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Preliminary notes on the W.V.A. Supersonic wind tunnels at Kochel, S. Germany

by

P.R. Owen, B.Sc.

R.A.E. Ref: Aero.1674.R/W/1/1

SUMMARY

A brief description is given of the W.V.A. supersonic tunnels and the work performed in them. These tunnels were originally at Peenemunde and they were used mainly for the development of rockets and projectiles and associated research problems.

Only a general outline of the apparatus and activities at Kochel are given in this note. A full description will be included in a subsequent visit report.

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1. Introduction

These notes are designed to give a very brief outline of the information obtained by the writer during his investigations at Kochel. All details and drawings are omitted but these will be included in a full report on the visit which will be issued later.

The purpose of the visit to Kochel was primarily to obtain data on the wind tunnels themselves and also to gather at first hand from the staff a general picture of their experimental methods. As far as actual results are concerned only an overall survey was made as these will eventually be made available to us through C.I.O.S. channels. In all, some 176 Kochel reports have been microfilmed, and the reproduction is proceeding at C.I.O.S. headquarters. There were, however, a number of exceptions; the results of tests which were considered to be of immediate interest, and, of course, results which were not written up, were collected in as much detail as possible.

2. History

The establishment at Kochel which was known as the Wasserbau Versuchs Anstalt (W.V.A.) was originally a part of the Heeres Versuchstelle at Peenemunde. The need for a supersonic tunnel in the development of projectiles was recognised in 1936 and the 10 x 15 cm. tunnel at Aachen was used for this purpose. In about 1938 the present tunnels were planned, and the first 40 x 40 cm. intermittent tunnel was built at Peenemunde in 1939. The first tests were made in it during the early days of the war. A second identical tunnel using the same power supply and vacuum sphere was then constructed and then followed a 18 x 18 cm. continuous tunnel. The two former tunnels were intended purely for projectile work; the continuous tunnel was designed for fundamental research on supersonic flow.

In August 1943, it was decided to move the tunnels from Peenemunde to Kochel, the latter place being chosen because of the availability of electric power from the neighbouring Walchensee hydro-electric plant. The apparatus was completely shifted by the middle of 1944 and an intermittent tunnel was in operation by October of that year. Owing to damage to essential equipment the second intermittent tunnel as well as the continuous tunnel was never run at Kochel.

3. Description of plant

The principal features of the tunnels are tabulated below;

Tunnel No.	Type	Dimensions of working section	Type of working section	Maximum Mach No.	Time of run approximately secs.
1	Intermittent	40x40 cms.	open	4.4	20
2	"	"	"	4.4	20
3	Continuous	18x18 cms.	½ closed	3.3	-

A rough sketch of the intermittent tunnel is given in Fig.1.

3.1 Power supply

The three tunnels were connected to a common sphere 12.5 m. dia. and 1000 cu.m. capacity which was evacuated by three Demag rotary vacuum pumping units*. Each unit which consisted of a motor driving two pumps had a power of 270 kw.

3.1.1 Intermittent tunnels

The connections to the sphere were such that only one tunnel could be in operation at any given time. During the first part of the evacuation, the three pumps worked in parallel; in order to obtain the final low pressure the connections were arranged such that one pump acted as a second stage in series with the other two. The initial pumping time was from 3 to 9 minutes depending on the degree of vacuum required in the sphere. This latter is, in turn, a function of the Mach number required and the time of run. Some representative rough values are given in the following table.

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* The arrangement at Kochel was different owing to damage to the sphere in transit from Peenemunde. At this stage, only the apparatus as used at Peenemunde will be described.

M	Sphere pressure for a 15 sec. run. mm. mercury
1.22	110
1.56	90
1.86	75
2.92	40
3.24	30
4.38	10

When the required pressure was obtained in the sphere a rapidly operating valve was opened (the time taken to open the valve was of the order of 2 secs.) and air was drawn from the atmosphere, through a silica-gel drier at the entrance to the contraction cone, into the tunnel and thence to the sphere. The drier ensured that the specific humidity of the air was less than 0.5 gr./Kg.

Two pumps were normally kept in operation during the run so as to increase the running time. The interval between runs was of the order of 3 minutes.

