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Development of a Model Technique for Investigating the Performance of Soft-Ground Arresters for Aircraft

by

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DEVELOPMENT OF A MODEL TECHNIQUE FOR INVESTIGATING THE PERFORMANCE OF SOFT-GROUND ARRESTERS FOR AIRCRAFT

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SUMMARY

This Report describes work undertaken in an attempt to establish the feasibility of using models to investigate the performance of gravel arresters for aircraft. The experiments were designed using the techniques of physical similarity and dimensional analysis. Tests were carried out with 1:9.3 scale models of Lightning and Canberra aircraft in two types of sand, and the results compared with those obtained in earlier full scale experiments. Despite difficulties in scaling some soil parameters, these results showed that the distance required to stop in the gravel bed for a given entry speed could be predicted with an accuracy of ±10 to 15%.

It is concluded that model experiments based on this work would allow the feasibility of gravel arresters for use by larger aircraft to be established.

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CONTENTS

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1 INTRODUCTION

Full scale tests have been made at RAE[1] to investigate the feasibility of using a gravel bed as an emergency arrester for certain aircraft in aborted take-off and landing over-runs. For these experiments a Lightning and a Canberra aircraft were used, running into 0.46 m (18 in) and 0.76 m (30 in) deep gravel beds at speeds up to 70 knots and through distances of up to 195 m (640 ft). Target speeds to be investigated for large aircraft were up to 120 knots entry speed with a run-out distance up to 300 m (1000 ft).

The practical and economic difficulties involved in extending these experiments to cover higher speeds, larger aircraft with different undercarriage configurations, and different arrester bed profiles, pointed to the desirability of resorting to a scale model technique where parameters could be changed more easily and comparatively cheaply.

This Report describes the work undertaken in an attempt to produce a model technique for the investigation of the performance of gravel arresters. The objectives were to be able to reproduce full scale results with reasonable accuracy using as simple a model as possible and to identify the dominant soil and aircraft parameters. It was considered that the achievement of the objectives would make it possible for tests to be conducted with models representative of larger aircraft with multi-wheel undercarriages, thus establishing the feasibility or otherwise of gravel arresters for large civil aircraft. Such experiments were subsequently carried out, based on the findings of this work and these are reported in Ref.2.

During the course of this work several methods of soil testing were used in an attempt to relate full scale and model material characteristics, and a simple technique was evolved for the construction of small pneumatic tyres.

2 IDENTIFICATION OF AIRCRAFT AND GRAVEL PARAMETERS

Although considerable effort has been expended on the subject of wheel drag in soils, notably in the United States, the interaction of pneumatic tyred wheels and soils is not well understood, particularly at the high speeds associated with the gravel arresting problem. However, in order to be able to determine the model scaling relationships it is necessary only to identify the important parameters which are thought to govern the behaviour. These can then be arranged as non-dimensional ratios which must be maintained equal between model and prototype to ensure dynamic similarity. The accuracy of the relationship between model and prototype is dependent on successfully identifying all significant parameters.

If a wheel and tyre are lowered slowly on to a soil surface without forward motion the soil or the tyre, or both, deform until the mean soil pressure and the horizontal projection of the contact area between the two are such as to provide a vertical force equal to the wheel load. The mean soil pressure may be equal to or less than the tyre inflation pressure and arises from the frictional and cohesive forces developed in the soil. These forces are traditionally quantified by measurements of the angle of internal friction ϕ_F and the cohesion c, respectively and are known to be dependent among other things on the type of soil, the soil particle size, particle size distribution, particle shape, soil moisture content, degree of compaction, confining pressure and sinkage. The last named determines the local pressures due to the surcharge of soil above the loaded surface and is dependent on soil particle density and voids ratio (ratio of the volume of air spaces to the volume of solids) or more generally the bulk density. The ability to bear load is also known to be dependent on loading area: for shallow footings for buildings the stress required for a given sinkage increases almost linearly with increase in area. Similar effects might be expected for tyred wheels, so that sinkage can be expected to depend on wheel load, tyre size and inflation pressure.

