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HIGH SPEED TUNNELS AND OTHER RESEARCH IN GERMANY

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HIGH SPEED TUNNELS AND OTHER RESEARCH IN GERMANY

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SUMMARY

A resume is given of information collected during a visit to North Germany, 17th to 29th June 1945. The favorable power factor of German tunnels is attributed to their greater diffuser length. This and the large power available allow them to use a higher density and so a higher Reynolds Number. This is considered to be essential. Much fundamental work has been done on aerofoils, shock waves, boundary layer stability, etc. The large icing tunnel being built at Gottingen is also described and in an appendix a more detailed description of the Brunswick tunnels is given.

1. Introduction.

The following notes are the results of a visit to the LFA (Brunswick) and to the AFA and KWA at Gottingen. The primary object of the visit was to examine the technique and methods of correction used in the large subsonic tunnels and to find what had been achieved. These matters were also discussed with leading workers from the DVL, Berlin.

At Gottingen recent general researches were discussed and an examination was made of the water tunnels and the icing tunnels, complete and incomplete.

2. Wind tunnels in Germany.

Table 1 gives a list of some of the more important German tunnels. The list is very incomplete and omits all firms tunnels.

The large 8 m.dia. Brunswick tunnel (No.5) was kept fully occupied by firms tests, as was probably also the variable pressure tunnel at Gottingen. Complete models of aeroplanes could also be put into the high speed tunnels Nos. 1 and 2 and some work of this nature has been done. It seems however that this ad hoc type of research formed relatively a smaller part of the German effort than of ours. The same conclusion can be drawn from the many smaller tunnels in Germany, each designed for a specific study at subsonic, transonic or supersonic speeds. Thus there are the boundary layer tunnels and the cavitation tunnels at Gottingen and the smaller tunnels at LFA, A6/7 (Nos. 10 and 11). Further examples are the two vertical tunnels LFA A9 (Nos. 12 and 13) which represent a serious attempt to solve the problem of the effect at high speed of the finite boundaries of the working section. This was being done by testing the model first in an open jet and than in a closed section. It has been shown theoretically that the free air case lies between that of the open and closed throat but that at high subsonic speeds it is considerably nearer the former. It may be that other considerations such as unsteadiness (see § 8) and recompression difficulties will tell in favor of the closed section. It must be emphasized that while these tunnels A6/7 and A9 may be small geometrically, the design and construction work involved is very great and the compressors and other plant represent something very much larger than anything in this country. (c.f. 16,000 HP in No. 12, 13).

Obviously the work which had been started in these tunnels must

be continued. It should be rendered easier by the equipment, optical and mechanical, which we have acquired. The necessity for a thorough study of the interferometer methods being developed in Germany is too obvious to need stressing here, but it might be mentioned that the large interferometer reported by Smelt as being developed at Brunswick is no longer there. Smelt, who saw this magnificent instrument in operation, reports that among other refinements the prism adjustments were motorized so that the final adjustments could be made in position. It took simultaneously an ordinary Schlieren picture of the field and a picture of the interference bands A (Fig. 7). The latter picture can be interpreted to give the density changes throughout the field and from these (by using the front stagnation points as a scale) can be deduced the velocity distribution. The two instruments left at LFA are by Zeiss. The field is smaller (from memory 7 in. x 5 in.) the adjustment is clumsier and according to Schmitt, the Schlieren and interference pictures are not simultaneous.

The pictures reproduced in Fig. 7 were picked up at Brunswick and were presumably taken in the large interferometer now gone. Better pictures of the interference bands than those shown can be obtained, but this group shows the set up of an aerofoil and the simultaneous Schlieren photographs at a number of Mach Numbers.

2.1 Use of the second Throat.

Several of the supersonic tunnels make use of the following device for increasing their efficiency. Flexible walls are arranged at the exit from the working section. When supersonic flow has been established these walls are immediately brought nearer together to form a second throat. The partial recompression thus produced isentropically results in the final shock being very weak and thus the overall loss is very much reduced. In the intermittent tunnels which operate by discharge from the atmosphere into an evacuated chamber, this chamber can, by the above arrangement, be used to a higher pressure before the speed is affected than would be otherwise possible.

2.2. Some Tunnel Results (See also Ref. 26 & 27)

The result of the above mentioned concentration on fundamentals has been the collection of a certain amount of data of a highly useful general nature. For example, a systematic series of aerofoils had been studied up to $M = 0.88$ with varying t/c and varying position of the maximum thickness. Also pressure plotting of various series of wings had been done and a number of experiments on sweepback had been made.

In the DVL tunnel drag was normally studied on a wing of aspect ratio 5 to 6, chord ≈ 35 cm., by pilot comb behind the centre section but some considerable distance downstream (in the expansion cone in fact). The low total head loss just outside of the core of the wake (noticed here also) is explained by the lower end of the shock breaking up into a multiple shock. Since the front waves of the subdivision are inclined, the total loss is less than would occur if the pressure rise took place

through one normal shock. The theory of the forked shock is discussed fully by Weise. Some experiments had apparently been made on a tadpole-like aerofoil in an attempt to break up the shock under conditions when it would otherwise have remained single.

The work done at DVL on aerofoils at high subsonic speeds has enabled Gothert to form some definite opinions. He considers that Reynolds number has a very marked effect on the position and type of the shock wave. This is explained by the effect of scale on the boundary layer thickness. The thicker the boundary layer the more easily can the downstream effects be propagated along it past the inner edge of the supersonic region. With no boundary layer the pressure rise at the shock would be very sudden. The thicker the layer the more gradual becomes the pressure rise.

Thus any pressure plots over a wing, obtained in a tunnel, which do not show a fairly sharp pressure rise are considered as suspect. It should be borne in mind, however, that unsteadiness of the shock wave will produce a similar effect.

Gothert also considered that for a high speed aeroplane the symmetrical section is superior to the cambered. While the shock may occur earlier on the former, boundary layer differences make it so much less violent that the cambered section becomes definitely inferior at higher speeds.

Trailing edge angle is considered to be an important parameter, and a rough DVL rule for the T.E. angle is that the product of the position of the maximum thickness, expressed as a percentage of the chord, and the trailing edge angle, in degrees, should not exceed about 4.5.

2.3 Tunnel-Flight Comparison

Gothert stated that good agreement had been obtained on tunnel-flight comparisons up to $M = 0.85$ on the Me 262. Further checks have also been obtained by dropping model fuselages and bombs from great heights and observing (optically ??) the rate of descent.

2.4 Transition.

Observations of transition in the tunnel were made by starting with a clean metal surface on the wing. After 10 minutes running sufficient oil is deposited from the air in the turbulent region to show up the transition clearly - or alternatively to show the wedge shaped regions of turbulence produced by local imperfections.

2.5 Swanback.

It will be some time before all the German information is collected. It seems that under favorable circumstances about half the theoretical gain can be expected. Some early results published in 1941 are shown in Fig. 22. Gothert now considers it desirable to cut off the wing tips parallel to the plane of symmetry and not at right angles to the wing

centre line as was done in these early experiments. Work has been done on the effect of sweepback on maximum lift. The increment in maximum lift due to flaps is very much reduced by sweepback.

2.6 Entries at Supersonic Speeds.

Busemann showed an attempt to reduce the loss at entry to the diffuser of a supersonic tunnel. Two dimensionally the idea is to push forward a wedge midway between the sides of the entry duct until the "bowwave" from the wedge just fall on the leading edges of the entry and so do not extend further. In this condition there is no main bowwave from the combination as a whole and so losses are reduced. It is known here (Ref.25) that there are two possible values of the angle defining the shock wave from the wedge. Busemann stated that he had succeeded in obtaining both of these, in fact by displacing the wedge to one side he had accidentally obtained both at once, one on one side and one on the other.

3. High Speed Tunnel Design.

Dealing with the larger type of tunnel, designed primarily to work at Mach numbers just under, but close to unity, there were two tunnels in use (Nos. 1 and 2) and two (Nos. 3 and 4) under construction.

In general, cooling was by air exchange in the return circuit, so that the working section pressure was about half atmospheric. It is claimed that the Power Factors were very much better than we achieve here, so it appears that a very generous margin was provided on horsepower. The very low power consumption is to be attributed primarily to the very long expansion cone used for all these tunnels resulting in very low power loss on the first bends. A breakaway originally occurred in the DVL tunnel, which caused static pressure fluctuations of the order $\pm 1\%$, but this was reduced to $\pm 14\%$ by the insertion of a net or wire grid halfway down the diffuser. The mesh of this grid was much more open at the edges than over the remaining area where the wires were about 3mm. diameter x 20 mm. pitch. The grid was tied back at the edges by long wires or cables arranged so that the whole had sufficient resilience to stop a model. Several times in the past six years, models have broken away and have been successfully held in the grid. With the net in position, values of the power factor claimed for the DVL tunnel are

M	P.F.
0.4	0.12
0.7	0.087
0.95	0.081

The LFA tunnel had a similar safety device in a slightly more developed form. Oil shock absorbers were provided to anchor the ends of the main cables holding the grid.

3.1 Contraction Cone and Working Section.

An examination of the longitudinal sections (Figs. 9-12) shows that while the contraction cones are generally similar to ours, the transition between the cone and the working section is very much shorter and sharper than in the R.A.E. tunnel. A similar remark applies to the diffuser.

3.2 Velocity Distribution.

The effect of this sharp transition between the contraction cone and the working section on the velocity along the wall in the empty tunnel at high speeds is interesting. It appears that the low pressure region produced resulted in a slightly higher velocity at the front end of the working section (on the wall at least) c.f. Fig.6. At high speed, the wall velocity in the R.A.E. tunnel rises to a peak some way down the empty working section and then falls off. Exactly the opposite occurs in the DVL tunnel, where the thickening boundary layer does not produce a throat until the end of the working section.

The DVL method of measuring velocity is to use a very long static tube placed parallel to the axis and projecting forward from the diffuser where it is carried on wires. The total head is assumed constant and equal to that in the settling chamber. The discrepancy in top speed is possibly partly to be accounted for by different methods of calibration.

When a model is put in the tunnel, the whole condition changes, especially at high subsonic speeds, and in the present state of our knowledge it is not possible to argue the relative merits of tunnels from their characteristics when empty. In this connection, it has been remarked that German results on model tests are often given up to $M = 0.92$ or higher, whereas no R.A.E. results have been given hitherto above $M = 0.83$. While it is possible that our calibration is slightly in error (due perhaps to insufficient allowance having been made for the presence of the support strut mentioned above) there are two other possible causes of the difference. The first is that smaller models were probably used in Germany, the Reynold's number being raised by pressure rather than size. The second possible cause lies in different blockage corrections.

