COMMERCIAL—IN—CONFIDENCE

CHANNEL TUNNEL

REPORT OF THE JOINT ANGLO/FRENCH WORKING PARTY ON AERODYNAMIC AND HEATING PROBLEMS AFFECTING THE TUNNEL DIMENSIONS

FOR SUBMISSION TO THE JOINT TECHNICAL WORKING GROUP OF THE BRITISH AND FRENCH GOVERNMENTS

MINISTRY OF TRANSPORT

MAY 1970

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THE TUNNEL DIMENSIONS

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AIM OF THIS REPORT

1. The purpose of this report is to determine the minimum dimensions of the various parts of the tunnel necessary to provide clearances for safe train operation and to provide space for all services.

2. These minimum dimensions are then considered from the point of view of the problems of resistances to forward movement, drainage and ventilation, as well as facilities for maintenance and repairs; this is the subject of Part One.

3. The second part examines the problems of Heating and Humidity.

4. The General Conclusions are contained in Part Three.

INTRODUCTION

Short description of the Project (see figure Annexe 1A)

1. The geology of the Channel area is made up of a series of chalk layers resting on a primary base, known as Greensand. Above this there is a bed of Gault varying from 10 to 40 m thickness and then, after a transition bed of Glauconitic Marl, the Lower Chalk which has a thickness under the Channel of 65 m (French side) to 80 m (English side). This strata is covered by Middle Chalk and Upper Chalk. These strata have a slight North-easterly slope, all the way across the Channel.

2. The quality of the Lower Chalk and, in particular, the impermeability of its lower, slightly clayey (Blue Chalk) levels has led the authors of the tunnel plans to take advantage of the regularity of this layer.

3. In order to ensure the flow of water, which in spite of the impermeability of the Blue Chalk, may penetrate the tunnel, the cross-section proposed is a W formation, the middle sections of which are very flat (1:1000 slope) and are extended by drainage tunnels to the point where the water will be pumped and removed through the drainage shafts. The sides of the W will be on a (10:1000) slope except at the French end where the entry tunnel, with traffic normally running downhill, will have a slope of about (12:1000).

4. The tunnels have been aligned in such a way as to keep them mainly in the most favourable part of the Lower Chalk. However, the tunnels at the extreme French end must, in order to avoid any excessive deviations, pass through the Middle and Upper Chalk which are of poor quality and the surface clays saturated with water.

5. It would be difficult to keep the whole of a twin track railway tunnel within the restricted thickness of the most favourable Lower Chalk layer. For this reason the structure has been designed in the form of two separate main tunnels. These tunnels will be excavated some 15 m on each side of a tunnel with a smaller diameter which will serve, during construction, as a pilot tunnel and, during operation, as a service tunnel. In the lower part of the W, this tunnel will also be used to collect the water from the main tunnels and to provide free flow to the drainage tunnels. At either end it will climb to the surface following the route of the main tunnels (at the French end, following that of the exit tunnel).

6. Cross-overs at intervals will enable traffic in both directions to change from one main tunnel to the other. Moreover, in order to facilitate servicing and maintenance work, small diameter adits, perpendicular to the axis of the main tunnels will be provided at intervals in order to give access from the service tunnel to the main tunnels.

7. NOTE Annexe 1A shows the assumed alignment of the tunnel based on information contained in the Channel Tunnel Study Group report entitled "Channel Tunnel - Site Investigation in the Strait of Dover 1964-1965".

CONSTITUTION OF THE TRAFFIC

1. The tunnel traffic will consist of very different elements:

   1.1 Double-decker ferry trains for the transport of private motor cars: these trains will be 750 m in length, will carry 270 cars and will be of some 1200 tons. They will be 4.98 m high and 3.15 m wide and will move at a maximum speed of 140 km/h.

   1.2 Single-deck ferry trains, known as "mixed trains", including covered wagons for the transport of coaches and cars with caravans and flat low loader wagons for the transport of lorries, vans and similar vehicles. As with the double deck wagons, these trains will have a maximum length of 750 m: they will be restricted to 1200 tons and to a maximum speed of 140 km/h. Their make-up will vary according to need: during slack periods, they will also be used for the transport of private cars.

   1.3 As their name indicates, the ferry trains will run only between the English and French ferry terminals.

   1.4 TEE trains built to a restricted loading gauge consisting of twelve coaches and a van 22.8 m (75 feet) in length. Their total weight will be restricted to 672 tons: their speed in the tunnel may reach 160 km/h. These trains will provide fast links between London and Paris or London-Lille-Brussels and beyond

   1.5 Ordinary passenger trains of which some may be made up of stock of restricted loading gauge and will provide various links between Continental towns and those of Great Britain. Other trains and, in particular, seasonal and special trains will consist of standard international rolling stock from the Continental networks: their journey in England will only extend to the interchange station which will be constructed near the tunnel exit, unless U.I.C. clearances are extended to London.

   1.6 Possible trains with sleeping berths some also carrying cars.

   1.7 Freight trains which will either be express (1000 tons - 120 km/h) or ordinary (1500 tons - 80 km/h)

   1.8 The trend of traffic, the assumed traffic pattern, and the monthly and weekly distributions are shown in Annexe 2.

   1.9 The effect of a variation in the level of traffic on the temperature at which thermal balance occurs is shown in Annexe 20. This shows that an increase in traffic results in only a small increase in the thermal equilibrium temperature.

PART ONE

TUNNEL DIMENSIONS

1. MAIN TUNNELS (see sketch at Annexe 1B)

1.1 Height of largest vehicles

1.1.1 The traffic flow at peak times requires the use of double deck wagons.

1.1.2 So that passengers may leave their vehicles and move about within the wagons - it is thought necessary that each deck should have a clear height of 1.80 m, giving a total wagon height above the rails of 4.98 m.

1.1.3 With respect to coaches, it was thought possible to restrict the height of vehicles likely to be carried to 3.45 m. (The average height of coaches is, in fact, about 3.10 m and those exceeding 3.45 m are used for special purposes and are unlikely to cross the Channel). The wagons envisaged for the transport of buses and coaches of such a size would have a total height of 4.75 m.

1.1.4 As for lorries for which there is no statutory height restriction in Britain or France, it has been accepted that they could be carried provided that their height does not exceed 4.00 m over a width of 2.50 m: this included almost all the non-specialised vehicles in existance. With a flat wagon with 0.760 m diameter wheels (0.68 after maximum wear), the height above rails will not exceed 4.98 m.

1.2 Overhead Electrification Equipment

1.2.1 The minimum electrical clearances at present recommended by U.I.C. for 25 Kv are very large and, at the suggestion of British Railways the U.I.C. expects to reduce them considerably.

1.2.2 However, B.R. have concluded - and the S.N.C.F. has accepted their point of view - that for an important new structure such as the Channel Tunnel, the main construction of which cannot be modified in the future, the principal arrangements must be established in the light of existing clearances - it being understood that, after study, reduced clearances could, if necessary, be used at certain points. On these bases, B.R. and S.N.C.F. agreed to adopt the general overhead line equipment arrangements shown at Annexe 1B and to keep a gap of 0.90 m between the top of the loading gauge and the soffit of the tunnels.

1.3 Shape of Invert

1.3.1 In order to reduce the construction depth and also to permit the insertion, between the rails, of a drainage channel the track will be laid on concrete. Recent and present developments connected with this method do not allow any firm details to be given, but the analysis of possible solutions has led B.R. and the S.N.C.F. to agree on the height of the rail above the invert of the tunnel as 0.70 m.

1.4 Conclusion

1.4.1 Bringing together these various considerations, the result is that, for constructional and operational reasons, the minimum diameter of the main tunnel must be:

$4.98 + 0.90 + 0.70 = 6.58$ m.

1.4.2 It is probable, however, that the line of the boring machines will not be absolutely accurate, and that the centre of the excavated volume may be some way from the required theoretical centre. If e is the value of the displacement which will not be exceeded, it is essential, in order that the track may be exactly sited and controlled, that the actual diameter of the tunnel should be greater than the strict minimum diameter by 2e.

1.5 Checks

The diameter defined above must now be checked for the needs of essential fittings.

1.5.1 Walkways

1.5.1.1 During high-speed traffic tests in the Simplon tunnel, it was shown that the passage of trains causes extremely violent (greater than 50 km/h) local air movement in the main tunnels and especially in the adits (100 km/h). Although the cross-section of the adits envisaged for the Channel Tunnel are, as mentioned below, much greater than that of those at Simplon, the tests carried out by the St Cyr aerotechnical laboratory show that the strength of the air movement would be comparable. (These tests at St Cyr do not give any values to air movement in various tunnels. According to R.A.E. Farnborough, the speed of the air currents in the adits would reach 50 to 80% of the speed of the trains. In the service tunnel it would be at least about half that in the adits).

1.5.1.2 From this, it is clear that the presence of any staff in the main tunnel must be strictly prohibited while the trains are operating, and must be avoided in the adits as far as possible.

1.5.1.3 Thus, in the main tunnels, only the following are envisaged:

Movement of passengers along tunnels closed to traffic if evacuation is necessary.

Movement of staff along tunnels closed to traffic or with only slow-moving traffic.

Movement of maintenance or supervisory staff through the tunnels at times when there is no traffic.

1.5.1.4 For this, it is necessary to provide for walkways on either side of the track. The sketch at annexe 1B shows that a diameter of 6.58 m will accommodate walkways, as follows:-

One 0.30 m above rail level: this is the normal height of the low platforms of Continental networks. The width of the walkway would then be 0.65 m (clearance is 1.00 m at 0.50 m above).

The other 0.70 m above rail level, which would facilitate the exit from double decker wagons; the width of the walkway could then be 1.00 m.

1.5.2 Clearance for fitting of equipment

1.5.2.1 The tunnel and its equipment must not only give clearance with adequate safety margins for the maximum size of stock running in the tunnel, but must also permit the evacuation of a train which is stationary at any point. For this purpose, it was thought necessary to adopt the structure gauge shown at Annexe 1B, which shows that these clearances can be effectively contained within a tunnel 6.58 m diameter.

1.5.2.2 It leaves the necessary space to permit the installation in the upper part of signals and possibly a ventilation duct of about 0.75 m^2 cross-section.

1.5.3 Drainage

1.5.3.1 The arrangement of setting the track on concrete permits the insertion between the rails of a semi-circular gutter 0.70 m in width, or with a radius of 0.35 m. Provision should be made for covering the channel where required.

1.5.3.2 The application of the formula

$$\text{Water speed } U = \sqrt{\frac{R \times i}{0.0002\left(1 + \frac{0.10}{R}\right)}} \text{ m/s}$$

(in which R is the ratio of the cross-section to the wetted perimeter, i is the gradient and 0.0002 is a coefficient corresponding to the average roughness) shows that for a gradient i = 0.001 and with a water depth of 0.20 m, the average rate of flow should be 0.546 m/s and the output

49.2 litres/s, or, in round figures, 50 litres/s. For a completely full gutter (h = 0.35) the output reaches 145 litres/s, which would be sufficient since the water may run towards the service tunnel through the adits.

1.5.3.3 As stated in the second part of our report (Heating), page 22, the conditions of cooling depend essentially on the manner in which the infiltrating water - which is bound to exist - enters the tunnel and on the temperature at which it enters.

1.5.3.4 To maintain an acceptable maximum temperature for the traffic level expected for year 2005, it would suffice to have a supply of infiltrating water of 112 litres/s at each tunnel head if the water seeps slowly through the walls and enters the tunnels at the temperature of the latter.

1.5.3.5 But if the water enters through larger fissures, at the temperature of the surrounding rock, thermal transfer would have to take place while the water was flowing along the channels and this would be at a very low rate. The necessary volume of water would in that case be much greater and, in the worst case, could reach 420 litres/s at each tunnel head.

1.5.3.6 This volume exceeds the volume of infiltrating water which could be tolerated. It would therefore be necessary to introduce water from the surface. To distribute such water, it is appropriate to retain the possibility of placing in the tunnels pipes of the required dimensions. The passage of the water along these pipes would itself bring about a partial cooling.

1.5.3.7 A simple calculation shows that a pipe of 0.380 m internal diameter would allow the supply of 160 litres per second in each of the main tunnels with an acceptable loss of head (81 m of water for 20 km).

1.5.3.8 The sketch at annexe 1B shows that a pipe approaching this diameter could be positioned under the 0.30 m high walkway.

1.5.4 Arch scaffolding

1.5.4.1 In order to permit large-scale repairs, it is essential to be able to insert scaffolding and it is desirable that this operation be done without interrupting the passage of trains - or at least the engineers' trains. However, it is obvious that, when such repairs are necessary, speeds must be reduced and the normal catenary must be replaced by a simplified, overhead electrification equipment using a single contact wire placed at the normal contact height, which is 5.27 m above rail level. The fitting of this temporary equipment will provide clearance of 0.25 m which will be adequate.

2. SERVICE TUNNEL (see sketch at Annexe 1C)

The service tunnel, which, during construction, will be used as a pilot tunnel, will later be used for the movement of supervisory and maintenance staff and, in the event of an emergency permit the evacuation of passengers - or at least their transfer into a relief train. The movement of staff and possible movement of materials necessary for maintenance will be provided by service vehicles. The service tunnel will also be used as a drainage tunnel; collecting through the adits, the infiltrated water in excess of the cooling needs of the main tunnels. The upper part will form a ventilation duct: finally, it is in this service tunnel that the electric cables for traction and lighting and those for signalling and both long and short-distance telephones must be placed.

2.1 Service Vehicles

2.1.1 The clear height required for the movement of these vehicles must be 2.20 m. The service tunnel must permit the passing of two such vehicles each 1.50 m wide, leaving a clearance of 0.50 m between them so that a man may pass between two such (stationary) vehicles.

2.1.2 These dimensions require a minimum diameter of 4.14 m.

2.2 Drainage

2.2.1 The service tunnel must collect, through the adits, the seepage water from the main tunnels. It must, moreover, be able to cope with any water seeping through its own lining. The total output of such water will be restricted by sealing and injection.

2.2.2 The service tunnel must also be able to cope with a sudden unexpected flow of water, such that even if, in the main tunnels, it can be accepted that a sudden accidental flow of water exceeds the upper level of the drainage channels and even wets the track, it is essential that the floor of the service tunnel remains clear.

2.2.3 The application of the formula already used for the water flow in the main tunnel drainage channels, with $i = 0.001$, giving

$$U = 2.23 \sqrt{\frac{R}{1 + \frac{0.1}{R}}}$$

shows that, by assuming that the floor of the service tunnel is supported by two little walls (or lines of posts) each 0.10 m thick and 1.10 m apart, the under-floor height needed to guarantee a flow of 700 litres/s would be

	0.52 m	if the diameter of the tunnel is 4.20 m
	0.50 m	" " " 4.50 m
and	0.49 m	" " " 4.80 m

2.3 Ventilation

2.3.1 Several different ventilation systems have been studied. They all involve an air flow of about 10 m^3/s from each end of the tunnel. This air will be circulated in a duct in the upperpart of the service tunnel. Due to the great length and necessarily restricted cross-section of this duct, it will itself be the main resistance which has to be overcome in circulating the air. So that this resistance is not too great, the speed of the air must be restricted to about 2.50 m/s. The useful cross-section of the duct must therefore be about 4.00 m^2.

2.3.2 The height of the corresponding segment will be:

1.38 m if the tunnel diameter is			4.20 m
1.35 m	"	"	4.50 m
1.30 m	"	"	4.80 m

2.4 Conclusion

2.4.1 Bearing in mind that the thickness of the floor slabs will be about 0.20 m and of the roof about 0.15 m (lower surface of the ventilating duct including the air sealing layer), giving a total of 0.35 m, the total height would be:

for a tunnel diameter of	4.20 m	4.50 m	4.80 m
- free height	2.20	2.20	2.20
- minimum height of drainage channel	0.52	0.50	0.49
- height of duct	1.38	1.35	1.30
- slab thickness	0.35	0.35	0.35
TOTAL	4.45	4.40	4.34

2.4.2 It may be seen that the 4.45 m height exceeds the 4.20 m height of tunnel: there is, therefore, an incompatibility.

2.4.3 The Minimum diameter adopted for thus study has therefore been set at 4.50 m as shown at Annexe 1C.

3. ADITS

3.1 The tunnel design provides for adits at intervals which permit passage from the main tunnel to the service tunnel and vice-versa. These passages will also be used for the out-flow of seepage water to the service tunnel and for the fitting of ventilation ducts.

3.2 In order not to exclude the possibility of using the same boring machines, the diameter of these tunnels has been assumed to be the same as that of the service tunnel, ie 4.50 m.

3.3 The maximum distance between these adits was, for safety reasons, set at 250 m.

AERODYNAMIC STUDIES AND POWER REQUIREMENTS

4.1 In order to determine the resistance to movement of trains through a tunnel system of the dimensions adopted as a result of the foregoing considerations, it has been necessary to carry out a series of aerodynamic studies.

4.2 As with all aerodynamic problems, these studies posed difficult questions of similarity: so they were pursued both theoretically, using scale models, and by taking measurements in existing tunnels. They were done in England, where a few measurements in the Standedge Tunnel were taken by B.R., and theoretical studies and scale model tests were done at R.A.E. Farnborough. On the French side, the S.N.C.F looked for single-bore tunnels with the characteristic (ratio of tunnel cross-section to that of the trains) as near as possible to that of the future Channel Tunnel and, through the goodwill of the Swiss Federal Railways, were authorised to carry out tests in the Simplon Tunnel. The results obtained were supplemented by those of less thorough earlier tests carried out by the Swiss Railways themselves in the Ricken and St Gotthard Tunnels: the theoretical studies and scale model tests were entrusted to the Institut Aerotechnique de St Cyr.

4.3 These various studies form a very large volume of documentation - too large to be annexed to this report. A summary of the methods used and the principal results are in Annexes 3, 4, 5, 6 and 7.

4.4 Important differences between the Standedge and Simplon tunnel tests, as well as the differing approaches to the problems adopted by R.A.E. and St Cyr seemed initially to give contradictory conclusions. A meeting between those carrying out the research quickly threw light on the importance of the effects of cross adits. Although the movement of a car-carrying train at 140 km/h in a tunnel 53 km long without adits required more than 15 000 kW (20 000 hp), the presence of adits greatly reduced the resistance, the power then being only 6 000 kW (8 000 hp). This exchange of views led to further studies being undertaken on tunnels with adits, and further measurements using scale models, separately in France and in England. The results are given on the power-speed curves at Annexe 6 for British results, and Annexe 7 for French results.

4.5 The basic data used in each country was that currently envisaged for the Channel Tunnel at the time that the investigation and test were made. This resulted in some differences, in particular the French used higher $\frac{\text{train cross section}}{\text{tunnel cross section}}$ ratios.

The English results are given at Annexe 6, and the French at Annexe 7. The English values have been taken as the basis for the power requirements, which in order to provide a true comparison necessitated making an appropriate allowance to the French results as follows.

An overall electrical efficiency of 82% is taken to allow for part-load conditions. (The English results at Annexe 6 are based on an electrical efficiency of $87\frac{1}{2}$%).

The aerodynamic drags in the tunnel were then adjusted to the English $\frac{\text{train cross section}}{\text{tunnel cross section}}$ ratio by the Institut Aerotechnique de St Cyr curves (see value of C_X in Fig 5 of Annexe 5). These curves suggest a 9% drop in aerodynamic resistance associated with a double decker car carrier wagon, which corresponds to a 6% drop in total resistance, and hence in total power.

Similarly for the TEE train, equivalent figures give a 12% reduction in aerodynamic drag, taken as an 3% reduction in total resistance and hence in total power.

The figures for overall electrical traction power now become

Total electrical power in kW (level track)	Double decker car carrier trains at 140 km/h		TEE at 160 km/h	
	Open air	tunnel	open air	tunnel
British study	5000	6250	3300	3500
French study	5350	6600	3400	3900

The power figures now show reasonable agreement, the average French results being 7% greater than the British. If some allowance be made for the smaller adit cross-section of the French tunnel data, it can be tentatively taken that final results agree to about 5% and the differences are not significant.

4.6 The differences remaining are small enough to permit the following conclusions from the test results:-

The influence of the adits on the power necessary varies considerably on whether the adits are 250 or 500 m apart. For a double decker car carrier train of 1200 tons moving at 140 km/h on the level, the power required in the tunnel is about 55% more than that in the open air if the adits are 500 m apart, and only about 25% if they are 250 m apart.

A further reduction in adit spacing to 200 m reduced energy consumption by about 4%. But, as a short calculation (Annexe 8) shows, the corresponding economies would not, even at peak period, justify the expense of providing the additional adits. From a strictly economic point of view the optimum distance between adits would be more than 250 m. However, a 250 m spacing should be retained for reasons of safety.

The locomotives of 6000 kW (output) which have been studied in the meantime have enough power to cope with the programme required.

4.7 The use of the speed-resistance curves in an analogue computer to represent the Channel Tunnel characteristics permits the calculation of the energy consumed, measured at the sub-stations, during Channel crossing by a double decker car carrier train. The energy is 2000 kWh, the crossing time would be 26 minutes, for a maximum speed of 140 km/h.

The power consumption by a TEE train of 672 tons and with a maximum speed of 160 km/h would be approximately 60% of that for the double decker car carrier train.

PART TWO

HEAT AND HUMIDITY

1. GENERAL

1.1 Until recently, the question of heating was important only for tunnels passing through rock where the geothermal effect is significant, particularly in the long Alpine tunnels. Due to the natural ventilation on these mountain sites and the cold Alpine winters, the temperatures of these tunnels remains acceptable without any special precautions taken, and passengers hardly notice their passage through the warm zones.

1.2 The increase in traffic on urban underground railways - and particularly those in London and Paris - has for some years caused a rise in temperature requiring a considerable increase in ventilation and the addition of cooling equipment.

1.3 It therefore seemed necessary to study the question of heating in relation to the Channel Tunnel where the amount of traffic, the power of the locomotives and the difficulties of ventilation could, in the long term, cause excessive increases in temperature.

1.4 All the energy entering the tunnel for traction or for the auxiliary equipment will be converted into heat, even if it is used mechanically. The trains will slow down on rising gradients and leave the tunnels at a slightly lower speed than that at which they entered: within the tunnel they will thus release a certain amount of kinetic energy which will also be converted into heat.

1.5 The calculation of the temperature to be expected and of the variation in the temperature is therefore shown as a thermal balance sheet, the various factors of which must be carefully examined.

1.6 However, before examining these factors, it is advisable to evaluate the natural temperature of the rock at the level at which the tunnel will be bored, and the amplitude of the variations in this temperature as a function of the temperature at the bottom of the English Channel.

2. TEMPERATURE OF THE ROCK AT TUNNEL LEVEL

2.1 During the geological surveys, the temperature was measured in June 1965, in a borehole in the sea bed (R.255) Annexe 10. This single measurement however gave no indication of any seasonal variations which may be expected: in spite of the care taken with this measurement, it is feared that the temperature in situ had been altered by carrying out the survey, which involved intrusion into the borehole by sea water and, later, by convection currents within the water surveyed.

2.2 If the bottom of the sea is likened to a plane to which is applied a sinusoidal temperature variation of $\propto$ with an average θ_0 and frequency (inverse of the period) ω, and the rock to a semi-infinite solid restricted by this plane, the temperature θ of the rock at moment t and a point χ units away from the plane is given by the formula:

$$\theta = \theta_0 + 2\frac{\theta_\rho - \theta_0}{\sqrt{\pi}} \int_0^{\frac{\chi}{2\sqrt{at}}} \theta_\rho . e^{-u^2} du + \propto . \rho .^{-\sqrt{\frac{\omega}{2a}}\chi} \sin(\omega t - \sqrt{\frac{\omega}{2a}}\chi)$$

where θ_ρ is the temperature of the solid at an infinite distance from the plane the plane ($\chi = \infty$) and $a = \frac{\lambda}{c\rho}$ is the quotient of the thermal conductivity λ of

the chalk divided by volumetric heat, (the product of the specific heat C by the density ρ).

2.3 Using the term $\rho^{-\sqrt{\frac{\omega}{2a}}\chi}$ the amount of temperature variation at the point χ the abscissa diminishes rapidly as χ increases.

2.4 It can be taken that, following the disturbance caused by the tides, the temperature of the rock for a small value of χ and for low frequencies does not differ from the temperature of the water.

2.5 If we take the following values for the chalk:

λ = 0.0056)
c = 0.20) in calories, centimetres, seconds and grammes
ρ = 2.20)

we find that the size of an annual variation $\propto$ on the plane $\chi = 0$

$\omega = \frac{2\pi}{356\ 000}$ is reduced to:

0.015 $\propto$ at 15 m and to
0.00025 $\propto$ at 30 m.

These ratios would be considerably smaller for weekly or daily variations.

2.6 It may thus be concluded that daily, weekly or annual variations of temperature at the sea-bottom are practically nil at the depth of the tunnel.

2.7 As regards heating problems therefore, these variations can be ignored: only the average temperature needs to be considered.

2.8 According to the hydrographic services, the average temperature of the sea, both at the bottom and the surface would be 11°C (See Annexe 9).

2.9 However, the measurement taken in borehole R.255 showed the rock temperature at tunnel level of 12°C, increasing to 12.7°C at the foot of the borehole (170 m) (see Annexe 10).

2.10 This recalls a measurement made in 1883 at the extremity of the survey heading on the French side some 1840 m from well No 1: the temperature was stabilised at 13°C and remained steady for several days.

2.11 It may therefore be assumed that the temperature of the rock is influenced by a certain geothermic gradient, and that this is slightly higher near to firm soil than it is under the sea.

2.12 As the tunnel will mainly be dug under the sea, the average temperature of the rock which is to be considered may be taken as 12.5°C.

3. THERMAL BALANCE

3.1 Kinetic and tractive energy

3.1.1 As has already been shown in Part I, the power of the locomotives will be 6000 kW.

3.1.2 By using specialised analogue computers, it is possible to trace the movements corresponding to the various ways of driving a given train and to calculate the energy consumed. For a 1200 metric ton car train, 750 m long, passage through the tunnel may take 26 minutes, with a 5% margin for error. The energy consumed, bearing in mind the resistance losses by the joule effect of the overhead line equipment increased by the loss of kinetic energy of the train between entry into and exit from the tunnel, is about 2000 kWh -- or some 1 720'000 kilocalories.

3.2 Energy used by fixed auxiliary Equipment

3.2.1 The drainage pumps will be placed in the drainage shafts themselves (submersible pumps) or in the sump beneath these shafts. Thus the heat emitted by the motors of these pumps need not be included in the thermal balance sheet of the main and services tunnels.

3.2.2 On the other hand, the energy necessary for lighting and possibly a part of that necessary for ventilation should diffused ventilation be used will have to be included in the balance sheet.

3.2.3 The calculation of this energy will require the completion of lighting and ventilation plans, which have only been roughly estimated. It is only known that a double lighting system will be provided: relatively subdued for normal lighting and a stronger system for maintenance and times of emergencies.

3.2.4 It is accepted that the energy used will be about 350 kW per main tunnel, a round figure very probably higher than that actually necessary.

3.3 Thermal changes of a train

3.3.1 When a train is stabled for some time outside a tunnel it is more or less in thermal balance with the outside air. The temperature of this air is T_E (see at Annexe 11 the data on air temperatures at Calais and Dunkerque).

3.3.2 When it enters the tunnel, it tends to achieve thermal balance with the air in the tunnel: speed, however, changes this balance in a complex way. It causes on the one hand friction on the walls of the train and, on the other, adiabatic compression, which is produced in front of the locomotive, and also compression and expansion due to the roughness of the walls. These phenomena are also complicated by the existence of boundary layers which alter the conditions of these exchanges.

3.3.3 The research which has been done into this question (in particular for the study of the forward edge of aircraft wings) has shown that the difference between the temperature of the moving object and that of the fluid in which it is moving is given by the formula.

$$1) \quad \Delta\theta_{pm} = \frac{fl(Q)}{2JCp} \quad V_o^2 + T_o \left[1 - \left(\frac{P}{Pc}\right) \frac{Cp-Cv}{C_p} \right] (fl(Q)-1)$$

where J is the mechanical equivalent of heat.

3.3.4 Q is the Prandtl number and fl(Q) is a slowly variable function of Q. For the air, Q = 0.72 and fl(Q) varies from 0.845 under laminar conditions (Reynolds numbers less than 5×10^3) to 0.889 in turbulent conditions (according to Ackermann).

3.3.5 Cp and Cv are the specific heats at constant pressure and constant volume. Thus:

$$JC_p = 10 \times 10^6 \text{ and}$$

$$\frac{Cp-Cv}{Cp} = \frac{\gamma - 1}{\gamma} = 0.29$$

where P/Po is the ratio between the fluid pressure on the surface of moving object and that further away. It can be deduced from tests carried out in the Simplon tunnel that ratio P/Po is:

$$1 + \frac{0.0094}{1.033} = 1.0091 \text{ (see Annexe 12)}$$

3.3.6 This pressure remains constant in the circular space between the train and the tunnel walls and has a tendency to increase (see tests by Messrs Tomoshigo Hara and Jun Okushi described in JNR Railway Technical Research Institute Report Vol. 2 No. 2 1962).

3.3.7 If we assume that V = 140 km/h, so that ν = 3900 cm/s and T_o = 273 + 25 = 298° the application of the formula given above gives

only applies to nose of train?

$$\Delta\theta = 0.643 + 0.120 = 0.763 \text{ degrees Centrigrade.}$$

3.3.8 This being so, the heat, expressed in thermal units, brought in by a train entering the tunnel is KMT_E, where T_E is the temperature of the outside air. in summer

3.3.9 The heat released by the train leaving the tunnel is similar, and is expressed as kM (T_r + heating) where T_r represents the temperature in the tunnel. in winter

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3.3.10 The Scientific and Technica. Building Centre (C.S.T.B.) has made a theoretical study of the heat arising from the passage of a train through the tunnel. Basing their study on the tables given by Hottel, Groeber and Heissler, they drew up graphs showing the ratio between the number of calories generated and the total heat capacity as a function of the thickness of the various parts of the train and for various values of the convection co-efficient h. Although any assessment of the convection co-efficients is difficult, the C.S.T.B. believes that, for a single passage through the tunnel, the average value of this ratio will be about 60%.