When the wheel is moving slowly forward the motion is resisted by the soil frictional and cohesive forces, but the act of disturbing the soil ahead of the wheel may decrease or increase the forces from their undisturbed values by causing compaction or dilation of the soil structure. Drag also arises due to the heaping up of soil ahead of the wheel in the form of a wave. As the speed increases impingement of the soil on the wheel and tyre create a dynamic pressure which might further modify the local state of compaction and hence the shear resistance. Whether shear resistance increases or decreases probably depends upon the undisturbed state of compaction. The pressure acting on the tyre gives rise to lift and drag forces on the wheel which in turn have the effect of increasing the tyre deflection, so increasing effective soil bearing strength and reducing sinkage. Although the dynamic drag force continues to increase with increasing speed a stage is reached when sinkage is reduced to such an extent that the net drag force is also reduced. Under these conditions it is probable that the inertia forces are dominant although the speed at which this

For the gravel arrester, because of the large size of voids and particles, there was no possibility of significant cohesion even when wet so this parameter was ignored.

3 DETERMINATION OF NON-DIMENSIONAL RATIOS AND SCALE FACTORS

The parameters listed above can be considered as eight independent quantities:-

length	ℓ
velocity	v
acceleration (gravity)	g
density	ρ
force	F
angle of friction	ϕ
voids ratio	e
pressure	p

Application of the Pi theorem (see for example Ref.5) gives five non-dimensional products:-

$$\frac{F}{\rho g \ell^3} ; \quad \frac{v^2}{g\ell} ; \quad \frac{p}{\rho v^2} ; \quad \phi ; \quad e.$$

For any two dynamic processes to be similar it is necessary for these ratios to be equal for each case, together with geometric similarity of the models and prototypes. If the scale factors are denoted by:-

$$\lambda_\ell, \quad \lambda_F, \quad \lambda_g, \quad \lambda_p, \quad \lambda_v, \quad \lambda_\phi, \quad \lambda_\rho, \quad \lambda_e$$

where $\lambda_\ell = \frac{\ell_{model}}{\ell_{prototype}}$ etc., the relationships between them are determined by equating to unity the ratios of the non-dimensional products for model and prototype. Thus:-

$$\frac{\lambda_F}{\lambda_\rho \lambda_g \lambda_\ell^3} = \frac{\lambda_v^2}{\lambda_g \lambda_\ell} = \frac{\lambda_p}{\lambda_\rho \lambda_v^2} = \lambda_\phi = \lambda_e = 1. \qquad (1)$$

In order to be able to use naturally occurring sands as scaled gravel, and to avoid the difficulties of creating artificial gravitational fields, density and acceleration were maintained equal for model and prototype, i.e.

$$\lambda_\rho = \lambda_g = 1.$$

Substituting for λ_g and λ_ρ in the scale relationships (equation (1)) and rearranging in terms of λ_ℓ gives:

$$\lambda_F = \lambda_\ell^3; \quad \lambda_v = \sqrt{\lambda_\ell}; \quad \lambda_p = \lambda_\ell; \quad \lambda_\phi = 1; \quad \lambda_e = 1 .$$

A length scale factor $\lambda_\ell \triangleq 0.1$ was considered sensible since it gave reasonable dimensions for the manufacture of models, at the same time keeping model weights to a manageable level. Availability of suitable model tyres determined an actual length scale factor of 1:9.3 ($\lambda_\ell = 0.1075$). The scale factors for the basic quantities then became:-

$$\begin{aligned}
\lambda_\ell &= 1/9.3 &&= 0.1075\\
\lambda_v &= 1/9.3^{\frac{1}{2}} &&= 0.328\\
\lambda_F &= 1/9.3^3 &&= 0.00124\\
\lambda_p &= 1/9.3 &&= 0.1075 .
\end{aligned}$$

Scale factors for other quantities were derived from these according to their dimensions, e.g.:

moment of inertia $I \quad \lambda_I = \lambda_\ell^5 = 1/9.3^5 = 0.0000143$

spring stiffness $k \quad \lambda_k = \lambda_\ell^2 = 1/9.3^2 = 0.0116$.