3.3 Blockage.

In this country, for the sake of uniformity, we have continued to use the linear perturbation theory to evaluate blockage corrections, although we have realized that it probably gave values

which were too low at the extreme upper end of the speed range. This has been demonstrated in several R.A.E. papers recently, but it is difficult to decide on the exact amount by which the linear perturbation theory requires correction in any particular case, except perhaps two-dimensional experiments. It appears that in certain simple cases, the Germans have been using the wall pressure method which was developed in this country also. This is known to give a greater correction than the linear perturbation theory at high Mach numbers, but neither here nor in Germany has it yet been shown to be satisfactory for complete models, since considerable complications are introduced by the presence of the supports. In both countries, the theoretical values of the necessary factors have been evaluated for certain cases. Gothert divides the wall increment by 3 for two dimensional cases and by 2 for three dimensional cases, which seems to us to be an oversimplification

4. Construction of Tunnels.

Circular sections seem to be favored in Germany for all parts of the duct of subsonic tunnels, but in spite of this, the favorite material is concrete. The shell does not have a continuous foundation as in our tunnels but is shuttered externally to a circular form supported at intervals by external ribs. These ribs in turn are carried on concrete pedestals with a reinforced concrete hinge. Thus the tunnel as a whole is freely supported and free to expand. In the LFA Tunnel a very great deal of trouble was experienced from dust thought to be given off by the concrete. A rubber coating, sprayed in several coats over the inside of the concrete, had been tried but we gathered that the dust problem had not been solved. This is not surprising in view of the troubles we have had even with steel construction.

5. Cooling.

Cooling is mostly effected by air exchange in the return circuit, a method which does not readily lend itself to the control of humidity. Certainly some, and possibly all of the German tunnels run hotter than ours, which in itself provides some alleviation of the moisture difficulty.

This method was used in LFA Tunnel A7 (No.11) which at the commencement of an experiment, was run continuously until the temperature had risen enough to dry the air. In A6 no provision is made and the incoming air must often be relatively moist. In the similar tunnel at Kochel a silica gel screen surrounds the mouth of the tunnel and acts like a heat exchanger, that is, it is intermittently dried by dry air being passed outwards through it. The incoming air thus first meets the less dry silica gel on the outside, and as it passes through and becomes less moist, it passes the drier crystals on the inside. This permits working for considerable periods without complete desiccation of the silica gel. A silica gel drier can also be seen on the tunnels at Gottingen. Experience at Kochel shows that the slight dust from the silica gel causes some abrasion of the models.

6. Model Supports.

Swept back supports are favored by Gothert as shown in Fig. 1.

The point of attachment to the wing should be at 60% chord, or further back if possible. In addition to having a lower drag, the swept back arrangement spreads the shock on the strut, or between the struts, over different tunnel sections and Gothert considers that this may reduce the general disturbance in the tunnel. For fuselages, Gothert supports the model by a spindle from behind, but the spindle is offset from the center of the model by an inclined strut. The central spindle is considered to have an undesirable stabilizing effect on the wake.

7. Propeller Tests.

DVL was fitted with a propeller motor of 180 H.P. (dimensions of motor excluding fairing are 25 cm. diameter x 80 cm. long). This is used for propellers about 1 metre diameter. The thrust is obtained by measuring, electrically, the shaft tension. This obviously includes the forces on the spinner, thus presenting a serious problem which apparently has not been completely solved. At high values of M , the longitudinal force from the spinner may be 5 times the propeller thrust. Experiments were in hand to test a propeller running at supersonic speeds. The hub was large so that the Mach number of the inner end of the blade was 1.3 while that at the tip was 2.0. The thickness ratio varied from 8% at the root to 4% at the tip. The efficiency was expected to be high due to the lower drag coefficients which occur after the velocity of sound has been passed.

8. Tunnel steadiness.

As already mentioned considerable improvement was effected in the DVL tunnel by a suitable screen halfway down the diffuser but the turbulence problem does not in general seem to have been treated so seriously in Germany as in America. The Germans seem to rely to a great extent on sphere measurements. (Prandtl was evidently developing a three element hot wire unit to obtain, by shadow methods, the velocity component correlations in turbulent flow).

Busemann and Eggink showed work dealing with shock waves running upstream in open and closed jet tunnels at high subsonic wind velocities. These were caused by disturbances on the edges of the jet, or, in the case of closed jet tunnels, by breakaway in the diffuser. As the Mach number is raised these disturbances travel more slowly but they become stronger. It appears that they are able to cause the fluctuations of shock waves often observed on a model wing. Photographs were shown demonstrating that when the travelling waves were absent, the shock above a wing became stationary.

9. Sensitive Pressure Gauge.

Prof. Prandtl demonstrated a pressure gauge which is said to read pitot pressures down to air speeds of about 1 cm/sec. This consisted (fig.2) of a glass rod bent accurately to an arc of a circle. The rod is suspended at the centre of the arc on a fibre so that as it rotates (in a horizontal plane) it passes freely through a hole in a plate forming the dividing wall of the chamber. The pressure difference is applied to opposite sides of this plate and so causes rotation of the rod about

the arc center, against the fibre torque. All connecting tubes must be large enough to prevent friction errors due to the slight flow through the leak at the rod.

It was considered that the minimum size of Pitot mouth for this gauge was about 2mm. diameter.

10. Use of Water Tunnels at Göttingen.

Considerable use has been made of water tunnels for work which in this country would have been done in a wind tunnel. There are three tunnels of this type in the AVA, the largest (Fig. 16) having a test section 75 x 100 cm. and a maximum speed of 20 ft/sec. The other two tunnels are much smaller. A full description of these tunnels was brought back (Ref. 14). The tunnels are of the usual return circuit layout used for wind tunnels and have closed working sections with glass sides. In addition, the KWA has a small water tunnel on the same lines, but with an open working section, the space around the free jet being filled with air which can be put under very low pressures. For the same Reynolds Number and model size, the water tunnel gives forces 4.5 that of air, but the speed is reduced in the ratio 1/13.15. The low speed enables fluctuating flows to be conveniently observed and this seems to be one of the main advantages of this type of tunnel. It is particularly convenient for unsteady flows such as occur during flutter, but it has also been found useful in such problems as the design of radiator ducts, by showing where breakaway occurs. The models are of transparent material. By steadily lowering the pressure round the jet until cavitation occurs on the model an indication was obtained of the position and magnitude of the maximum suction.

The KWA arrangement gives constant pressure across the test section and was being used to obtain the external shapes of turbine nacelle entries having constant velocity over the surface only slightly above the forward speed. The behavior of the nacelle in combination with the wing could be observed over a range of incidences.

11. Stability of Laminar Flow.

11.1 Work in U.S.A.

Prof. Milliken of C.I.T. was at Brunswick and he mentioned that an important report on this subject is about to be issued in U.S.A. The new theoretical approach avoids the weakness of the original treatment by Schlichting, and when the stability boundaries are recalculated by the new method, even better agreement with experimental results is obtained than before. Prof. Milliken was, however, very doubtful about the possibilities of extensive laminar flow under practical flying conditions.

11.2 Work at Göttingen.

The work was discussed with Prof. Betz, Prof. Tollmien and Dr. Pretsch.

Prof. Tollmien stated he had shown that, at very large Reynolds Number, the velocity profile would develop an inflection and would be unstable. He had developed a rigorous mathematical treatment of the effect of a disturbance in the laminar boundary layer and this has been used by Pretsch to calculate the variation of the stability boundaries with Reynolds Number for a large range of pressure gradients both stabilizing and destabilizing. Dr. Pretsch's paper, which won the Lilienthal Gesellschaft Competition in 1940, gives a very clear account of the work, and a copy was supplied to us. In Fig. 8, the ratio of $2\pi x$ displacement thickness to wavelength of the disturbance is plotted against the Reynolds Number of the boundary layer. The Reynolds Number is based on the displacement thickness of the boundary layer. The curves show the boundaries within which disturbances are magnified as the flow passes from left to right across the diagram. The values of B give the velocity gradient from the relation $U \propto x^{B/(2-B)}$. When B is zero, the velocity gradient is zero and values -0.1, 1 and 2 of B correspond respectively to values -2, 7 and 12 of the Polhausen parameter, i.e.

$$\frac{\delta^2}{v} \frac{dU}{dx}$$

It will be seen that with increase of B , i.e. of the stabilizing gradient, the left hand boundary of the curves does not move beyond Reynolds Number of about 14,000. Thus, disturbances are liable to amplification for Reynolds numbers higher than 14,000, if the disturbances contain components of suitable frequencies, even with a high stabilizing velocity gradient.

In a further paper, Pretsch shows that by sucking the boundary layer into the surface so that it does not increase in thickness as it moves downstream, a great increase in the stability region is possible. The stable region is increased 80 times and the excitement of disturbances is one seventh. Prof. Betz seemed to be of the opinion that laminar flow at flight Reynolds Number would only be possible if some scheme on these lines was adapted. They stated, however, that no suitable experimental work had been done on this subject. What comparison there is with theory suggests that the stability criterion demanded may be unnecessarily high, for even in a rather turbulent tunnel, the distance from the leading edge to the transition point is about twice that from the leading edge to the point where theoretical instability begins. Of course, a little distance is required for the oscillations to build up, and the tunnel flow may have been particularly free from the disturbance frequency effective at the minimum Reynolds Number. The matter requires much consideration. Work in U.S.A. has completely confirmed the theory in showing the amplification which an artificial disturbance of definite frequency receives, but more information is needed on the effect of the random disturbances occurring under flight conditions.

12. Resistance of Surface Imperfections in Turbulent Boundary Layer Work under Prof. Prandtl at KWA.

The KWA is well equipped with apparatus for fundamental research on turbulence, boundary layer, effect of temperature on boundary layer stability and measurements at very low speed, and also for work on cavitation. Prof. Prandtl is anxious to have his laboratory completely separate from the AVA so that it can continue as part of the University to work on fundamental problems. He claims that the low speed apparatus might for example be used to investigate the physiological effect of draughts. Its use in the study of mine ventilation is obvious.

Prof. Prandtl drew our attention to recent work on the drag of obstructions and surface imperfections in a turbulent boundary layer. A portion of the surface under test was carried by a sensitive balance and the drag of the various imperfection, e.g. rivet heads, was found from the increase of resistance when they were added to this portion of the surface. A copy of the report giving the latest results (UM 6619) was brought back.

