anti-aircraft missile.

Rocket-Powered Vehicles Group (1)

A-3 Vehicle

A forerunner of A-4, this craft had a body shape similar to the A-4, but with long, narrow fins with a ring at their end required for containing radio antennas (see Figure 7). Aerodynamic data (three-components) measured by the author in the supersonic wind tunnel at Aachen with 10 cm x 10 cm cross section in 1936 and early 1937. A-3 was the first vehicle, provided by wind tunnel tests, to be fin-stabilized in the supersonic range (up to M = 3.3). It had a slender body of eight caliber length with sharp pointed nose for minimum resistance in supersonic flight. It was fired four times in December 1937, reaching only moderate height (400 m) and subsonic speed. The A-3 was aerodynamically stable around its center of gravity (C.G.) (no "somersaulting"), and its trajectory went into the wind, as required for aerodynamically stable vehicles. The reason for the short flights was that the gyro control system was too slow and the moment produced by the exhaust jet rudders too small to counteract heavy winds (about 25 m/sec).

A-5 Vehicle

The A-5 was also a forerunner of A-4. Due to the trajectory failures encountered with the A-3, another small vehicle was developed with thrust, weight and body size about the same as the A-3, but with a fast control system to avoid the deficiencies of the A-3. Four large air rudders were added at the end of the fins, to produce pitch, yaw and rolling moments to counteract strong natural winds (100 m/sec) at higher altitudes. It was called A-5, since A-4 was already on the drawing board. The fin and rudder assembly was named V12. On purpose, the body of A-5 had the same geometry as that of A-4. Nearly all aerodynamic data gained for A-5-V12 could be used later for the A-4-V12. Starting in October 1939, and continuing through 1941, about 70 to 80 of the A-5 vehicles, with the completely new control system using a stabilized platform, were successfully launched, reaching a ceiling of 8 km, a range of 15 km and a maximum speed about 300 m/sec, close to M = 1.

A-4 Vehicle

Basic Aerodynamic Data. The political name of this rocket was V-2. The configuration of the A-4 can be seen in Figure 8, and the shape as a wind tunnel model can be seen in Figure 9. As outlined above, all aerodynamic data, such as drag, lift and center of pressure (C.P.) and others needed for development were measured. These were obtained in subsonic tunnels up to M = 0.85 and in supersonic tunnels for M = 1.2 and up to M = 4.4. For M = 1, it was not possible to test at this time, since transonic tunnels, in the present sense of that word, did not exist. The center of pressure measurements on both sides of M = 1 showed forward motion, indicating possible instability. Hence, the author suggested, in July 1938, a drop test from airplanes at 7,000 meters, of rocket models about 1.5 meters in length, built from steel. These tests were carried out in 1939 by the Air Force, but under direction of and evaluation by the staff of the Peenemünde supersonic tunnel. The models reached transition through M = 1 at about 1,000 meters in altitude, which could be observed with cameras from the ground. The results were satisfactory, and they laid to rest the concern about instability in the transition region. It is important that the transition itself is of very short duration, since the actual vehicles are under strong acceleration. (Note, that all the curves in Figure 9 have been drawn solidly through M = 1, in order to have consistent values for aerodynamic, structural and trajectory calculations. They present the best estimate of the aerodynamics and shall not imply that these values have been obtained.)