3.3.11 In order to confirm this theoretical study and avoid a subjective choice of the convection co-efficient, the S.N.C.F. asked the O.R.E. laboratory at Vienna-Ar[illegible] to carry out some tests (see Annexe 13). These tests showed that ... arious parts of the train do not have equal effects with respect to thermal changes. The steel of the bodywork rapidly reaches the ambient temperature; the temperature of the bogies changes more slowly but would approximately reach the average temperature in a time corresponding to that necessary for passage through the tunnel, while the temperature inside the fittings on the coaches will vary little. It can be said, from details of the measurements which have been taken, that the masses of the bod, steel, the bogies and the external fittings of the vehicles (61% of the total weight) will move into thermal balance with the air in the tunnel, while the mass of the internal fittings (39% of the total weight) is unaffected. For a train with a mass of 1200 metric tons, we therefore take for M only.

$$1200 \times \frac{61}{100} = 732 \text{ Metric tons}$$

We shall give to k the value 0.12 (specific heat of steel).

3.3.12 On the other hand, as has been mentioned at paragraph 3.1, the energy brought into the tunnel by a train, both in kinetic and electric form, is about 2000 kWh, or 1 720 000 kilocalories for a 1200 T car carrying train (other trains will be likened to trains of this type).

3.3.13 We may therefore set out the net heat released in the tunnel by a train passing through the tunnel in the following way:

$$1\,720\,000 - 0.12 \times 732\,000\,(T_r + 0.76 - T_E)$$

$$= 1\,653\,000 - 88\,000\,(T_r - T_E) \text{ kilocalories or}$$

$$= 1.653 - 0.088\,(T_r - T_E) \text{ million kilocalories}$$

3.4 Thermal transfer between tunnel and terrain

3.4.1 The phenomena examined in this chapter are cyclic in character, and the thermal transfer between the tunnel and terrain in which it is dug may be summed up as:

3.4.1.1 a constant part corresponding to a permanent flow of heat from the area which, on average, is the warmest towards that which, on average, is the coolest and building the latter up.

Annexe 15 shows that the amount of heat transferred from the tunnel towards the bottom of the sea is given by the expression:

$$Q = 3.12\ (T_M - 12.5^\circ C);\ \text{and}$$

3.4.1.2 a variable part moving from the tunnel to the rock during periods when the input of heat into the tunnel is large and growing, or from the rock to the tunnel when the traffic decreases.

Annexe 15 shows that the varying transfer between tunnel and terrain is expressed by the following equation:

$$Q = A \propto \Big[\cos 2\pi \quad (\omega t + \Phi)\Big]_{t_1}^{t_2}$$

where $\propto$ is the semi-amplitude of the variations and ω the period of variation considered.

3.4.1.3 A and Φ are the size and phase co-efficients and have the following values:

		A	Φ
daily variation	$\left(\omega = \frac{1}{24}\right)$	15.046	$\frac{0.8}{24}$
weekly variation	$\left(\omega = \frac{1}{7 \times 24}\right)$	71.92	$\frac{0.465}{7}$
annual variation	$\left(\omega = \frac{1}{365 \times 24}\right)$	843.8	$\frac{40.9}{365}$

The rock plays a dual role of thermal conductor and heat sink.

3.5 Heat extracted by air movement

3.5.1 Due to the low density of the air, its volumetric heat is very small: 0.00031.

3.5.2 The air movement which is envisaged of 10 m^3/s each end of the tunnel would therefore absorb only 270 000 kilocalories per day per degree Centrigrade of difference between fresh air and extracted air. This is a very small amount compared to the heat generated; it will not be taken into account.

3.6 Infiltrating water

3.6.1 The water in the surrounding terrain is normally at 12.5°C.

3.6.2 In spite of special ground treatment which will be required of the constructors, the tunnel will not be completely water tight and some infiltration is inevitable.

3.6.3 The water may filter slowly through the rock and the concrete lining; this, according to the experts is what will probably happen. In this case, the temperature will rise progressively and the water will enter the tunnel at the temperature of the tunnel walls 26°C having completely exhausted its cooling role. In these circumstances it will be necessary to cover the drainage channels to prevent increase in humidity.

3.6.4 The number of calories absorbed will be equal to the product of the mass of water entering the tunnel and the number of degrees through which it has been warmed.

3.6.5 It is possible, however, that the water will find a quicker route through more or less open fissures and may enter the tunnel at a temperature lower than that of the walls. It will then flow along the gutter in the main tunnels until it is taken through the adits to the service tunnel, drainage tunnel and the extraction shaft. According to the C. S. T. B. study, the thermal transfer between this water and the air in the tunnel, either by direct convection or by transmission through concrete, will be very small. If the water entered the tunnel at the natural temperature of the surrounding rock - this is an extreme assumption and not a likely one - and if it flowed in constant quanrity for 12 kilometres, the heat absorbed per metre and per degree of difference between its temperature and that of the air would be, as a function of the water supply, that given in Annexe 16.

3.6.6 If the inflow does not reach the level required to maintain an acceptable temperature, the balance will have to be made up from the surface and sent, through pipes, to the centre of the tunnel.

3.7 Humidity

3.7.1 It may be asked whether leaving the water to enter the tunnel and flow through the main tunnels will not tend to increase the degree of humidity beyond limits acceptable not only for the comfort of passengers but also for the safety of workers.

3.7.2 Work in hot and humid places is not without its dangers and certain countries lay down very strict rules on this subject.

3.7.3 However, although tunnels and deep mines are usually dug in rocks where the geothermal gradient makes these effects felt and although the water which penetrates there is relatively warm, the situation of the Channel Tunnel will be the opposite, and the water which enters there will be cold.

3.7.4 An examination of the diagram of vapour tensions attached to Annexe 17 shows that, if the water found in the main tunnels is at a temperature below the dew point, it will tend to cause condensation of the humid atmosphere.

3.7.5 According to the diagram, for an air temperature of 26°C and a relative humidity of 75%, which can be considered acceptable, the temperature of the dew point is 22.4°C. If the temperature of the water flowing through the channels in the main tunnels remains lower than 22 degrees, this will therefore be enough to maintain an acceptable level of humidity.

Not according to the LIVE Psychrometric chart

3.7.6 This being so, when water at temperature θ (variable) flows at speed ν in an atmosphere at temperature T (which is presumed steady or only slowly variable), it may be shown that

$$\theta - T = \rho^{\frac{k}{\nu}x} \quad (\theta_o - T)$$

3.7.7 If the length over which the flow occurs in the main tunnels is restricted - by diverting the water in the lower part of the service tunnel - in such a way that $\rho^{\frac{-k}{\nu}x}$ is always greater than a certain value, for example 0.3, the flowing water will not raise the temperature by $(T-\theta_o)$ but only by 0.7 $(T-\theta_o)$, no matter what the value of T: humidity will be kept at an acceptable level without any special steps being taken.

3.7.8 If the water entered the tunnels at the temperature of the surrounding rock, the thermal transfer taking place while the water flowed along the channels would be low, and the temperature of the water would always remain lower than that envisaged above.

4. THERMAL BALANCE

4.1 Having thus examined the various elements involved, it should be possible draw up the overall thermal balance sheet for the tunnel for each month and to calculate the temperature to be reached as a function of the number of trains envisaged. For this, we have assumed that a balanced operation will be achieved in 2005 and that, after that date, the traffic pattern will remain stable. (See below, in paragraph 6.6, for consideration of the rate of increase of the temperature).

4.2 However, if we represent the outside temperature as a sinusoidal function of annual frequency, the balance sheet of thermal transfer during any period affects the product of this function and the sinusoidal function for the same period which was used for counting the number of trains: (if one represented the number of trains by a sinusoidal function, the product would be the sum of two sinusoids of different frequencies).

4.3 The formula giving the flow of heat through the walls, which assumes a simple sinusoidal variation in the temperature of the fluid in contact, cannot, therefore, properly be applied.

4.4 It is, however, possible to resolve this problem by approximation. If we have, a priori, the tunnel temperature as a sinusoidal function of time, the application of the formula to calculate the flow is acceptable: we can then draw up the thermal balance sheet and thus deduce the acceptable number of trains. We can calculate the unknowns (heat transfer, average temperature, size of variations, phase changes in relation to the exterior temperature) in such a way that the acceptable number of trains is as near as possible to the forecast traffic level. We can thus grope our way forward, which frees us from the need to liken the variation in the external temperature to a sinusoidal function of time.

4.5 For each month we have:

4.5.1 the temperature T resulting from the formula given a priori. If the formula is:

$$T = T_M + \propto \sin \quad [30(m-\varphi)]^{\circ}$$

we take m = 1 for January, 2 for February ... 12 for December;

4.5.2 the external temperature T_E for which we have decided to take the average temperature of the diurnal hours (07.00 to 22.00)

4.5.3 the amount of heat transferred through the walls. This includes both the constant flow between the tunnel and the bottom of the sea and the variations resulting from the thermal inertia of the walls;

4.5.3.1 the calculation of the flow of heat through the walls towards the sea bottom by using the formula which we have established causes no difficulty: (see para 3.4.1.1)

4.5.3.2 we have seen in the analysis of transfer with the terrain that the amount of the flow corresponding to the annual variations will be:

$$Q = -843.8 \propto . \cos \left[2\pi \frac{\overline{24} + 40.9}{365} \right]_{t_1}^{t_2} = -843.8 \propto \cos \left[30(m+40^{\circ}20') \right]_{t_1}^{t_2}$$

In taking account of the choice made for the origin of m (ie m = Q when $T = T_M$) the value of the flow in month m is:

$$Q = -843.8\,\alpha \cos\ [30(m-\phi) + 40^{\circ}20'\,]\Big|_{m-0.5}^{m+0.5}$$

$$= 843.8\,\alpha\, 2 \sin 15^{\circ} \sin\ [30(m-0) + 40^{\circ}20']$$

$$= 436.78\,\alpha \sin\ [30(m-\phi) + 40^{\circ}20']$$

4.5.4 The calculation of the heat taken away by the infiltrating water does not raise any difficulty if the thermal transfers take place in the surrounding rock. It would be seen that an infiltration of 112 litres per second at each tunnel head is enough to maintain an acceptable temperature. But if one assumes, pessimistically, that water will infiltrate at the temperature of the surrounding rock, the entire transfer of heat between the air in the tunnel and the infiltrating water will have to occur while the water is passing along the drain channels. In such a case it is necessary to apply the C. S. T. B. study and in particular the curves given in Annexe 16 attached. It may be seen that the effectiveness of the heat exchange falls considerably when the supply of water exceeds 120 litres per second for a 12 kilometre section. On the assumption of a floor for the whole of the service tunnel, and assuming a coefficient of heat transfer of 6 kcal/m^2h $^{\circ}$C, this corresponds to an average heat flow of about 9.5 kcal/m^2h $^{\circ}$C.

4.5.5 if from the total of the removed quantities of heat thus calculated we deduct the amount due to fixed equipment, the remainder of the extraction corresponds to the heat introduced by the trains;

4.5.6 the amount for a train may be calculated by using the formula drawn up at 3.3 above, the monthly number of trains corresponding to the temperature curve which has been fixed a priori deduced from it.

4.6 Calculation by trial and error, which is lengthy but presents no difficulty in respect of the three variables defining the temperature (which, let us recall, are the average temperature, the amplitude and the phase lag of the variations) and the output, permit adjustment of the result so that the acceptable number of trains, is, for each month, equal to the maximum number envisaged for the busiest day.

4.7 The table at Annexe 18 shows that if it is assumed that the infiltrating water seeps slowly through the lining, entering the tunnel at the ambient temperature, with an inflow of 112 litre/s at each tunnel head, a mean montly temperature

$$T = 22.05 + 3.25 \sin\ [30(m-5.1]^{\circ}$$

would correspond to a larger train programme each month than that envisaged for year 2005.

4.8 Conversely if it is assumed that water would enter the tunnel at the ground temperature and that the heat exchange would only occur whilst it was passing along the drainage channels then the flow required would be 420 litre/s at each tunnel head. (See Annexe 16, para 5.2). We are therefore able to state with certainty that even under the worst conditions that with a flow of 420 litre/s at each tunnel head, the mean montly temperature would not exceed

$$22.05 + 3.25 = 25.3^{\circ}C$$

4.9 A similar calculation could be made for the daily and weekly temperature variations. However, as the temperature variations are less great in a day or a week than in a year, the following simplified calculation will suffice.

4.10 We have established (3.3.13 above) that a train introduces into the tunnel:

$$1.653 - 0.088\ (T_r - T_E) \text{ million kilocalories}$$

or a maximum (taking account of the minimum value of $T_r - T_E$ corresponding to the busiest period) of 0.993 million kilocalories.

4.11 It can be deduced from the evaluation of the assumed traffic patterns that the number of trains above the weekly average in the busiest halfweek of the Summer of year 2005 will not exceed 100, or 50 in each direction.

4.12 The amount of heat to be absorbed by the walls during this busy 3.5 days is: 50 x 993 000 = 49 650 000 kilocalories or 960 kcal per metre of tunnel, which, according to the calculation of thermal capacity of the walls (para 3.4, Annexe 15 thermal transfer with the terrain: Variations) corresponds to a maximum increase in temperature of:

$$\propto = \frac{960}{2766} = 0.35^{\circ}C$$

4.13 Similarly, the number of trains passing between 09.00 hrs and 21.00 hrs on an extremely busy day exceeds the average by $250 - \frac{366}{2} = 67$ trains.

or 34 per tunnel and the amount of heat to be absorbed by the walls during this 12 hours is:

$$34 \times 993\,000 = 33\,800\,000 \text{ kilocalories}$$

or 650 kcal per metre of tunnel, which corresponds to a temperature rise of:

$$\propto = \frac{650}{578.7} = 1.12^{\circ}C$$

4.14 In brief, we can be sure that, under the conditions used for this calculation, the average daily temperature will not exceed

$$25.3 + 0.35 = 25.65^{\circ}C$$

and the tunnel temperature will not exceed $25.3 + 0.35 + 1.12 = 26.77^{\circ}C$ during hours of peak traffic at Summer week-ends.

5. ALTERNATIVE - MECHANICAL COOLING

5.1 Allowance, however, must be made for the conditions assumed in these calculations not being satisfied: the heat introduced may exceed that predicted, the heat exchange between the water flowing through the central channel and the air in the Tunnel may be poor, or the quantity of seepage water may be inadequate.

5.2 It will then be necessary either to introduce water from outside or to provide mechanical cooling.

5.3 In order to avoid having large numbers of cooling stations in the tunnels, which would probably require a certain amount of attention for operation and maintenance, however reliable they may be, they could be installed at the lowest point of the tunnels (points W1 and W2) or at the foot of the shafts or even in the open air; heating of the cooling water would then no longer have any effect on the heat balance of the tunnels. Only the exchangers would be installed in the adits.

5.4 It can be shown that even if the tunnel were completely dry it would be possible by these means to maintain an acceptable ambient temperature. However considering the present state of sealing techniques a completely watertight tunnel is unlikely. The cost of installation and the power used would probably be considerable, but this would be offset by the revenues from the increased volume of traffic which would make it necessary.

5.5 In any case, such a cooling system would need to be installed only in the relatively distant future, and it does not seem advisable to make a choice at present between the various alternatives, since such a choice would certainly be overtaken before long by the development of techniques.

6. CONCLUSIONS ON HEAT REMOVAL

6.1 The calculations evolved in this chapter show that if the volume of infiltrated water reaches 112 litres/s per tunnel head, (1) which is a realistic estimate the temperature in the tunnels will not exceed 26.8°C during the hours of peak traffic. As this peak will arise during the summer months, when the outside temperature sometimes reaches or exceeds 26°C it would not appear that the temperature in the tunnel can be regarded as excessively high.

6.2 During the winter months it will be lower: varying in January between 18°C and 20°C according to the temperature-curves which were fixed a priori. But the effective number of trains in October, November and December will be decidedly less than that which would be possible on thermal grounds. It would seem that during those periods some train heating for passengers would still be required, which would not cause any difficulty.

6.3 The calculations in this Study are of an overall nature, while the distribution of the heat produced by the air turbulence and the passage of trains will be irregular, as also, doubtless, will be those of the infiltrated water used for cooling purposes. It would seem certain that the violent draughts created by the passage of trains will ensure the equilisation of the temperature, both as between the 3 tunnels and also throughout the length of each.

(1) or 420 litres/s - see paragraph 4.8.

6.4 If hot zones do appear, it will be necessary to treat them either by a suitable re-arrangement of the distribution of the cooling water, by means of the pipes installed for that purpose or by installing refrigeration plant.

6.5 It should also be noted that the calculations of temperature have been based on the assumption that conditions are stable. Now, for the first few years, the surrounding soil will still be cold and will absorb more heat than will be the case when conditions have stabilised. What is more, the traffic will not have reached the levels envisaged for the year 2005 which were used in the calculations. During the first few years the temperature in the tunnel will remain relatively cool.

6.6 The British Railways Research Department has studied how the temperature of the tunnel structure will increase with the passage of time. Starting with the equation:

$$T_r = \frac{Q}{4\pi k} \; E\left(\frac{r^2}{4\alpha t}\right)$$

in which E represents the exponential function.

$$E_{(x)} = \int_{x}^{\infty} \frac{e^{-u}}{u} \, du$$

they have calculated that, ignoring the heat extracted by the infiltrated water, and assuming a constant traffic of 100 trains each way per day, the temperature of the tunnel wall would be:

$$T_r = \frac{(12.5 \times 4\pi k) + 0.582E\left(\frac{r^2}{4\alpha t}\right)}{4\pi k + 0.0214\,E\left(\frac{r^2}{4\alpha t}\right)}$$

6.7 The asymptotic temperature of equilibrium would be 27.2°C, but the average temperature after 50 years of operation would still only be 21.8°C (see Annexe 19, curve A).

6.8 The calculations were repeated to allow on the one hand for the maximum volume of traffic at present envisaged – 144 trains each way per day – and on the other hand for the heat extracted by a volume of infiltrated water of 112 litres/s per tunnel head or 420 litres/s per tunnel head see paragraph 4.8. In this case the asymptotic temperature of equilibrium would only be 21.8°C and the average temperature after 50 years, 20.0°C (curve B).

6.9 The calculations were again repeated to allow for the progressive increase in traffic, rising from 70 trains when the tunnel is opened, to 100 trains after 10 years and to 144 trains after 30 years. The asymptotic temperature of equilibrium naturally would remain at 21.8°C but the temperatures would rise much more slowly and would only reach 19.65°C after 50 years (curve C).

PART THREE

GENERAL CONCLUSIONS

1. None of the factors examined in the present report indicate that it is either necessary or advantageous to increase the diameter which has been fixed in accordance with the proposed dimensions of the rolling stock and fixed track installations.

2. It is not inconceivable that new factors will emerge in the future such that the limitation of the clear diameter to 6.58 m will be regretted. However, a fundamental design feature of the tunnel as expensive as the diameter cannot possibly be fixed on the basis of an utterly unknown eventuality.

3. The present study therefore recommends the retention and final adoption of a clear diameter of 6.58 m.

4. To cater for the minimum space requirements of service vehicles, ventilation duct and drainage channel, the diameter recommended for the service tunnel is 4.50 m.

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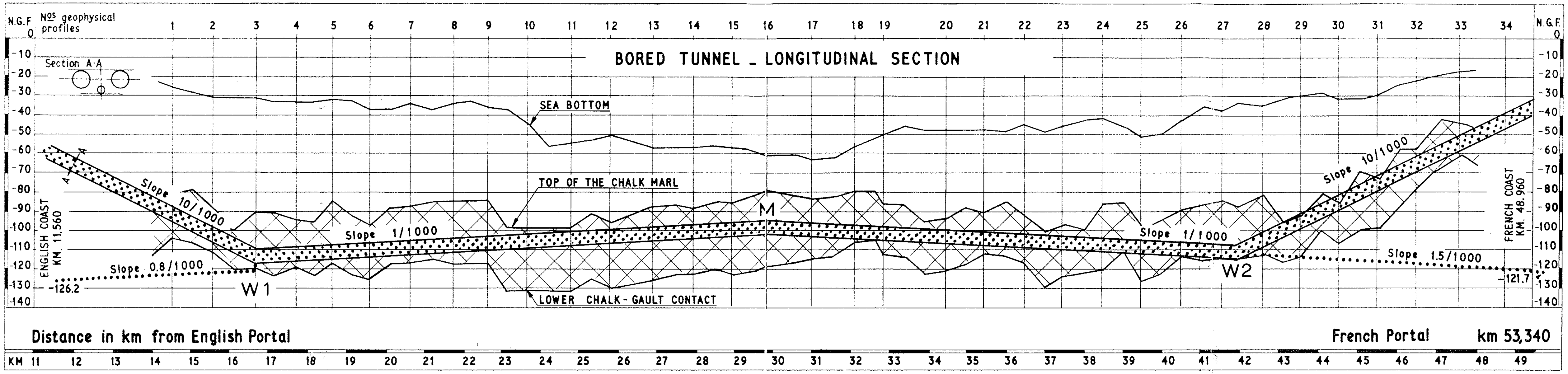
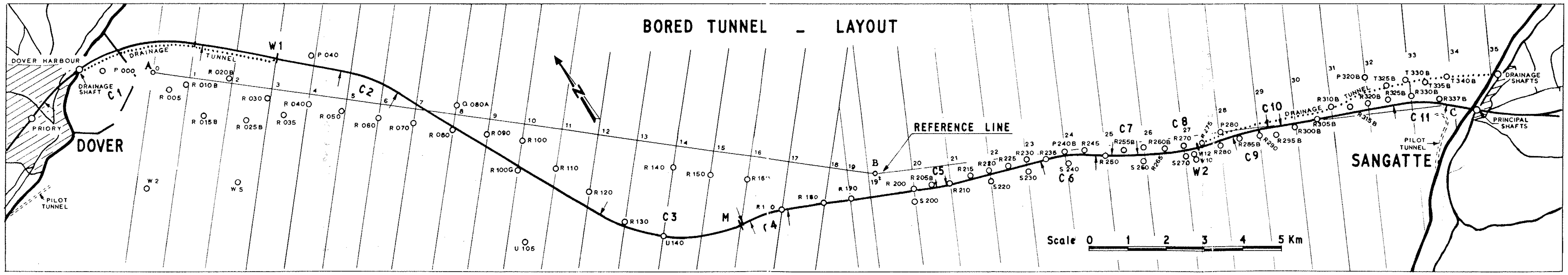
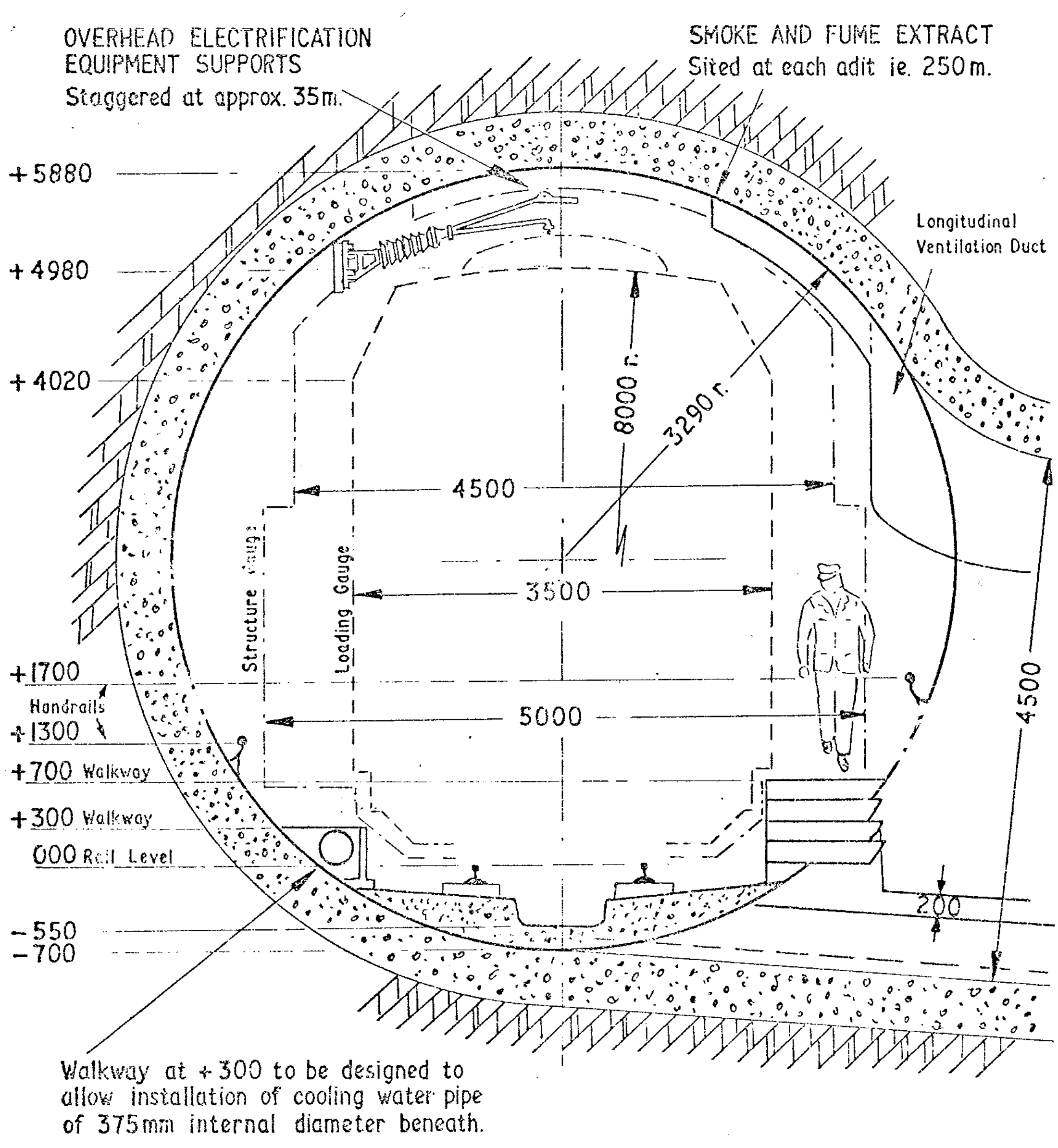
ANNEXE 1A

ASSUMED ALIGNMENT BASED ON THE CHANNEL TUNNEL STUDY GROUP REPORT "CHANNEL TUNNEL"- SITE INVESTIGATION IN THE STRAIT OF DOVER 1964-1965





MAIN TUNNEL - ESSENTIAL FIXTURES

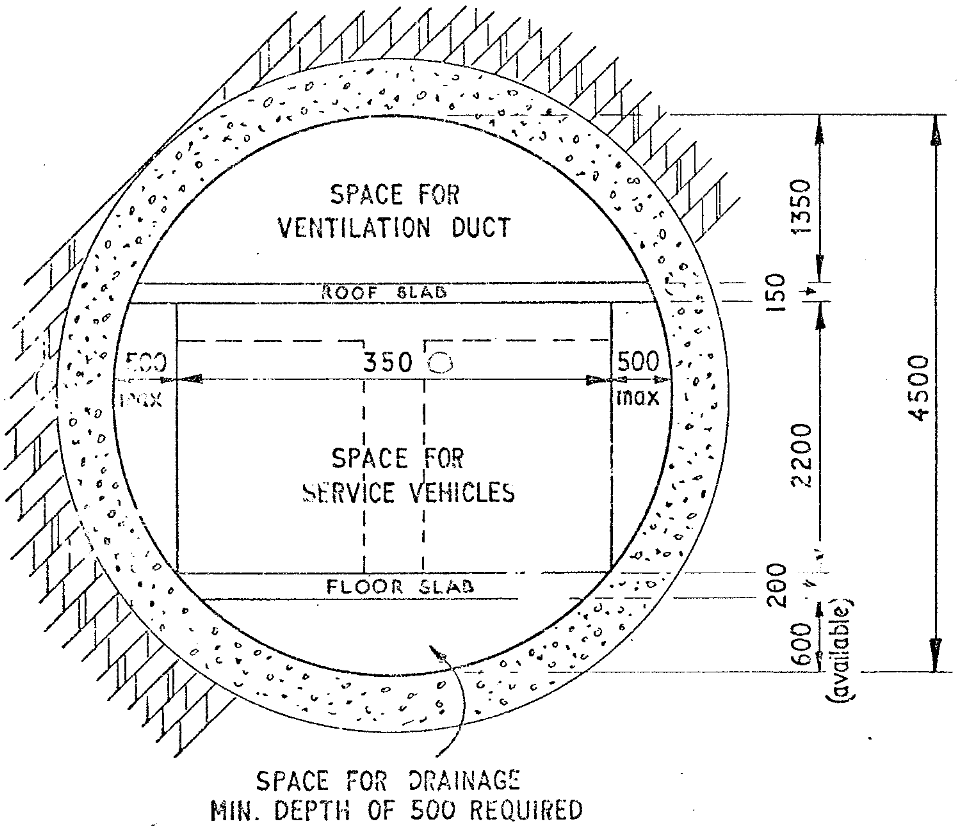


All dimensions in millimetres except where stated otherwise

SCALE - 1:50

NOT TO SCALE

CROSS-SECTION OF SERVICE TUNNEL



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All dimensions in millimetres

TUNNEL TRAFFIC

1. The trend of traffic will be the subject of various studies. Government experts have used the following figures for the tunnel traffic in both directions.