4 AIRCRAFT MODELS

Models representing the Lightning and Canberra were made using the scaling factors set out in section 3. Since the aircraft behaviour was believed to be due principally to the interaction of the tyres with the gravel, no attempt was made to produce structurally or visually similar models. All that was required was a simple structure to support scaled wheels and tyres in geometrically correct positions under scaled static and dynamic loads. The models are shown in Figs.1 and 2. Each comprised a rigid lightweight cruciform structure of duralumin, the extremities of the cross pieces supporting rigid undercarriage legs to which were attached the main wheels. At the front on the central members were located the nose undercarriages. These were initially rigid but were replaced by sprung units after the rigid leg had been found to cause excessive pitching motion. Both models had castering nose wheels. Lead ballast weights were attached to the central members in such positions as to give the correct horizontal and vertical weight distribution and radii of gyration in pitch.

No attempt was made to scale radii of gyration in roll and yaw. The radii of gyration were checked by treating the models as compound pendulums. No attempt was made to install instrumentation for measurement of loads and accelerations.

The wheels and tyres used were of various constructions. Pneumatic tyres which could be inflated without growth were not available for either model. Since it was necessary to assess very quickly the likely success of the model technique it was decided to make use of some readily available foam rubber model aircraft tyres. Sizes were available which could be trimmed to the correct undeflected Lightning main and nose wheel tyre profiles. These determined the length scale factor of 9.3:1. The foam rubber tyres were located between two circular aluminium plates representing the wheel rims. Load/deflection curves for the Lightning model foam rubber main wheel tyres are shown in Fig.3, scaled up for comparison with the full scale characteristic. It is seen that at a single wheel load of 55.6 kN (12500 lb) the foam rubber tyre deflects an equivalent of approximately 50% more than the full scale tyre inflated at the experimental tyre pressure of 1793 kN/m^2 (260 psi). Also shown in Fig.3 is the load/deflection curve of a solid rubber tyre made for the Lightning model main wheels. This only realizes 25% of the full scale deflection for the same radial load.

For the Canberra model foam rubber tyres were available only for the nose wheels. Main wheel tyres were moulded to the undeflected tyre profile from a resilient natural rubber. These had too high a radial stiffness and were unsatisfactory even when turned down to a flat profile at the normal rolling radius. Thin walled hollow tyres produced considerable improvements and eventually pneumatic tyres were made which could withstand scaled inflation pressures without growth. These were fabricated in a manner similar to the manufacture of full scale tyres by laying up alternately rubber impregnated cotton gauze and uncured natural rubber sheet on a plaster of Paris former. Curing was carried out in a steel mould with the former in place - this being removed afterwards. Due to lack of continuous pressure throughout the curing process the tyres so produced tended to be porous so that re-inflation was necessary immediately prior to test. Further development of the technique was carried out for model work with larger models and this is reported separately in Ref.6.

From the load/deflection characteristics given in Fig.4 it can be seen that although the tyres were not perfect they represented a considerable improvement upon the foam rubber tyres of the Lightning model, being generally within 15-20% of the equivalent full scale deflection for a given load.

In addition a pneumatic tyre gave a more realistic footprint shape than the tyres made with foamed rubber. With the virtually inextensible carcase of the pneumatic tyre increase in deflection caused increases in the width and length of the footprint. For the foamed rubber tyre, increase in deflection merely caused collapse of the air spaces with little bulging of the side wall and consequent increase in footprint width.

Locking up of the wheels due to ingress of sand particles caused directional instabilities. Great care was therefore taken to ensure that clearances were adequate so that particles could not become trapped between wheels and undercarriage legs. Wheel bearings were of PTFE or Glacier DU materials to avoid lubrication problems in the dusty environment.

The principal dimensions and weights of the full scale and model aircraft are given in Table 1.

5 METHODS OF SELECTING MODEL ARRESTER MATERIALS

Four material parameters were considered: particle size (and shape), particle density, voids ratio and angle of internal friction.

The angle of internal friction depends on the particle size distribution (as distinct from size), shape and voids ratio, as well as the surface roughness and other factors affecting friction at the asperities in contact between particles. If these characteristics were correctly represented in the model material the angle of internal friction would be expected to be the same as the full scale. Attention was therefore first directed to finding a material with a representative particle size distribution and shape and of a similar type of rock, it being reasoned that this would be most likely to produce the correct internal friction at the same voids ratio, which could be verified by shear tests.