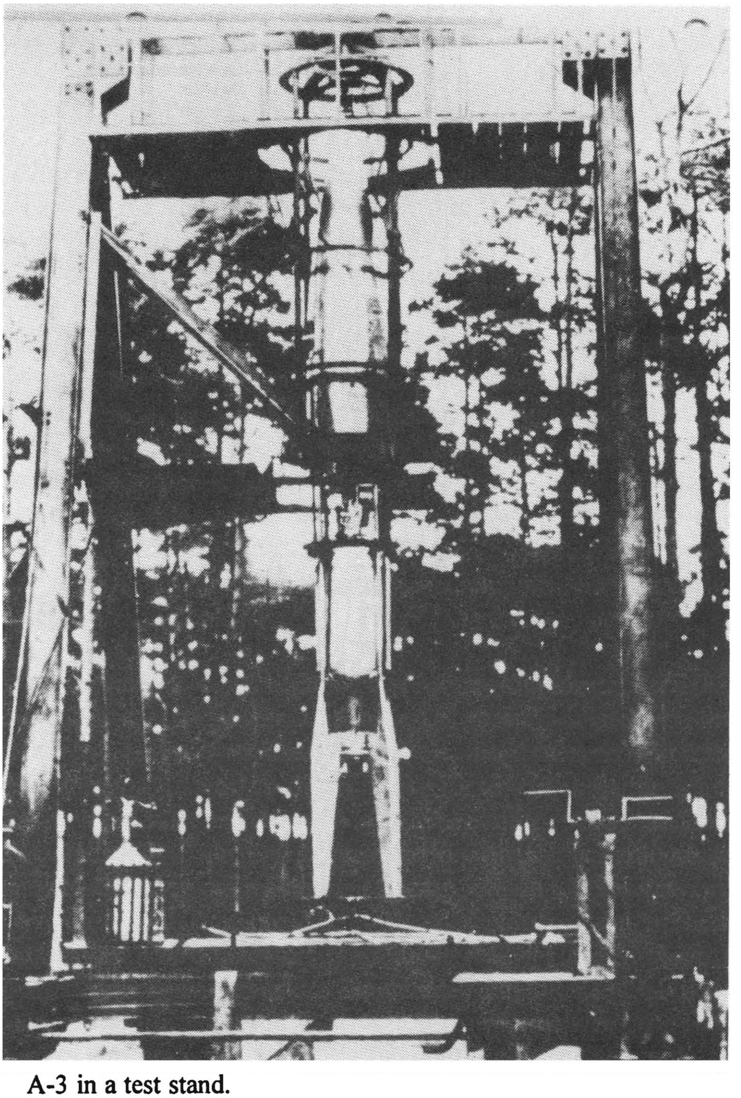

Figure 7 A-3 in a test stand.