Motor Vehicles (Thousands)			Passengers (in Thousands)		Freight (Thousands of Tons)	
Year	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
1975	2050	1675	3610	3100	4490	4130
1980	2540	1905	3810	3230	6010	5220
1985	2860	2125	4010	3370	7730	6420
1990	3100	2210	4180	3490	9570	7550
1995	3330	2275	4340	3590	11 430	8580
2000	3520	2310	4490	3690	13 280	9510
2005	3660	2325	4640	3770	15 140	10 290

2. The assumed traffic pattern envisaged to cope with these flows are summarised below:-

	No of trains per day (total both directions)					No. of journeys of all types during the busiest hour
	Car carrier trains	Coach lorry and mixed trains	TEE	Ordinary passenger trains	Freight trains	
In 1976						
Average day	-	74	14	26	from 23 to 32	10
Busiest day	114	98		14	-	15
In 1985						
Average day	-	104	16	33	from 32 to 50	14
Busiest day	160	138	16	40	-	20
In 2005						
Average day	-	122	20	50	from 50 to 100	20
Busiest day	188	162	20	60	-	30

3. Average daily number of trains in both directions in year 2005 has been assessed as follows:-

		1990			[illegible]
January	264	206	July	340	[illegible]
February	261	[illegible]	August	364	[illegible]
March	254	[illegible]	September	346	[illegible]
April	261	252	October	254	232
May	267	[illegible]	November	251	[illegible]
June	329	[illegible]	December	261	[illegible]

Not consistent with table on page 102

4. Daily trends during the Winter of year 2005 are forecast as:

Monday	227
Tuesday	247
Wednesday	251
Thursday	248
Friday	259
Saturday	267
Sunday	246

5. In mid-week, freight traffic will make up for the drop in passenger traffic. Traffic during the second half of the week will exceed half of the total by 24 train loads.

6. Forecasts for the Summer period are much more difficult. It can be said that the imbalance between half the Traffic and that during the second half of the week will not exceed 100 train loads, or 50 each way.

7. Finally, the hourly division of traffic in both directions on a busy day has been studied: of 366 trains (average 15.2 per hour), 250 will run between 0900 hrs and 2100 hrs.

SUMMARY OF WORK DONE BY ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH, ON RESISTANCE OF TRAINS IN LONG TUNNELS

1. As part of the Channel Tunnel investigation, a search was first made of available literature, which showed that little was known on the air resistance of trains in tunnels. The R.A.E. were asked to produce a theory for the aerodynamic processes involved, and correlate it with known practical results.

2. Work done by the R.A.E. and the results obtained have been published in R.A.E. Tech. Memo. Aero. 1132, March 1969, "Some Calculated Power Requirements for Trains using the Channel Tunnel", by P B Earnshaw and T B Owen, while the aerodynamic studies have been reported in detail in a paper "On the aerodynamic resistance to long trains passing through long close fitting tunnels, Part I, Equilibrium flow" by P B Earnshaw. Part II, on "Wave Drag", the effects of impulsive pressure, is to follow, but has not yet been received.

3. The R.A.E. work was based on treating the train/tunnel system as a rough loosely fitting circular long piston in a rough concentric cylindrical pipe. An expression was found for the flow in the annulus in terms of the train and tunnel lengths and equivalent roughnesses, trains speed and tunnel wall speed relative to air, and the pressure difference head to tail of the train. This pressure difference also sets up a flow along the tunnel from end to end. The sum of these airflows was equated to the displacement due to the train, and the whole flow system could then be computed, leading to the values of the pressure differences on a train and of the aerodynamic power requirements. Corresponding calculations were also made for free air conditions. The tunnel was taken as 53 km (32.3 miles) long.

4. All velocities and pressures are computed on the assumption that only one train is passing through the tunnel system at any one time.

5. STEADY-STATE CALCULATIONS (PART I)

5.1 Calculations were made assuming fully developed turbulent pipe flow in a long continuous single tunnel. A reasonably reliable equivalent train roughness, inferred from free air train resistance tests and model tests in various countries, was assumed at 55 mm. A tunnel equivalent roughness was taken as 1.35 mm, (half that of BR Standedge tests, where the tunnel walls were much rougher than proposed for the Channel Tunnel). Calculations then showed that for a car-carrier train of 31 wagons, 1200 tons trailing, the locomotive would require to be of about 15 000 kW (20 000 h.p.). This value was unexpectedly high. Table I first two columns, gives the results (with allowance for wave drag from Part II).

5.2 In order to check this figure by using actual values of aerodynamic resistance and locomotive power, it was decided to make practical tests to supplement the theoretical work described. These tests were made by BR in Standedge tunnel, a single-bore tunnel 3.0 miles (4.9 km) long. Tests were reported in BR Research Dept. Report E595, "Channel Tunnel, Tests at Standedge Tunnel" by J H Littlewood and D W Peacock, Oct 1966.

5.3 The tests enabled values to be obtained for the train and tunnel roughnesses, which were found to be reasonably similar to those assumed, and which therefore confirmed the estimate of high power requirement. The actual power found in the test, when scaled up to Channel Tunnel conditions, also gave an estimated value of about 15 000 kW (20 000 h.p.) for a level track.

5.4 In view of these, and other circumstances, it was then decided to connect the two main tunnels by a series of cross-passages (adits), situated at 250 m intervals, which connect with the main tunnels and the centrally placed service tunnel. The airflow and power problem was thus considerably altered, basically because the air displaced by the train has now a number of short alternative return passages. The R.A.E. extended their theoretical investigation into this modified arrangement, and it was found necessary to carry out tests on a model, to ascertain loss coefficients at the junctions between tunnels and adits, for a configuration typical of that of the Channel Tunnel.

5.5 Using this practical information, the air resistance and powers were re-calculated and gave values as shown in Table 1, results for the adit spacing of 250 m being given.

TABLE 1

RESISTANCE COEFFICIENTS, AIR RESISTANCE POWER

Powers given in kW, and at maximum train speed.

NOTE: for total locomotive power, see Annexe 6

Car-carrying train, 31 wagons, cross-section 13.20 m^2

Trans-European Express 14 wagons, cross-section 7.78 m^2

Berne-gauge Passenger 16 wagons, cross section 9.25 m^2

Trains	Maximum Speed km/h	Open Air		TUNNEL			
				No adits		Adits at 250 m spacing	
		Resistance coefficient	Air resistance Power kW	Resistance coefficient	Air resistance Power kW	Resistance coefficient	Air resistance Power kW
Car-carrying	140	4.11	1955	26.14	12 560	6.68	3177
Trans-European Express	160	3.43	1435	9.96	4167	4.05	1694
Berne-gauge Passenger	140	3.29	1097	11.43	3810	4.12	1373

$$\text{Resistance coefficient} = \frac{\text{Resistance}}{\text{Cross-section area x dynamic head}}$$

Dynamic Heads:- 140 km/h = 927 N/m^2 160 km/h = 1210 N/m^2

5.6 Results for an adit spacing of 200 m were also obtained, and showed small reductions on the 250 m adit values; the spacing of 250 m has however been fixed for safety reasons.

5.7 A number of tests were also made on the effect of rounding the adit junctions, but the small improvement obtained must be balanced against the increased costs of construction.

5.8 The most important features of the air resistance results are the high powers needed for the car-carrier in a long continuous tunnel, and the striking reduction produced by the presence of adits. With adits, the difference of power from open air is quite small, and except for the car-carrier train, not unduly significant. This is confirmed by the total electrical power curves of Annexe 6.

5.9 A number of subsidiary studies were made, the principal one being to establish the pressure difference front to rear of a train, and the draught speeds in the tunnels.

5.10 Pressure differences are shown in Table 2, in each case at the maximum train speed.

TABLE 2

PRESSURE DIFFERENCE FRONT TO REAR OF TRAINS

Train	Maximum Speed km/h	Pressure Difference Front to Rear			
		No Adits		Adits at 250 m spacing	
		kN/m^2	lb/ft^2	kN/m^2	lb/ft^2
Car carrier	140	11.3	235	2.4	49
Trans-European Express	160	3.5	74	1.2	26
Berne-gauge Passenger	140	3.6	74	1.1	24

5.11 The effect of these pressure differences is discussed. It is emphasised that they may cause considerable internal draught along the train, if allowed, and that adequate coach body strength will be required to resist possible air loadings.

5.12 A discussion is also given on the probable value of tunnel draughts, Table 3, which combines the effects in main tunnels and adits and service tunnels. Draught speeds are a constant proportion of train speed, and are so shown in the Table.

TABLE 3

TUNNEL DRAUGHTS, EXPRESSED AS PROPORTION OF TRAIN SPEED

Train	Max Speed km/h	NO Adits Steady flow	Adits at 250 m spacing			
			Main Tunnel Just Ahead of Train	Other Main Tunnel Track Opposite Train	Adits Nearest Train	Service Tunnel Opposite Train
Car Carrier	140	0.32	0.66	0.49	0.79	0.41
Trans-European Express	160	0.16	0.48	0.32	0.51	0.30
Berne-gauge Passenger	140	0.19	0.52	0.34	0.57	0.33

5.13 It is also possible that when two trains pass travelling in opposite directions even higher local draughts can be set up in the tunnel with adits.

5.14 Hence the presence of these draughts will cause considerable nuisance, or even danger, to men working in the tunnels.

6. EFFECTS OF IMPULSIVE PRESSURES (PART II)

6.1 The effects of impulsive pressure changes as the head and tail of the trains cover and uncover adits is to cause abrupt changes in the flow pattern, as the train sets up new patterns; and the flow can never be strictly regarded as steady. The train can be regarded as driving a travelling wave along the tunnel. For the particular configuration, this wave drag can be regarded as a correction to the steady state system, and to avoid unreasonably difficult calculations, for wave drag calculation the system was taken as equivalent to a double system with adits. Calculations showed that the mean aerodynamic drag might be expected to be somewhat greater than for the steady-state condition, possibly by as much as 24% for the car-carrier train. An allowance for wave drag has been made in the values given in Table I.

MEASUREMENT OF THE RESISTANCE TO FORWARD MOTION OF TRAINS IN THE SIMPLON TUNNEL

1. The Simplon is the longest rail tunnel at present in use. It is 20 km long. It has two parallel tunnels with a cross-section of 23.25 m^2, smaller than that of the principal tunnels of the Channel Tunnel. But the trains in the latter will be carrying accompanied cars, in wagons which are higher than the Berne gauge, and because of this there is about the same ratio between the maximum cross-sections of the rolling stock and the tunnel section in both cases.

2. Figure 1 gives the section of the Simplon Tunnel and that of the vehicles used during the tests, with a maximum cross-sectional area of 9.25 m^2.

3. A cross-over between the main tunnels is provided at the centre of the Simplon, so that, as with the Channel Tunnel, the main tunnels are composed of lengths of 10 km without a break. These tunnels are in addition linked by 42 transverse tunnels with a section of about 4 m^2, with an average of 500 m between them (shortest distance apart - 75 m. Longest distance apart - 1580 m).

4. Hence there are similarities between a number of characteristics of the Simplon tunnel and of that under the Channel. This was one of the reasons which led the S.N.C.F. to undertake its tests in the Simplon.

5. The tests took place in November 1965 thanks to the co-operation of the Swiss Federal Railways who provided an Ae 6/6 locomotive and a train of coaches, and did all that was necessary to ensure the success of the tests.

6. A number of runs were made in each direction between BRIGUE and ISELLE, the stations near the two ends of the tunnel.

7. A certain number of runs were made also between BRIGUE and VIEGE so as to measure the resistance to motion of the same equipment in the open air.

8. During the tests, the Ae 6/6 locomotive weighing 120 T. pulled trains of 8 and 16 coaches, including an S.N.C.F. test-coach weighing 70 T.

9. The CFF coaches were of unified Type B, 23.7 m long excluding buffers, and of 27-28 T. tare according to their series.

10. The measurements were taken either with the train pulling at constant speeds, or coasting.

11. The train of 8 coaches weighed together 263 T. making 383 T. with the locomotive: the 16-coach train weighed 481 T. or 601 T. with the locomotive.

12. So as to simulate the ventilation openings of the car-carrying wagons intended for the Channel Tunnel, the ventilators in one compartment of each coach (except the test-coach) were kept open during the test runs.

13. Measurements were taken of:-

13.1 The current taken by each motor, by means of recording ammeters installed in the test coach. From this was deduced the sum of the forces at the locomotive wheel rims, using the known characteristics of the motors and allowing for the reduction gearing and the exact diameter of the wheels on each axle.

13.2 The forces of the couplings at different parts of the train, particularly that where the locomotive was attached, the one at the front of the test-coach, and the one between the last two coaches.

14. The recording table gave the following simultaneous values:-

14.1 the speed of the train

14.2 the acceleration

14.3 the distance run from the beginning of each test

14.4 the time-scale

15. Continuous recordings of meteorological conditions during the tests were made by means of a barometer, thermometer and hygrometer, mounted on the outside of the test-coach.

16. The determination of the resistance to forward motion of all or part of the train was made by three different methods:-

16.1 from the measurement of the instantaneous forces

16.2 by reckoning the electrical or mechanical energy for a certain duration

16.3 by the method of "coasting" runs which at the limit, on a downward slope, become runs at a constant balanced speed.

17. In each case the determination was based on the law which defines the equation of the train's movement:-

$$F = R + (L+P)(i + \frac{800}{\rho}) + (\frac{k_1 L + k_2 P}{g}) \quad \gamma \quad 10^3$$

where:-

F = motor force in kg
R = resistance to forward motion in kg
L = weight of the locomotive in tonnes
P = weight of the train being hauled - in tonnes
i = declivity in $^o/oo$ (or mm per metre) this term being positive for an upward slope, and negative for a downward slope.
$\frac{800}{\rho}$ = supplementary resistance attributable to the curves, with ρ radius of curve in metres - which does not arise in the Simplon because the track there is straight for almost all the length.
k_1, k_2 = coefficient of inertia of the rotating masses of the locomotive and train of coaches.

g = acceleration due to gravity in m/sec^2

γ = acceleration of the entire train in m/sec^2, this term being positive when speed is decreasing.

18. RESULTS OBTAINED

18.1 The graphs at figures 2 and 3 give the curves resulting from the total measurements for the train of 8 coaches and that of 16 coaches. In the five figures we have shown, as a function of the speed, the resistance forces of the entire train (locomotive and coaches) and of the various sections from which measurements were taken.

18.2 From those curves it was possible to construct graphs representing the values of resistance measured throughout the train in both its forms, and for speeds of 100, 120 and 140 km/h. Figure 4 relates to the 140 km/h speed. It will be seen that the specific resistance of the vehicles is less for the longer train, which is accounted for by the action of the induced air-currents, and that though the piston-effect increases the resistance of the leading vehicles no trace of the phenomenon ofdepression was observed behind the rear vehicle.

18.3 It was also observed that the passage of other trains in either of the tunnels did not cause any measurable influence on the resistance of the test train to forward motion.

19. AERODYNAMIC RESISTANCE DEDUCED FROM THE TESTS

19.1 It was certain, at the beginning, that the curve of the air resistance could be expressed in the form of a term proportional to V^2.

19.2 However, on analysing the experimental curves, it appeared possible to represent them by the classic formula which includes a constant term (rolling and friction resistance) a term in V (friction of the flanges on the rails and mechanical hysterisis of the suspension) and a term proportional to V^2 (resistance of the air).

$$R = A + BV + CV^2$$

19.3 As regards the constant term, the expression used by the S.N.C.F. was adopted outright. This gives in kg/tonnes.

$$a = 1.5 \sqrt{\frac{10}{p}}$$

(p = weight per axle, in tonnes)

By adopting this coefficient and taking into account what follows, concordant and homogeneous results were obtained for the speeds ranging between 40 and 140 km/h at which the tests were conducted.

19.4 The following constant forces A were arrived at, as a result:

	- for the Ae 6/6 locomotive	127 kg[1]
	- for the test coach	79 kg
	- for 7 CFF coaches	349 kg
	- for 15 CFF coaches	745 kg
ie	for the train of 8 coaches	555 kg
	for the train of 16 coaches	951 kg

19.5 The difference between the curves showing the test results and the constant terms listed above gives the sum:

$$BV + CV^2$$

19.6 We know that B is proportional to the weight of the complete train. For the 8-coach train as well as for the 16-coach train, it was found that the equation would not be satisfied unless the term in V was given a coefficient equal, in round figures, to

$$B = 0.010\ P$$

a result which gives remarkable confirmation to an expression which has become traditional.

19.7 As for the coefficient of the term in V^2, it works out at:

$C = 0.242$ for the train of 8 coaches
$C = 0.309$ for the train of 16 coaches

19.8 The resistance of the entire train is thus given by the following relations, where R is in kg and V in km/h.

- 8 coach train

$$R = 555 + 3.83V + 0.242\ V^2$$

- 16 coach train

$$R = 951 + 6.01V + 0.309\ V^2$$

20. RESISTANCE TO FORWARD MOTION IN OPEN AIR

20.1 The results of the tests in open air, which were very incomplete, show considerable variation because of the short length of the Viege-Brigue section on which the tests were carried out. Quite often measurements were taken during periods of rapid acceleration which added to the frequent variations in profile, caused a certain amount of inaccuracies.

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(1) This resistance does not include the mechanical losses of the motors nor those of the transmission. This is logical since it is the motive force at the wheel rims which we are seeking to determine.

20.2 Results obtained were:

At 140 km/h a resistance to forward motion of 3050 kg for the 8-coach train and of 4700 kg for the 16-coach train.

20.3 From the coefficients used previously for the constant term and the term in V, for the 8-coach train, travelling at 140 km/h.

$A + BV = 555 + (3.83 \times 140) = 1091$ kg

or, for the term in CV^2:

$3050 - 1091 = 1959$ kg

whence $C = 0.100$

The resistance of the air in the tunnel is thus:

$\frac{0.242}{0.100} = 2.42$ times greater than in open air

20.4 For the 16-coach train the terms A + BV have the values:-

$951 + (6.01 \times 140) = 1792$ kg

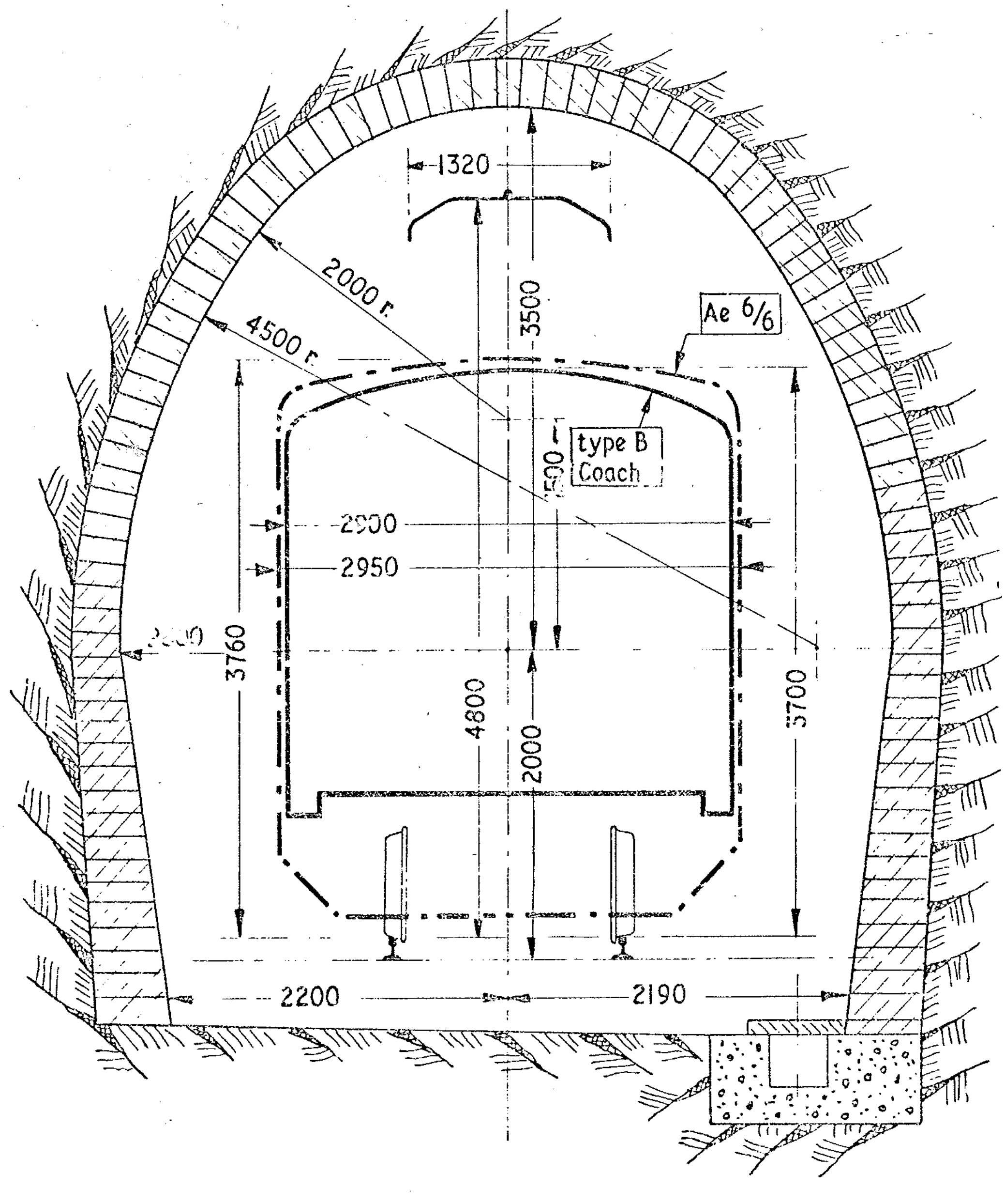
hence, for the term CV^2

$4700 - 1792 = 2908$ kg

or, $C = 0.148$

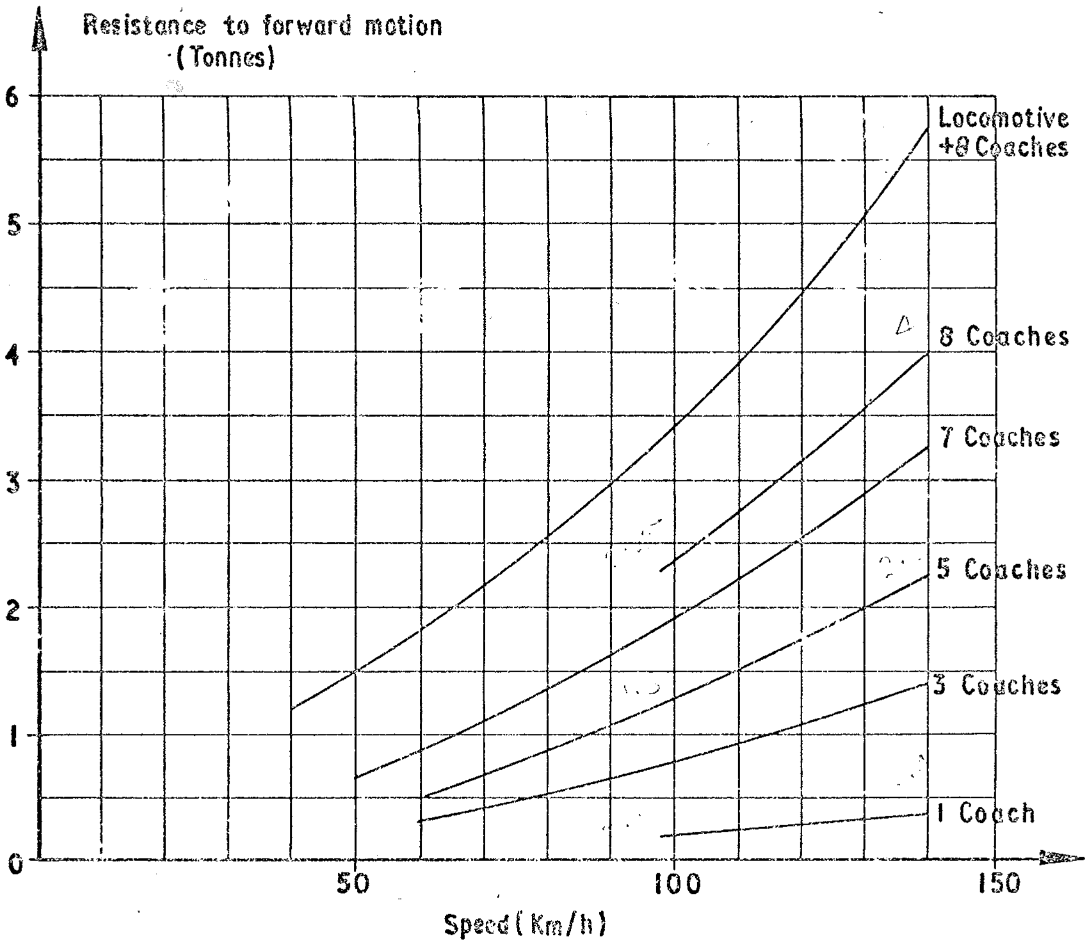
ie, the air resistance is $\frac{0.309}{0.148} = 2.08$ times greater in the tunnel than in the open air.

VERTICAL CROSS SECTIONS OF THE SIMPLON TUNNEL, A CFF COACH TYPE B. UNIFIED, AND AN Ae 6/6 LOCOMOTIVE

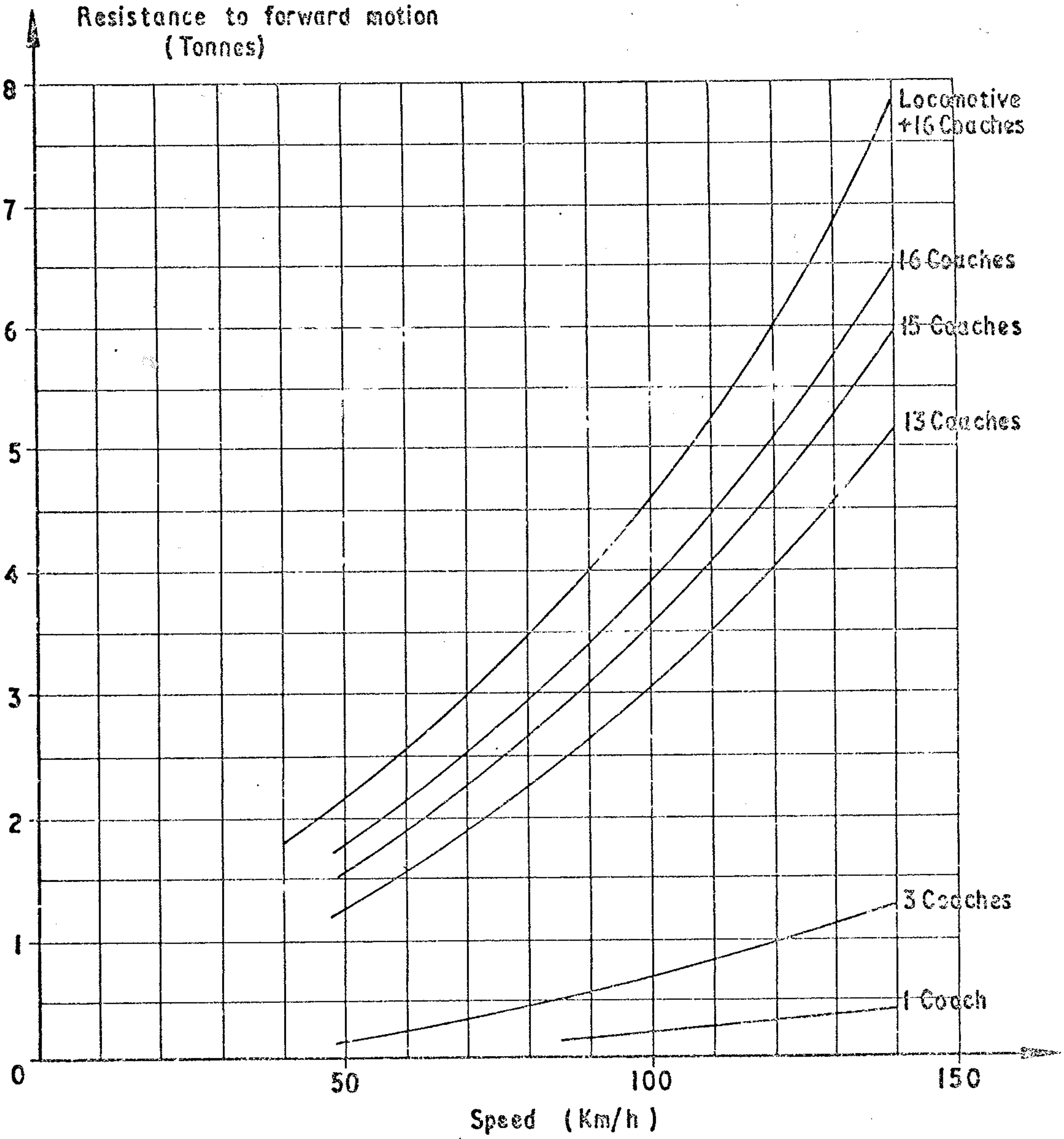


Not to Scale - ~~1:40~~

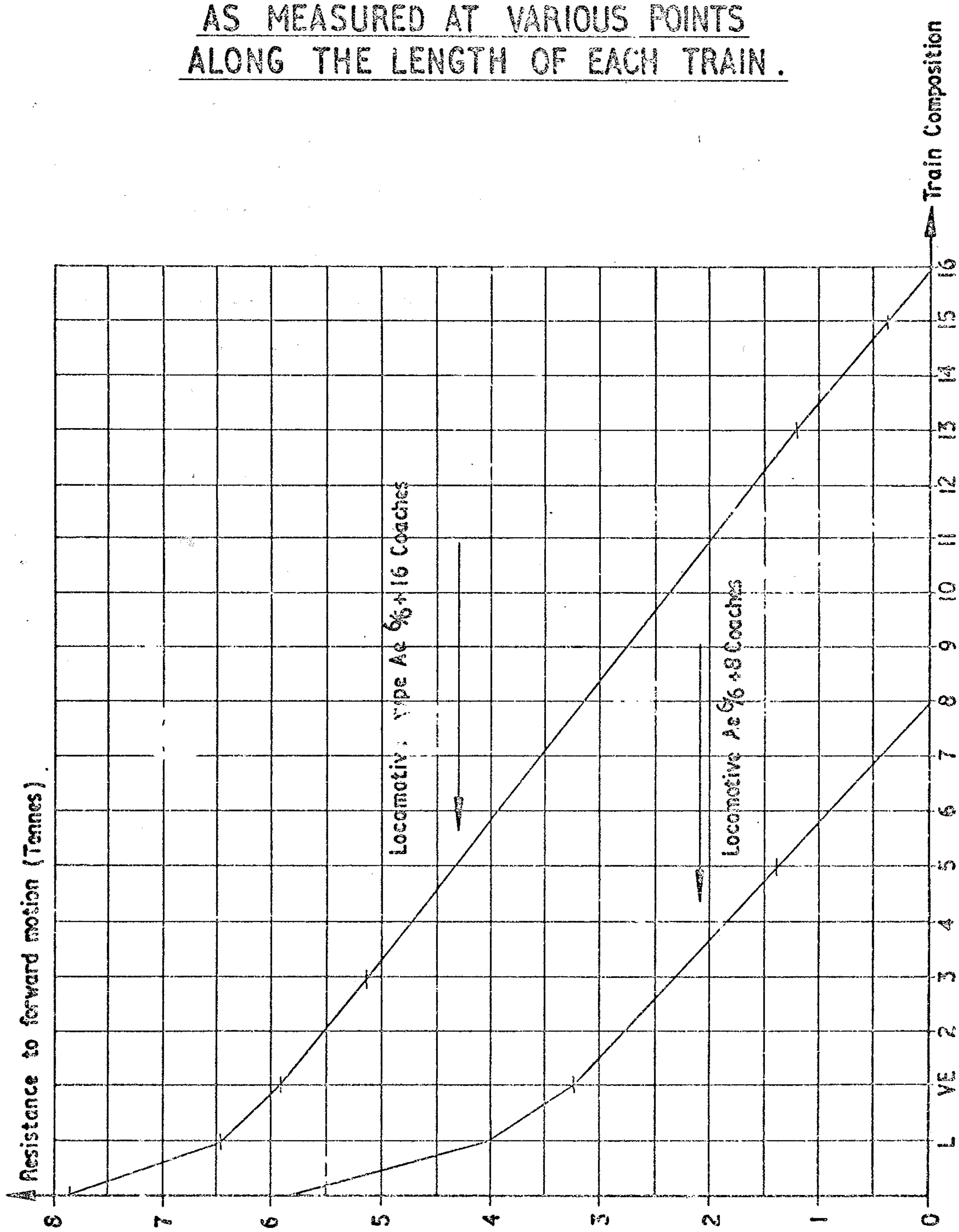
RESISTANCE TO FORWARD MOTION OF AN 8 COACH TRAIN, EXPRESSED AS A FUNCTION OF THE SPEED, AS MEASURED IN THE SIMPLON TUNNEL



RESISTANCE TO FORWARD MOTION OF A 16 COACH TRAIN, EXPRESSED AS A FUNCTION OF THE SPEED, AS MEASURED IN THE SIMPLON TUNNEL



RESISTANCE TO FORWARD MOTION OF 8 COACH AND 16 COACH TRAINS IN THE SIMPLON TUNNEL, AS MEASURED AT VARIOUS POINTS ALONG THE LENGTH OF EACH TRAIN.