The required particle size distribution was obtained by first sieving the 19 mm - 6 mm ($\frac{3}{4}$ in - $\frac{1}{4}$ in) gravel and plotting the percentages passing certain sieves on a standard chart. This is shown in Fig.5. The linear dimensions of the sieve meshes (lower scale of graph) were then scaled down by the linear scale factor and replotted (left hand curve, Fig.5). The intercepts of this curve and the British standard sieve sizes marked on the upper scale then gave the particle size distribution required of the model material. With the assistance of the Sand and Gravel Association of Great Britain (SAGA) a material was found which matched very closely the required size distribution. This was a rounded flint sand graded -7 +14 BS sieve from Ardleigh, Essex: its size distribution is also shown in Fig.5. (Note: this material was referred to as Ardleigh 8-16 in Refs.1 and 2.) Although this material was noticeably more smooth and rounded than the gravel (cf. Fig.6 and Fig.7a) and therefore expected to have lower frictional characteristics it was readily available in quantity and relatively cheap, being widely used as a filter medium. It was thus decided to obtain this material for some initial experiments.

At the same time samples of the full scale and model materials were sent to Imperial College, London for testing in triaxial compression machines to establish relative values of friction angle. Tests showed that under almost scaled confining pressures and in scaled test machines bulk densities were within approximately 3% of one another. However, the value of the angle of internal friction (ϕ_F) differed considerably being 41° for the gravel and 36° for the Ardleigh sand, corresponding approximately to a 16% difference in shear resistance. This result was borne out by the tracks left by the model in the sand which were too deep and too wide. Fuller details of the triaxial tests are given in Appendix A and the results are listed in Table 2.

Subsequently it was decided that a material was required with higher shear resistance. Again making use of the expertise of SAGA, three further materials were selected for closer examination. These were a carboniferous lime-stone from Carnforth, a jurassic lime-stone from South Cerney and a crushed quartzite from Weeford (Figs.7b, c and d). All were graded by sieving and closely matched the required particle size distribution. At that time it was not possible to have access to the triaxial test machine and it was decided to compare frictional characteristics of the three new materials together with the original Ardleigh sand and full scale gravel in single shear boxes. Tests were carried out by the Soils Section of a civil engineering contractor having access to a large box for testing the gravel, in addition to the standard small box suitable for the model materials. Because of the difficulty of assessing the *in situ* density of the gravel it was decided to test each material over as wide a range of densities as possible. This was achieved by rapid pouring to give loose packing and slow pouring and tamping in layers for high density. Four normal pressures were used on each material to determine the dependence of shear stress on normal stress.

These were again approximately scaled. Results of these tests are shown in Fig.8 which shows the ranges of values of tan ϕ and bulk density obtained for each material. This graph was used to select the most suitable model material which was taken to be the one with the ranges of values lying closest to that for the gravel. Unfortunately the calculated values of bulk density for gravel were incorrect due to errors in measurement of box dimensions. The values given are shown by the dashed line in Fig.8. This led to selection of the Weeford material. At a later date the values of density were revised giving the range for the gravel as shown by the solid line in Fig.8. This indicated that either Weeford or South Cerney sands would be possible choices. Subjective assessment of the full scale gravel arrester bed indicated a tendency towards the compact state so that given the correct gravel result the South Cerney sand would almost certainly have been selected. However, by this time, Weeford material had been obtained and since 20 tonnes had to be processed to produce the 1270 kg (1.25 tons) needed for the model experiment it was decided to continue work with the Weeford material.

Having two materials, Weeford possessing the required friction but low density and Ardleigh with low friction but high density, the possibility of achieving a better material by mixing was investigated. At the same time it was decided to try to introduce higher shear speeds into the test and selection method. Since no high speed shear boxes were available various other possible techniques were considered such as the firing or dropping of scaled projectiles into samples of full scale and model materials, rapid plate loading tests, and flow through orifices either forced or under gravity. Although each method was in general possible at scale most were ruled out by the size of equipment and forces required for tests on the full scale material. In the end it was decided to experiment with an extension of a flow method previously investigated as a means of determining angularity of particles[7]. These tests proved inconclusive but are described for the purposes of record in Appendix C.