The report should be of great value in assessing the drag of an aeroplane whose performance is disappointing.

13. Study of the Icing Problem at Gottingen.

13.1 General.

A very big effort had been made at Gottingen to provide apparatus for this research. At a rough guess buildings and equipment were being erected to the value of perhaps half a million pounds. When the large tunnel being constructed was accidentally destroyed by fire (in 1943 ?) they proceeded to repair it, but for lack of labor the project was finally abandoned after the heavy Hamburg raid. The cork insulation seems to have burned with almost explosive violence due, it was suggested, to its being impregnated with some gas given off by the bitumen. It is considered that the fire was caused by welding, but at the inquiry the possibility of spontaneous combustion was seriously considered.

13.2 Small Icing Tunnel (Fig. 15).

This tunnel is only a few square feet in working area but it seems to have been used a great deal and there are many written reports in Gottingen on icing of bombs, wing slots, etc. The cooler was of the liquid type.

13.2.1. Water Injection.

The actual mouths of the spray nozzles are heated by water jackets. Air and water pressure to the nozzles can be varied and so the drop size controlled. The type of nozzle used (Fig.3) was calibrated in Berlin by Prof. Gottingen for drop size spectrum against air and water pressure and this calibration is accepted. An optical method of calibration was used but

the details appear to be unknown in Gottingen. Betz thinks that scattered light was used.

An interesting piece of information is contained in Fig.4 which is an attempt to reproduce a sketch made by Dr. Ritz. He pointed out that the worst icing will occur at about the climbing speed of a fighter, just when it is trying to climb through the icing layer. At top speed it may not be so bad. Much work seems to have been done in this tunnel on the development of the large tunnel.

13.3 Large Icing Tunnel (Fig.17).

As already mentioned this was burned out and is in semi-repaired state. The compressors, electrical machinery and the fans all seem to have been recently delivered and so are unaffected by the fire.

13.3.1 Working Section. Is of open type with a maximum diameter of 4 m. which can be replaced by a smaller nozzle of elliptical section.

Max. air speed	6 l atmos,	=	70 m/s		
"	"	"	" 1/10 "	=	130 m/s

Air ducts were provided so that a full size motor could be tested running in the working section under any conditions of velocity, pressure or temperature. The steel parts for the nozzle and collectors were being used as air raid protection for motors etc. on other tunnels.

13.3.2 Collector and Expansion Cone.

This gave a preliminary expansion (perhaps $\times 2$) which was found necessary in order to keep down the circumferential speed required on the rotors R_1 .

13.3.3 Rotors.

Rotating cylinders are arranged to assist in the expansion at the first bends, and similar rotors help the air round the (contracting) corners at the other end. No flanges are necessary on the latter rotors. For the expansion rotors Dr. Ritz sketched some experimental results and an attempt has been made to reproduce these in Fig. 5a & 5b.

The distribution A is with no rotor. With end flanges and a speed equal to the local speed in the potential field, uniform distribution of velocity as at C was obtained. The flanges deal with the cross flow in the boundary layer on the floor and roof. The diameter was 2½m. There was no tendency for the rotors to collect ice.

A similar system had been tried successfully for duct entries.

13.3.4. Fans (1600 H.P.). These seemed to be single stage variable pitch. All the pitch changing mechanisms seemed to be on the site. The blades were steel fabricated around a spindle.

13.3.5. Cooler. The cooler was of plain piping with ammonia inside. To avoid too much difference in head, the cooler was in three sections at three different levels. The ammonia was compressed in four stages, the first two being rotary and the second two reciprocating.

The total capacity was:

2×10^6 cal per hour at -60°C
(or roughly 3,160 H.P.)

No liquid air cooler, surface or pipe was used.

13.3.6. Insulation and Pressure Seal.

The insulation was of cork arranged so that nowhere was the low temperature allowed to get at the concrete. This meant that the thickest insulation was on the inner walls A to allow the flow of heat from top and bottom in the concrete to overcome the loss through the cork. From memory there was about 12 in. on A and 6 to 7 in. on B.

All the outside at "a" was covered with aluminum foil, several layers set in bitumen. This was to hold the air pressure (vacuum) and to prevent the usual trouble of moisture penetrating the concrete.

13.3.7. Ice Dust.

Apparently Dr. Ritz did not think that this would accumulate in the air or that it would matter.

13.3.8. Sprays.

A similar system was to be used as already described for the small tunnel. Dr. Ritz is confident that the water drops become fully supercooled in a very short distance and certainly before they reach the model.

14. CONCLUSIONS.

The effort being put into pure aerodynamic research was very great and substantial progress had been made. The optical equipment especially is noteworthy.

The tunnels are all of much larger power than ours. Pressure is not under control and so Reynold's Number cannot be kept constant with varying Mach number - perhaps an unnecessary refinement if the scale is large enough. The circular section may be desirable but it certainly has some disadvantages.

Much can probably be learned by a closer study of the German transonic and supersonic tunnels and by measurements of the degree and type of unsteadiness of the larger tunnels.

In Brunswick there are full size tunnels of different types which could be used to supply far more information than could ever be obtained from a model.

Particulars of Some German Tunnels

No.	Tunnel	Working Section (metres)	Maximum Mach No.	HP Available	Type of Section	Working Pressure	Fig. No.	Remarks
1	DVL Berlin	2.7 dia.	0.95	17,000	Closed	0.5	9	
2	LFA Brunswick A2	2.8 "	0.95	16,000	"	0.5	10	
3	Munich	3.0 "	0.85		"	0.5	11	Incomplete
4	Munich (Ötztal)	8.0 "	0.95	100,000	"	0.5	12	Incomplete
5	LFA A3	8.0 "	0.23	16,000	"	1.0	13	
6	Göttingen	7 x 4.7 or 5.4 x 4.0	0.26 0.30	2,400	Open "	0.3 to 3 "	14	Variable pressure
7	Göttingen Water	1.0 x 0.75	5.7 (ft/sec)	60	Closed		16	Water tunnel
8	Göttingen Iceing	4.0 dia.	0.38 to 0.2	1,600	Open	0.1 to 1.0	17	Incomplete
9	Göttingen Iceing	Small					15	Working Section about 4 ft. 2
10	LFA A6	0.4 x 0.4 or 0.6 x 0.3	3	1,300	Closed		18	Intermittent
11	LFA A7	0.25 x 0.25 or 0.4 x 0.4	4	1,700?		0.06 to 1.0	18	

Table 1 (Contd.)

No.	Tunnel	Working Section (Metres)	Maximum Mach No.	HP Available	Type of Section	Working Pressure	Fig. No.	Remarks
12	LFA A9 (a)	0.9 dia.	1.05	16,000	Open	0.1 to 1.0	19 & 20	
13	LFA A9 (b)	0.8 "	1.5	16,000	Closed	0.1 to 1.0	19 & 21	
14	LFA A1	2.5 " or 3.0 x 2.2	0.16	375	Open	1.0		
15	DVL Berlin	1.2 dia.	0.18	250				
16	" "	2.5 dia.	0.18	500				
17	" "	8x6 or 7x5	0.21	2,750	Open			
18	" "	4.0 dia.	0.12					Vertical Spinning Tunnel
20	Darmstadt	2 dia.	0.17		Open			
21	-do-	4 dia.	0.12		"			
22	-do-	0.8 dia.	0.29		"			
23	Ailing	1.0 dia.						Free Flight Tunnel
24	-do-	1.0 dia.						Blower Tunnel For VI Motor Tests
25	Stuttgart/Ruit	0.56 dia.	0.10					Non return, low turbulence
26	-do-	Variable	0.53					Intermittent, operated by piston.

Table 1 (Contd.)

No.	Tunnel	Working Section (metres)	Maximum Mach No.	HP Available	Type of Section	Working Pressure	Fig. No.	Remarks
27	Stuttgart/Ruit	1.0 dia.	0.15					No balance
28	-do-	0.8 x 1.2	0.06					Blower Tunnel
29	-do-	0.3 dia.	0.75					Driven by steam or air injection
30	Southofen	0.8						
31	-do-	0.1 dia	Up to					
32	-do-	0.2 "	2.5					
33	-do-	0.3 "						
34	Munich	0.4 x 0.4	2.9					
35	-do-	0.25 x 0.25						
36	-do-	0.4 dia.	Low					
37	-do-	2 dia.	Low		Open			

Refrigerated Tunnel

Temperature down to -60°C .
Motors up to 3000 HP

Not assembled
Not assembled.
Intermittent.

Appendix

Wind Tunnels at L.F.A. Brunswick

The following description of these tunnels augmenting the information given earlier and in Table 1 has been collected from a variety of sources notably notes by McKinnon Wood and Smelt.

Tunnel A.1

This low speed small tunnel was equipped with two overhead balance bars each carrying 6 self balancing remote reading steelyard units. Two similar units were used for speed contro.

Tunnel A.2. Fig. 10

This tunnel can be arranged to work either "straight through" or with a return circuit. The change over is affected by moving the two upper cascades and opening the roof at the ends of the building (see Fig. 10). This was probably intended for tests of jets or rockets. The balance is a component recording type enclosed in an airtight glass case below the tunnel so that it is kept at the working section pressure. The contra-rotating fans are driven by two motors having a total capacity of 12,000 K.W. for 5 mins. (Speed 200 to 600 r/m.) The working section (2.8m diameter) increases 1 cm. in diameter in the total length of 4m. In common with the D.V.L. tunnel the cooling air is injected into the return circuit stream by means of an elaborate arrangement of aerofoil faired jets which of course are not used when the tunnel is running "straight through".

Tunnel A.3.

This large tunnel (Fig. 13) was built for two alternative systems of air removal. With both, the external air enters by admixture with the jet. The air removal system which was found to be satisfactory and which was always used consisted of an adjustable opening in the nose of the long body ahead of the fan boss - the air ultimately leaving the tunnel through radial vanes. The stepped gap just inside the collector was provided for an alternative exchange system 10 to 20% of air seems to have been exchanged. The power factor was about 0.37. The usual pulsation of flow in the open jet tunnel was experienced. The R.A.E. tabs round the jet were found to cause a rise in velocity near the nozzle outlet and Eiche stated that the trouble was ultimately cured -

- (a) by the addition of an aerofoil ring around the collector edge and
- (b) by a system of alternately inward and outward deflecting vanes around the nozzle (also used in tunnel No. 6 Table 1).

The flow is said to be accurate to 1/10 degree and the velocity distribution excellent over the central 3m rising a little in the outer part.