3.1.2 Continuous tunnel

In the case of the continuous tunnel the sphere was used simply to damp out the effects of pump fluctuations which would otherwise lead to fluctuations in the flow downstream of the working section and hence a greater amount of noise.

3.2 Flexible walled diffuser for the intermittent tunnels

In order to avoid compression or expansion shocks in the free jet, the pressure in the measuring chamber enclosing the jet was adjusted so as to be equal to the pressure at the end of the nozzle. This was done by adjusting the size of a second throat downstream of the jet.

The mechanism by which the pressure outside the jet is changed can be explained by considering the diffuser to act as a kind of vacuum pump insofar as the throat size affects the degree of mixing at the edge of the jet until equilibrium conditions are attained inside the measuring chamber. There is, thus, an important difference between the adjustable throat as used in an open jet tunnel and that used in a closed tunnel.

3.3 Balance

A three component electrical balance was used. A rough sketch is given in Fig.2. The model was fixed by a sting to a strut which was freely supported by three steel leaf springs. The springs were each mounted between two coils so that any change in the spring position resulted in a relative change of inductance of the coils. The forces on the model were then found from measurement of the deflection of these springs as given by the inductance change of the coils.

The maximum load on the balance was 18 Kg. and its precision under these conditions was 0.3%.

3.4 Strut interference

The strut support interference was found by using a split sting. The one half, which was attached to the model, was fixed onto the part of the strut connected to the balance springs, and the dummy half was fixed to a strut which was completely earthed, but always present. After the forces in this condition were measured the arrangement was reversed such that the model was fixed to the dummy strut. The difference then gave the model drag.

The two struts were similar in shape and except for a small gap of the order of 1 mm. formed a complete circular arc spanning the tunnel. Both struts moved synchronously during an incidence change.

It was stated that the lift and drag on the balance strut were about equal to the lift and drag on a representative model at an incidence of 5°.

3.5 Nozzles

There are two outstanding features of the nozzle designs. The first is that they represent the shortest length of nozzle which can be obtained with a circular arc throat for uniform flow at the exit. This was achieved by making the divergent angle the maximum possible at the point of inflexion where the Busemann part of the nozzle starts. This maximum angle is equal to the angle through which a sonic stream would be expanded in order to attain the Mach number at the exit of the nozzle.

The second feature is the ingenious method of construction. The liner of the nozzle was of a special cement known as "Monolith"*. The nozzles had a mild steel base with carefully constructed brass formers at the sides. The cement, while in a liquid state, was poured into the nozzle and shaped to the former profile with the aid of a straight edge.

After a nozzle was designed it was tested by making scratches in the Monolith and photographing the wavelets with a Schlieren apparatus. Small errors in the nozzle profile were then corrected by rubbing down the cement. When a satisfactory shape was established the Monolith was chipped off and recast to the new shape. Nozzles made in this way existed for the following Mach numbers; 1.22, 1.56, 1.86, 2.50, 2.92, 3.24, 4.38. Simple straight sided liners were also provided for subsonic speeds.

In the worst case the maximum velocity fluctuation along the axis of the supersonic nozzle was 5% of the mean velocity and, in the best case, 2% of the mean. The distribution at subsonic speeds was poor.

4. Technique and results

The tunnels had been used to a large extent for routine tests on projectiles and rockets, and, with the exception of one flak rocket, namely, Wasserfall the results were not examined in detail. On the other hand, the techniques used in making the tests were investigated.

The following subjects were discussed in some detail and the results of these discussions will be given fully in the final visit report. Only a few of the more salient points are given below.

4.1 Nozzle design and construction

In addition to the standard nozzles with circular arc throats, nozzles having sharp edged throats had been designed. In this way very short nozzles could be obtained. Tests up to about $M = 8.0$ suggested that the boundary layer at the throat did not cause any trouble.

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* Samples of the cement were taken and these have been sent to Materials Department R.A.E. for examination.

4.2 Construction and operation of drier

In all, about 12 tonnes of silica gel were used. On the average, the power required to dry the air was about 400 Kw. or, roughly, half that needed to drive the tunnel pumps.