6 TEST FACILITY

The test facility consisted of a pneumatically operated catapult for accelerating the models to the required test speed and a sand arrester pit of scaled dimensions.

6.1 Pneumatic catapult

The catapult was loaned by Naval Air Department, RAE, Bedford, and is shown in its modified form in Fig.9. It consisted of a 7.6 m (25 ft) long, 50 mm (2 in) bore tube mounted in a braced frame. Inside the tube was a piston to each end of which was attached a wire rope. The ropes were taken out through the ends of the tube via glands, round pulleys and connected to the front and rear of the launching trolley which was free to run along flanges on the bottom edge of the supporting frame. The whole was supported on frames in such a way that the trolley moved horizontally and parallel to a running board along which the models moved without vertically applied load. Models were located in the trolley against two thrust plates which applied accelerating forces to the cross members of the models.

To the front end of the tube was connected a pressurised air supply controlled by a solenoid valve. The air at a preselected pressure was released from the launching reservoir, accelerating the piston rearwards and the trolley and model forwards. After accelerating for 5 m (17 ft) the solenoid circuit was broken by a microswitch operated by the trolley, so cutting off the air supply. At the same time pressure remaining in the tube was vented to atmosphere through holes in the tube. The deceleration of the trolley was then achieved by compressing the air in the remaining length of the tube against a retarding pressure preset according to the launching speed being used. As the trolley decelerated the model was able to continue forward into the sand pit. Pressures in the range 0 to 700 kN/m^2 (0 to 100 psi) were used to achieve model speeds equivalent of 100 knots full scale.

After leaving the trolley the model passed through a light source and photoelectric cell arrangement, using two projections on the model to interrupt the light source and switch an electronic timing device to enable pit entry speed to be determined.

6.2 Sand arrester pit

The sand pit was initially a scaled reproduction of the full scale arrester bed with a ramp entry to 49 mm (1.93 in) depth of sand, equivalent to 0.46 m (18 in) full scale. The geometry of the pit is shown in Fig.10a. Some later tests were also carried out without a ramp (Fig.10b). The pit consisted of a base of interlocked block board sheets, to the upper sides of which were attached two wooden battens 1.31 m (4.3 ft) apart stretching the whole length of the pit which at its maximum was 33.5 m (110 ft). The battens served to retain the sand and also, being machined to the correct thickness, to provide surface levels. Relevelling following a test was achieved by dragging a straight edge along and across the tops of the battens. In order to provide some resistance to lateral displacement of the sand particles at the board surface a thin layer of sand was glued to the base boards.

7 TEST PROCEDURE

Test procedure was essentially the same for both models and followed the basic procedures for full scale experiments. The sand was levelled and the model located against the trolley which had previously been drawn to the rear of the catapult. Reservoirs were charged and the timing circuit zeroed. For the pneumatic tyred Canberra tyre pressures were checked just prior to release. Launching pressure was noted together with the calculated catapult exit speed. This enabled curves of pressure and speed to be plotted which showed not only the good repeatability of the system but also enabled very reasonable prediction of speeds for greater pressures.

The distance travelled through the pit was measured to the mean of the two main wheels of the model thus allowing for slight slewing which occurred on some occasions at the end of a run. However, the directional stability of both models was generally good and is typified by the track shown in Fig.11.

8 RESULTS

Results of the model experiments are presented in Figs.12 to 16 as curves of distance travelled through the pit against entry speed. All values have been converted to full scale equivalents. As an aid to assessing the model results actual full scale results are included on each graph.