In view of the design low turbulence is hardly to be expected.

A large elaborate six component balance was carried on a rigid overhead car. The records are printed on tables in the forebuilding.

For testing power units a travelling floor car is provided with an arrangement whereby the power unit is mounted on oil pads and drag can be read on a mechanical balance.

Tunnel A.6.

This intermittently running tunnel operates by atmospheric air discharging through the working section into a spherical container 30 ft. or more in diameter. This container is evacuated by a 1000 K.W. compressor (Fig. 18) which can also be used for running tunnel A.7. The duration of a run is under 30 secs. and the time taken to re-evacuate the sphere about 3 mins. There are two alternative working sections (see Table 1) and a Mach Number of 3 can be reached with the smaller. No air drier is provided on the tunnel as it stands.

Tunnel A.7. Fig. 18

With the smaller working section this tunnel can run continuously at a Mach number of over 3.

With the larger section the tunnel was intended to run intermittently (20 sec. run followed by 3 mins. break) but is not clear whether this was ever done.

The tunnel has also been used "straight through" to atmosphere for combustion experiments.

The equipment consists of:

- (a) "Gottingen" type 3 axis balance
- (b) Interferometer by Zeiss
- (c) Spark Generator (10^{-5} sec.) for use with (b).

Various working sections mostly in wood are used in both A.6 and A.7 for different supersonic Mach numbers.

The second throat is produced by flexing the walls after the establishment of supersonic flow. (See para. 2.1).

Tunnels A.9(a) and A.9(b)

Both of these, Figs. 19, 20, 21, are continuous running each being operated by a compressor (ratio 1.4) and a motor of 8000 hp. The two motors can be clutched together to drive either compressor which is then provided with 16000 hp. In both tunnels the discharge can be either to the return circuit or to atmosphere. The change over is effected by rotating the collector at the foot of the diffuser through 180° .

The collector is an interesting feature about which more information will be obtained. Both tunnels can operate at any pressure between 0.1 atmosphere and unity.

To get the low pressures in the open throat tunnel (A.9(a)) a large cylindrical cover comes down outside the working section and seals this off from the atmosphere.

A.9(b) is fitted with flexible walls at the end of the working section. The adjustment points are operated by cams driven by chains and sprockets in such a manner that the walls can be brought together quickly to the desired form by turning a single spindle after the supersonic flow is established.

A.9(a) is reported to suffer from bad vibration of the jet as the speed of sound is approached. In an attempt to combat this the length of the open section has been made variable.

The noise is so bad that while the rest of the building is sound proofed, extra sound absorbing material has been put on the walls of the room housing A.9 (a).

Workshops, etc.

Every tunnel building is provided with a complete workshop and machine shop and in addition there are very large Aero machine and wood-working shops. The main machine shop is elaborately provided with a variety of large planing machines, copying machines etc.

The accommodation for staff was on a generous scale and all manner of mechanical helps were provided. Well fitted out dark rooms were in every building and evidence was not lacking of the extensive photographic equipment which had been in existence.

No. 17240.5
 17240.5
 17240.5
 17240.5
 17240.5

FIG. 1-5

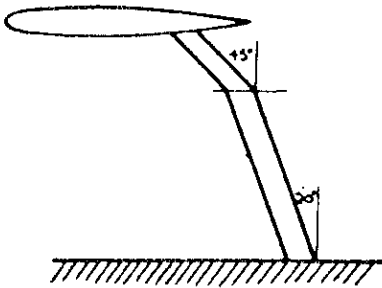


Fig. 1

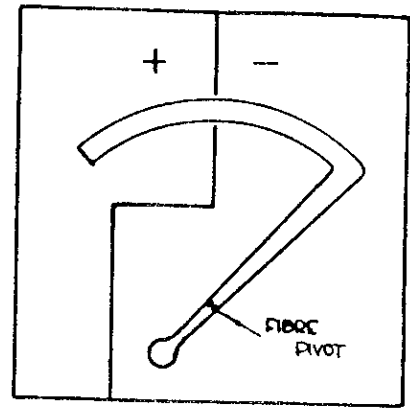


Fig. 2

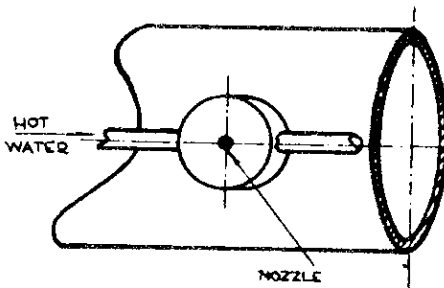


Fig. 3

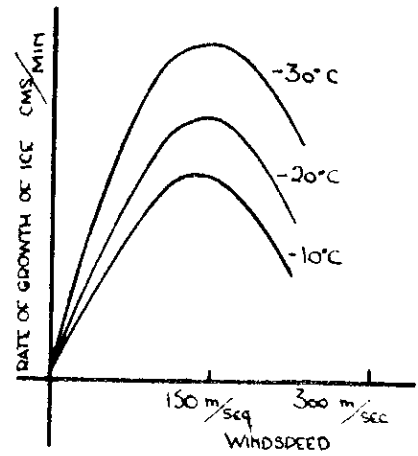


Fig. 4

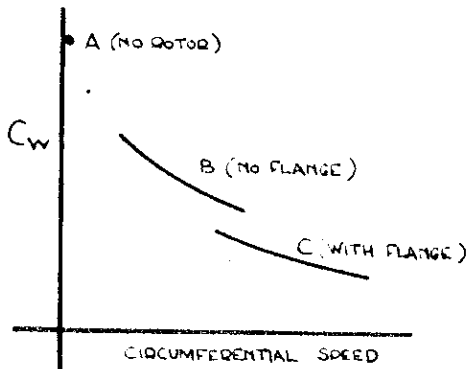


Fig. 5a

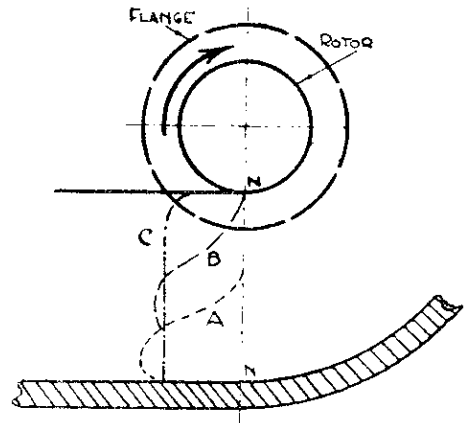
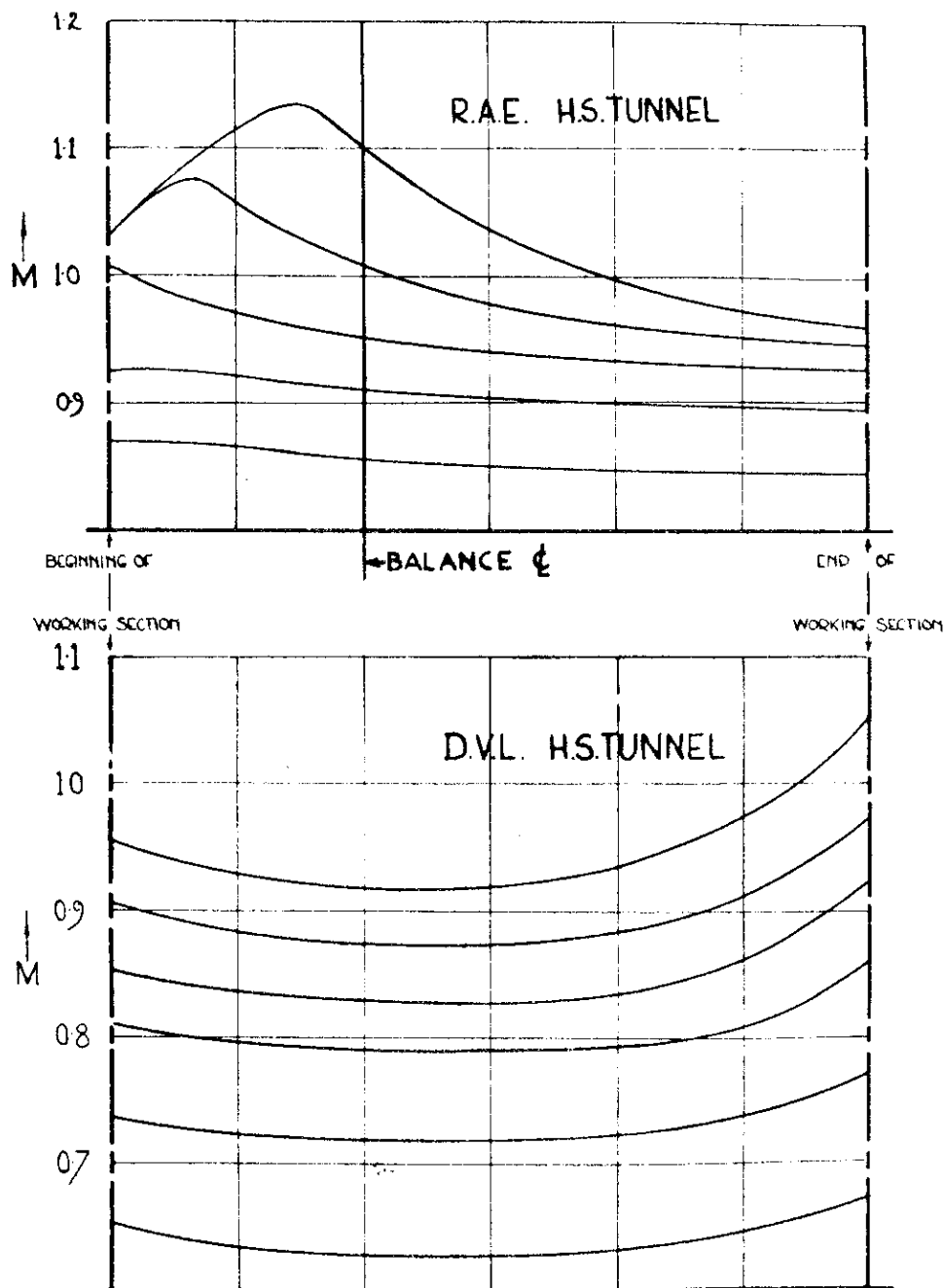
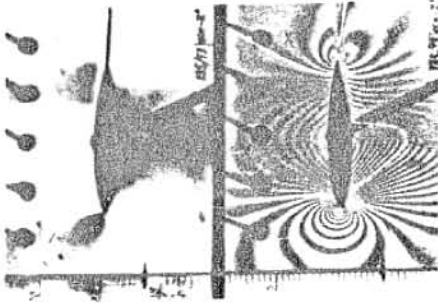