STUDIES BY L'INSTITUT AEROTECHNIQUE de ST CYR
SUMMARY OF STUDIES AND RESULTS OBTAINED

The studies carried out by l'Institut Aerotechnique de St Cyr on request by the S. N. C. F. were theoretical and experimental. They took place over two periods of time.

1. FIRST STUDIES: THEORETICAL SECTION

1.1 The theoretical study was intended to investigate the forces on a train running through a tunnel, and to formulate equations relating them to the various parameters.

1.2 Drag - the resistance to forward motion of a train, or the drag, is expressed by the coefficient of drag Cx (resistance divided by $\frac{\rho}{2} . SV^2$)

1.3 Drag is made up of:

1.3.1 - friction drag caused by the friction of the air on the external surfaces of train (perimeter x length) and proportional to the square of the relative speed of the train in relation to the surrounding air.

1.3.2 - a pressure drag which itself is the sum of the frontal pressure (form - drag) caused by air being thrust aside by the front of the locomotive, and of the loss of head in the space between the tunnel walls and the train. Thus loss of head is due to the friction of the air against the sides of the train, which carry the air along, and against the tunnel walls, in relation to which the direction of the air movement was not known at the beginning of the studies.

1.4 The loss of head (or difference in pressure) between the front and rear of the train is balanced itself by the flow of air, partly through the space between the train and the tunnel, and partly in the tunnel, where it is pushed back, through the connecting adits, along the opposite tunnel, and through the connecting adits once again to flow in behind the train.

1.5 Given the aerodynamic resistance of a length of the tunnel, and the effects of a change of direction, it is possible to calculate the resistance of the entire circuit consisting of the main tunnels and the adits which connect them, as a series of derivations depending each from the next, by recurring equations. The air currents diminish at each adit and finally disappear. The sum of the air currents in the adits should be equal to the air current displaced by the train. The calculations have to be made by trial and error: it is a laborious task and one which would justify the use of a small computer.

1.6 Given the coefficients of friction of the tunnel and of the train, the drag due to frontal shape and the resistance of the circuit of tunnels and cross-adits, it is possible by elimination of the speed in the different equations to calculate the drag coefficient of the train.

1.7 The same equations may be applied in the particular instance of tests on a model, which involve measuring the aerodynamic forces exercised by the air driven by a fan against a train fixed in position in a tunnel.

1.8 The equations then enable the results obtained from these measurements to be used to determine the coefficient of friction of air on the train and the drag coefficient due to frontal shape, as a function of the ratio $\frac{\text{train cross-section}}{\text{tunnel cross-section}}$.

1.9 It must be emphasised that such tests are not directly usable (they disregard the relative speeds).

2. EXPERIMENTAL STUDY

2.1 This was intended to measure:

2.1.1 - the drag coefficient due to frontal shape of the train when surrounded by the tunnel walls

2.1.2 - the coefficient of friction on the train surface and on the tunnel walls

and, in consequence, to enable the calculation of the drag coefficient of the train and its extrapolation to the conditions in the Channel Tunnel.

2.2 Tests were first made using commercial models of scales 1/86 (passenger coaches) and 1/99.2 (car-carrying trains).

2.3 Although the turbulence was low enough to justify ignoring the Reynolds number effects, on the other hand the similarity of the roughness led to the application of the curves produced by NIKURADSE for pipes and flat plates.

3. VERIFICATION

3.1 The resistances deduced from the various measurements show satisfactory agreement. Analysis showed that the influence of the boundary layer could not be neglected. The elimination of this boundary layer by alternate sucking and blowing was considered, but it would have presented difficulties of execution which would not have allowed sufficient accuracy.

3.2 A further verification was made by applying the results of the measurements to the test conditions carried out by the S. N. C. F. in the Simplon tunnel and those of the tests carried out by the Swiss Federal Railways in the Ricken and Gotthard tunnels. Unfortunately these tests were less complete and did not allow precise calculations to be made. Comparison with the resistances measured shows the following

3.2.1	Simplon	16 coaches	6.2% and 4.7%
		8 coaches	0.7% and 5.7%
3.2.2	Ricken	16 coaches	11.9% and 11.7%
		8 coaches	18.2% and 21.2%

3.2.3	Gotthard	16 coaches	1.09%
		8 coaches	11.7%

3.3 Allowing for the inaccuracies in the test data for the Ricken tunnel, this comparison shows that the orders of magnitude of the values calculated are suitable and that the method is justified.

Application to the Tunnel – Values of C x, with cross section of main tunnel 32.80 m^2, cross section of adits 8.55 m^2			
	Adits 250 m apart + junctions	Adits 500 m apart + junctions	No adits nor junctions 1 train in tunnel
Car train 31 coaches + locomotive (cross section 13.90 m^2)	8.02	10.75	35.9
Passenger train 13 coaches + locomotive (cross section 8.95 m^2)	4.41	5.0	10.6

3.5 The method used allows the parameters to be varied and the effects of this to be studied.

Plate 1. shows the variation of C x_o (value of C x for the model) as a function of the length of the train.

Plate 2. shows the effect on C x_o of the (tunnel + adit) resistance.

3.6 The effects of the presence of other trains in the tunnels were examined. Because of the rapid reductions of the air current in successive adits, the effect caused by a train does not extend to more than 5 km when the adits are 250 m apart, or to more than 10 km where the adits are 500 m apart. If a study is made of a tunnel without adits, the presence of 5 similar trains in the tunnel reduces the drag coefficient by 45% for the car carrying trains and by 25% for the passenger trains.

3.7 The calculations also demonstrate the variations of the drag coefficient as a function of the tunnel cross-section. The results are given in Plate 3. It will be seen that in the case of a tunnel with adits 250 m apart, the drag coefficient C x of a car-carrying train would be reduced by 7% by an increase in tunnel section of 20%.

4. SECOND SERIES OF STUDIES

4.1 The first studies showed that the drag coefficient of a train passing through a tunnel depends to a great extent on the characteristics of the tunnel, more precisely on the "coefficient of a loss of head" of the circuit which has to be taken by the air displaced by the train's movement. This coefficient had been calculated by successive approximations, based on a certain number of simplifying hypotheses, in particular by ignoring the presence of the longitudinal service tunnel. An experimental study was therefore necessary to study the influence of this 3rd longitudinal tunnel and to check the validity of the calculations. In addition, the dimensions of adits had in the meantime been increased, their diameter having been raised to 4.50 m. On the other hand, a more accurate assessment of the various obstacles which would be mounted in the main tunnels (floor, rail tracks, air intakes, catenary apparatus) led to the reduction of the usable cross-section from 32.8 m^2 to 27 m^2.

4.2 As some divergencies had been found between the results obtained from the first studies and those arising out of similar studies carried out by the British, it was decided to carry on with the study and to take fresh measurements on a model more closely resembling the working conditions as they are now envisaged. As with the first study, this was also conducted in two parts - theoretical and experimental.

5. THEORETICAL PART

5.1 The method which had been used to establish the coefficient of loss of head of air in the tunnels and which had proved a laborious one, would have been even more complicated when taking into account the service tunnel.

5.2 In setting out the ratio of the speeds in two successive sections of main tunnel, and the ratio of speeds in one section of main tunnel and an adjacent adit, and in then entering those expressions in the continuity equation (division of flow through one section between the adjacent adits and the next section) a very simple relationship was established between the resistance of one unit (2 sections of main tunnel and one adit), and resistance of an adit and the overall resistance of the system as a function of the sections of the different tunnels. Because of the hypotheses used, this relationship is only approximate, but it makes easy the study of the influence exerted by the various parameters and in particular by the resistance of an adit.

5.3 The study also permits the determination of the progression of the speeds in the sections or adits in relation to the speed in the initial section, and in addition the progression of the successive differences in pressure in relation to the dynamic pressure.

5.4 It gives evidence that a model of limited length, terminating in an air-tight or semi-air-tight compartment, is comparable with a tunnel of infinite length. Finally it allows an experimental check to be made of the point where the current of air reverses its direction in the return tunnel.

6. EXPERIMENTAL PART

6.1 This was intended to check the validity of the relationships determined by theory, to measure the coefficients necessary for the calculation of the drag coefficient being investigated, and it also allowed the effect of the service tunnel to be studied.

6.2 The model used was a reproduction of the tunnels to a scale of 1/100 as regards their transverse dimensions. The difference in scale of lengths and resistances was compensated for by using wire screens of more or less fine mesh. The effect of the movement of trains was reproduced by a fan which was capable of sucking or blowing.

6.3 By varying the resistance of the circuit from K = 1 corresponding to a distance between adits of 220 m to K = 3.5, corresponding to a distance of 780 m it was found that the resistance to be attributed to the adit should be 2.4, whereas in the first study it had been arbitrarily set at 1.5.

6.4 The effect of the ensuing amendments to be made, so as to take account of the limited length of the tunnel and the inclusion of the service tunnel is shown on Plate 4 attached.

6.5 By way of verification the calculation was made for the Simplon tunnel, allowing for its limited length. The comparison between the values of the drag coefficient, obtained by calculation and by measurement, is as follows:-

For 16 coaches in tunnel 8% -- for 16 coaches outside tunnel 4.7%
For 8 " " 9.3% - " " " 6.6%

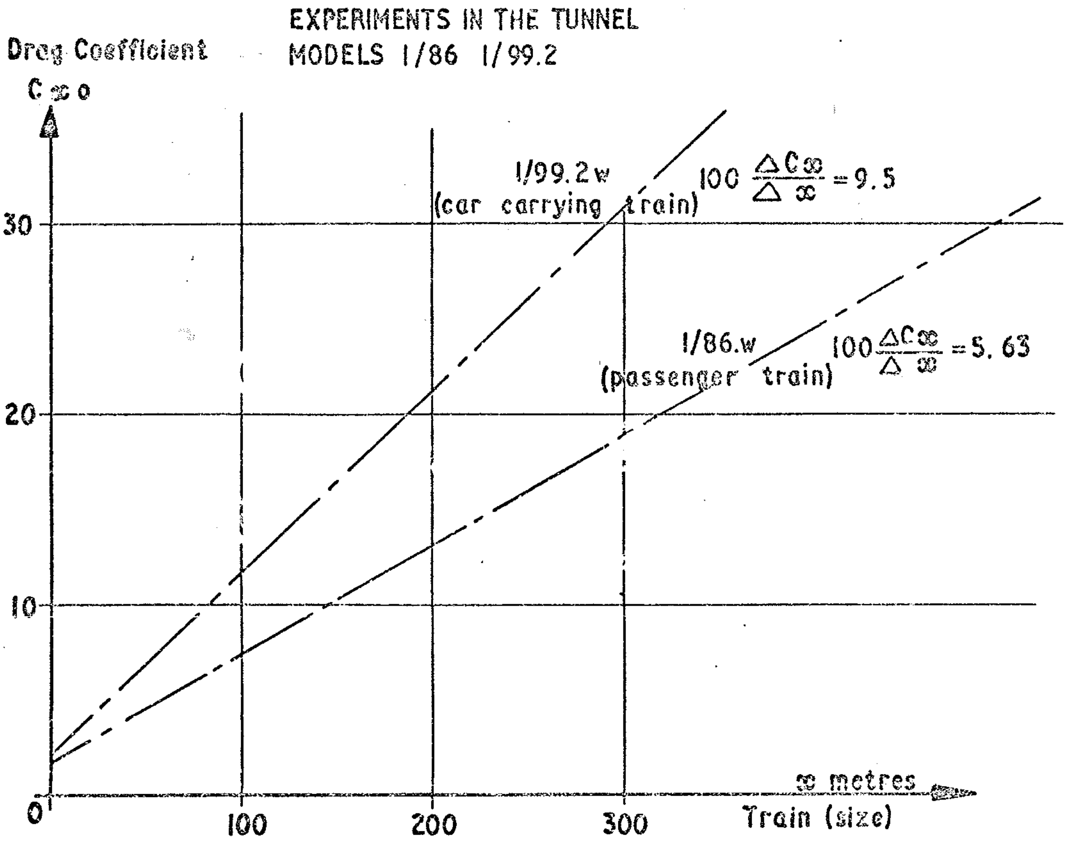
6.6

Application to the tunnel
Values of C x with: cross-section of main tunnel 27 m^2
Combined cross-section of service tunnel and adits 9.06 m^2 and 11.40 m^2

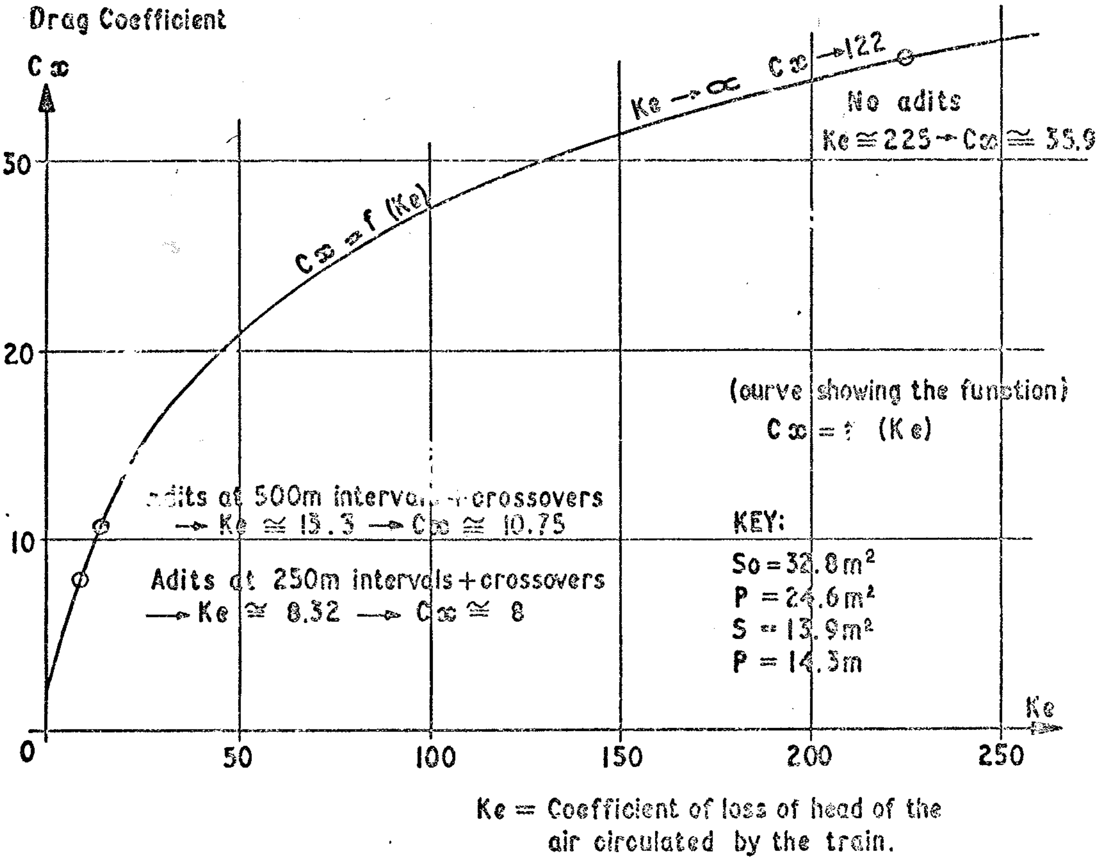
	Adits 250 m apart		Adits 500 m apart	
	Area of Cross-Sections		Area of Cross-Sections	
	9.06 (m^2)	11.4(m^2)	9.06(m^2)	11.4(m^2)
Car-carrying train 31 coaches + locomotive (cross-section 14.15 m^2)	8.22	7.90	10.78	10.30
Passenger train 13 coaches + locomotive (cross-section 8.95 m^2)	5.05	4.88	5.33	5.35

6.7 Figure 5 shows the variation in values of drag coefficient C x as a function of the cross-section of the tunnel.

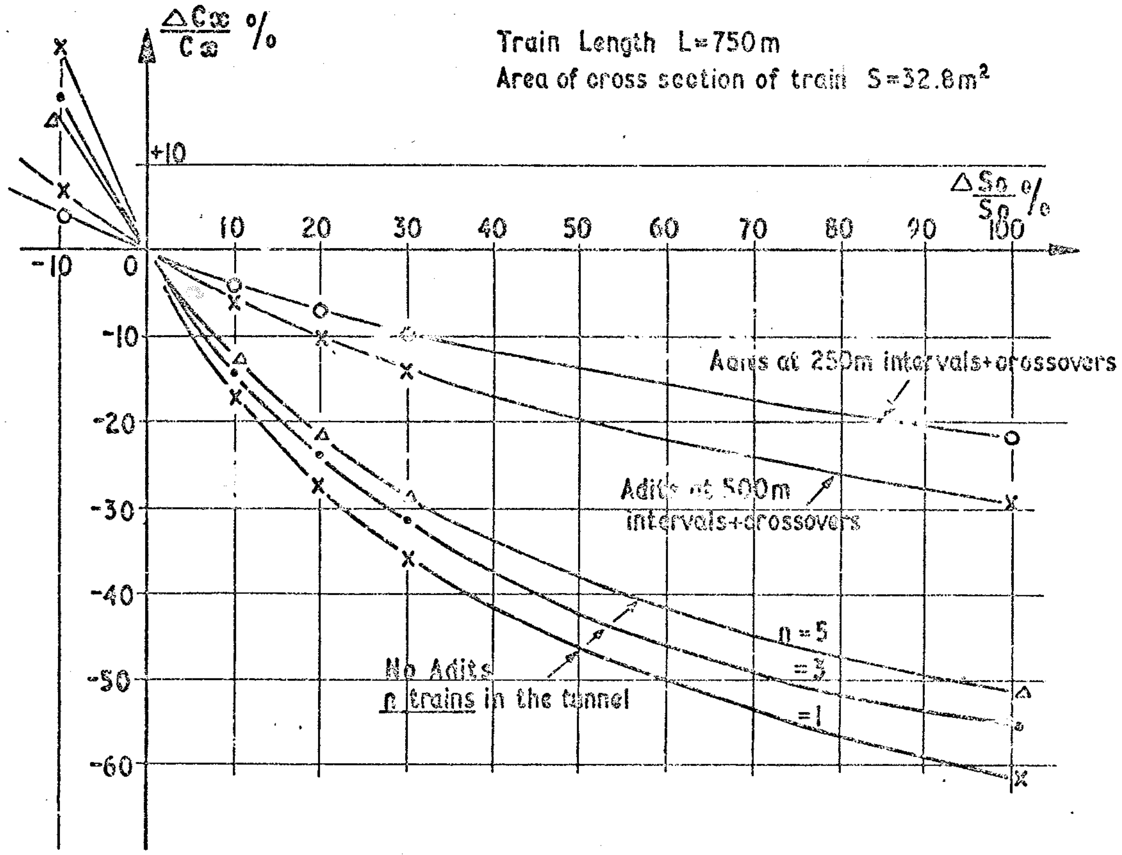
VARIATIONS IN DRAG COEFFICIENT EXPRESSED AS A FUNCTION OF THE TRAIN LENGTH.



EFFECT OF TUNNEL AND ADITS ON DRAG COEFFICIENT.

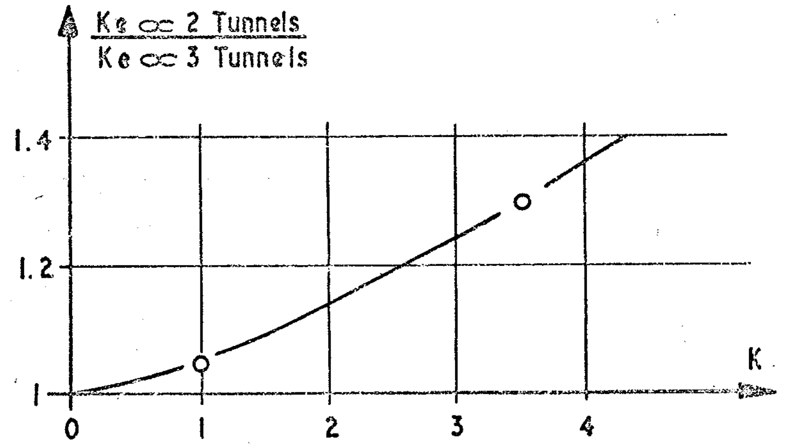


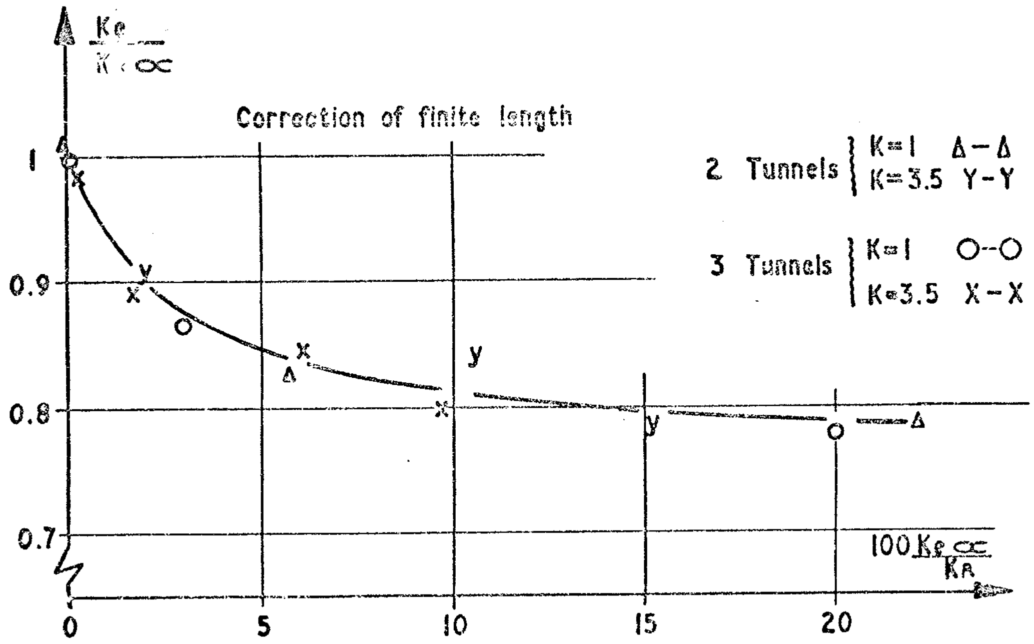
PERCENTAGE VARIATION IN DRAG COEFFICIENT EXPRESSED AS A FUNCTION OF THE TUNNEL CROSS SECTION.



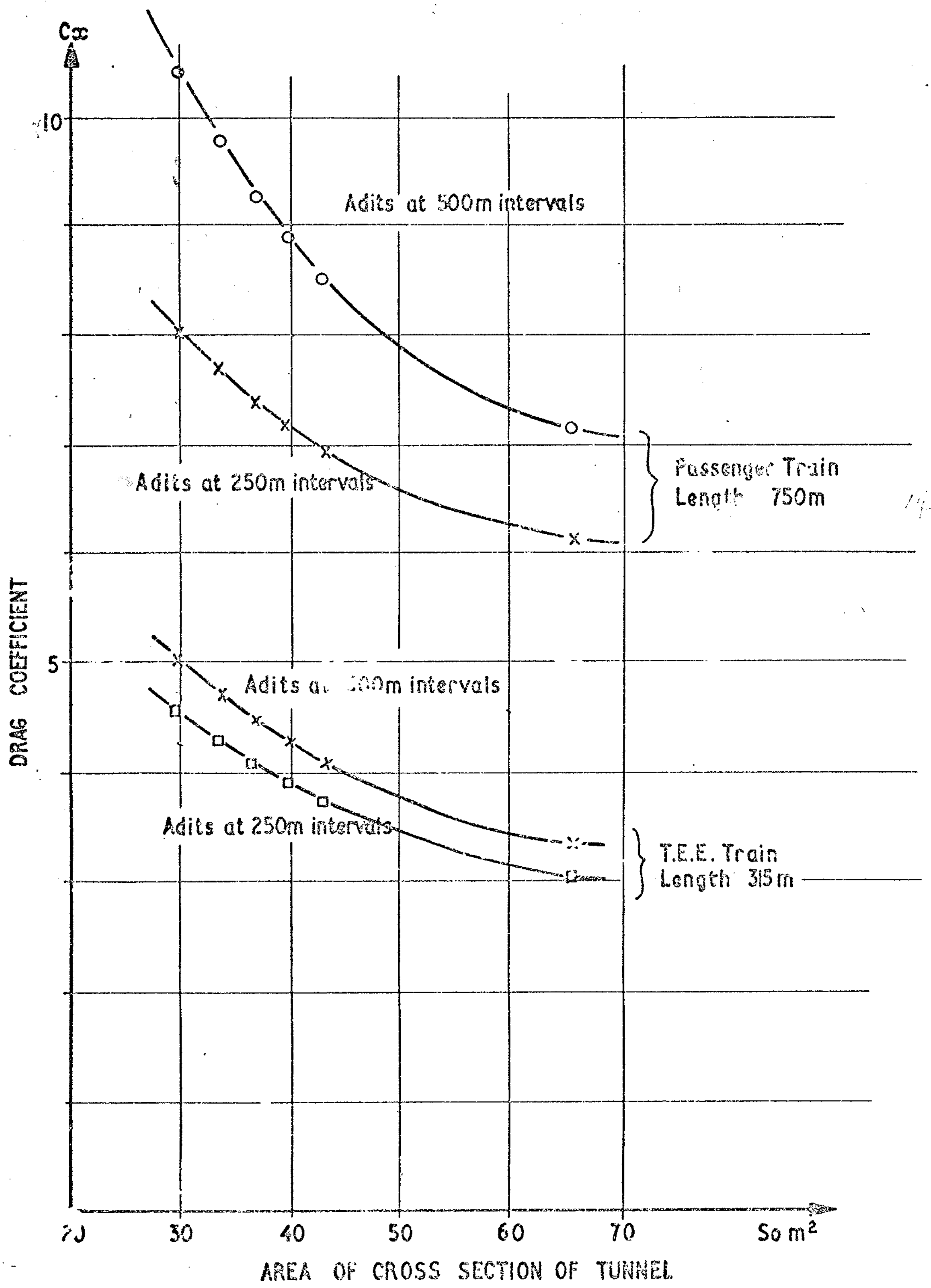
CALCULATIONS TO TAKE ACCOUNT OF LIMITED LENGTH OF EXPERIMENTAL TUNNEL AND THE INCLUSION OF A SERVICE TUNNEL.

42





VALUES OF DRAG COEFFICIENT C_∞ EXPRESSED AS A FUNCTION OF TUNNEL SECTION CROSS SECTIONAL AREA So.