9 DISCUSSION AND OBSERVATIONS

Fig.13 shows the results of the initial experiments with the model Lightning and Canberra in Ardleigh sand and with the pit profile of Fig.11a. Full scale results are also plotted for reference. The Lightning model, which had foam rubber tyres, showed a remarkable correspondence with the full scale results. It was noted however that the tracks left by the wheels were not only too wide but also appeared to be very much deeper than full scale. In fact the wheels seemed to have penetrated to the bottom of the pit, although this was difficult to establish due to in-filling after the wheel had passed. This indicated that the internal friction of the Ardleigh sand was too low which was subsequently confirmed by the results of the triaxial tests reported in Appendix A. On the other hand the results suggested that perhaps the frictional forces were not important compared with the inertia forces arising from imparting momentum to the sand particles. Because of the apparent correlation of the model results with full scale, speeds well above those tested full scale were simulated in order to see the possible trends which might be expected to occur in the event of an aircraft entering a pit at very high speeds. The original request for full scale work by RAE had asked for speeds up to 120 knots to be considered and run-out distances up to 300 m (1000 ft). It can be seen that at these higher speeds deceleration falls off markedly. It was clear from film of the model that there was very little penetration at high speeds, which led to an analogy with the aquaplaning problem.

Following the full scale work with the Lightning a few tests were made with the Canberra aircraft. The objective was to examine performance of an aircraft with a much larger tyre and with much lower inflation pressures. The leg load was very similar. Results for the full scale Canberra aircraft and model with solid rubber tyres are also shown in Fig.12. As expected, because of the better flotation of the larger lower pressure tyre, the aircraft travelled approximately 60% further for a similar entry speed. Model results on the other hand showed only about 10% increase in distance and were barely differentiable from those of the Lightning. Again the model appeared to penetrate to the bottom of the pit whereas the aircraft penetrated only some few inches. In order to see whether the lack of deflection of the solid tyre was responsible for the poor correlation the running surface of the tyre was cut off flat at the nominal rolling radius so that in section it resembled a modern racing car tyre. Tests with this produced no improvement. This led to the conclusion that tyre characteristics were perhaps not the main factors affecting the behaviour and that soil friction was more dominant than was at first thought. It was also considered that the remarkable results with the model Lightning were quite fortuitous and might be explained by the fact that the model, unlike the aircraft, was not able to find an equilibrium sinkage in the sand at low speeds because of the low friction, and that drag was limited only by the depth of the pit: a deeper pit would have produced reductions in distance travelled (see for example Fig.16).

The models were then tested in a more angular sand: Weeford. This material had low density but an angle of internal friction close to that of the full scale gravel. The results obtained for both models are shown in Fig.13, where those in Ardleigh are also presented for comparative purposes. It is noticeable that, although the Weeford material produced lower decelerations, either due to reduced bulk density or less sinkage, the separation between the two models is no greater than with the Ardleigh sand. The same type of result was acheived with variations in packing density in the Weeford sand (Fig.14). It was however noticeable that the wheel tracks left in the Weeford sand were less deep and corresponded better in shape with the full scale tracks, suggesting that the higher friction was, as expected, tending to increase flotation.

At this stage it was decided to investigate further the effect of tyre deflection. This decision was reinforced by evidence derived from some tyre footprint profiles obtained at that time in aquaplaning studies being carried out at Bristol University[8]. These profiles showed considerable flattening and concavity within the footprint, which it was reasoned would increase contact area and hence increase effective soil bearing capacity. The latter was known to increase approximately linearly with increase in area for footings for buildings. Since the low pressure Canberra tyre would be affected at lower speeds than the high pressure Lightning tyre it was thought that the lack of separation could be due to the unrepresentative tyre. As a result attempts were made to produce deflectable tyres for the Canberra model, firstly by making them hollow but uninflated and finally by producing scaled pneumatic tyres. Results with these tyres on the Canberra model in Weeford sand are shown in Fig.15. Results are also shown for the Lightning model with foam rubber tyres and also solid rubber tyres. Two tyre pressures were simulated for the Canberra model to show the effect of tyre pressure on the behaviour. It can be seen that there was a much greater separation between the two models. From Fig.3, which shows the load/deflection characteristics for the Lightning tyres used and the full scale tyre, it can be seen that the foam rubber tyre was lacking in radial stiffness, whereas the solid tyre was over-stiff. With correct scaling the result would be expected to lie somewhere intermediate between the results shown in Fig.15.