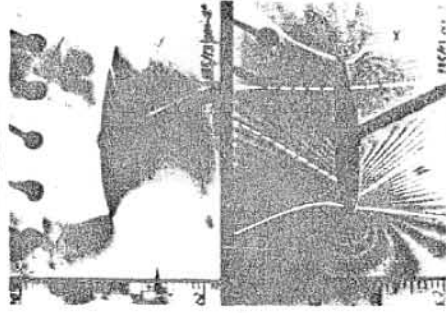
Fig 5b



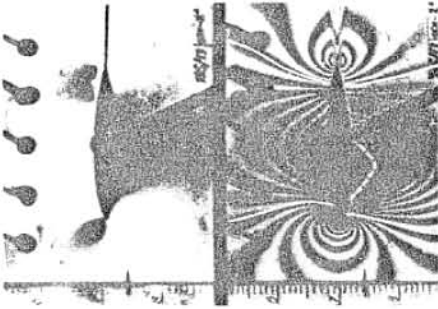
COMPARISON OF SPEEDS AT WALL
OF WORKING SECTIONS OF D.V.L. AND
R.A.E. HIGH SPEED WIND TUNNELS



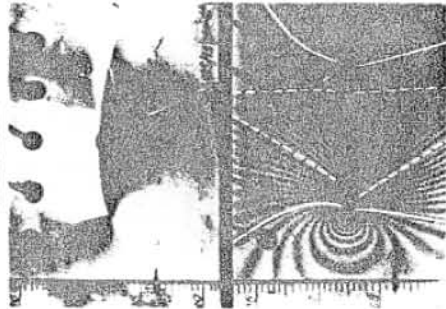
$M_{\infty} = 0.754$
 $\alpha = -1.5^\circ$
 $k = 0.0576$



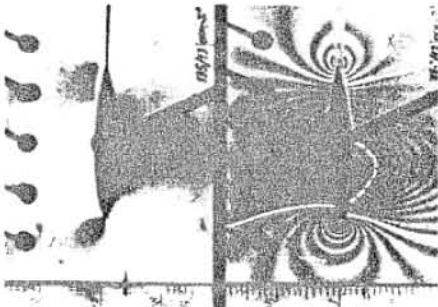
$M_{\infty} = 0.776$
 $\alpha = -1.5^\circ$
 $k = 0.0552$



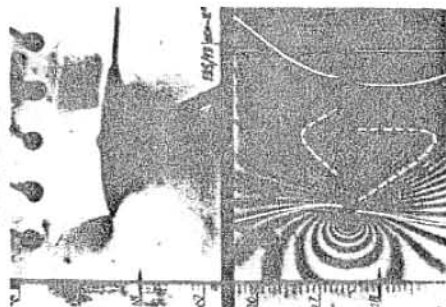
$M_{\infty} = 0.723$
 $\alpha = -1.5^\circ$
 $k = 0.0614$



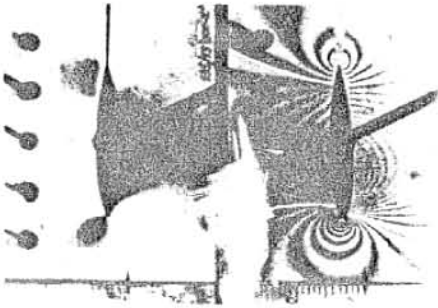
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 $\alpha = -1.5^\circ$
 $k = 0.0552$



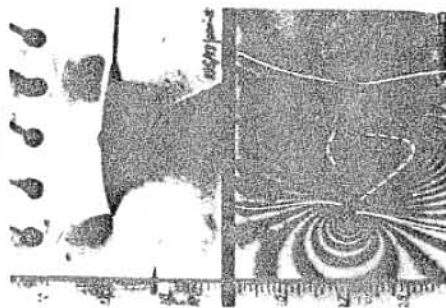
$M_{\infty} = 0.723$
 $\alpha = -1.5^\circ$
 $k = 0.0614$



$M_{\infty} = 0.770$
 $\alpha = -1.5^\circ$
 $k = 0.0558$



$M_{\infty} = 0.698$
 $\alpha = -1.5^\circ$
 $k = 0.0648$



$M_{\infty} = 0.754$
 $\alpha = -1.5^\circ$
 $k = 0.0576$

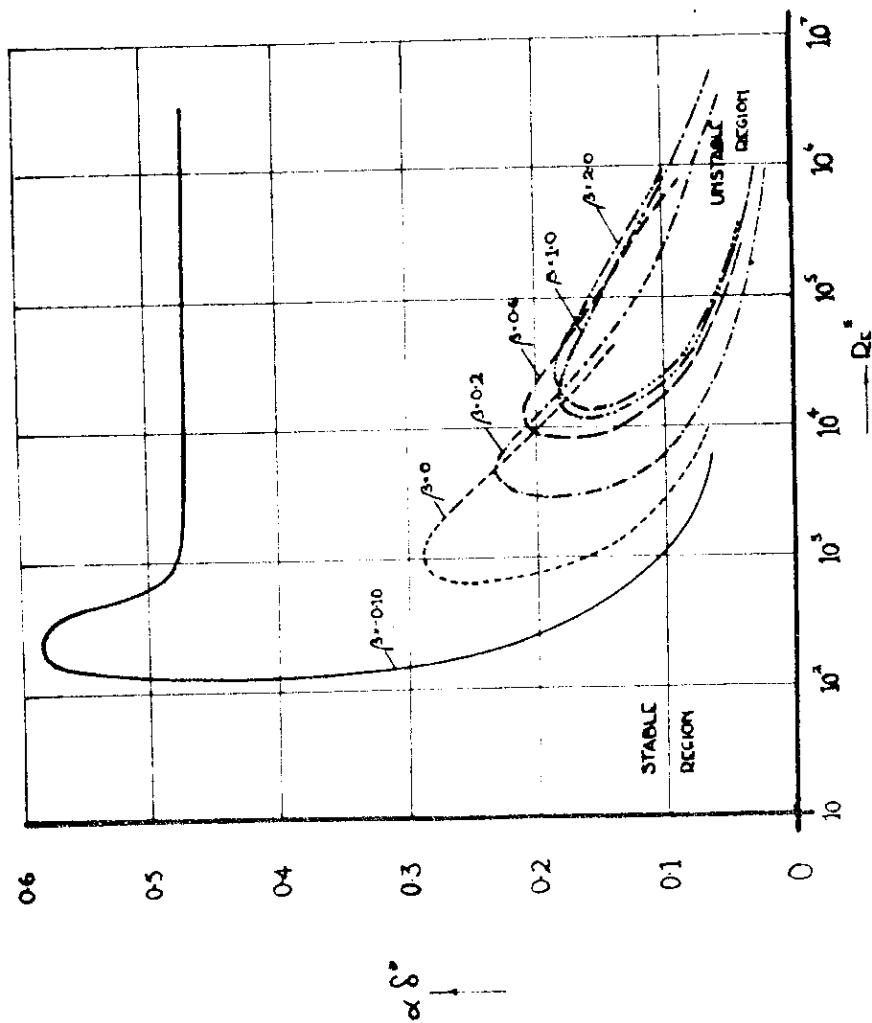
NACA 00015 055-40

Tafel II

ROYAL AIRCRAFT ESTABLISHMENT
 REPORT NO. 63735
 14.7.45

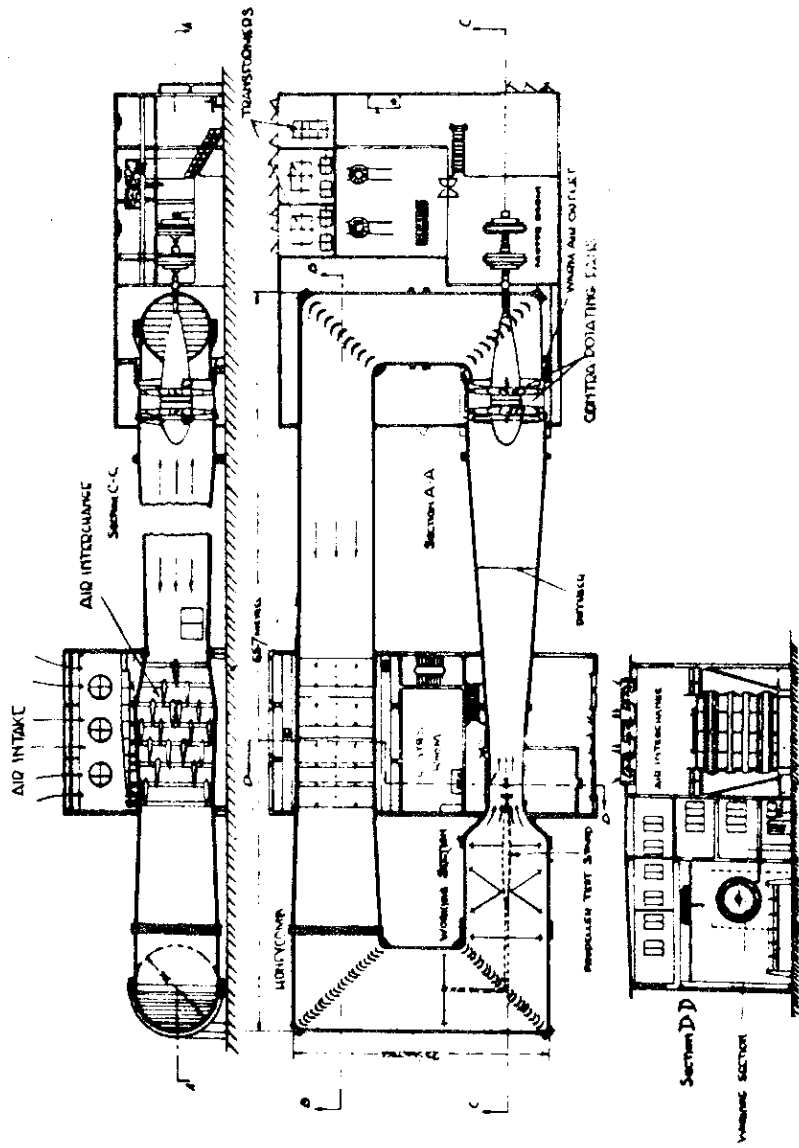
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 DO 22
 CR 22
 MR 22