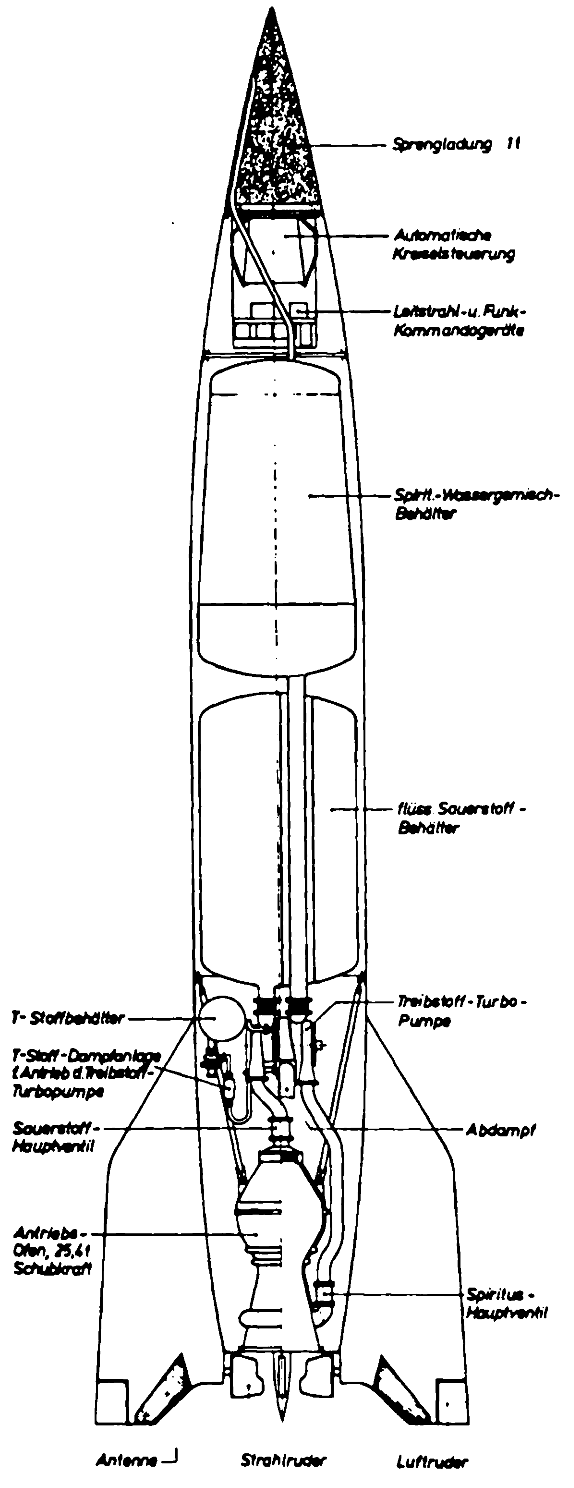

Figure 8 Configuration of German A-4.

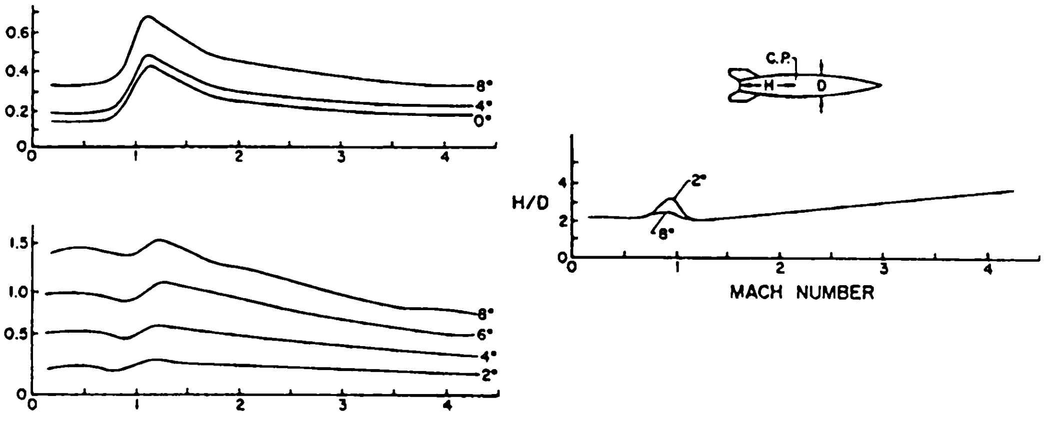

Figure 9 Drag, lift, and center pressure for A-4

Stability and Control. For aerodynamic stability, the difference Δ = C.G. − C.P. (measured from base of the vehicle) must be positive. However, it should be as small as possible, otherwise the vehicle cannot be controlled easily, since the control moment is proportional to Δ. When Δ is small, the air rudders can be small and then the hinge moment to turn the rudders were small—that is, the power was small, and weight was saved in construction of rudders, motors, and energy storage (batteries). The curves C.P. as function of M (or of time travelled) and C.G. as function of time travelled must be established very exactly, in order to fulfill the requirement for a small Δ. For A-4, Δ was mostly on the order of 0.3 of the diameter (0.3D); however, at M = 5.2 (end of powered trajectory) Δ was suspected to be 0.2 to 0.1D.

Note, that the C.P. position can be reliably measured with the 3-component balance only to about $\alpha = \pm 2°$. Towards $\alpha = 0°$ the value becomes indefinite, 0/0. Due to the importance of stability, several other independent methods had been developed but cannot be listed here.

Pressure Distribution Over A-4. Aerodynamic pressure distribution must be measured over the body, fins and air rudders, to obtain local loading needed for the structural design. One hundred-twenty finely drilled holes were used on the model, connected by 120 small tubes to 120 manometers. In the supersonic range a "half-model" method was developed. The model was bisected along its major axis and was backed by a flat plate with sharp leading edges. This enabled the attachment of the large number of tubes to the relatively small models used for supersonic testing. Nine velocities, sixteen angles of attack ($\alpha = \pm 8°$) were covered, each point measured four or five times, resulting in about 120,000 data points, all processed with great care by hand, since printouts or automatic calculators were unavailable. By integrating the measured pressure distribution along the body, the normal force distribution (per unit length of axis) for each of the above parameters was obtained, fulfilling the demands of the design engineers.