TOTAL POWER REQUIREMENTS FOR VARIOUS TRAINS, AS DETERMINED BY THE BRITISH RAILWAYS BOARD AND THE ROYAL AIRCRAFT ESTABLISHMENT, FARNBOROUGH

1. The basis of calculation in respect of graphs at Plates 1, 2 and 3 are as follows:-

Tunnel length		52 km
Main Tunnels:-	Diameter	6.66 m
	Cross-Sectional area	31.10 m^2
Service Tunnel:-	Diameter	4.50 m
	Cross-sectional area	11.15 m^2
Adits:-	Diameter	5.00 m
	Cross-sectional area	12.10 m^2
Tunnels equivalent roughness		1.35 mm
Tunnels surface friction coefficient		0.014
Adit spacing		250 m
Car-Carrier Train	Length (total)	797 m
	Cross-sectional area	13.20 m^2
	Train weight	1200 t
	Locomotive weight	150 t
	Ratio $\frac{\text{Train}}{\text{Tunnel}}$ cross-section	$42\frac{1}{2}$%
	Train equivalent roughness	55 m
Passenger Train	Length (total)	397 m
	Cross-sectional area	9.25 m^2
	Train weight	528 t
	Locomotive weight	100 t
	Ratio $\frac{\text{Train}}{\text{Tunnel}}$ cross-section	30%
	Train equivalent roughness	55 m
TEE Train	Length (total)	361 m
	Cross-sectional area	7.78 m^2
	Train weight	660 t
	Locomotive weight	100 t
	Ratio $\frac{\text{Train}}{\text{Tunnel}}$ cross-section	25%
	Train equivalent roughness	55 m

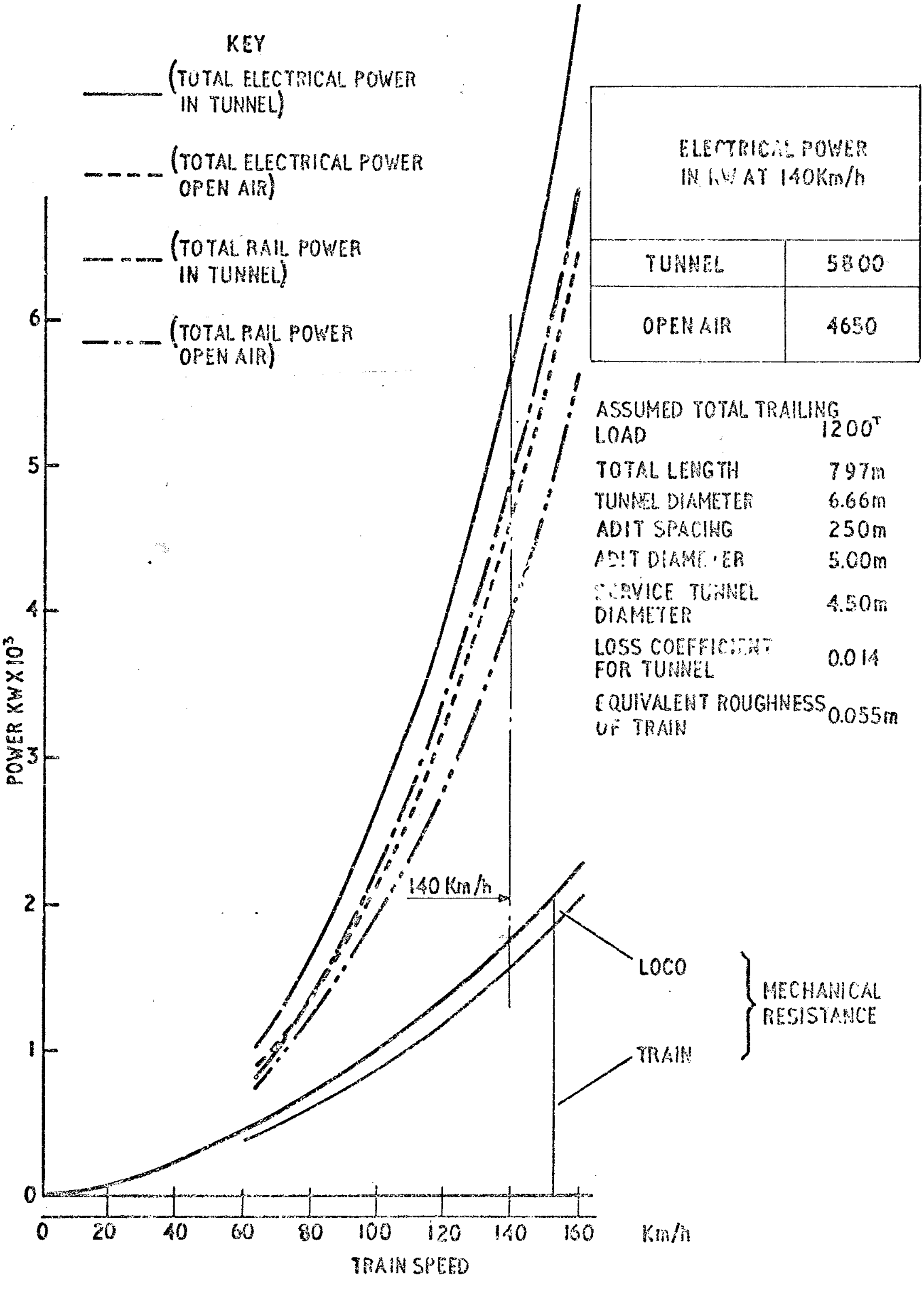
1.1 Results refer to level track.

1.2 Mechanical resistance obtained from British Railways formulae supplied to R.A.E. Farnborough.

1.3 Aerodynamic resistance, obtained from R.A.E. Tech. Memo AERO 1132

1.4 Electrical efficiency taken as $87\frac{1}{2}$%.

POWER REQUIREMENTS FOR CAR CARRIER TRAIN OF 31 COACHES PLUS LOCOMOTIVE.



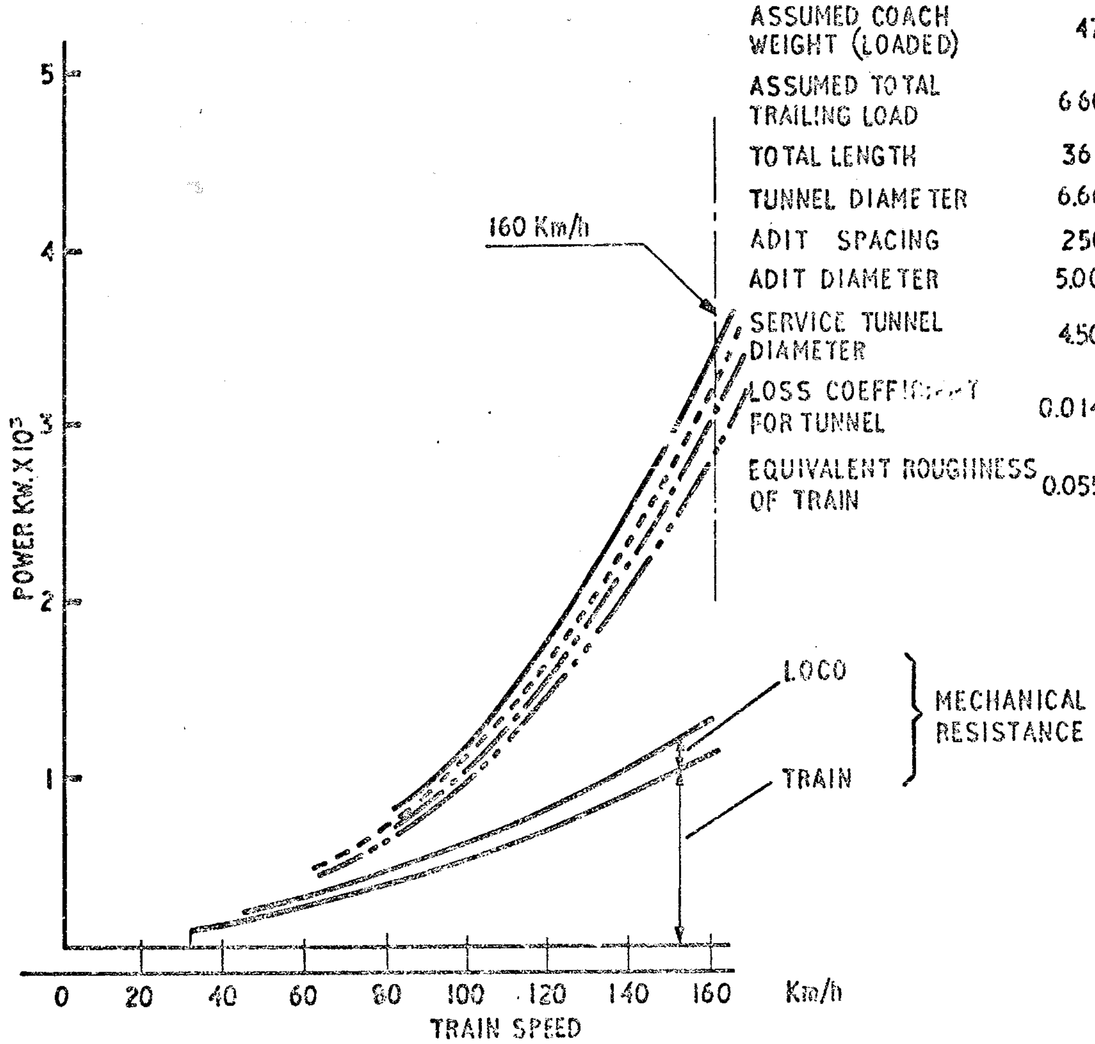
POWER REQUIREMENTS FOR T.E.E. TRAIN OF 14 COACHES PLUS LOCOMOTIVE.

KEY

- ______ (TOTAL ELECTRICAL POWER IN TUNNEL)
- _ _ _ _ (TOTAL ELECTRICAL POWER OPEN AIR)
- ___ . ___ (TOTAL RAIL POWER IN TUNNEL)
- ___ .. ___ (TOTAL RAIL POWER OPEN AIR)

ELECTRICAL POWER IN KW AT 160 Km/h	
TUNNEL	3350
OPEN AIR	3050

ASSUMED COACH WEIGHT (LOADED)	47T
ASSUMED TOTAL TRAILING LOAD	660T
TOTAL LENGTH	361m
TUNNEL DIAMETER	6.66m
ADIT SPACING	250m
ADIT DIAMETER	5.00m
SERVICE TUNNEL DIAMETER	4.50m
LOSS COEFFICIENT FOR TUNNEL	0.014
EQUIVALENT ROUGHNESS OF TRAIN	0.055m



POWER REQUIREMENTS FOR PASSENGER TRAIN OF 16 COACHES PLUS LOCOMOTIVE.

KEY

——— (TOTAL ELECTRICAL POWER IN TUNNEL)

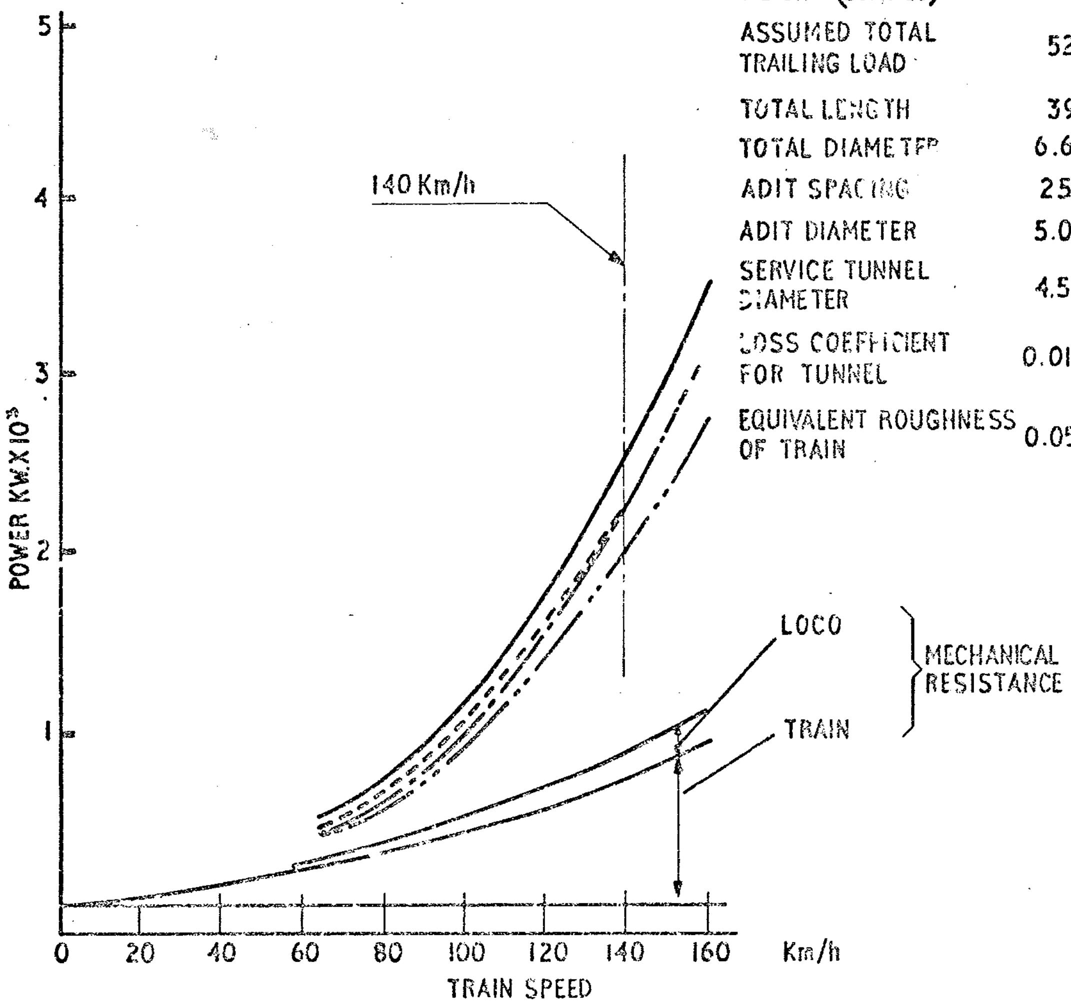
– – – – (TOTAL ELECTRICAL POWER OPEN AIR)

—·— (TOTAL RAIL POWER IN TUNNEL)

—··— (TOTAL RAIL POWER OPEN AIR)

ELECTRICAL POWER IN KW AT 140 Km/h	
TUNNEL	2460
OPEN AIR	2230

ASSUMED COACH WEIGHT (LOADED)	33T
ASSUMED TOTAL TRAILING LOAD	528T
TOTAL LENGTH	397m
TOTAL DIAMETER	6.66m
ADIT SPACING	250m
ADIT DIAMETER	5.00m
SERVICE TUNNEL DIAMETER	4.50m
LOSS COEFFICIENT FOR TUNNEL	0.014
EQUIVALENT ROUGHNESS OF TRAIN	0.055m



POWER REQUIREMENTS AT THE WHEEL RIM OF A CC 116 TON LOCOMOTIVE, AS DETERMINED BY S.N.C.F. AND L'INSTITUT AEROTECHNIQUE DE ST CYR

1. The basis of calculation in respect of graphs at Plates 1 and 2 are as follows:-

Tunnel length		50 km
Main Tunnels:-	Diameter	6.66 m
	Cross-sectional area	27.00 m^2
Service Tunnel:-	Diameter	4.50 m
	Cross-sectional area	11.40 m^2
Adits:-	Diameter	4.50 m
	Cross-sectional area	11.40 m^2
Tunnels equivalent roughness		-
Tunnels surface friction coefficient		0.006
Adit spacing		250 m, 500 m
CAR CARRIER TRAIN	Length (total)	750 m
	Cross-sectional area	13.90 m^2
	Train weight	1200 t
	Locomotive weight	116 t
	Ratio $\frac{\text{Train}}{\text{Tunnel}}$ cross-section	52%
	Train equivalent roughness	-
TEE TRAIN	Length (total)	363 m
	Cross-sectional area	8.95 m^2
	Train weight	672 t
	Locomotive weight	116 t
	Ratio $\frac{\text{Train}}{\text{Tunnel}}$ cross-section	33%
	Train equivalent roughness	-

1.1 Results refer to level track and for 1/100 rising gradient as shown.

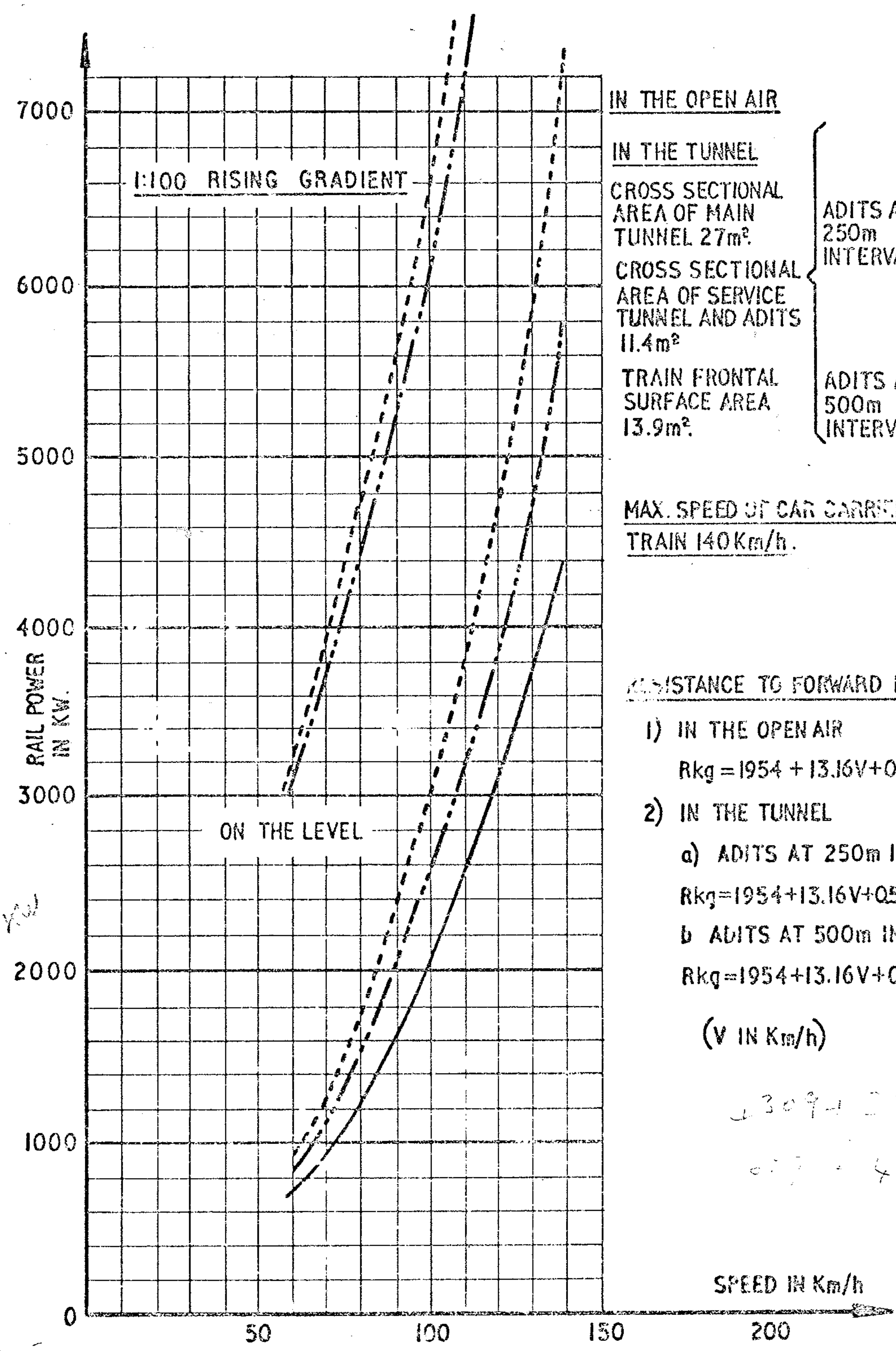
1.2 Mechanical resistance, obtained from results of tests undertaken in the Simplon Tunnel.

1.3 Aerodynamic resistance, obtained from L'Institut Aerotechnique de St Cyr test results.

PLATE 1

ANNEXE 7

POWER REQUIRED AT THE RAIL FROM TYPE CC 116 TON LOCOMOTIVE WHEN HAULING A CAR CARRIER TRAIN HAVING AN ASSUMED TRAILING LOAD OF 1200 TONS.



IN THE OPEN AIR

IN THE TUNNEL

CROSS SECTIONAL AREA OF MAIN TUNNEL $27m^2$.

CROSS SECTIONAL AREA OF SERVICE TUNNEL AND ADITS $11.4m^2$

TRAIN FRONTAL SURFACE AREA $13.9m^2$.

ADITS AT 250m INTERVALS

ADITS AT 500m INTERVALS

MAX. SPEED OF CAR CARRIER TRAIN 140 Km/h.

RESISTANCE TO FORWARD MOTION

1) IN THE OPEN AIR

$Rkg = 1954 + 13.16V + 0.390V^2$

2) IN THE TUNNEL

a) ADITS AT 250m INTERVALS.

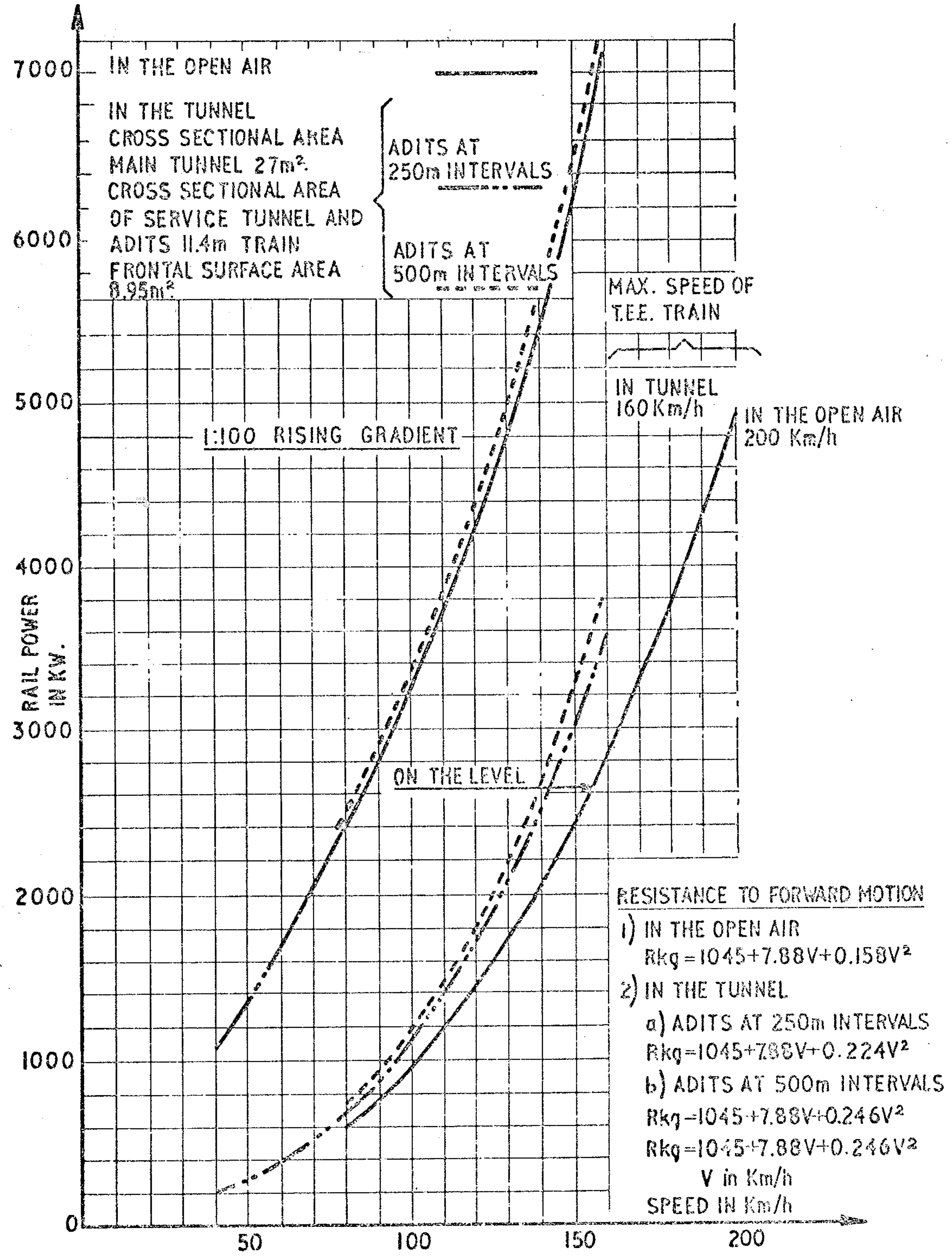
$Rkg = 1954 + 13.16V + 0.576V^2$

b ADITS AT 500m INTERVALS

$Rkg = 1954 + 13.16V + 0.754V^2$

(V IN Km/h)

POWER REQUIRED AT THE RAIL FROM A TYPE CC 116 TON LOCOMOTIVE WHEN HAULING A TEE PASSENGER TRAIN HAVING AN ASSUMED TRAILING LOAD OF 672 TONS.



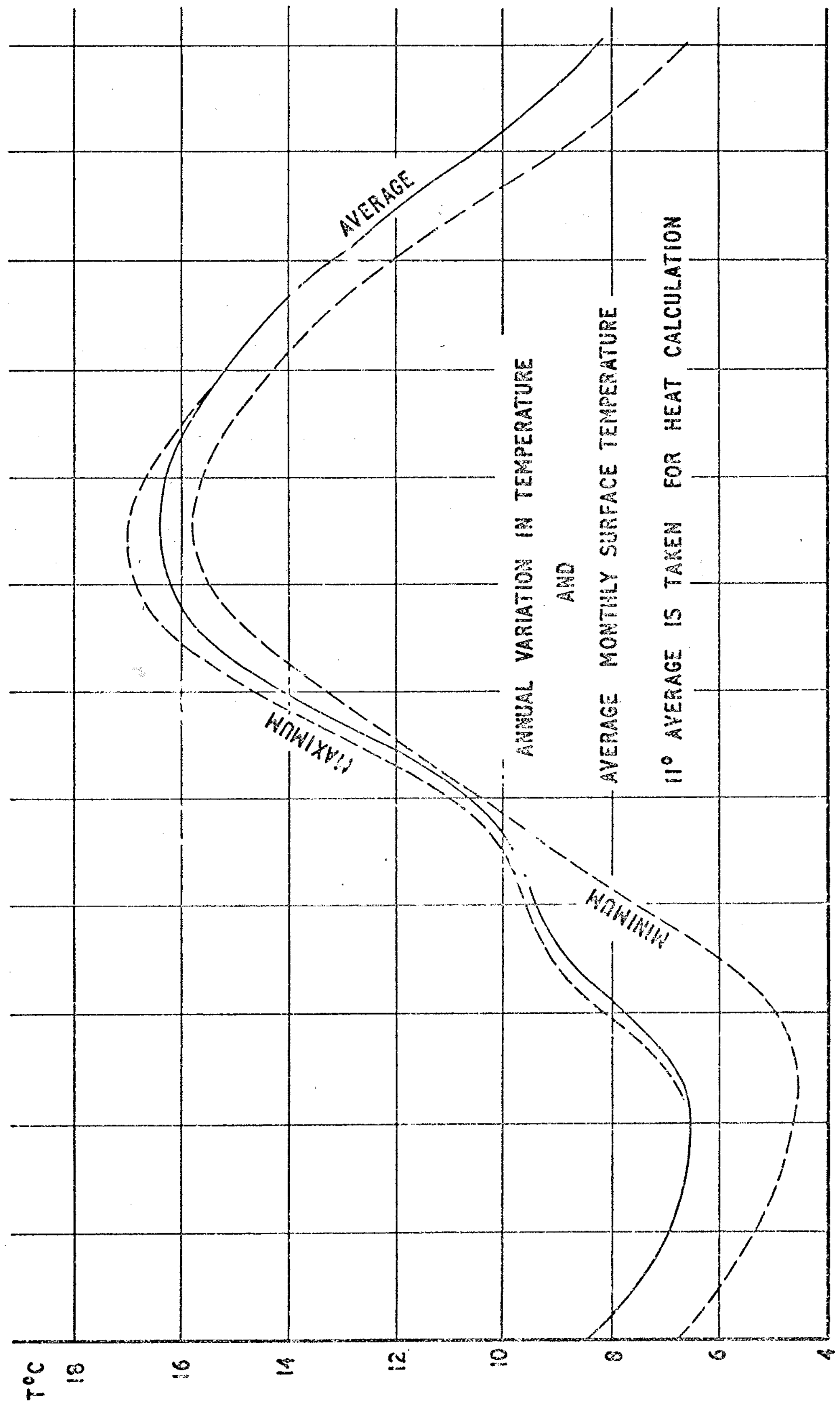
ECONOMIC ASPECT OF PLACING THE ADITS CLOSER TOGETHER AT 200 m SPACING

1. The drag coefficient of the double-decker car-carrier train weighing 1200 tonnes, travelling at 140 Km/h, is 10.78 when the adits are spaced 500 m apart, and 8.22 when they are 250 m apart. From this it can be seen that the reduction in drag coefficient corresponding to a reduction in adit spacing from 500 m to 250 m is about 23%. A further reduction in adit spacing from 250 m to 200 m only reduces the drag coefficient a further 6%. Allowing for the resistances other than those arising from the aerodynamic drag, the energy required would be reduced by 4% at most. The saving in energy for a train passing through a tunnel with adits spaced at 200 m instead of 250 m would thus be 80 kWh.

2. Assuming an average traffic flow of 200 trains per day, or 73 000 trains per year, and on an energy cost of 0.07 (francs) per kWh, including amortisation of installations, the annual saving would be 408 000 f.

3. Now the capital required for the boring of a 104 additional adits, which correspond to 1600 m of service tunnel, at an average 4 million francs per kilometre, would be 6.4 mf (and even more, since the cost of short length, with fabrication of the special shape required for widening at each end, is greater than that of a normal tunnel).