FIG.8



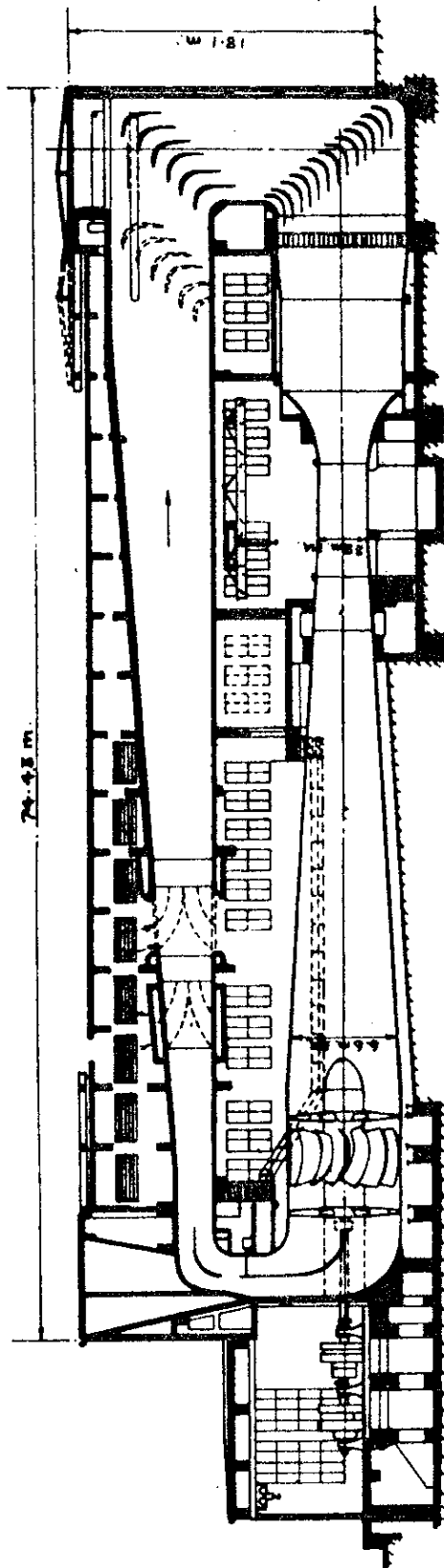
243.5

FIG. 9



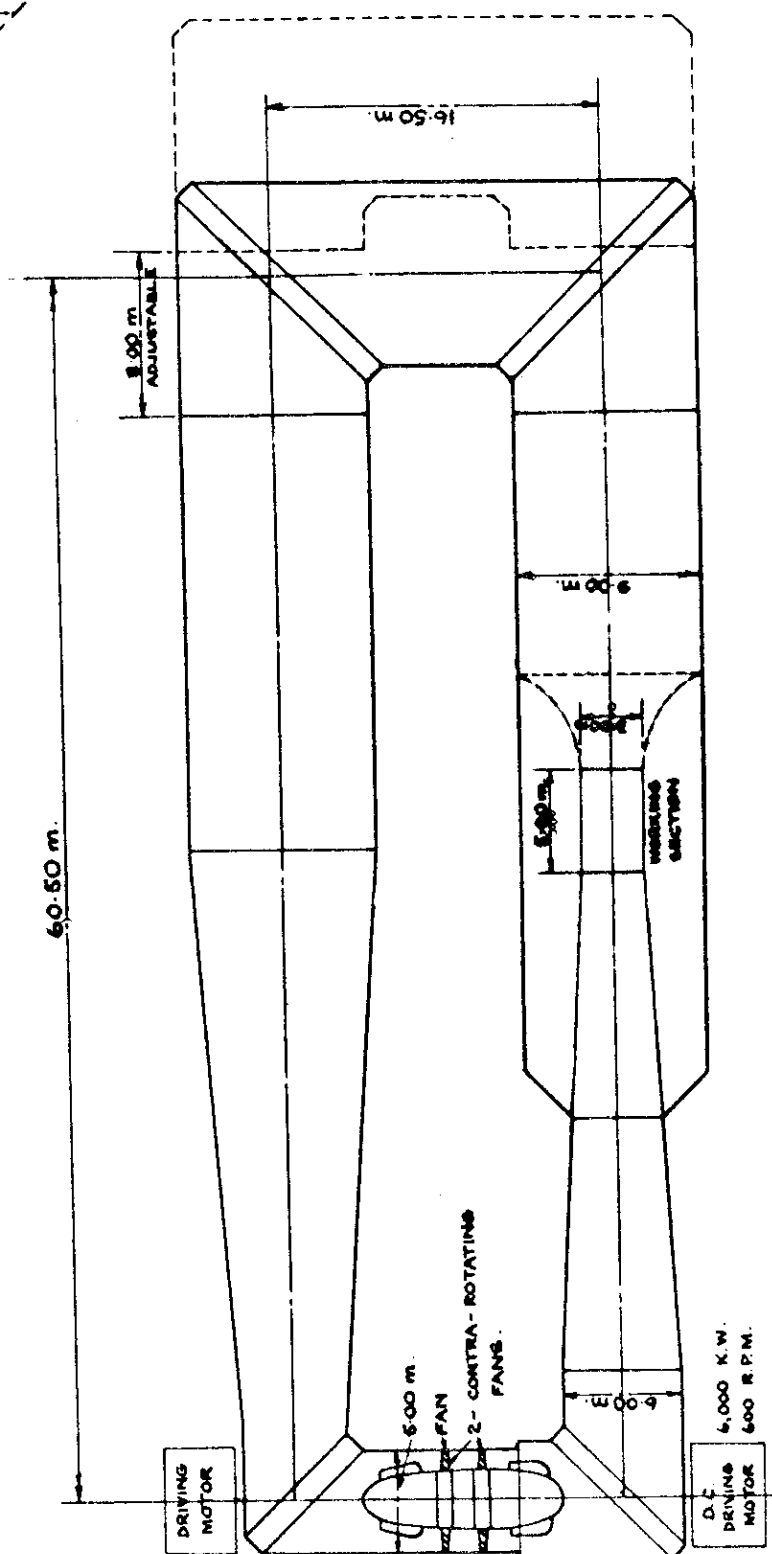
D.V.L. HIGH SPEED WIND TUNNEL.

FIG.10



2.8 m. HIGH SPEED WIND TUNNEL. A.2.

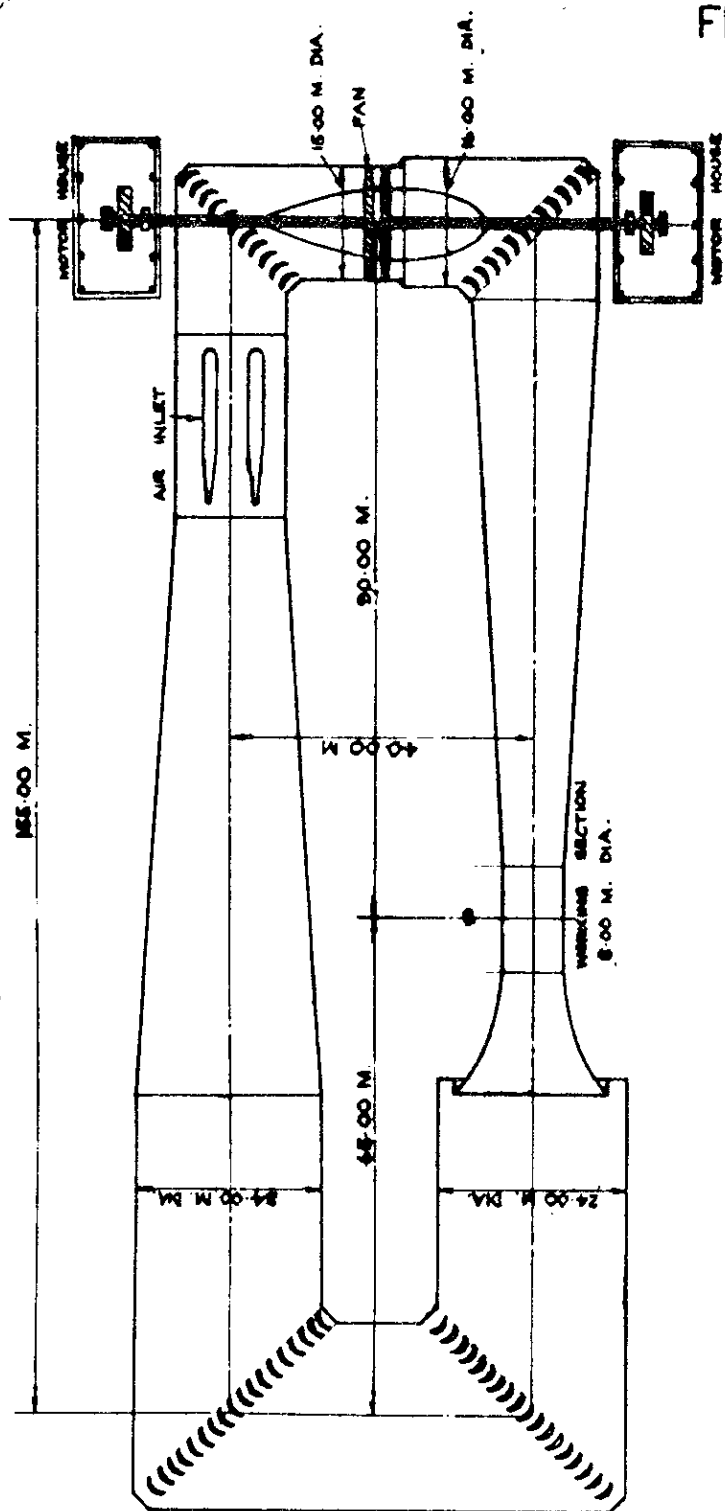
L.F.A. - BRUNSWICK.