Rocket-Powered Vehicles Group (2)

A photograph of the A-4B is shown in Figure 10. Note the A-4B's considerable wing area, to produce lift for certain missions, such as long-range gliding or anti-aircraft maneuverability. It was stabilized either by fin assembly at the very tail, or stabilization was taken over by the rear portion of the wing, when a delta wing was used, as in a V13e.

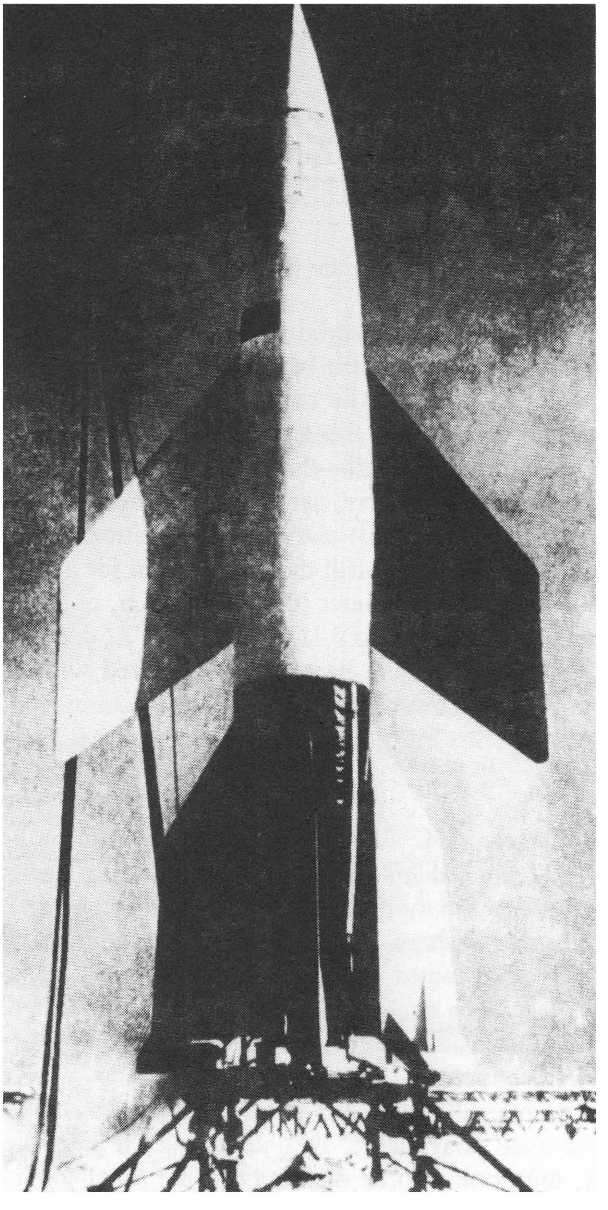

Figure 10 German A-4B.

"Glider A-9"-Type Vehicles

These rockets had different names at different times for different selling purposes, such as: "Flossengeschoss" (fin projectile) A-4, glider A-4, A-4b, A-9. Development started in 1940. Requirements were stringent: take the body of A-4, keep the total weight of propellants and of warhead the same as A-4 and attach wings. First wind tunnel tests were carried out in the summer of 1940 on type A-4 V12a, with trapezoidal wings without sweep and on A-4 V12c, with 45° swept wings. As an example, V12a had a lift/drag ratio of 4.2 at M = 1.86. The V12c was 10% better in L/D. Figure 11 shows V12c with two trajectories. Trajectory I has a propellant cut-off angle similar to A-4, resulting in a 80 km ceiling, oscillating trajectory and little gain in range. Trajectory II has a smaller angle, resulting in a 40 km ceiling with proper gliding trajectory, resulting in maximum range of 450-500 km. V12c had a good L/D ratio, but a motion of C.P. between subsonic and supersonic range of more than one diameter, almost prohibitive. Also, at certain angles of attack, the stability and controllability with the rudders were weak, since the fins were in a downwash of the wings. Hence, other glider-types were investigated. A-4 V13e was a delta wing, with curved leading edges, showing L/D ratio 20% smaller than for V12c. A delta wing, broken into three steps, A-4 V14f ("Stufen-Gleiter") produced lift on every step, with the third step (behind the C.G.) producing a stabilizing aerodynamic moment. The L/D ratio was a little less than for V12c but the travel of C.P. with Mach number was much less—an important characteristic.