4. Thus placing the adits closer together at 200 m spacing is certainly not an economic proposition.



SEA TEMPERATURES - DOVER STRAIT

TEMPERATURES AT BOREHOLE No. R. 255

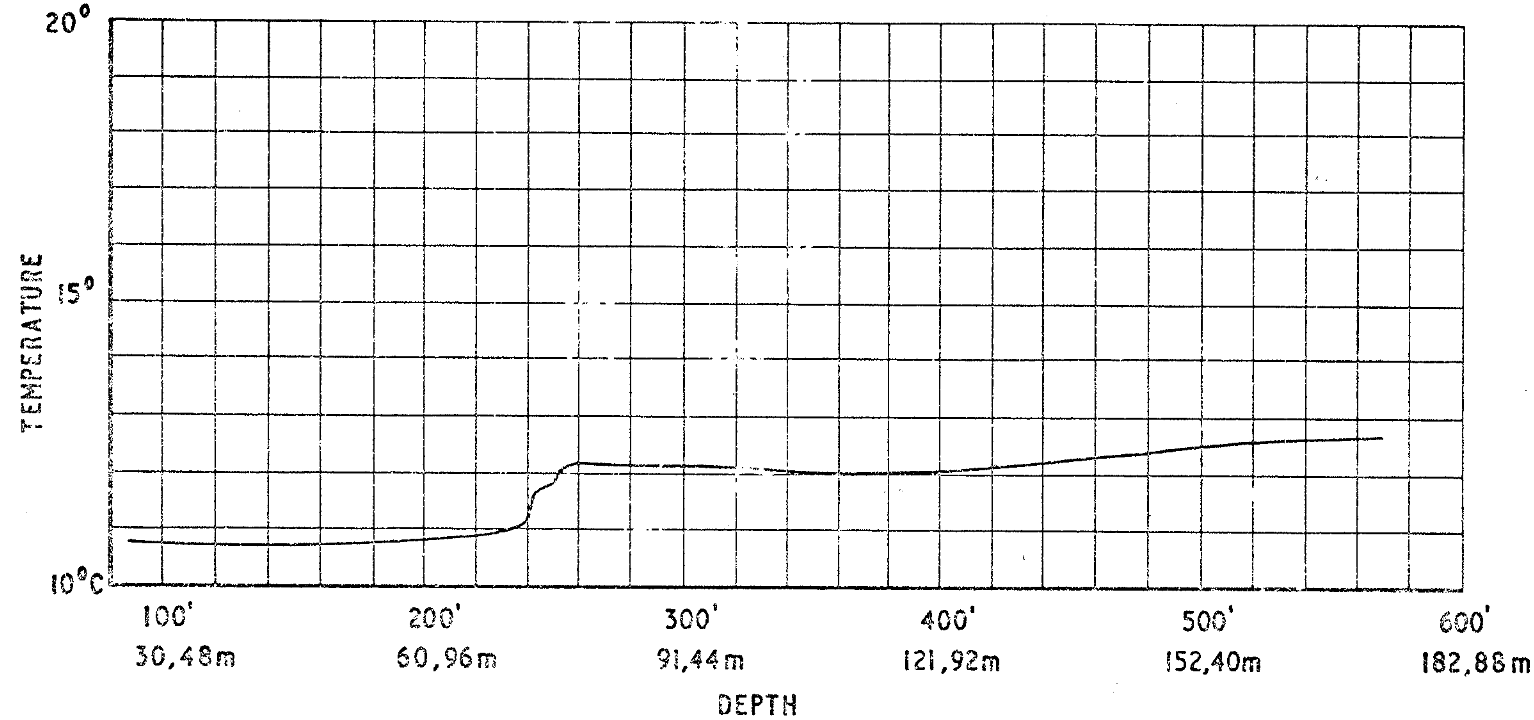
CO-ORDINATES U.T.M.: X = 403.960, Y = 5.648.700

SEA BED LEVEL: -45 m PROBABLE
TEST RIG LEVEL: +24 m

DATE: 11th JUNE 1965

FIRST READING — 86'
LAST READING — 575'
MEASURED DISTANCE — 489'
MAX. DEPTH ATTAINED — 575'
TOTAL DEPTH OF BOREHOLE - 580' (177m)
PENETRATION OF CASING — 246' (75m)

DIAMETER OF DRILL — $8\frac{7}{16}$"
DIAMETER OF CASING — $9\frac{5}{8}$"
DATUM LEVEL. TEST RIG LEVEL — TR
DRILLING MIXTURE - SEA WATER AND BENTONITE
WATER LEVEL - 24m BELOW TEST RIG
MAX. TEMPERATURE — 12.7° C



METEOROLOGICAL RECORDS

CALAIS - DUNKERQUE

DEPARTEMENT DU NORD

Meteorological Record for the Dunkerque Area

(altitude: 7 m)

PERIODS	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Monthly Average Temperature of Daily Maximums (in °C) Tx:													
1921-1950	6.5	7.8	9.6	12.3	15.4	18.6	21.0	21.2	19.3	14.9	10.0	6.7	13.5
Maximum Temperature:													
1946-1960	14.0	19.0	20.4	28.4	28.8	33.4	35.2	33.0	33.0	26.8	18.6	15.8	35.2 (1947)
Monthly Average Temperature of Daily Minimums (in °C) Tn:													
1921-1950	1.6	1.8	3.1	5.7	8.5	11.4	13.5	13.7	12.0	8.5	4.8	2.1	7.2
Minimum Temperature:													
1946-1960	-12.0	-13.0	-5.8	-1.4	2.0	4.0	6.6	7.0	4.0	-2.4	-6.8	-10.6	-13.0 (1947)
Average Monthly Temperatures $\frac{Tn + Tx}{2}$													
1921-1950	4.1	4.4	6.3	9.0	12.0	15.0	17.2	17.4	15.7	11.7	7.4	4.4	10.4
Average number of Days with Frost each Month (Tn ≤ 0°) (Shade temperature)													
1921-1950	11	9	6	0.4	0.1	.	.	.	.	0.4	3	8	37
Average Monthly Rainfall in Millimetres													
1921-1950	62	45	39	47	61	46	53	55	70	75	80	63	696
Maximum Rainfall in 24 Hours (in Millimetres)													
1946-1960	19	21	21	17	28	35	27	30	41	33	25	29	41 (1949) (1960)
Average Number of Days of Rain in each Month (RR ≥ 0.1 mm):													
1921-1950	18	14	12	13	12	11	12	12	13	15	17	17	166
Average Number of Days each Month													
Fog ≡	5	6	4	1	2	2	2	1	2	3	4	4	36
Thunder Storm	0	0	0	0.1	1	1	2	2	1	0.1	0.2	0.1	7
Hail ▲	0.4	0.4	0	0.1	0.2	0	0	0	0	0	0.1	0.2	1.4
Snow *	3	2	2	0.1	.	.	.	.	.	.	0.1	1	8

STRAITS OF DOVER

Meteorological Record for the Calais Area
(Altitude: 2 m.)

PERIODS	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
			Monthly Average Temperature of Daily Maximums: Tn in °C and 1/10										
1921-1950	6.0	6.4	8.8	11.7	14.5	17.5	20.2	20.5	18.6	14.4	9.4	6.4	12.9
			Monthly Average Temperature of Daily Minimums: Tx										
1921-1950	1.8	1.7	3.0	5.5	7.8	10.3	13.0	13.1	11.0	7.8	4.7	2.2	6.8
			Average Monthly Temperatures $\frac{Tn + Tx}{2}$										
1921-1950	3.9	4.0	5.9	8.6	11.2	13.9	16.6	16.8	14.8	11.1	7.1	4.3	9.9
			Average Monthly Rainfall in Millimetres										
1921-1950	65	50	40	45	50	40	60	55	70	80	90	65	710
			Maximum Rainfall in 24 Hours (in Millimetres)										
1957-1960	16	22	12	25	32	36	20	29	30	17	30	22	36 (1958)

AIR TEMPERATURES (IN THE SHADE) °C (x 10)

DUNKERQUE 1947 1958

LOCAL TIME / GMT	01 H / 00H	04 H / 03 H	07H / 06H	10 H / 09H	13H / 12H	16H / 15H	19H / 18 H	22H / 21 H	01H / 00H	AVERAGE OVER 24hrs
JAN	39	37	33	34	47	52	44	42	39	41
DEC	55	51	50	50	63	66	58	45	55	55
NOV	71	67	66	70	87	91	80	73	71	76
OCT	108	102	99	112	135	139	123	111	100	116
SEP	146	117	134	157	176	179	165	158	[illegible]	154
AUG	146	148	147	176	191	194	182	172	146	170
JUL	148	144	149	174	185	188	179	164	148	166
JUN	129	124	128	155	165	167	160	143	129	147
MAY	102	98	100	126	136	137	127	114	102	118
APR	65	68	65	90	104	104	94	86	65	85
MAR	58	42	40	55	76	80	68	58	58	60
FEB	25	27	23	27	45	50	39	37	25	34
JAN	39	37	33	34	47	52	44	42	39	41
AVERAGE OVER YEAR	91	85	86	102	118	121	110	100	91	102

PRESSURE RISE CAUSED BY A CAR-CARRIER TRAIN
PASSING THROUGH A TUNNEL AT 140 km/h

1. A moving train compresses the air in front of it and is thereby subjected to a large resistance of the form $k\ S\ V^2$. The pressure on its front surface is therefore kV^2.

2. Analysis of the experiments in the Simplon Tunnel showed that the resistance to the forward motion of a 16 car train in kg was:

$$A + B + CV^2 = 951 + 6.01\ V + 0.309\ V^2$$

(where V is expressed in km/h), and that the coefficient $C = 0.309$ could be broken down into:

K_1S representing the frontal resistance

K_2P_1 representing the resistance due to friction on the side walls.

3. Owing to the variation in air resistance along the train (figure 12 of the report on the tunnel tests), the value 0.265 is assigned to K_{2P_1} and 0.044 to K_1S. Since the frontal surface surface area of the train used in the Simplon test was $9.25\ m^2$:

$$K_1 = \frac{0.044}{9.25} = 0.00475 \text{ (V in km/h), } (K_1\ V^2 \text{ in kg/m}^2)$$

ie $0.00475 \times 3.6^2 = 0.062$ (V in m/s).

4. The variations in pressure no doubt depend on the relationship between the respective areas and roughnesses of the tunnel and the train; if it is assumed that the pressure does not increase but remains constant along the entire length of the train, the excess pressure in which the train is travelling is:

$$0.062 \times 39^2 = 94\ 302\ \text{kg/m}^2 = 9251 \text{ baryes}$$

SUMMARY OF THE RECORD OF THE TESTS CARRIED OUT BY THE AEROTHERMIC LABORATORY AT VIENNA-ARSENAL

1. The S.N.C.F. asked the laboratory at VIENNA to study the thermal behaviour of a conventional passenger coach, that is to say the speed with which the component parts of the coach and the interior of the compartments reach thermal equilibrium with the outside temperature.

2. EQUIPMENT USED

The VIENNA laboratory has available for such thermal tests, two insulated test chambers capable of taking the coaches for experiment. One of these chambers is intended for "static" tests; in the other, the"dynamic", fans allow a current of air to be created which simulates the speed of the vehicle.

2.1 In each chamber, a variable heating control allows, in principle, a constant temperature to be maintained (1).

2.2 In a tunnel, the airflow between the vehicle and the tunnel walls has an average speed which is not insignificant and, because of eddies, the coefficients of convection of the shell and components of the vehicle are different from those which may be measured in open air. The same considerations apply in the test chamber. It is therefore necessary to establish comparative performances - open air - tunnel - test chamber.

3. 1st PHASE: ESTABLISHING THE PERFORMANCE (calibration of the test chamber)

3.1 To obtain these comparative performances, the laboratory replaced one window of a coach by a sheet of plywood in which was set an insulating block of polyurethane. To the block was fixed a copper plate, heated by a resistance. The intensity of the current was so regulated that the temperature of the plate remained constant.

3.2 Given the surface S of the plate, and the Quantity of heat Q being dissipated, the coefficient of convection α is determined by the equation

$$Q = \alpha S(t-t')$$

3.3 This measurement having been made:

1st - in open air
2nd - in a tunnel whose cross-section in relation to that of the vehicles was similar to that of the Channel Tunnel
3rd - in the test chamber

(1) The temperature control depends on the skill of the operators. From this, differences arise which render difficult any comparison between measurements taken in successive tests.

This allows on the one hand the establishment of the relation between the speed at which the trains run and the speed of the air in the annular space between the vehicle and the tunnel walls (2), and on the other hand the placing of the vehicles in the test chamber in conditions corresponding to a determined speed.

3.4 The calibration of the test chamber was done between 19 and 22 November 1968 with an OBB coach type X, series 31-1 on the SPITAL-SELZTAL line and in the single-track BOSRUCK TUNNEL (Length 4.8 km, section 27.09 m^2).

3.5 The measurements were made using a rake of 6 coaches, with the OBB recording coach and two electric locomotives. The following results were obtained:

3.5.1 in open air

Running speed km/h	coefficient of convection m^2 h °C
70	62
90	73
110	85

3.5.2 in tunnel

running speed km/h	speed of air in annular space km/h	coefficient of convection m^2 h °C
40	46	48
70	78	70
90	101	85
110	126	95

3.5.3 as for the measurements in the test chamber, they produced the following:-

speed of air in in the annular space of the Chamber km/h	coefficient of convection by measurement m^2 h °C	conditions approximately comparable
60	63	70 km/h open air(α = 62)
67	68	70 km/h tunnel (α = 70)
90	85	110 km/h open air(α = 85)
103	94	110 km/h tunnel (α = 95)

4. 2nd PHASE: MEASUREMENT METHOD

4.1 These measurements were made in the S.N.C.F. passenger coach B 10 13324 from 20 to 24 January. This coach had been fitted with 32 thermo measuring instruments 16 of type PT 100 linked to the first HONEYWELL recorder, 16 others of type Fe/KO linked to a second recorder of the same type.

(2) In fact, it is known that this relation depends essentially on the resistance of the circuit and the distance between the adits. The relation determined in an existing tunnel without adits is not necessarily that which will obtain in the Channel Tunnel. The speed must not therefore be regarded as exact.

4.2 The first 16 air temperature measuring instruments were installed inside the coach (front and rear vestibules, corridor and compartments). Of the 16 others, 6 measured the temperatures of the metal sheets of the shell (external and internal measurements) 4 measured the temperature of the interior lining of the coach, 4 that of the front, rear and internal faces of the rear bogie, and 2 that of the front and rear faces of the front bogie.

4.3 The coach, at a known temperature (0°, 10°, 20° or 25°C) was first placed in the static chamber. Then it was rapidly transferred to the "dynamic" chamber, the heating of the chambers and of the coach, if necessary, being suspended during the transfer.

4.4 The blower was then started up and regulated for the desired speed and the heating was regulated to reach a temperature of 30°C and maintain it as near constant as possible.

4.5 To allow for disturbances caused by the introduction of the coach into the dynamic chamber, a period of from 1-5 minutes was allowed before the measurements began.

5. MEASUREMENTS TAKEN

5.1 As we have seen, the heating of the dynamic chamber was so arranged as to obtain, after the introduction of the coach, an ambient temperature of 30°C and to maintain it constant, but in several of the tests the ambient temperature exceeded 30°C (33°C in test 10).

5.2 The temperature on the coach on entry into the dynamic chamber was 0°, 10°, 20° and 25°C: in the first two cases, the tests were made without or with the coach heating. The two other cases correspond to summer conditions but the ventilation was rendered inoperative.

5.3 The blower was regulated to correspond to speeds of 70 and 110 km/h.

6. RESULTS

6.1 The HONEYWELL recordings were entered on 12 tables giving, for each measurement, the temperatures 5 in 5 minutes of the 32 points being observed. Interpretation was further simplified by a presentation in graph form (120 sheets).

6.2 Comparison of the graphs was made difficult by the differences in regulation of the ambient temperature (3). However, the corresponding curves have similar forms and arrange themselves distinctly in 3 categories.

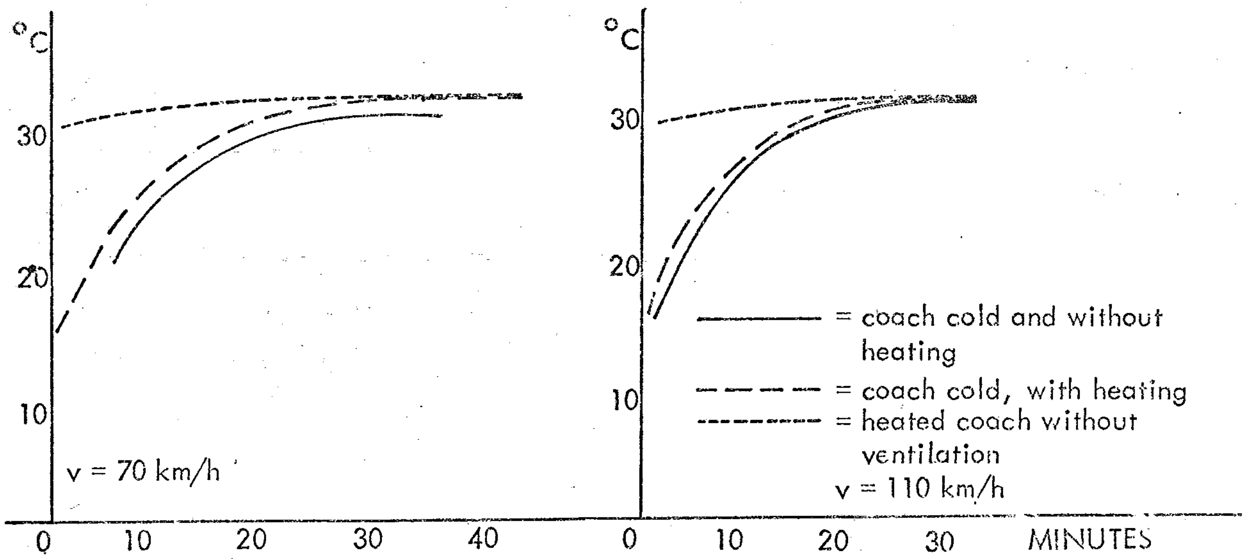
---

(3) For example, the curves of heat rise from 10°C (or 20°C) to 30°C should superimpose on the corresponding curves of heat rise from 0°C to 30°C when the temperature of 10°C (or 20°C) is reached.

6.2.1 Those which show the temperature of the metal sheets of the coach shells, which very quickly reach thermal equilibrium with the ambient temperature, 20 minutes at 70 km/h, 10 minutes at 110 km/h.

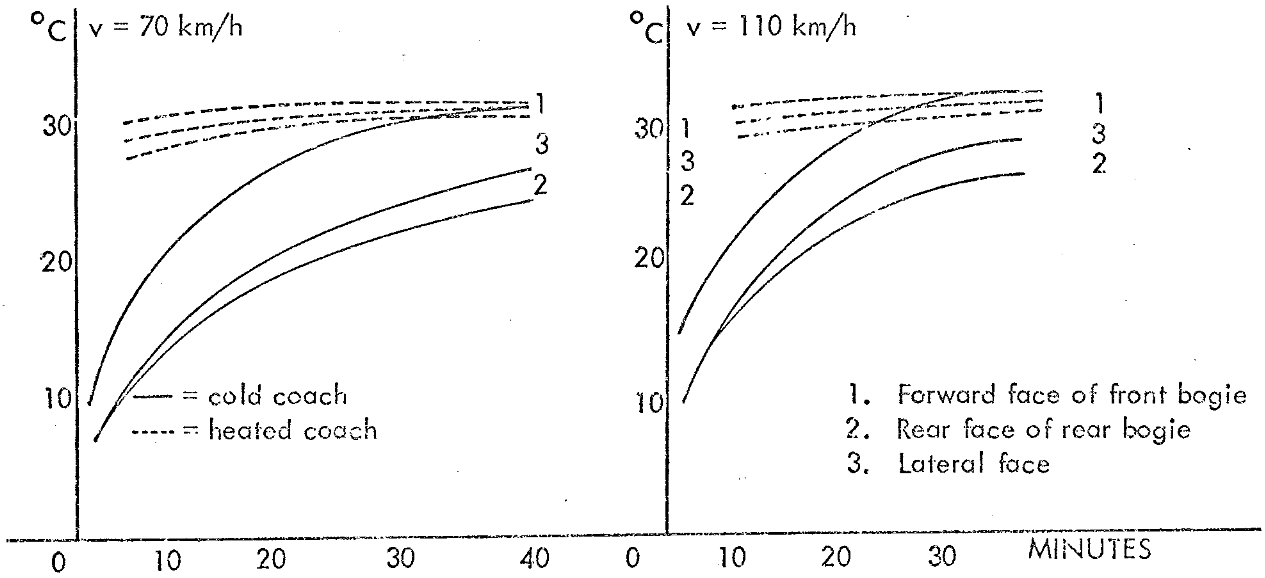
Certain curves go beyond the ambient temperature: the difference varies between 0.4°C to more than 1.5°C (4).

METAL SHEETS OF THE SHELL



6.2.2 The readings recording the temperature of the bogies, which diverge considerably: the forward faces reach equilibrium rapidly, nearly as quickly as the metal sheets of the coach shell: the rear faces, less well ventilated, only reach the equilibrium temperature more slowly. Finally, the lateral faces are between the two.

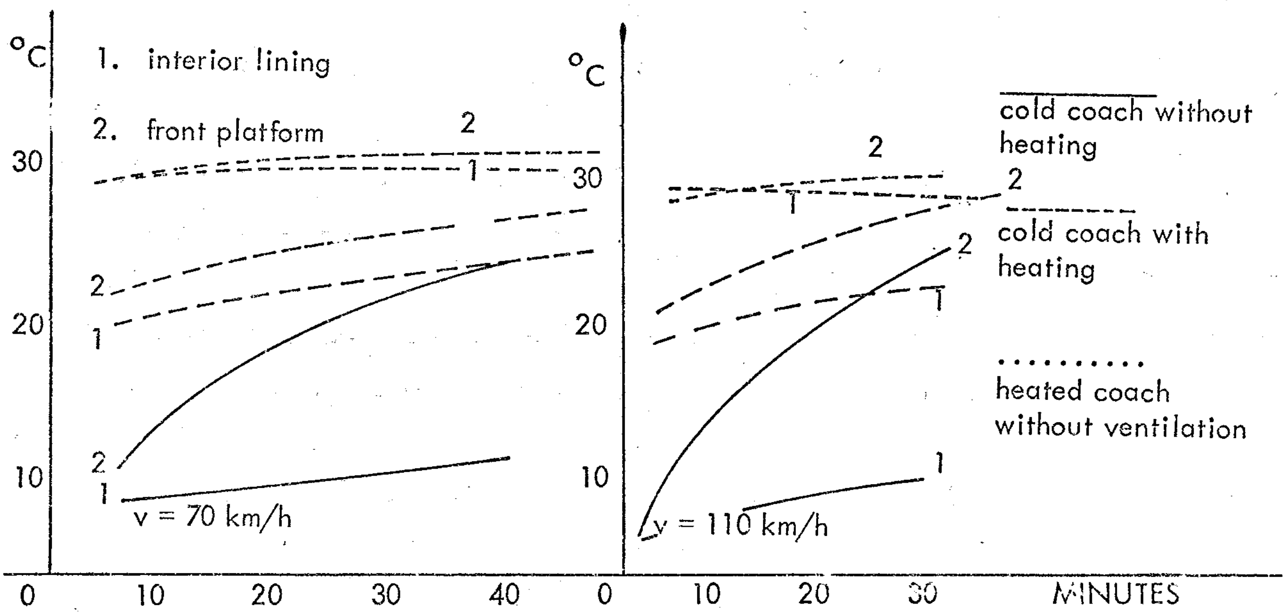
BOGIES



(4) This could be explained by the compression of air at certain points.

6.2.3 The readings which record the internal temperatures of the coach and which, except for the end vestibule, are isotherms: some few degrees of temperature rise for an exterior difference of 30°C.

INTERNAL TEMPERATURES



7. CONCLUSIONS

7.1 At 70 km/h and even more so at 110 km/h the complete surface area of the external metal sheets very rapidly attained thermal equilibrium with the ambient air.

7.2 For the bogies, the temperature-rise was slower but nevertheless equilibrium was more or less reached at the end of half-an-hour.

7.3 As for the interior fittings, they were influenced only slightly by a variation in the outside temperature: the variation in internal temperature did not exceed more than a few degrees during the time corresponding to a passage through the tunnel.

7.4 For information, the weight of the S.N.C.F. coach on which the tests were made, is divided up as follows:-

metal sheets of the shell	12 T
bogies	11 T
accessories carried under the shell, (dynamo, batteries etc)	2 T
interior fittings	16 T
	41 T

7.5 Ratio of $\frac{\text{Exterior Weight}}{\text{Total Weight}} = \frac{25}{41} = 61\%$

JUSTIFICATION FOR USING PLANE WALL CALCULATIONS FOR CYLINDRICAL CAVITIES

1. The general heat flow equation for a cylindrical cavity surrounded by an infinite expanse of solid matter is:

$$\frac{\lambda}{c\rho}\left[\frac{\partial^2\theta}{\partial r^2}+\frac{1}{r}\frac{\partial\theta}{\partial r}\right]=\frac{\partial\theta}{\partial t}$$

2. The solution to this equation satisfying the condition that $\theta = \theta_\rho$ when r is infinity is of the form

$$\theta = \theta_\rho + \Sigma B_n \rho^{-n^2 at} J_o(n,r)$$

and the surface condition is expressed by

$$nRJ_1(n,r) = \frac{\alpha R}{\lambda} J_o(n,r)$$

where J_o and J_1 represent zero and first order Bessel functions.

3. Using tables, it is possible by means of these transcendental functions to calculate the roots n_1 for the different values of $\frac{\alpha R}{\lambda}$; but the introduction of the surface coefficient would be extremely complicated; in addition, calculation of the quantities of heat alternately stored and returned by the surrounding ground would necessitate integration of the half pseudo-periods of the Bessel functions, which does not appear possible.

4. It therefore appears advantageous to employ the graphic method (Schmidt's method) as refined by Nessi, Nisolle and MacAdams. The basis of this method is that with a one-dimensional plane

$$a\frac{\partial^2\theta}{\partial x^2}=\frac{\partial\theta}{\partial t}$$

the mean temperature at the time t of the two points $x + \Delta x$ and $x - \Delta x$ is equal to the temperature at the point x on the time $t + \Delta t$ with

$$\Delta t = \frac{(\Delta x)^2}{2a}$$

5. By means of this method it is possible to deal with the case of composite walls (tunnel with chalk surrounding the concrete lining) by modifying the intervals Δx in accordance with the thermal conductivity of the different materials.

6. It is then also possible to allow for the surface exchange coefficient, which takes the form of an equivalent distance

$$\Delta x = \frac{\lambda}{h}$$

7. Finally if the time intervals Δt are not too great it also applies in the case of the cylinder by replacing the Δr, calculated as above for the case of a plane wall by

$$\frac{\Delta r}{\frac{r_{n-1} + r_n}{2}}$$, r_{n-1} and r_n being the radii corresponding to the interval in question;

the equivalent distance λ/h corresponding to the surface exchange coefficient is replaced by $\frac{\lambda}{h\, r_l}$, r_l being the radius of the exchange surface. By means of this method, starting with any distribution of temperature at an instant $t = 0$, the isotherms for Δt, $2\,\Delta t$, $3\,\Delta t$ ..... can be calculated.

8. For a given external temperature law - eg air temperature varying sinusoidally - the initial variation considered at the instant $t = 0$ may be arbitrary; its influence on the isotherm $n\,\Delta t$ falls as n rises.

9. By means of the isotherms obtained in this way, it is possible to determine the values of $\frac{\partial\theta}{\partial x}$ at any point, especially for $x = 0$, and hence the quantities of heat stored and returned by the lining and surrounding ground.

10. The following conclusions may be drawn from an examination of the graphs drawn up on this basis (Plates 1 and 2) for a cylindrical tunnel 6.64 m diameter with a lining of concrete 0.40 m thick in contact with the chalk and for a plane wall of concrete 0.40 m thick in contact with chalk:

10.1 the points plotted for the cylinder and for the wall coincide exactly within the accuracy of the graph (approximately one fiftieth of a degree) from the third construction; it is therefore possible without serious error to replace the cylinder by its inside area; this is not evident a priori (1).

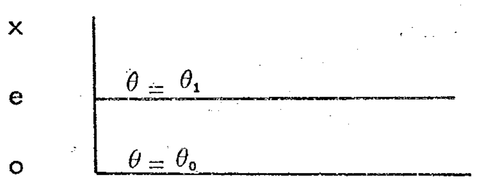
10.2 the values taken from the graph for a wall for both the temperatures and their gradients $\frac{\partial\theta}{\partial x}$ are exactly (within the accuracy of the graph) those resulting from the theoretical formulae.

There is therefore justification for applying the formulae for plane walls in the calculation of the cyclical heat exchanges of the Tunnel.

(1) Page 14.3 overleaf includes a calculation leading to the same conclusion without using Schmidt's method. This demonstration however is not rigorous.

Comparison of the steady heat flux through a plane wall and a cylindrical wall, the two surfaces of which are kept at constant temperatures.