A further improvement in separation between models would have been expected using a sand with higher bulk density. The onset of 'planing' would have been expected to occur at lower speeds; the 'planing' speed for the lower pressure Canberra tyre being more likely to occur within the experimental speed range than that for the higher pressure Lightning tyre. Run out distances would thus be expected to increase to a greater extent for the Canberra than for the Lightning. There is some indication of this increased separation from a few tests made at a later date with the original Ardleigh sand (Fig.16). Unfortunately by that time the pit profile had been modified for some other experiments to that shown in Fig.10b, so that results could not be compared directly. In addition, although the pit depth was nominally the same as the original, i.e. 49 mm (1.93 in), a further difference arose due to the fact that the pit was by then supported off the ground on trestles. The trestles allowed the centreline of the pit to 'sag' relative to the edges giving an effective increase in sand depth at the centre of the order of 6 mm ($\frac{1}{4}$ in). Wheel penetration was thus able to increase, which probably accounts for the reduced stopping distances recorded in Fig.16.

Nevertheless it was demonstrated that the increased separation between models was maintained in the Ardleigh sand, where previously, without pneumatic tyres, there had been virtually no separation.

It was therefore concluded that on the evidence available, it was possible to use model experiments to reproduce the general behaviour of the Lightning and Canberra aircraft in a gravel pit. Due mainly to difficulties in scaling some of the soil properties of the full scale Thames Valley gravel, it was not possible to predict the performance with an accuracy greater than ±10 to 15% on stopping distance for a given entry speed. Nevertheless, it was considered that experiments made with models representative of larger aircraft using the scaling laws set out in section 3 could be used to indicate the feasibility of gravel as an emergency arresting medium. Either Weeford or Ardleigh sand could be used. The low level of friction and consequently reduced bearing strength of the Ardleigh sand would be expected to give the greater penetration and any results could probably be regarded as indicative of the best that might be achieved with naturally occurring gravels.

10 CONCLUSIONS

As a result of the work described in this Report, the following conclusions were reached in relation to modelling the passage of pneumatic tyred wheels at high speeds through cohesionless sands and gravels.

(i) The most significant parameters appeared to be those associated with the tyre, in particular the correctness of scaling of tyre pressure and load/deflection characteristics.

(ii) The shear resistance, as quantified by the angle of internal friction, and the bulk density of the model materials should be correctly related to the full scale material although the correctness appears to be somewhat less critical than that of the tyre characteristics.

(iii) It was not possible to predict results for the Lightning and Canberra aircraft with an accuracy better than ±10 to 15% on stopping distance using the Weeford sand, probably due to errors in scaling friction and density. It was, however, considered possible to use Weeford or Ardleigh sand in model experiments to determine the feasibility of gravel beds as emergency arresters for larger aircraft.

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Appendix A

TRIAXIAL COMPRESSION TESTS

The triaxial compression test is a laboratory method for determining the vertical pressure required to cause failure in a soil specimen subjected to a radial confining pressure which can be set to represent the local soil pressures. The specimen is in the form of a cylinder, generally with the length: diameter ratio of 2:1. The axial load is applied through two circular platens whilst the radial load is applied hydrostatically, the water being kept from the specimen by a thin rubber membrane. The tests can be conducted either drained or undrained. In the former case with highly porous material such as sands and gravel, the load is taken entirely by the stones whereas in the undrained case some load is taken by the pore water. In the 19 mm - 6 mm ($\frac{3}{4}$ in - $\frac{1}{4}$ in) gravel the voids ratio was high so that drainage in the pit was assumed to be complete. All triaxial tests were therefore conducted under drained conditions; the volume of water expelled during tests being used to measure the volumetric strain of the specimen. Knowing the axial strain and the volumetric strain the mean cross-sectional area could be calculated and hence the axial stress σ_1 determined assuming the specimen remains as a right cylinder. The radial stress σ_3 can be maintained constant or allowed to vary and is easily measured. The relationships between the stresses can be presented graphically as a Möhr stress circle, which enables the angle of internal friction ϕ_F to be readily determined. Further details of the triaxial tests can be found in most text books on Soil Mechanics, such as Ref.9. The triaxial tests reported here were conducted by the Soils Section of the Department of Civil Engineering, Imperial College, London. The 19 mm - 6 mm ($\frac{3}{4}$ in - $\frac{1}{4}$ in) gravel was tested in samples 30.5 mm (12 in) diameter by 61 mm (24 in) high. These were built up in layers, being well tamped to give a high degree of compaction. Densities were measured after testing when the material had been oven dried. Four levels of confining pressure σ_3 were used namely 69, 138, 276 and 552 kN/m^2 (10, 20, 40 and 80 psi) which were maintained constant throughout each test. The axial stress σ_1 was progressively increased to give a strain rate of approximately 9% per hour. The angle of internal friction was determined graphically from the Möhr stress circles for each level of confining pressure and the results are listed in Table 2. Apart from one test at 69 kN/m^2 (10 psi), the results were consistent showing a small reduction of ϕ_F with increase in confining pressure. This was regarded as characteristic of a one size gravel at the pressures tested.