In order to develop aerodynamic rudders with maximum control effect (maximum lift on the rudder), with minimum hinge moments, pressure distribution measurements along the rudder were conducted with great success, both for the A-9 glider and for "Wasserfall."

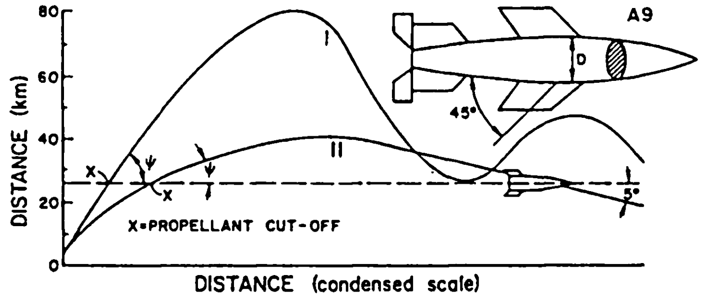

Figure 11 "Glider A-9" with two calculated trajectories.

"Wasserfall"—A Short Summary

The "Wasserfall" belonged to Group (2), as a rocket-powered vehicle, with considerable wing area and stabilized by an extra fin assembly; see Figure 3 for a wind tunnel model. The "Wasserfall" flew aerodynamically stable with subsonic, transonic speeds, developed up to M = 3. As an anti-aircraft missile, and in order to maneuver in sharp curves in all directions and from all positions, four wings were necessary, and large air rudders were placed at the tail. In the subsonic region, about 15° angle of attack was necessary; in supersonic region, about 8°. Many models with various wings, fin assemblies and rudder forms were tested. The first type used the wing cross twisted 45° against the fin assembly cross to avoid that the fins and rudders would be in the trailing vortex street of the wings. This is correct for a small angle of attack, but not for the large ones needed. One type used a concentric ring as a wing, being aerodynamically identical for any angle of attack. The final type was the wing cross and fin cross parallel to each other. The greatest achievement was that the Δ = C.G. – C.P. for the total Mach number range from 0 to 3.0 was almost constant, about Δ = 0.2D for angle of attack from 2° to 8°.

Mission requirements in trajectory and flight mechanics, aerodynamic qualities to fulfill those requirements, rudder effectiveness to produce the moments, hinge moments aerodynamically needed, but limited by the servosystem and power available—all relations are so complex, that only a detailed treatment can do justice. Here, this summary must suffice. Important is the fact that after 16 months of intensive work at the wind tunnels first in Peenemünde, then in Kochel, all requirements were fulfilled. (First report was written in April 1943; major work was completed in August of 1944; some additional details on rudders through December 1944.)

Influence of the Jet Exhaust on the Aerodynamics of the Vehicles

The influence of the jet exhaust on the aerodynamics was significant, but different in the subsonic and supersonic arenas. It requires theoretical understanding of the jet expansion from the pressure simulating the rocket chamber combustion pressure to the static pressure of the surrounding air at a given flight Mach number. Those expansions are theoretically known for the two-dimensional case, and expansion into air at rest. Here, the case is two-dimensional only at the corner, then it is axisymmetric. The expanding jet flow is hit by the outside flow, producing shock waves as on solid cones. An equilibrium is established between the expanding cone flow and the pressure behind the shock wave. Finding out the correct simulation parameters between free flight and wind tunnel test is complex. The experimental difficulties of simulation are so large that only "cold" combustion chamber air was used, not hot combustion gases. Even then, the challenge of measurement of drag and stability was carried out. The mounting of the models was from the top, near the center of gravity, using a hollow pipe, for feeding the simulated exhaust jet. The model was freely movable around the pipe as vertical axis. This arrangement was basically the same for subsonic and supersonic testing, except for the large size of the tunnel and model in subsonic testing and the small size in transonic and supersonic testing (Figure 12).