4.3 Schlieren apparatus

The method was standard, but special care was taken in the design of the mirrors to correct for astigmatism. The field of view was 50 cm. diameter; the focal length of each mirror was about $5\frac{1}{2}$ m. Although extremely sensitive for most purposes, it was found that the apparatus could not satisfactorily detect Mach wavelets at speeds greater than about M = 3 owing to the very low densities in the working section.

4.4 Pressure measurements in the diffuser of the 40 x 40 cm. tunnel

During the run, the shock wave, starting at the sphere, travelled up the tunnel at the rate of about 1 m/sec.

The efficiency of the diffuser at the end of the run was such that the sphere pressure was about 0.6 times the pitot pressure in the working section.

4.5 Pressure ratios across 40 x 40 cm. tunnel

The ratios of sphere pressure to tunnel entry pressure at the end of a run are tabulated below.

M	sphere pressure / entry pressure
1.22	0.69
1.56	0.62
1.86	0.53
2.92	0.24
3.24	0.17
4.38	0.06

4.6 Measurement of absolute velocity in the working section

A method proposed was to emit sound waves of known frequency from a source upstream of the nozzle and then Schlieren photograph the wave fronts as they passed the working section. This was not successful since the sound waves were not visible by the Schlieren method. It was intended later to use the interferometer to detect the wave fronts.

4.7 Measurement of centre of pressure position on projectiles

The accuracy of the balance for pitching moment measurements was poor and a more accurate method was developed. The model was suspended freely at its C.G. and the incidence varied until the moment about the C.G. was zero. A number of C.G. positions were obtained by adding weights to the nose of the model and in this manner the variation of centre of pressure position over a large incidence range was determined. The accuracy with which the centre of pressure could be found was claimed to be within 0.1 body diameters.

4.8 Pressure plotting

A special method for pressure plotting missiles and projectiles was developed which enabled 120 tubes to be led from a model whose dimensions in a typical case might be; length 30 cm, maximum diameter 4 cm. This involved the use of a half-model attached to a "reflexion plate". At supersonic speeds the conditions on the one side of the plate have no influence on those on the other side so that it is possible to use robust struts for leading the tubes from the model to the outside of the tunnel.

A comparison of the distributions obtained on half-models and complete models showed that the plate boundary layer had no appreciable effect.

It may be of interest to note that when the A.4 was pressure plotted in this way some 120,000 pressure readings were recorded.

4.9 Oscillation experiments

Damping and static stability of projectiles were determined by the free oscillation method. In earlier tests the model was suspended on a wire stretched in the direction of the pitching axis, but a later development employed the half-model technique; both model and plate were allowed to oscillate.

4.10 Measurements with cold jets

Pressure distribution and oscillation measurements were made on rockets with jet flow. The jet conditions satisfied were that the jet Mach number and expansion angle should be the same as at full scale.

The drag of the A.4 rocket with and without jet is of interest, and is given below.

M	C_D	
	Without jet	With jet
0.1	0.13	0.24
0.5	0.12	0.19
0.9	0.19	0.21
1.5	0.29	0.27
2.0	0.20	0.17
3.0	0.17	0.14
3.5	0.16	0.12

4.11 Spinning models

The effect of spin, up to 18,000 r.p.m. model scale, on the lift, drag and centre of pressure position on projectiles was shown to be very small.

4.12 Rolling moment measurements

Rolling moments were measured by supporting the body axially on ball bearings or knife edges and applying a torque to the model in roll by means of a Bowden cable. The torque was adjusted so as just to balance the aerodynamic rolling moment by ensuring that no movement of the model in roll occurred.

The accuracy of the method was said to be about 1 gr.cm. in rolling moment.

4.13 Thermodynamic measurements

Kinetic temperature and heat transfer measurements were made on cones, a plate thermometer, a circular cylinder, stagnation plate and head (stauscheibe and stausonde) etc. Kinetic temperatures were also measured along the body of A4 and along the tunnel axis.

Very briefly, it was found that, for cones, provided the shock wave was attached, the following formula could be used:

$$T_H = T_o + 0.85 \left(\frac{u_o^2}{2\ C_p}\right)$$

where T_H is the kinetic temperature and T_o and u_o are, respectively, the static temperature and velocity behind the nose shock wave. This formula was found to hold over the whole Mach number range explored, $1.2 < M < 3.0$, and for all the cones tested, 10° to 80°.