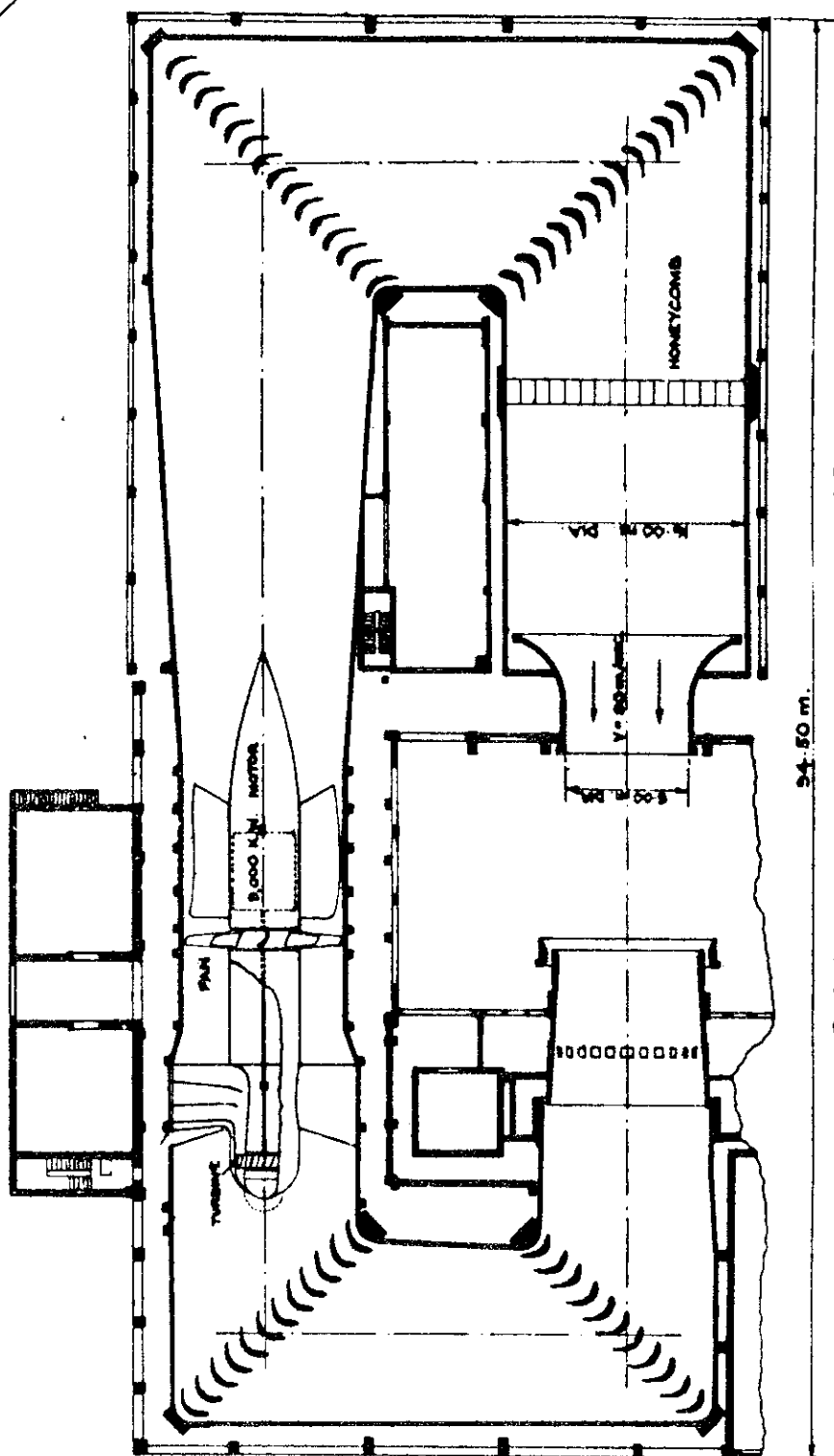
3 m. HIGH SPEED WIND TUNNEL.
MUNICH.

12246.5

FIG. 12



8 m. HIGH SPEED WIND TUNNEL.
MUNICH.



No 17248.8.
 DR. ~~17248.8.~~
 TR. ~~17248.8.~~
 CH. ~~17248.8.~~
 APP. ~~17248.8.~~

FIG. 14+15

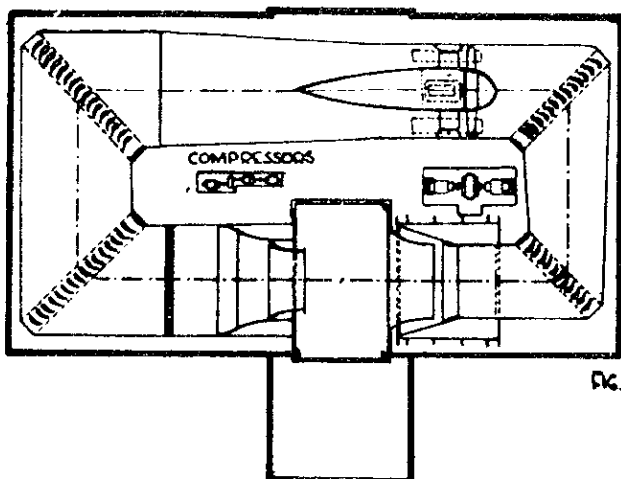
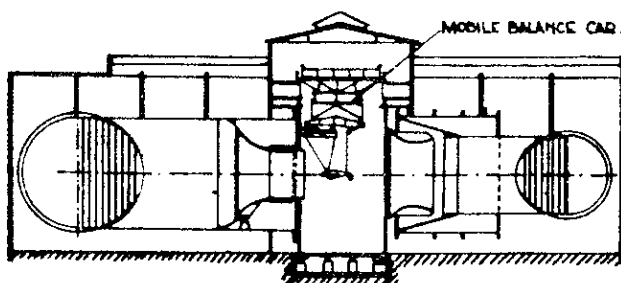


FIG. 14

COMPRESSED AIR TUNNEL
 GÖTTINGEN

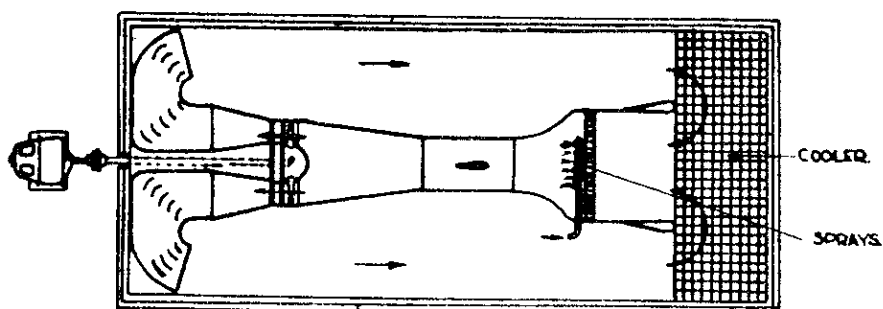
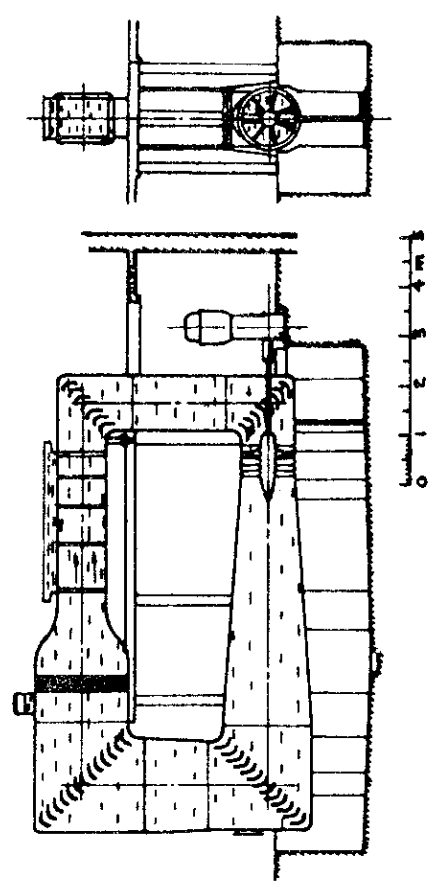


FIG. 15.

SMALL ICING TUNNEL
 GÖTTINGEN

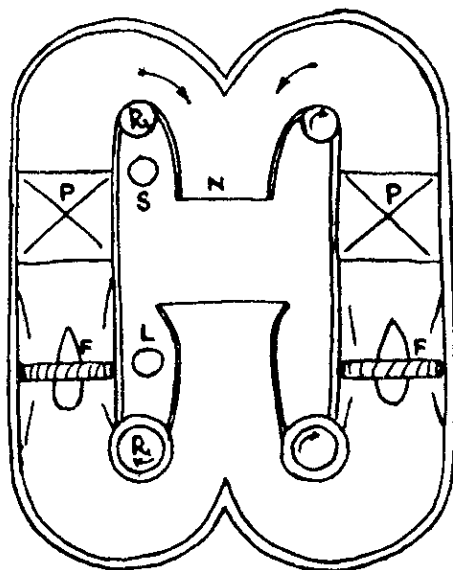
No. 1 2 4 9 5
Pl. 24
Tr. 24
Gr. 24
Pl. 24

FIG. 16

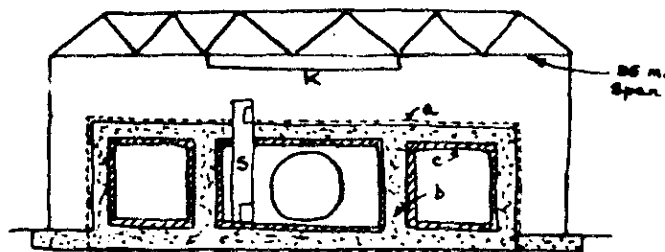


WATER TUNNEL
GÖTTINGEN

FIG. 17



- N - NOZZLE, 4 m. DIA.
- P - PIPE COOLER
- F - FAN
- R₁ - ROTOR WITH FLANGES
- R₂ - ROTOR WITHOUT FLANGES
- S - SPIRAL STAVE WITH PRESSURE LOCKS AND OBSERVATION WINDOWS
- L - LIFT WITH PRESSURE LOCKS
- K - 50 TON CRANE
- b - CONCRETE
- c - CORK
- a - ALUMINUM FOIL