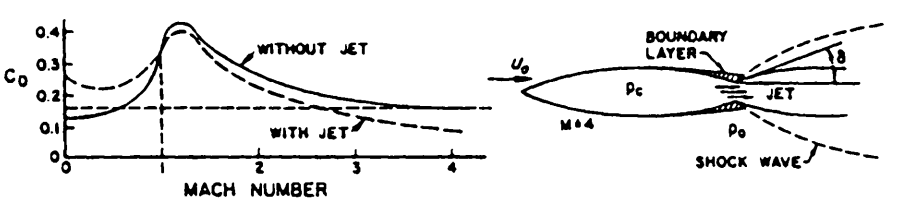

Figure 12 Drag coefficient of A-4 and jet interaction.

Effect on Drag

The subsonic region was covered from M = 0.13 through M = 0.85. At M = 0.13, the A-5 was used (which is nearly geometrically identical to A-4). The exhaust jet had M = 1.5. Pressure distribution with small holes, attached to manometers, along six meridians was obtained. Without exhaust jet there is over-pressure on the nose, some negative pressure along the cylindrical portion and slight positive pressure at the converging tail portion—the first and third contribute to the drag. With exhaust jet the surrounding air is induced like a jet pump, resulting in strong negative pressure at the tail. This results in a drag increase at subsonic speeds, see Figure 12, which is $\Delta C_D = +0.13$, nearly 100% at M = 0.13, but nearly disappears at transonic speeds. At supersonic speeds the effect is opposite, and the drag decrease about $\Delta C_D = -0.05$ for higher Mach numbers. Note that in this region the drag is decreased nearly 50 percent. The reason is an interaction of the shock wave, produced by the expanding exhaust jet, with the boundary layer at the convergent tail portion. This results in a pressure increase on that portion, equivalent to a decrease of C_D.

Effect on Stability

The evaluation of the pressure distribution mentioned above showed that the C.P. was displaced about 0.5D towards the tail with the exhaust jet on, causing the A-5 (or A-4) to become more stable. This is proven by the experiment, permitting free oscillations of the model around its C.G., after elongation to a certain initial angle, here 15°, see Figure 13. The faster oscillation means larger aerodynamic moments, also larger stability. The larger model velocities are causing faster damping which is also very welcome. Oscillation experiments were also carried out in the supersonic range for the A-4, the glider A-4 V12c, and the "Wasserfall."

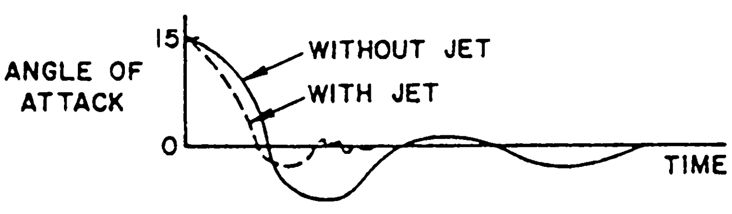

Figure 13 Stability experiments on A-5.

Conclusion

Two distinguished persons were mentioned in the beginning. I avoided mentioning others since the list would be very long. My deepest gratitude however goes to Walter Dornberger. From 1937 through 1945, in all his positions as Chief of a Department of the Army Ordnance, later as commander at Peenemünde, and later as Chief of all rocket development, he was always my direct superior. He was a profound engineer and a man of technical vision, energy, and leadership. This work could never have been accomplished without his constant personal interest, his guidance, sharp criticism, encouragement and constant support. He continued as a friend over the years.

Published reports by the author are available from 1936 through 1945, with several of summary nature. About 200 reports by members of the Wind Tunnel Group 66 are recorded as Peenemünde or Kochel Archive Reports numbered 66/1 (January 1938) through 66/205 (September 1945). Copies of all are in the possession of the author.