When quantities were similarly calculated appropriate to conditions behind the nose shock it was found the heat transfer across the surface of cones at supersonic speeds was given by,

$$N_u = 0.0107 R^{0.82}$$

where N_u is the Nusselt number and R the Reynolds number.

4.14 Skin temperature calculations for A.4 and Wasserfall

The variation of the skin temperatures over the trajectories was calculated; the following maxima were obtained:

A.4	675°C.
Wasserfall	240°C.

4.15 Exploration of upper atmosphere with A.4

Six standard A.4 rockets had been allocated to Prof. Regener at Darmstadt for exploring atmospheric conditions at an altitude of 45 Km. The following measurements were to have been made; brightness of background (Himmelshelligkeit), quantity of ozone, pressure, density and temperature. The instruments were contained in a box fitted inside the nose of the A.4. The rocket was to have been fired vertically; at the end of the burning period the rocket walls were to be removed by explosive bolts and the box parachuted down. Measurements were to have been made during the descent.

Details were obtained only of the proposed methods of temperature measurement.

4.16 Humidity measuring apparatus

The method of measuring the specific humidity in the tunnel was based on the measurement of the heat of absorption in concentrated H_2SO_4 of the water content of the air. A reading could be taken in about 15 seconds. The sensitivity of the apparatus was such that a specific humidity of 0.001 gr/Kg could be detected.

4.17 Interferometer

The tests made with the interferometer were designed only to explore the technique of using the instrument. Preliminary measurements in the 18 x 18 cm. tunnel had been made of the density field in the empty tunnel and around a cone. Two somewhat interesting instruments had been designed to analyse the fringe patterns.

4.18 X-rays

An apparatus had been constructed but the method of using it was still in the development stage.

Measurements had been made of the density distribution through a shock wave.

4.19 Electrical pressure gauge

Very compact electrical gauges were used at the higher Mach numbers where the low pressures in the tunnel working section and short running times made a mercury manometer impracticable. In principle, the functioning of the gauge depended on the change of inductance of a coil due to variations in the size of air gap. This latter, in turn, depended on the movement of a disc attached to a pressure capsule.

Gauges having various degrees of sensitivity were in use; the most sensitive had a pressure range of 5 mm. of mercury, and, in this range, pressure differences of 0.005 mm. of mercury could be measured.

Fluctuating pressures up to a frequency of 200-300 cycles per second could be recorded.

The gauge had been used to measure the changing pressure distribution in the tunnel diffuser during a run.

4.20 Pitot tubes

The standard pitot tubes used for calibrating the tunnel were of an interesting design. The outside diameter of the tubes was about 5 mm. and inside diameter about ¾ mm. The reason for this large ratio of diameters was to ensure that the bow wave in the neighbourhood of the bore was normal to the direction of flow. Conditions would then be such that Rayleigh's formula could be applied with a high degree of certainty.

4.21 Reynolds number effects

The Kochel group claimed that, at the Reynolds number at which they worked, of the order of 3×10^6, there should be little scale effect between tunnel and full scale. This was, in general, borne out by comparison with firing trials. They pointed out, moreover, that, in a particular case, the results of Walchner's tests, made at a much smaller Reynolds number in the Göttingen tunnel, differed from theirs by as much as 20% in drag.

There had not been much work done to determine boundary layer characteristics at supersonic speeds with the exception of measuring the boundary layer thickness on flat plates.

Normally, the subsonic laws for skin friction, velocity profile and thickness were assumed. As far as the skin friction was concerned, tests, where balance drag and form drag had been measured, suggested that the assumption of the low-speed laws was sufficiently good for most practical purposes up to a Mach number of about 3.0. It is also interesting to note that the rate of growth of thickness of a turbulent boundary layer along a flat plate was found to be only slightly greater at supersonic speeds than at subsonic speeds.

4.22 Centre of pressure position on aerofoils of small aspect ratio

Centre of pressure and normal force measurements had been made on a series of aerofoils of small aspect ratio and having a variety of profiles.

The incidence range was from 0° to 30° and the Mach number range from 0.4 to 2.92.