Plane wall



The basic equation is:

$$\frac{\partial^2\theta}{\partial x^2} = 0$$

hence

$$\theta = \theta_0 + (\theta_1 - \theta_0)\ \frac{x}{\rho}$$

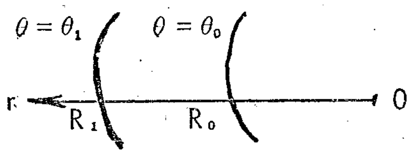
The quantity of heat passing through each isothermal plane of area S during the time t is

$$Q = -\lambda S \frac{\partial\theta}{\partial x} t = -\ \lambda S t\ \frac{\theta_1 - \theta_0}{\rho}$$

or, by unit of area,

$$Q = -\ \lambda S\ \frac{\theta_1 - \theta_0}{\rho}$$

Cylindrical wall



The basic equation is:

$$r\ \frac{\partial^2\theta}{\partial r^2} + \frac{\partial\theta}{\partial r} = 0$$

hence
$$\theta = \frac{\theta_1 - \theta_0}{\text{Log}\ \frac{R_1}{R_0}}\ \text{Log}\ r + \frac{\theta_0\ \text{Log}\ R_1 - \theta_1 \text{Log}\ R_0}{\text{Log}\ \frac{R_1}{R_0}}$$

The quantity of heat passing through each isothermal surface cylinder $2\pi r$ during the time t is

$$Q = -\ \lambda(2\pi r)\frac{\partial\theta}{\partial r}\ dt = -\ \lambda(2\pi r)\frac{\theta_1 - \theta_0}{r\,\text{Log}\ \frac{R_1}{R_0}}\,t$$

For the cylinder r = Ro, the result per unit of surface is

$$Q = -\ \lambda t\ \frac{\theta_1 - \theta_0}{R_0\ \text{Log}\ \frac{R_1}{R_0}}$$

The quantity of heat is the same as that passing through the plane wall of thickness

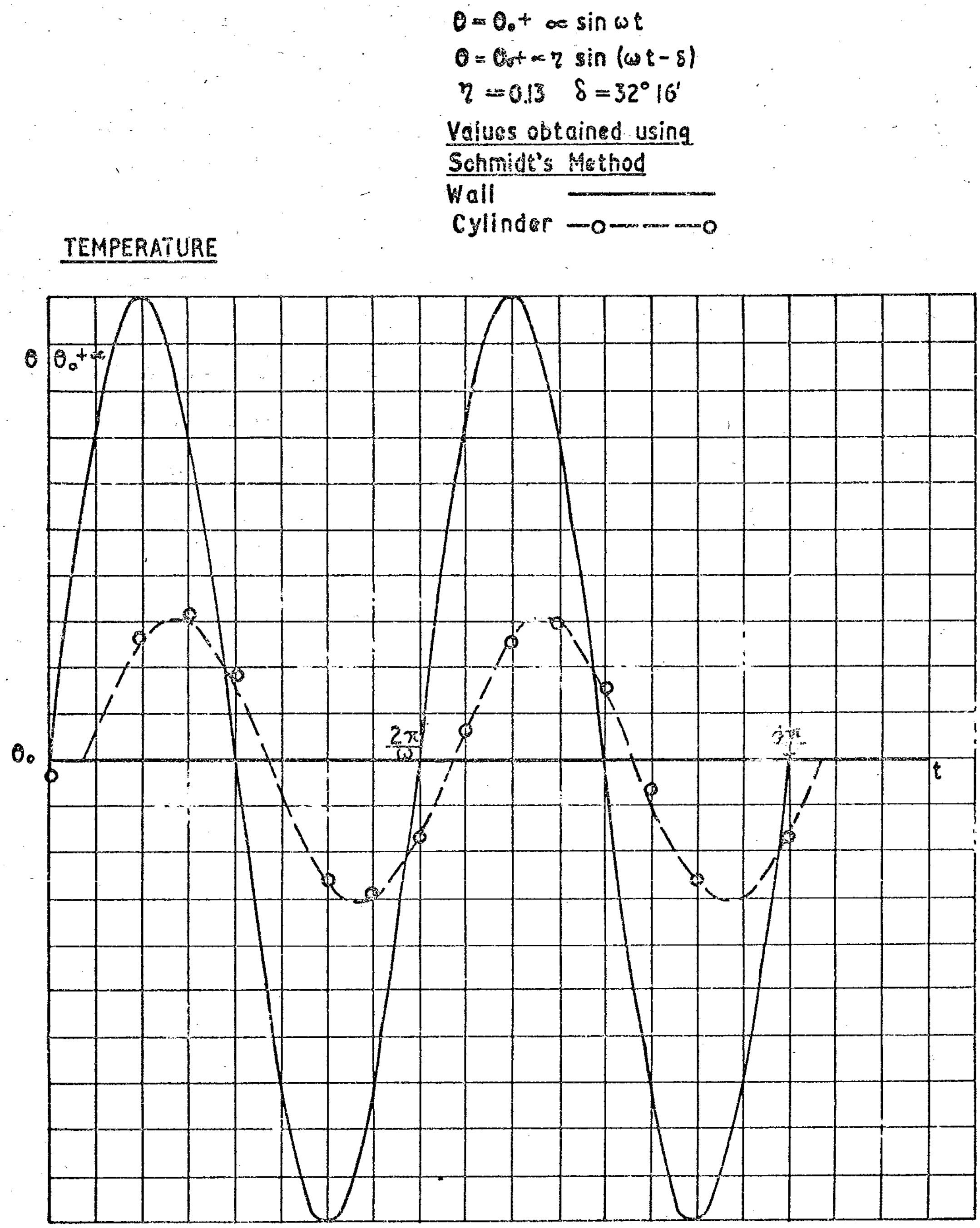
$$e = Ro\ \log \frac{R_1}{Ro}$$

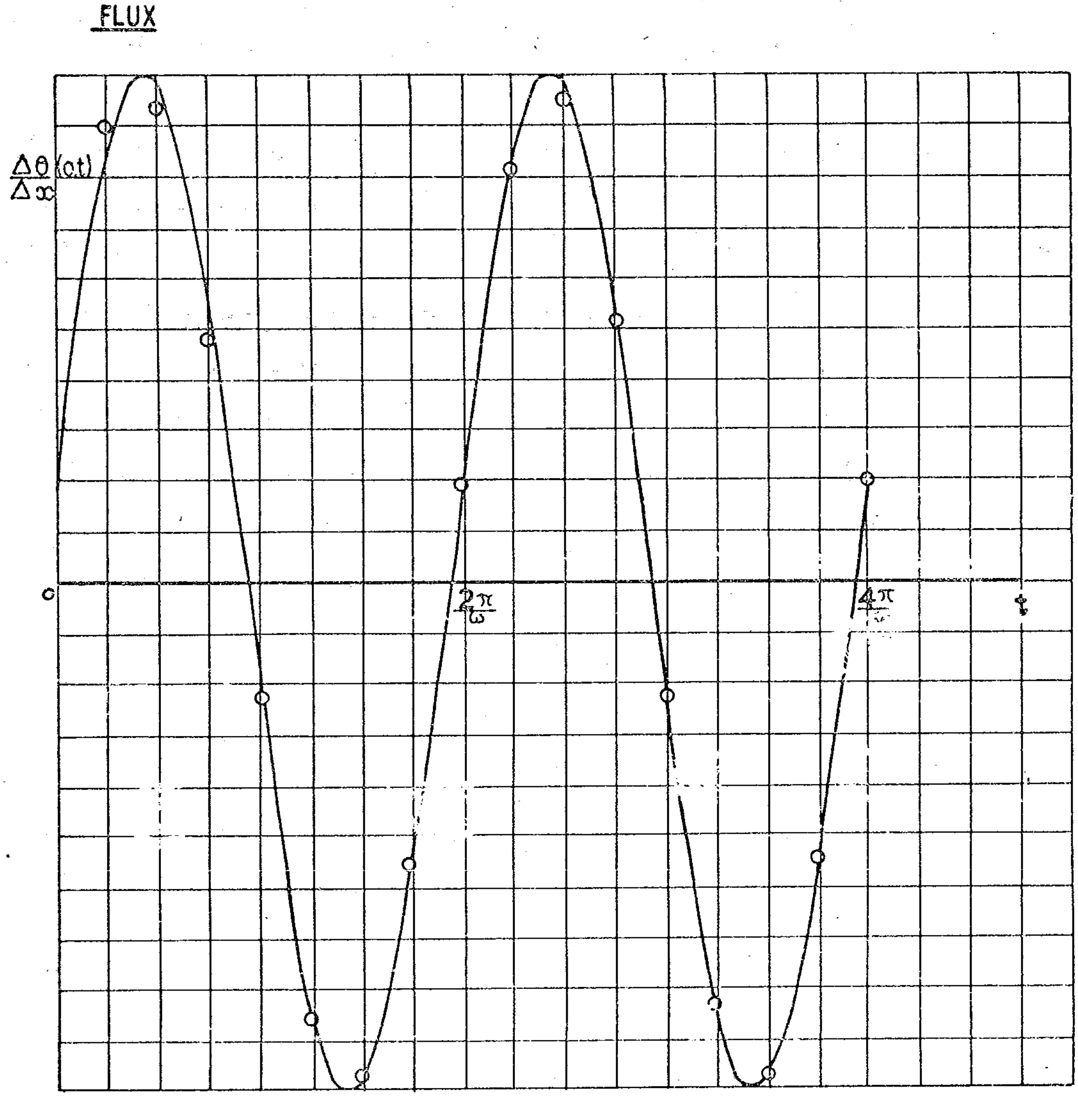
Application: $R_o = 3.32$ m$R_1 = 3.72$ m

$R_1 - R_o = 3.72 - 3.32 = 0.40$ m

$e = 3.32\ \log \frac{3.72}{3.32} = 0.378$ m

Conclusion: For the radii under consideration, heat absorption by the cylindrical wall differs very little from that of a plane wall of the same thickness.


$\theta = \theta_o + \propto \sin \omega t$
$\theta = \theta_o + \propto \eta \sin(\omega t - \delta)$
$\eta = 0.13 \quad \delta = 32° 16'$
Values obtained using
Schmidt's Method
Wall
Cylinder
TEMPERATURE
θ
$\theta_o + \propto$
θ_o
$\frac{2\pi}{\omega}$
t


FLUX
$\frac{\Delta\theta}{\Delta x}(o,t)$
o
$\frac{2\pi}{\omega}$
$\frac{4\pi}{\omega}$
t

FORMULATION OF EQUATIONS RELATING TO THE THERMAL EXCHANGES BETWEEN TUNNEL AND SURROUNDING GROUND

1.1 The differential equations relating to the exchange of heat between a cylindrical cavity and the ground in which it is dug are difficult to handle. See, in this respect the study by A W Pratt and L F Dawe "Heat transfer in underground tunnels" Research Paper No 26 of the National Building Studies, published by H. M. S. O.

1.2 But it can be shown (see Annexe 14) that when the intervals of time are not too great, no appreciable error arises if the equations for a cylinder are replaced by those for a developed plane surface of equivalent dimensions, which are much easier to deal with.

1.3 In the case of a semi-infinite plane wall, the general heat equation is written:-

$$\frac{\lambda}{c\rho} \quad \frac{\partial^2 \theta}{\partial x^2} = \frac{\partial \theta}{\partial t}$$

Assuming on the one hand that the temperature of a point situated at infinity is θ_p, and on the other hand that the temperature of the plane limiting the the wall follows a sinusoidal variation of equation

$$[\theta]_{x=o} = \theta_o + \alpha \sin \omega t$$

the solution of the differential equation (i) satisfying these conditions, with limits, is:

$$\theta = \theta_o + 2\,\frac{\theta_p - \theta_o}{\sqrt{\pi}} \int_0^{\frac{x}{2\sqrt{at}}} \rho^{-u^2} du + \alpha \rho^{-\sqrt{\frac{\omega}{2a}}\,x} \sin\left(\omega t - \sqrt{\frac{\omega}{2a}}\,x\right)$$

where $a = \frac{\lambda}{c\rho}$

1.4 In the contact of the two materials, the surface of separation constitutes a thermal obstacle which is characterised by a coefficient of exchange h. The corresponding resistance $\frac{1}{h}$ is very small and may consequently be ignored, in the contact between wet rock and water in motion. The same does not apply to the contact between air and concrete. For dry concrete and air which is not motionless, it may be taken:

h = 0.00014 cal/cm^2, Sec. °C(if the concrete were wet then h would reach 0.0002)

1.5 If, instead of taking the temperature of the wall face it be considered that $\theta_o + \alpha \sin \omega t$ represents the temperature of the air in contact with the wall face, the temperature at infinity being θ_p as above, the integration of the differential equation 1.3 is more laborious (1). The last term of the value of θ given by formula 1.3 would be replaced by:

(1) See G Ribaud, Conduction of Heat under variable conditions. Chapter 4. 4-2.

0·00014 cal/cm^2, sec, °C = 5·86 W/m^2, K

$$\propto \eta \, \rho^{-\sqrt{\frac{\omega}{2a}}x} \sin \left[\omega t - \left(\delta + x\sqrt{\frac{\omega}{2a}} \right) \right]$$

where $\eta = \dfrac{1}{\sqrt{1 + \frac{\omega \lambda c \rho}{h^2} + \sqrt{\frac{2\omega\lambda c \rho}{h^2}}}}$ and δ = arctg $\dfrac{1}{1 + \sqrt{\frac{2h^2}{\omega \lambda c \rho}}}$

1.6 Everything takes place as if the variation in surface temperature were altered in phase by δ, and reduced in amplitude η in relation to the variation of the air temperature.

1.7 The expression given above allows the calculation of the value of the temperature of the wall face in contact with the air, and, in consequence, the quantity of heat which it will absorb during the half-period, and give back again during the following half-period.

2. STEADY HEAT LOSS

2.1 It can easily be shown that halfway between the tunnel and the sea bed the cyclic variations in the temperature are not felt (1). The result is that the steady heat flux traversing this plane is independent of variations and depends only upon the average temperatures.

2.2 We have seen that the normal temperature of the rock at the level of the tunnel can be assumed equal to 12.5°C. This means that in the absence of any transfer of heat from the tunnel, the ground between it and the sea-bed would contain a heat flux corresponding to the difference between 12.5°C and 11°C.

2.3 If the tunnel provided heat and if its average temperature is T_M, the flux will alter and will correspond to this difference between T_M and 11°C. The quantity of heat transferred from the tunnel to the sea-bed will thus be proportional to T_M - 12.5°C.

2.4 If the overall flux of heat coming from a main tunnel were not affected by the presence of the other tunnels, the expression of this flux would be:

$$Q = \frac{2\pi R \lambda (TM - 12.5^\circ)}{1.15 R. \log \dfrac{h + \sqrt{h^2 - R^2}}{h - \sqrt{h^2 - R^2}}} \quad \Delta t \text{ kcal/m}$$

By making λ = 0.0056 cal/cm sec °C = 2 kcal/m.h. °C
R = 3.28 m

---

(1) These variations cancel each other out at a distance from the tunnel wall where pulsations appear which are equal to 5 times the quantity $\Sigma = \sqrt{\dfrac{2\lambda}{\omega c \rho}}$ known "skin thickness".

In the case of the Channel Tunnel, the skin thickness for an annual variation is Σ = 2.87 m in concrete and 3.54 m in chalk.

we should find

for h = 35 m. $Q = 4.11\ (T_M - 12.5^o)$ kcal/m.h. °C

for h = 80 m. $Q = 3.24\ (T_M - 12.5^o)$ kcal/m.h. °C

2.5 The Scientific and Technical Building Centre (CSTB) has studied what would be the effect of the proximity of the tunnels. The isotherms, instead of being circular curves, are then Cassin's ovals, which makes the mathematical study very much more complex. Hence the CSTB carried out the analysis of the thermal field by an analogy method (resistance tank) on a model at 1/100 scale. (See annexe 16). In this model, the superficial resistance between the air and the tunnel walls were not represented, as it had been shown that these resistances are negligible in relation to that of the surrounding ground.

2.6 The CSTB found in this manner:-

for h = 35 m. Q = 3.25 kcal/m.h. °C

for h = 80 m. Q = 2.25 kcal/m.h. °C

After examining the profile the CSTB decided on an average value of

Q = 2.5 kcal/m.h. °C corresponding to a thickness of covering of 60 m.

2.7 The quantity of heat transferred from a tunnel towards the sea-bed in one day will therefore be:-

$Q = 3.12\ (T_M - 12.5^o) \times 10^6$ kcal/day-tunnel

3 PULSATIONS

3.1 In the absence of any permanent flow, i.e. assuming $\theta_{,\rho} = \theta_o$, the expression for the temperature at a distance from the surface of a wall in contact with a volume of air whose temperature varies in a sinusoidal manner, is reduced to

$$\theta' = \theta_{,} + \alpha\eta\ \rho^{-\sqrt{\frac{\omega}{2a}}}\ \text{Sin}\left[\omega t - \left(\delta + \chi\sqrt{\frac{\omega}{2a}}\right)\right]$$

and the flux is:-

$$dQ = -\lambda S \frac{\partial\theta}{\partial\chi}\ dt = \lambda S\alpha\eta\sqrt{\frac{\omega}{2a}}\ \sqrt{2}\ \ \rho^{-\sqrt{\frac{\omega}{2a}}\chi}\ \text{Sin}\left[\omega t - \left(\delta + \sqrt{\frac{\omega}{2a}}\right) + \frac{\pi}{4}\right] dt$$

for $\chi = 0$ (Surface)

$$dQ = \lambda S\ \alpha\eta\ \sqrt{\frac{\omega}{a}}\ \text{Sin}\left[\omega t - \delta + \frac{\pi}{4}\right] dt$$

with

$$\eta = \frac{1}{\sqrt{1 + \frac{\omega\lambda c\rho}{h^2} + \sqrt{\frac{2\omega\lambda c\rho}{h^2}}}}$$

$$\delta = \text{arc. tg} \frac{1}{1 + \sqrt{\dfrac{2h^2}{\omega \lambda c \rho}}}$$

3.2 In the case of the Channel Tunnel, $\lambda = 0.0036$ (1), $c = 0.2$, $\rho = 2.2$, $h = 0.00014$ and in taking for S the total surface of one tunnel (perimeter rounded-up to 20 m x average length of 52 000 m) we should have, in millions of kilo-calories:

for a daily variation:

$$Q = -15.046 \; \alpha_j \cos \left[2\pi \frac{t + 0.8}{24} \right]_{t1}^{t2}$$

or, for a half-period

$Q = \mp 30.092$ millions of kilocalories

or, 578.7 kilocalories per metre of tunnel

for a weekly variation

$$Q = -71.92 \; \alpha_h \cos \left[2\pi \frac{\frac{t}{24} + 0.465}{7} \right]_{t1}^{t2}$$

or, for a half period

$Q = \mp 143.84$ million kilocalories

or 2.766 kilo calories per metre of tunnel

and for an annual variation

$$Q = -\text{[illegible]}3.8 \; \alpha \cos \left[2\pi \frac{\frac{t}{24} + 40.9}{365} \right]$$

or, for a half period

$Q = \mp 1687.6 \; \alpha$ millions of kilocalories

or 32 455 α kilo calories per metre of tunnel

α_j, α_h and α being half amplitude of the daily, weekly and annual variations in temperature.

(1) We take $\lambda = 0.0036$ which is the value of the thermal conductivity of reinforced concrete, and not that of chalk saturated with water which would be $\lambda = 0.0056$. Indeed, it can be shown that the daily thermal pulsations and the weekly ones will virtually not go further than the thickness of the concrete. The annual pulsations will be felt in the chalk but will be already well damped-out before they reach it.

SUMMARY OF STUDIES UNDERTAKEN BY THE CENTRE SCIENTIFIQUE ET TECHNIQUE DU BATIMENT (C. S. T. B.)

1.1 Besides the theoretical study on the heat exchanges of trains, which is mentioned in Chapter IX, 3C, the C. S. T. B. studies dealt with the evacuation of heat from the Tunnel to the sea by conduction through the ground, and with the exchanges between the air in the tunnel and the water flowing in the tunnels.

1.2 After a preliminary study in June/July 1967, the C. S. T. B. assumed, in an initial study, that the flow of water in the main tunnels would occur in two channels, situated on either side of the track in those tunnels; they also took account of an electricity cable which at one time it was proposed to have running along the tunnels. In a second study, the cable was assumed not to be present, and the two channels in each tunnel, whose construction would have posed difficult problems, were replaced by a single central channel.

1.3 The number of trains assumed by the C. S. T. B. in both studies is lower than that now assumed; but the number is only used to determine orders of size; the study allows the calculation of heat flows as a function of the values of the different parameters; so its results are perfectly usable. On the other hand the variant analysed by the C. S. T. B. in each study, and involving the assumption that there would be no floor to the service tunnel, or at least that there would be a wide opening allowing thermal exchange by convection, has not been adopted because of the constructional difficulties which it would present.

1.4 As a great proportion of the material in the first study, though incomplete, remains valid, the C. S. T. B. did not redraft it, but merely indicated in a "Report complementary to the final study", dated July 1969, the modifications which the new data make necessary to the first results. By the same "Complementary Report", the Centre adds new material to certain calculations. For this reason it is difficult to read the C. S. T. B. documents and annexes as a whole. It is impossible to give their detailed argumentation in the present summary, but the summary will indicate their general process of argument and the main results, taking account of the modifications or additions made in the complementary report.

2. THE STUDY IS DIVIDED INTO 3 PARTS

- Measurement of the characteristics necessary for the calculations;

- Calculation of local heat exchanges as a function of temperature;

- Calculation of air temperature.

2.1 Measurement of the characteristics necessary for the calculations.

2.1.1 Measurement of the thermal conductivity of the rock

This measurement was carried out on two of the four core samples supplied to the C.S.T.B.

The method employed is that termed "the heating wire in variable conditions". This method permits the measurement of the conductivity of a wet material and is well adapted to measurements on core-samples because it is based on the flow of a heat flux radially in a cylinder.

The results were as follows:-

Core references	Density dry (kg/m^3)	Moisture weight ζ m	Maximum moisture in weight	λ dry	λ wet per m
		(% of dry weight)		(kcal/mh°C)	
No 1 C 12A R 310 47.40-47.52 m m	2130	9.80	10(*)	1.32	1.97
No 7 C 6 A R 190 25.54-25.78 m m	2140	9.82	10(*)	1.31	2.01

These measurements lead to the retention of the value $\lambda = 2$ kcal/mh °C, which had been adopted subjectively at the outset of the studies.

(*) These values were obtained on the assumption that the chalk density is 2700 kg/m^3.

2.1.2 Transfer of heat between the tunnel and the sea by conduction through the ground.

2.1.2.1 If a single tunnel is considered, of diameter 2R, whose axis is situated at a distance h from the sea bed (presumed level), the value of the flux leaving the tunnel per unit length as a function of the difference in temperature $\Delta\theta$ between the tunnel and the sea bed is given by the expression

$$\Phi = \frac{2 \pi R \lambda}{1.15 R \log \dfrac{h + \sqrt{h^2 - R^2}}{h - \sqrt{h^2 - R^2}}} \Delta\theta$$

By making $R = 3.28$, $\lambda = 2$ and $h = 35$ m we find that

$\Phi = 4.1 \; \Delta\theta$ kcal/m.h.

2.1.2.2 Since the proximity of the 3 tunnels does not allow the problem to be stated by an equation, it became necessary to determine Φ experimentally by an electrical analogy.

The fundamental equations for plane thermal exchanges

$$\begin{cases} \dfrac{\partial^2\theta}{\partial x^2} + \dfrac{\partial^2\theta}{\partial y^2} = 0 \\ \dfrac{\partial^2 Q}{\partial x^2} + \dfrac{\partial^2 Q}{\partial y^2} = 0 \end{cases}$$

are exactly similar to those for flows of electricity in a plane conductor:

$$\begin{cases} \dfrac{\partial^2 V}{\partial x^2} + \dfrac{\partial^2 V}{\partial y^2} = 0 \\ \dfrac{\partial^2 W}{\partial x^2} + \dfrac{\partial^2 W}{\partial y^2} = 0 \end{cases}$$

It is thus possible to make

either (voltages correspond to temperature)
(energies correspond to flux,)

which will be used in the study of the shape of the isothermic lines and in the measurements of flux,

or (voltages correspond to flux)
(energies correspond to temperature,)

which will be used for the study of the shape of the lines of flux.

2.1.2.3 The analogy must be effected in such a way as to provide the limiting conditions, namely:

Dirichlet's conditions, corresponding to a temperature imposed along a boundary, and which is represented by a known potential difference along the line representing the boundary; this can be achieved in a discontinuous fashion by a number of electrodes disposed along the boundary.

Neumann's conditions, corresponding to the law of normal flux changes along the boundary.

$$\frac{\Delta\Phi}{\Delta S} = -\lambda \frac{\Delta\theta}{\Delta\eta}$$

which will be represented by:

$$\frac{\Delta I}{\Delta S'} = -\sigma \frac{\Delta u}{\Delta \eta} \; .$$

and will be effected by regulating the intensity of current in the electrodes.

Fourier's conditions, which will give a relationship between temperature and the normal flux change, which will be effected by resistances in series with the electrodes.

2.1.2.4 The calculation of the electrical resistances is made by using the equation

$$R = \frac{\lambda}{\sigma} \; \frac{b}{h} \; \frac{1}{\Delta S'} = \frac{\lambda b \rho'}{hL}$$

where R is the resistance, b the geometric scale ($=\sqrt{\frac{\Delta S}{\Delta S'}}$), ρ' the resistance of the conductor, h the coefficient of exchange and L the distance between the axes of the electrodes.

2.1.2.5 The calculation of the flux is given by:

$$\Phi = \frac{\lambda \rho'}{R} \; \frac{\Delta U}{B} \quad \text{or} \quad \lambda \rho' \frac{I}{U} \; \Delta\theta$$

where B is the voltage/degree ratio $B = \frac{\Delta U}{\Delta \theta}$

2.1.2.6 To permit the use of as large a scale as possible, regard was paid to the fact that, since traffic in the two main tunnels will be roughly equal, the figure has an axis of normal symmetry from the sea-bed passing through the centre of the service tunnel. It is thus possible to restrict measurements to those for a half-plane.

2.1.2.7 Further, so as to allow the consideration of an infinite field, a circle was traced with centre 0 (intersection of the axis of symmetry with the sea-bed) and with radius R, large enough to include the main tunnel. To represent that part of the field situated outside the circle, an inversion was made with centre 0 and with strength R^2. All the points transformed from the boundary lines (axis, sea, circle of radius R) retain their initial properties [(1)].

The space situated below the sea-bed will thus be entirely represented in a quarter-circle of radius R.

2.1.2.8 The study was first carried out using conductive paper. The scale was determined (1/100) by the maximum width of the conductive paper (0.80 m): 16 electrodes were arranged on the periphery of the main tunnel and 7 on that of the service tunnel. 2 electrodes represented the drainage channels in the 2 tunnels.

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(1) See A DELRIEU & F TREVES - Heat and industry, No 312, July 1951.

It was thus possible to obtain curves giving the main tunnel and the service tunnel the flux between the tunnel and the sea-bed, as well as between the air in the tunnel and the infiltrating water, by superficial exchange and by conduction through the lining, as a function of the variations of temperature between the water and the sea on the one hand and between the air of the tunnel and the sea on the other hand.

2.1.2.9 But the accuracy of this study appeared to be unsatisfactory because of the inadequacy of the radius of inversion R (0.70m) in relation to the scale adopted, and because of the anisotropy of the electrical characteristics of the paper. Besides, it was not possible to vary the different parameters, particularly the resistance of the paper (1800 ohms per cm^2). It was thought necessary to continue the study by constructing a tank in the shape of a quarter-circle in which conduction would be assured by a very homogeneous liquid electrolyte. The scale of 1/100 was retained, but the radius of inversion was raised to 1 m.

2.1.2.10 The studies showed that, in determining the thermal exchanges between the tunnel and the sea, the surface resistance between the air and the tunnel walls was negligible in relation to the resistance of the ground.

2.1.2.11 The thermal conductivity thus measured varied from 3.[illegible]5 to 2.25 kcal/m.h. °C when the depth of the ground between the tunnel and the sea-bed varied from 35 to 80 m. Having regard to the proposed Tunnel line, the C.S.T.B. concluded that a coefficient of 2.5 should be adopted, corresponding to a depth of 60 m.

$\Phi = 2.5$ kcal/m.h. °C

2.1.3 Determination of the coefficients of surface exchange

In the flow of heat between the tunnel and the sea, which is the subject of para 1.2 above, the influence of the surfaces of contact between the air and the ground and between the ground and the sea is negligible in relation to the conductivity of the chalk.

But this is not the case with the local exchanges between the air and the lining, but the intermediary of which part of the local heat exchanges occur. It is therefore necessary to determine the coefficients of surface exchange which applies to them.

The exchanges occur by radiation and by convection.

2.1.3.1 In the case of temperatures of the order of 20°C and materials of matt grey colour, like chalk or concrete, the coefficient of exchange by radiation is not far off 4 kcal/m^2 h°C.

The C.S.T.B. uses this value.

2.1.3.2 In order to work out the coefficient of exchange by convection the C. S. T. B. uses the readings of temperatures and air speeds collected in the Simplon, at two accurately fixed points, during the tests of November 1965.

Applying a formula established by McAdams for a similar geometric arrangement,

$$\alpha c = 0.0156\ C\rho\ \frac{V_q^{0.8}}{D^{0.2}}$$

the C. S. T. B. determined the average value of

$\alpha c = 6.5\ \mathrm{kcal/m^2\ h\ ^\circ C}$

By careful analogy, the C. S. T. B. adopts for the Channel Tunnel the value

$\alpha c = 6\ \mathrm{kcal/m^2\ h\ ^\circ C}$

and, in total, an overall coefficient of exchange of

$10\ \mathrm{kcal/m^2\ h\ ^\circ C}$

2.1.3.3 This coefficient is, however, subject to considerable variation. In still air ("natural" convection) it varies from 4.5 for descending flows to 9.4 for ascending flows. With forced convection, it can considerably exceed 10. The latter coefficient corresponds to an air speed of 3 to 4 m/sec which, in the Simplon, resulted from a traffic of 4 trains per hour; these conditions seem little different from those which will prevail in the Channel Tunnel.

2.2 Determination of the thermal exchanges between the air, the water in the drainage channels and the sea, as a function of the temperature.

The exchanges of heat between the air in the tunnel, the water in the drainage channels and the sea are functions of the differences in temperature between the air (temperature t), the water in the drainage channels of the main tunnels (temperature θp), the water in the service tunnel (θs) and the water at the sea-bed (temp. T_m). As these exchanges are not independent, the C. S. T. B. made an overall study of them by means of analogous measurements carried out with the resistance tank and using the coefficients determined as per para 1 above.