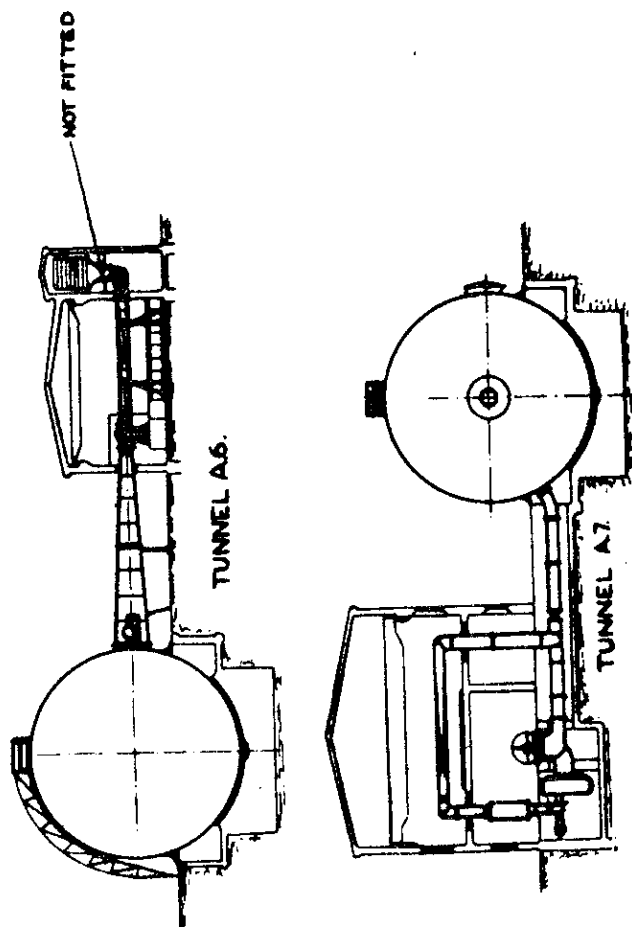
LARGE ICING TUNNEL

GÖTTINGEN

(NOTE: DRAWINGS NOT TO SCALE)

172515
TE
CH
APP

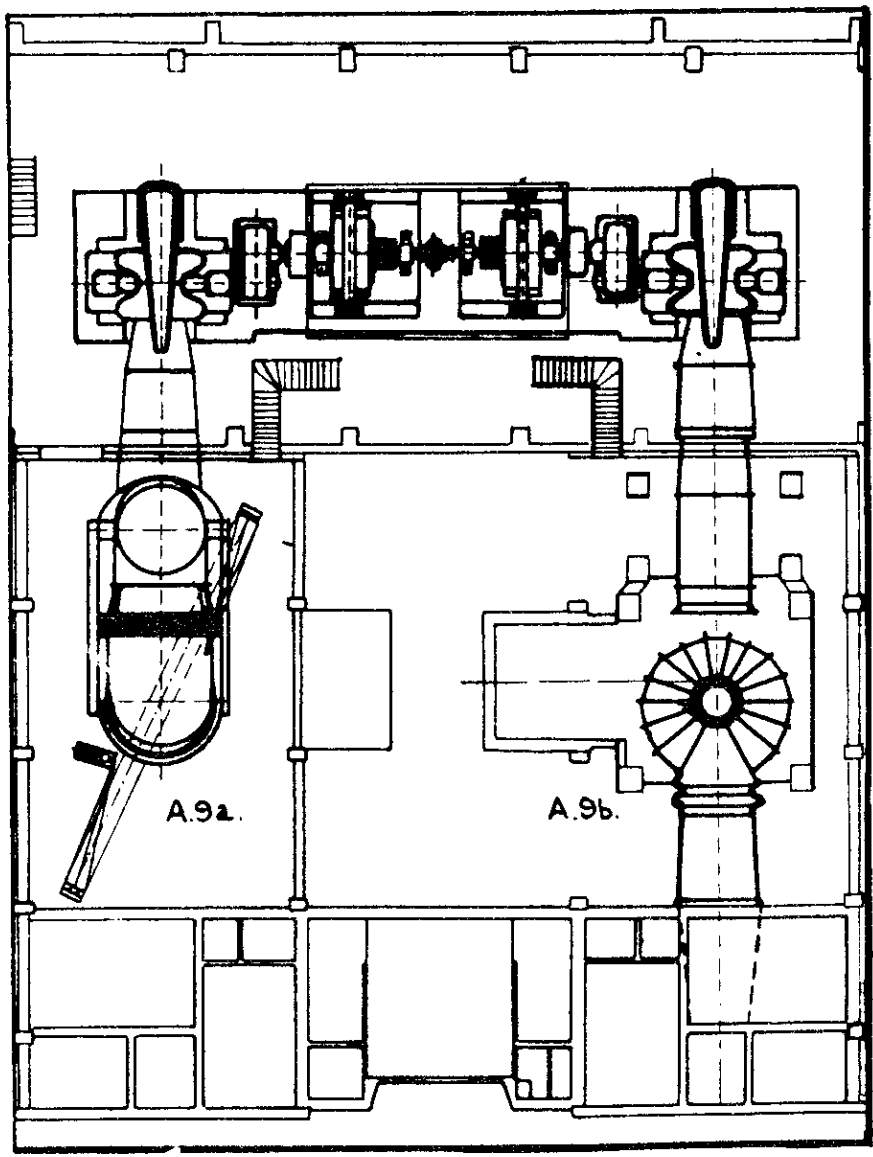
FIG. 18



WIND TUNNELS A6/7
L.F.A. BRUNSWICK.

No. 17252 S
Date
By
Mr.

FIG. 19

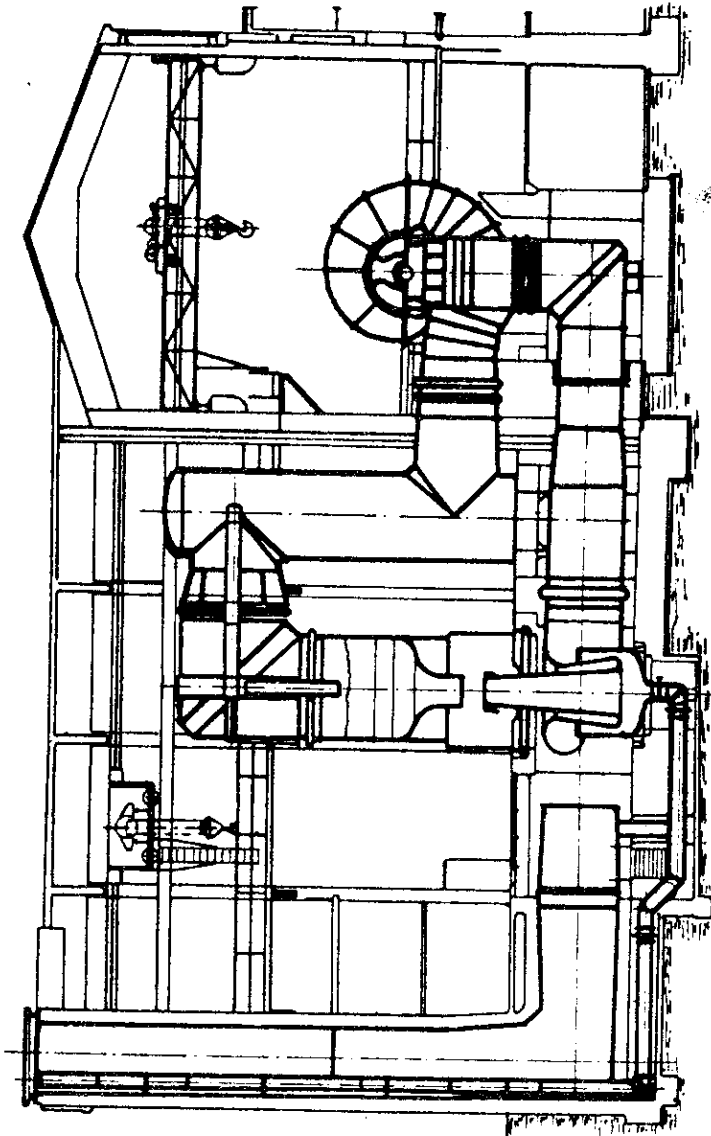


(A.92 PLAN)

(A.96. PLAN BELOW GROUND)

PLAN OF WIND TUNNELS A.92. AND A.96.

L.F.A. BRUNSWICK.

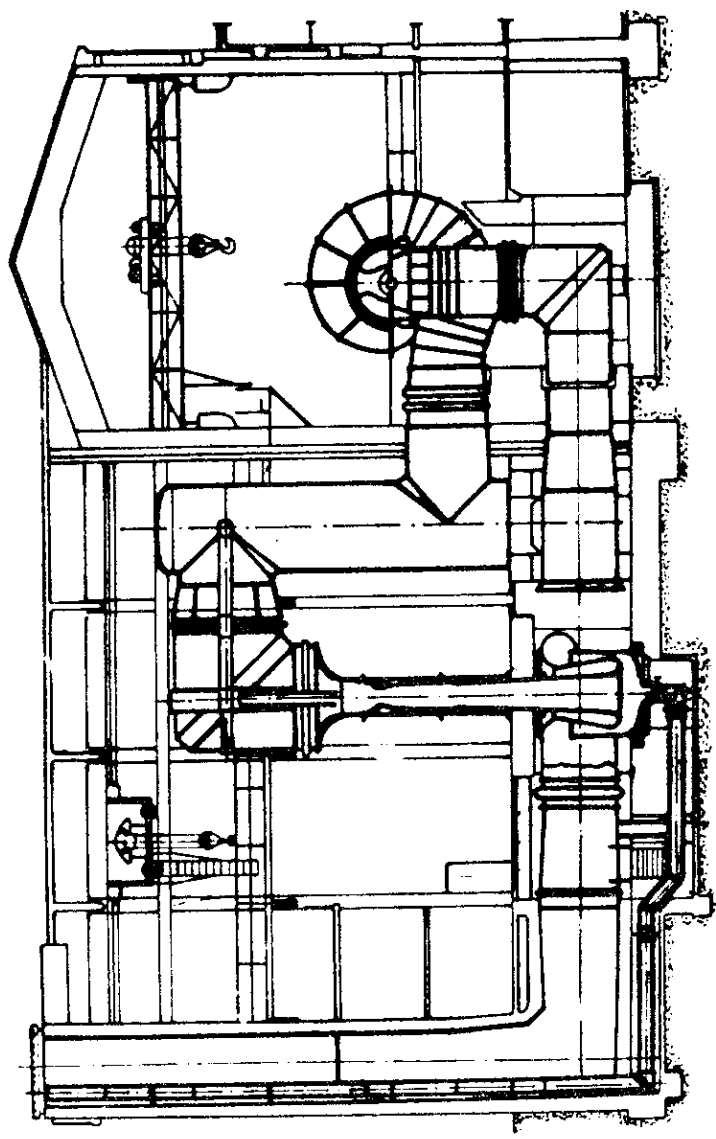


ELEVATION OF WIND TUNNEL A.92.

L.F.A. BRUNSWICK.

17254.5

FIG. 21



ELEVATION OF WIND TUNNEL A.B.L.
L.F.A. BRUNSWICK.

No. 13-5495-5
 DB. MM
 TS. 500
 CH.
 MY.

FIG. 22