No comparison had been made with theory but the results have been collected in entirety and it is hoped to make this comparison here.

4.23 Shock waves from cones

Measurements were made of the Mach number for which shock wave detachment occurs from the noses of cones. A series of cones was used; the total cone angles varied from 47.5° to 111.5° in 2° intervals. The Mach number range was from 1.2 to 4.2.

It was found that, at a given Mach number, the cone angle for initial detachment was some 3° to 4° greater than that given by theory.

The distances of the detached bow waves from the noses of the cones over a range of Mach number were also measured.

4.24 Base pressure on bodies with conical noses

The results, which are not entirely free from suspicion, gave the following variation of base pressure with Mach number. These figures were deduced from tests on three bodies having different cone angles and different lengths of the straight cylindrical portion.

M	$\frac{p-p_0}{\frac{1}{2}\rho U^2}$
1.5	-0.24
2.5	-0.12
3.5	-0.01
4.5	+0.07

p_0, ρ and U are the free stream static pressure, density and velocity respectively: p is the base pressure.

4.25 Wasserfall

Wasserfall was a guided flak rocket developed at Peenemunde. The design maximum Mach number was 2.5.

Experiments, over a period of about one year, were made at the W.V.A. to determine the correct combination of wings and fins to give a minimum centre of pressure travel over the flying range. They succeeded in doing this, without any recourse to the theory of wings of finite aspect ratio, and the main result is given below.

M	Distance of C.P. from nose in terms of body length	
	$\alpha = 2°$	$\alpha = 8°$
Low-speed	0.56	0.59
2.5	0.60	0.63

4.26 Drag of spheres

The drag of a sphere had been measured between M = 0.3 and M = 4.3.

The results at supersonic speeds were in good agreement with those found from tests in the Göttingen tunnel and also with firing trials made by Rheinmetall Börsig.

4.27 The Oswatitsch diffuser

The athodyd design of Oswatitsch at Göttingen had been tested at Kochel without combustion. The conical bridge at the duct entry as designed by the Oswatitsch group was shown to lead to very efficient diffusion.

At M = 3.3 the pressure in the combustion chamber was 1.6 times the free stream pitot pressure. In other words the diffusion was roughly 60% more efficient than it would have been if subsonic conditions were attained through a straight shock at the entry.

The Kochel group could not supply much detail about Oswatitsch's work as the tests had been done very hurriedly under the supervision of one of Oswatitsch's staff.

If this has not already been done it is suggested that the work of Oswatitsch should be investigated very thoroughly. He is still at Göttingen.

4.28 Project "A"

Project "A", or, alternatively "Windkanal Sud", was the name given to the design of a group of four supersonic wind tunnels to be built in the vicinity of Kochel. The power supply was to be obtained directly from the Walchensee lake* and amounted to 57,000 Kw (i.e. about 80,000 H.P.).

Work had been concentrated on one of these tunnels which was to have had a working section of 1 x 1 m. and a maximum speed of 2,000 m/sec., corresponding to M = 10. The scheme for this tunnel was well past the proposal stage and some of the castings for the pumps had been made, as well as the rough blocks for the Schlieren mirrors.

The pumps were in seven stages. Four of the stages were geared directly to the water driven turbines; the last three were driven through intermediate electric motors. The maximum pressure ratio attainable with the seven stages in operation was 850:1.

The tunnel could be run as a direct flow type, in which case the entry pressure was roughly atmospheric, or it could be converted to a return flow type with an entry pressure of up to four atmospheres. In the latter case, the tunnel entry was to be connected to the pump exhausts.

The air was dried by silica gel to a specific humidity of less than 0.5 gr./Kg.

Heaters upstream of the nozzle were provided so as to avoid partial liquifaction of the air at the higher Mach numbers.

The nozzles were to be about 6m. long; above about M = 5 the throats were to be sharp edged, Nozzle designs had been made up to M = 11. An interesting point in this latter connection is that having designed a nozzle with a sharp throat for M = 11, nozzles for smaller Mach numbers can be obtained very rapidly by using the same basic wavelet system but discarding the outer part of the wavelet pattern.

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* There is a difference of level of some 200 m. between the Walchensee and Kochelsee.