2.2.1 Taking as a reference the temperature of the sea T_m, it first studies the flows exchanged under the influence of an increase in the temperature only of the air in the tunnel. If Q_l, is the total flux lost by the air, and Q_{ls}, Q_{lp} and Q_{lm} those transferred to the water of the service tunnel, the main tunnel and the sea, we have:

$$Q_l = Q_{ls} + Q_{lp} + Q_{lm}$$

or

$$k_l\ (t-T_m) = k_{ls}\ (t-T_m) + k_{lp}\ (t-T_m) + k_{lm}\ (t-T_m)$$

i.e.

$$k_l = k_{ls} + k_{lp} + k_{lm}$$

2.2.2 Similarly, in differentiating from T_m only the temperature of the service tunnel, then that of the main tunnel, one has:

$$k_2 = k_{2s} - k_{2p} - k_{2m}$$

$$k_3 = -k_{3s} + k_{2p} - k_{3m}$$

Moreover,

$$k_2 = k_{ls}, \; k_3 = k_{lp} \text{ and } k_{2p} = k_{3s}.$$

2.2.3 The C. S. T. B. was thus able to draw up a table of coefficients of overall and partial exchange (natural and forced convection):-

Difference of temperature between	Coefficients of exchange			
	overall	with the service tunnel water	with the main tunnel water	with the sea
Tunnel Air/Sea	k_l = 12.04/15.96	k_{ls} = 3.65/4.20	k_{lp} = 6.16/9.35	k_{klm} = 2.23/2.31
Service Tunnel Water/Sea	k_2 = 3.65/4.[illegible]	k_{2s} = 3.83/4.45	k_{2p} = 0.06/0.05	k_{2m} = 0.12/0.10
Main Tunnel water/Sea	$k_{[illegible]}$ = 6.16/9.35	k_{3s} = 0.06/0.0[illegible]	k_{3p} = 6.40/9.53	k_{3m} = 0.18/0.13

If one dispenses with the service tunnel floor, the coefficients k_n and k_{ns} are of course much higher; for example, k_l = 15.09/23.31.

3. CALCULATION OF THE TEMPERATURE OF THE AIR IN THE TUNNEL

The dissipation of heat flux F for a length dx of half-tunnel is:-

$$F\,dx = k_l\,(t-T_m) - k_2\,(\theta s-T_m) - k_3\,(\theta p-T_m)\,dx.$$

It 2 Ds and Dp are the flows of water in the channel of the service tunnel and that of the main tunnel respectively,

$$Ds\,d\,\theta s = k_{ls}(t-T_m) - k_{2s}\,(\theta s-T_m) - k_{3s}\,(\theta p-T_m)\,dx$$

$$Dp\,d\,\theta p = k_{lp}\,(t-T_m) - k_{2p}\,(\theta s-T_m) - k_{3p}\,(\theta p-T_m)\,dx$$

3.1 This being so, the C. S. T. B. first considered the case where, because of a considerable input of fresh air, the temperature of the air remains constant T_a.

We then have

$$F = k_1 - \frac{k_2^{\ 2}}{k_{2s}\ k_{3s}} - \frac{k_3^{\ 2}}{k_{3p}-k_{2p}}\ (t_a - T_m) + \frac{k_2}{k_{2s} - k_{3s}}\ qms + \frac{k_3}{k_{3p} - k_{2p}}\ qmp$$

qms, flux absorbed by one-half of the water flowing in the service tunnel, being

$$qms = \frac{k_2 (T_a - T_m)}{k_{2s} - k_{3s}}\ (\theta_o - T_m)\ \frac{Ds}{L} \left(1 - \rho \frac{-k_{2s} - k_{3s}}{Ds}\ L \right)$$

and qmp, corresponding flux in the main tunnel, being

$$qmp = \frac{k_3\ (T_a - T_m)}{k_{3p} - k_{2p}}\ (\theta_o - T_m)\ \frac{Dp}{L}\ (1 - e\ \frac{-k_{3p} - k_{2p}}{Dp}\ L)$$

If qmm is the average flux transferred by conduction to the sea, then:-

F = qms + qmp + qmm

3.2 But as the replacement of the air will be limited, the temperature t cannot b be regarded as constant.

The temperature at the x axis will be

$$t_x = A_e^{\ mx} + Be^{r2x} + C$$

and the average temperature over a section of length L

$$t_{AVERAGE} = \frac{A}{r_1 L}\ (e^{r_1 L} - 1) + \frac{B}{r_2 L}\ (e^{r_2 L} - 1) + C$$

where A, B, C, r_1 and r_2 are functions of the 9 coefficients k_1, k_{1s}, k_{1p}, k_2, k_{2s}, k_{2p}, k_3, k_{3s}, k_{3p} and Ds and dp, T_m, θ_o and of flux F.

3.3 The numerical calculation, which was somewhat lengthy, was made on the assumption that the infiltrating water reaches the highest points in the tunnels at a temperature equal to that of the sea-bed, 12.5°C. The C.S.T.B. regards this as the most unfavourable condition since "water entering the tunnel at a temperature T_1 higher than that of the sea T_m will already have absorbed the flux $d(T_1 - T_m)$".

3.4 If the infiltration should be confined to localised points, the water will have to be circulated to the high points or distributed in the tunnels.

3.5 The results are shown by curves which give, for tunnel sections of 12 km, the average flux absorbed by the infiltrating water as a function of the flows: see annexed diagram.

3.6 Other curves give, again for 12 or 17 kms, for natural and forced convection, the relative increases in heat of the air and the water in relation to the difference between the average temperature of the air and of the sea.

4. NOTES

4.1 In its calculations, as in the annexed diagram, the C.S.T.B. assumed that the water flowed in the main tunnel channel until it attained a flow of 100 litres/sec (maximum capacity of these channels) and that the surplus was directed into the service tunnel.

4.2 The C.S.T.B. also considered the case in which the water was transferred from the main tunnel to the service tunnel every 3 kms, and showed that this solution was not favourable.

5. OBSERVATIONS

5.1 The C.S.T.B. considers it necessary to dispense with the floor of the service tunnel in order to reconcile the maintenance of a relatively low average temperature with an acceptable volume for the inflow of infiltrating water.

In practice the C.S.T.B. seeks to keep the average temperature below 20°C: it is this requirement which leads to their conclusions.

Now, a moderate increase in the average temperature leads to a considerable increase in the heat flows evacuated (see, on this, Annexe 20).

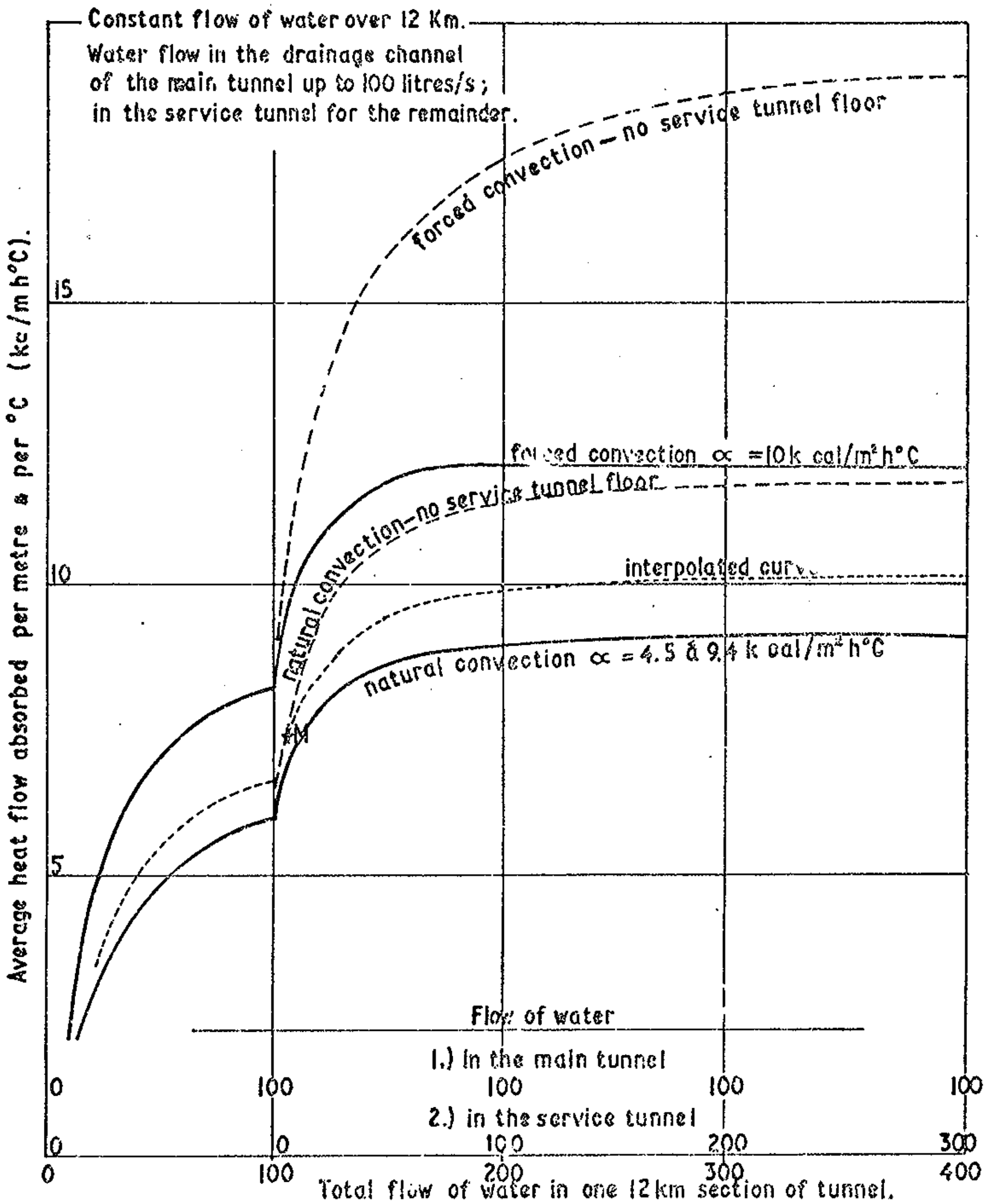
5.2 The heavy traffic which would cause large heat transfers will improve convection; the curve representing the heat transfer against the water inflows will lie between the curve of natural and the curve of forced convection. On the curve so interpolated, point M, corresponding to a total water flow of 105 litres/s per section, or 420 litres/s at each end of the tunnel, gives an absorbed heat flow of 8 kcal/mh°C, and that without dispensing with the floor of the service tunnel This heat flow gives a daily evacuation of heat of

$8 \times 25 \times 52\ 000 = 10 \times 10^6$ kcal per degree of difference of temperature between the air of the natural rock. As can be deduced from the table at Annexe 18, this evacuation is sufficient to maintain an average temperature of 22.05°C, and this with a traffic level higher than that initially assumed.

5.3 In the above, the most unfavourable case is considered, i.e. that in which the water would enter the tunnel at the temperature of the natural rock, without having been heated at all in passing through the rock near to the tunnel. This hypothesis is hardly likely, except, possibly, in the case where the water came from the sea-bed via a relatively large size fissure; but in that case, the initial temperature to consider would not be that of the natural rock (12.5°C), but the average temperature of the bottom of the sea, say 11°C.

5.4 In conclusion, it seems that the quantity of infiltrating water sufficient to ensure the maintenance of an acceptable average temperature for the proposed level of traffic, will lie between 112 litres/s at each tunnel head if the water seeps slowly through the walls and 420 litres/s at each tunnel head in the most unfavourable opposite case. It does not appear possible to achieve more precision without knowing the conditions in which the infiltrating water enters. According to expert opinion, it seems probable that in practice one will find oneself nearer the first case (112 litres/s).

HEAT ABSORBED BY THE WATER FLOWING IN THE DRAINAGE CHANNELS PER METRE OF HALF TUNNEL, PER DEGREE OF DIFFERENCE OF TEMPERATURE BETWEEN AIR IN THE TUNNEL AND THE SEA, EXPRESSED AS A FUNCTION OF THE QUANTITY OF WATER FLOWING IN THE DRAINAGE CHANNELS.



VARIATION IN THE HUMIDITY OF AIR IN CONTACT WITH FLOWING WATER

1. The variation in the humidity of air in contact with flowing water is given by Mollier's diagram or one derived from it.

2. We shall use the diagram published by Messrs Ventil, which is well suited to an examination within the temperature limits with which we are concerned. (See Plate 1).

3. Air at 26°C at 75% humidity is represented on the diagram by the point M. The corresponding wet bulb temperature is 22.4°C and the dew point is 21.15°C.

4. If this air is put in the presence of water, its content of water vapour per cubic metre will tend towards that of saturated air having the same temperature as the water.

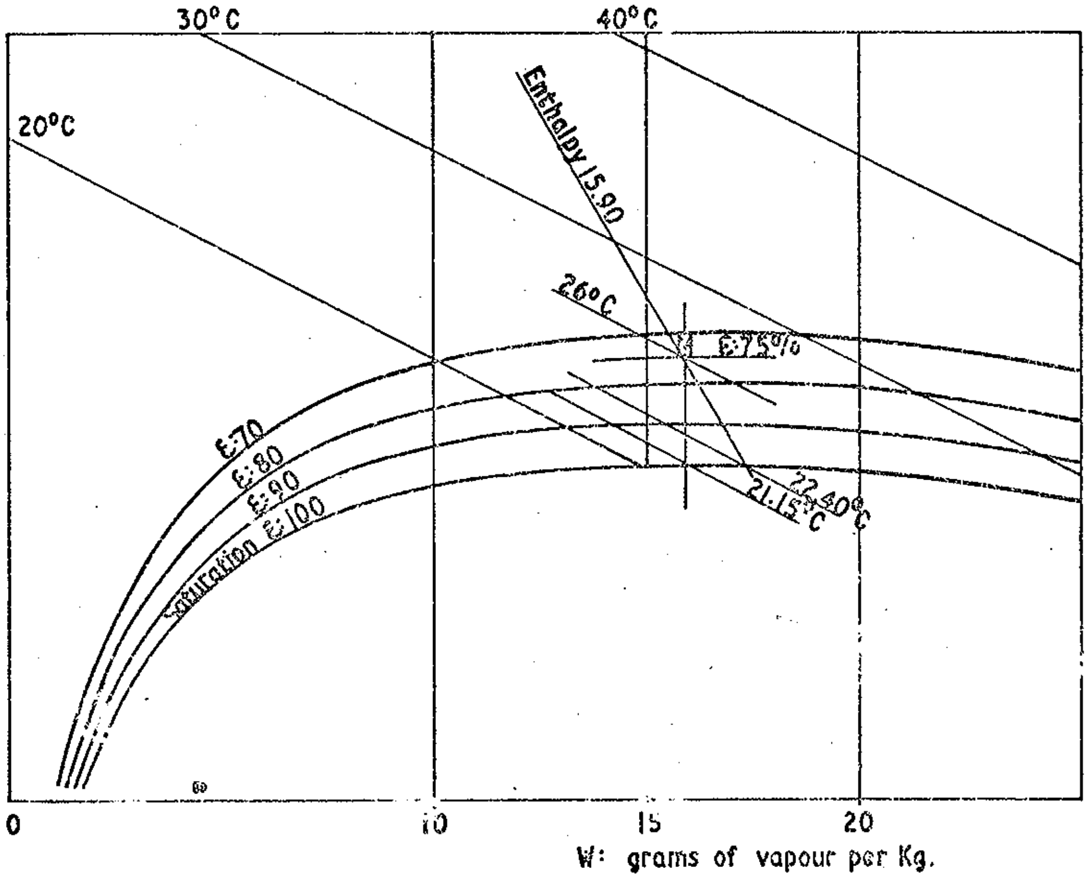
5. Consequently, if the water temperature is higher than the dew point, the representative point M of the air will be shifted towards the right of the diagram; at constant temperature its humidity will rise.

6. If on the other hand the water is at a lower temperature than that of the air dew point, the point M will tend to shift towards the left of the diagram, and its humidity will fall, if the temperature remains constant.

7. The conclusion is that it is advantageous to keep water in contact with the air provided that its temperature is below the proposed air dew point.

TERMS USED IN PLATE 1

Caracteristiques du point M	= Characteristics of point M
Teneur en vapeur d'eau	= Content of water vapour
Enthalpie	= Enthalpy
Temperature	= Temperature
Temperature humide	= Wet bulb temperature
Temperature de rosee	= Dew point temperature
Humidite relative	= Relative humidity
Tension de vapeur	= Vapour pressure
Volume	= Volume
W: g. de vapeur pr kg.	= W: grams of vapour per kg



CHARACTERISTICS OF POINT M

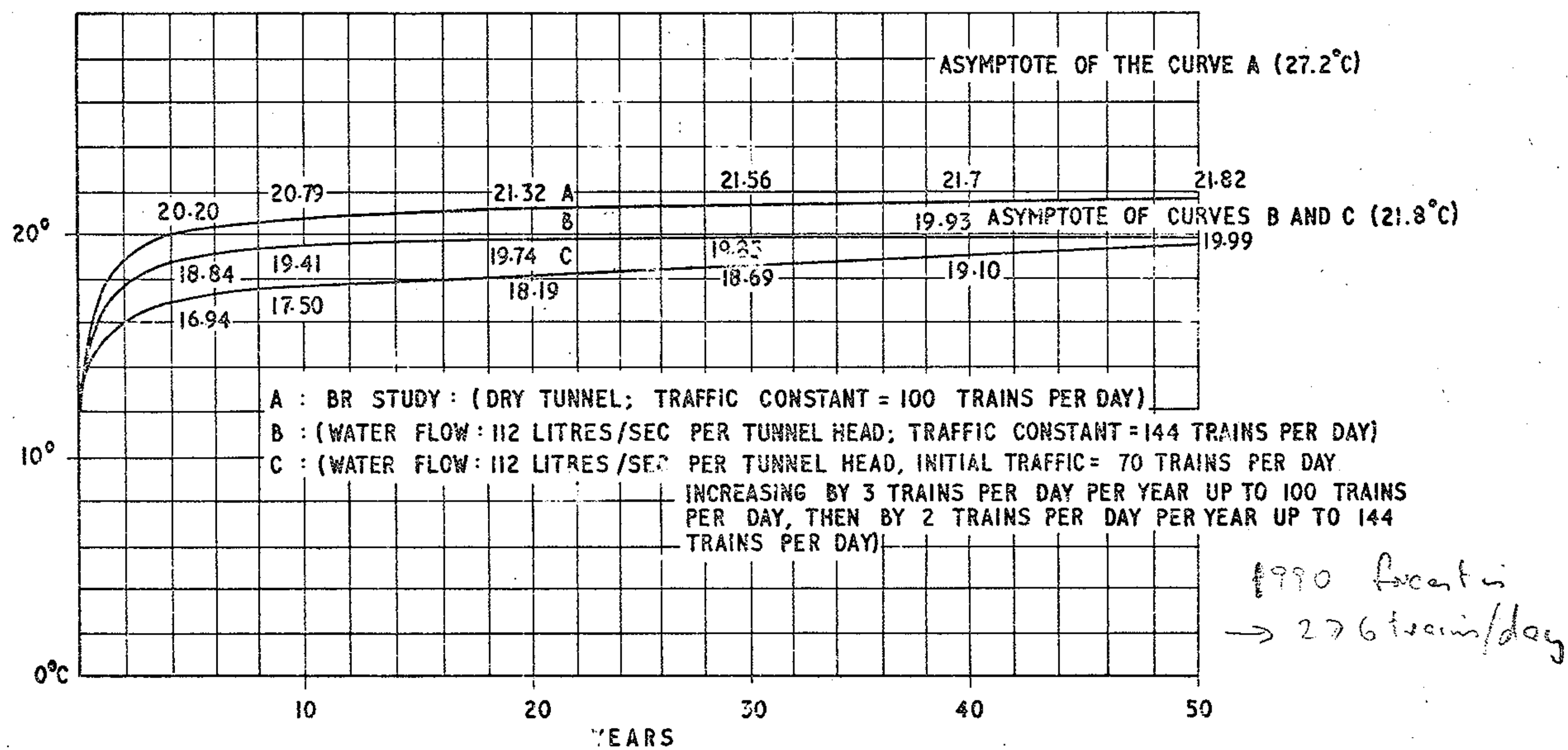
Content of water vapour	W	15.85	g/Kg
Enthalpy	H	15.90	mth/Kg
Temperature	t	26	oC
Wet bulb temperature	t'	22.40	oC
Dew point temperature	tr	21.15	oC
Relative humidity	E	75	%
Vapour pressure	f	25.20	mb
Volume	V	0.868	m^3/Kg

MONTHLY THERMAL BALANCE SHEET

AVERAGE VALUES: $T_M = 22.05$ $\alpha = 3.25$ $d = 112$ $= 5.1$

	J	F	M	A	M	J	J	A	S	O	N	D
Sin $[30^\circ (m - 5.1)]$	-0.837	-0.999	-0.891	-0.545	-0.052	0.454	0.839	0.999	0.891	0.545	0.052	-0.454
T (temperature in the tunnel) = 22.05 + 3.25 Sin $[30^\circ (m - 5.1)]$	19.23	18.80	19.15	20.28	21.88	23.53	24.78	25.30	24.95	23.82	22.22	20.57
T_E (average external temp 07.00 to 22.00 hrs)	4.2	3.7	6.3	9.1	14	15.3	17.3	17.8	16.1	12	7.8	5.7
Sin $[30^\circ (m - 112^\circ 41')]$	-0.992	-0.795	-0.386	-0.127	0.606	0.923	0.992	0.795	0.386	-0.127	-0.606	-0.923
Pulsation (Thermal inertia of walls) 436.78 × Sin $[30^\circ (m - 112^\circ 41')]$ = A	- 1408	- 1129	- 548	180	860	1310	1408	1129	548	- 180	- 860	- 1310
Heat transfer through the sea 3.12 (T_M - 12.5) x number of days = 29.769 number of days = B	924	834	924	894	924	894	924	924	894	924	894	924
T - 12.5	6.82	6.30	6.65	7.78	9.38	11.03	12.28	12.80	12.45	11.32	9.72	8.07
Heat transfer through water in drainage channels 112 x 3600 x 24 x 10^{-6} (T - 12.5) x number of days 9.677 x number of days x (T - 12.5) = C	2046	1707	1995	2259	2814	3202	3684	3840	3614	3396	2822	2421
Heat input of fixed auxiliary equipment 7.2 x number of days = D	223	202	223	216	223	216	223	223	216	223	216	223
A + B + C - D	1339	1210	2148	3117	4375	5190	5793	5670	4840	3917	2640	1812
$T - T_E$	15.12	15.10	12.85	11.18	7.88	8.23	7.48	7.50	8.85	11.82	14.42	14.87
	.9819	.9986	1.0592	1.15	1.306	1.29	1.324	1.323	1.263	1.133	1.0183	.9987
Heat input by train 1.653 - 0.088 ($T - T_E$) = E	0.322	0.324	0.5[illegible]	0.669	0.960	0.929	0.995	0.993	0.874	0.613	0.384	0.344
Number of trains (possible) $\frac{A + B + C - D}{E}$	4158	3735	4115	4659	4557	5587	5822	5710	5538	6390	6875	5267
Number of trains (anticipated)	4092	3660	3967	[illegible]	4138	4935	5270	5642	5190	3937	3765	4045

half between average 1.1560 ie 70% fixed



THEORETICAL CURVES SHOWING PROGRESSIVE RISE IN TUNNEL TEMPERATURE.

SENSITIVITY OF THE TEMPERATURE CALCULATIONS

1. GENERAL

1.1 The calculation in Annexe 18 is based on the theory of sinusoidal temperature variations within a hollow body. One assumes a priori a sinusoidal variation in temperature and calculates the heat exchanges from which it results, which corresponds to a number of train movements. One then adjusts the sinusoid (average value, amplitude and phase) in such a way that the number of trains calculated as above is not lower in any month than that given by the traffic forecasts.

1.2 It can be shown that the acceptance of a small increase in the average temperature allows a significant increase in the number of trains.

2. RELATIONSHIP BETWEEN AVERAGE TEMPERATURE AND NUMBER OF TRAINS

Consider the equation in Annexe 18

Let N be the No of trains $= \dfrac{A + B + C - D}{E}$

Only the terms B, C and E are functions of the temperature T in the tunnel or of its average value T_M; the terms A and D are independent of it

Let this temperature be increased by ΔT, a small increment, then

(as $\Delta T = \Delta T_M$),

(i) B = number of days x 3.12 x $(T_M + \Delta T_M - 12.5)$

(ii) C = number of days x 9.667 x $(T + \Delta T_M - 12.5)$

that is, B + C is increased by

number of days x 12.797 x ΔT_M,

or 370 in February

383 in April, June, September and November

396 during the rest of the year

or a x ΔT_M in which a is a constant appropriate to the month

(iii) $E = 1.653 - 0.088\ (T + \Delta T - T_E)$

that is, the value of E is reduced by

$0.088\ \Delta T$

It results from this that the number N of trains rises to

$$N + N = \frac{(A + B + C - D) + a\,\Delta T}{E - 0.088\ \Delta T}$$

And that the effects of a small increase in the average equilibrium temperature can be calculated directly.

However it is more convenient to determine the effect on the temperature of an increase in the level of traffic -

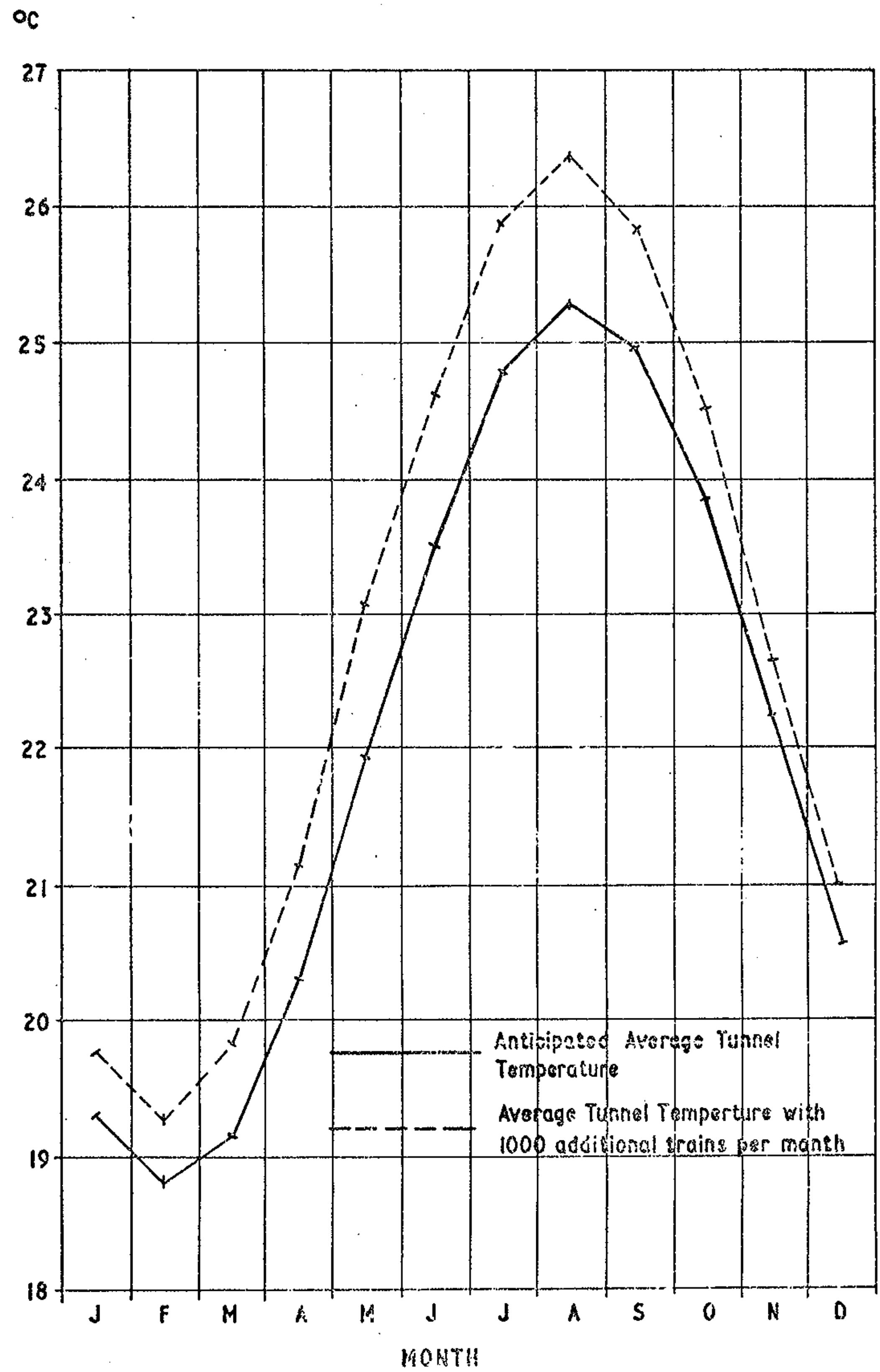
by inverting

$$T = \frac{\Delta n \times E}{(N + \Delta N) \times 0.088 + a}$$

The numerical values corresponding to an increase of 1000 trains in the equilibrium level of traffic are tabulated at page 20.3 and the results plotted graphically at page 20.4. It will be seen that the temperature at which thermal equilibrium occurs is not greatly influenced by the volume of traffic passing in August. The value of 25.3°C, corresponding to the passage of 5710 trains through the tunnel, is only increased by 0.11° by an additional 100 trains and by 1.01° by an additional 1000 trains.

TEMPERATURE AND TRAFFIC FORECAST PER TUNNEL FOR YEAR 2005

Month	J	F	M	A	M	Jn.	Jy.	A	S	O	N	D
Anticipated average tunnel temperature	19.32	18.80	19.15	20.28	21.88	23.53	24.78	25.30	24.95	23.82	22.22	20.57
Corresponding number of trains	4158	3735	4115	4659	4557	5587	5822	5710	5538	6390	6875	5267
Increase in average tunnel temperature due to additional 1000 trains	0.38	0.41	0.62	0.76	1.08	0.97	1.00	1.01	0.91	0.59	0.36	0.36
Resultant temperature due to additional 1000 trains	19.70	19.21	19.77	21.04	22.96	24.50	25.78	26.31	25.86	24.41	22.58	20.93


°C
27
26
25
24
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MONTH
Anticipated Average Tunnel Temperature
Average Tunnel Temperture with 1000 additional trains per month

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