The jet was to be half-closed, followed by a diffuser having adjustable walls, so that the size and position of the second throat, as well as the diffuser expansion angle, could be varied.

A balance working on the same principle as that used on the 40 x 40 cm. tunnel was envisaged.

4.28 Athodyd tunnel

A proposal had been made to convert a 40 x 40 cm. tunnel into one suitable for testing hot athodyds. No design work had been done but preliminary calculations suggested that the addition of a vessel of about 300 cu.m. capacity containing air at a pressure of 35 atmospheres should suffice to give a 10 to 15 seconds run at a working section pressure of 1 atmosphere.

The air would be dried prior to compression and then heated to about 330°C so that standard temperature conditions would be reached in the working section.

Attached:

Fig. 1 and 2 - Drg. No.17625.S

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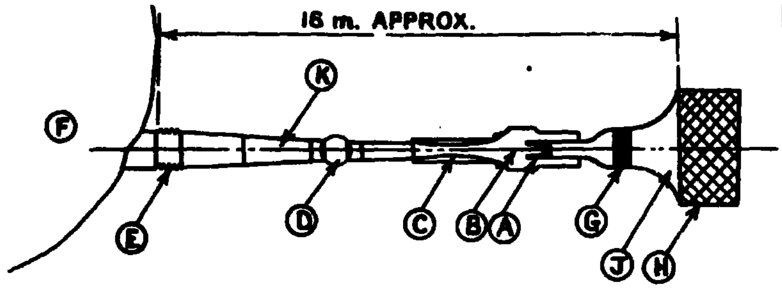
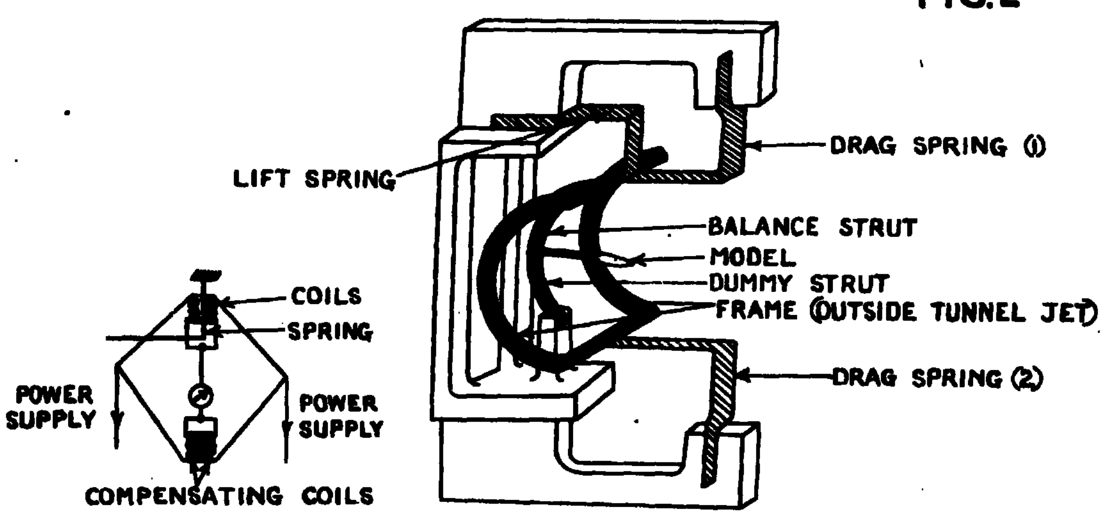
FIG. 1



A	NOZZLE
B	WORKING SECTION
C	VARIABLE SECTION THROAT
D	RAPIDLY OPERATING VALVE
E	SYLPHON BELLOWS
F	VACUUM SPHERE
G	HONEYCOMB
H	SILICA GEL DRIER
J	CONTRACTION CONE
K	DIFFUSOR

SKETCH OF 40cm. x 40cm. INTERMITTENT TUNNEL

FIG. 2



SKETCH OF ELECTROMAGNETIC CIRCUIT

PITCHING MOMENT IS PROPORTIONAL TO THE DIFFERENCE BETWEEN DRAGS (1) AND (2)

DIAGRAMMATIC SKETCH OF BALANCE

REEL

C 35

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