Tests on the Ardleigh -7 +14 sand were made in a similar manner using small test machines with samples 38.1 mm (1.5 in) diameter by 76.2 mm (3.0 in) high. The intention was to test these at scaled confining pressures. Unfortunately the apparatus was too insensitive at these pressures and the samples were eventually tested at the same pressures as the full scale material. The results are listed in Table 2. The evelope of the Möhr stress circles was bounded by a straight line passing through the origin indicating constant friction over the stress range considered. This was consistent with the properties of dense sands.

For the purposes of evaluation of the model and full scale materials a comparison of ϕ_F was made at 69 kN/m^2 (10 psi) and 552 kN/m^2 (80 psi) respectively. This showed (Table 2) the full scale material to have a value of ϕ_F equal to 41^o compared with 36^o for the Ardleigh, representing approximately a 16% reduction of shear resistance for the model material.

Bulk densities were calculated for the start of the tests and at failure and these are shown in Table 2. It can be seen that there was a tendency for the density of Ardleigh material to be slightly greater (approximately 3%) than the 19 mm - 6 mm ($\frac{3}{4}$ in - $\frac{1}{4}$ in) gravel.

These results confirmed the initial experimental results with the model where evidence of track width and wheel penetration suggested too little frictional resistance. The difference in density was small and well within the experimental error expected in this type of work.

Appendix B

SHEAR BOX TESTS

The single shear box test is a simple method for determining the resistance to shear of a confined sample of soil subjected to a normal load. The apparatus consists basically of an open-topped box, the sides of which are cut in two by a plane parallel to the base. One half of the box is rigidly attached to the machine frame whilst the other half is able to move relative to it under the influence of a horizontal load. A plate fitting into the open top of the box provides the means of applying a vertical dead load to the enclosed soil sample. Shear strain is measured for increasing shear load. Failure of the sample is taken as the point at which there is no increase in shear load for increases in shear strain. The ratio of shear stress to normal load gives the tangent of the angle of internal friction ϕ_F .

Although the shear box test was less controllable than triaxial tests it had the advantage of being easier to perform and allowed the materials to be tested in a dry condition, so reducing the possibility of false cohesion due to surface tension effects which might arise with wet small particles.

A large box 30.5 × 22.9 × 14 mm high (12 in × 9 in × 5.5 in high) was located through a civil engineering company. This was used for testing the 19 mm - 6 mm ($\frac{3}{4}$ in - $\frac{1}{4}$ in) gravel. The four model materials, Ardleigh, Weeford, South Cerney and Carnforth sands, were each tested in small standard boxes 60 × 60 × 29 mm high (2.36 in × 2.36 in × 1.5 in high). Since the *in situ* bulk density was not readily determinable it was decided to investigate the range of values of bulk density and angle of internal friction that the materials were able to realise. A loose bulk density was achieved by pouring the materials rapidly into the shear boxes whilst a dense packing state was obtained by pouring and tamping in layers. Normal pressures applied by dead load were the same as those for the triaxial tests for the full scale material, namely 69, 138, 276 and 552 kN/m^2 (10, 20, 40 and 80 psi). Pressures for the model materials were 6.9, 13.8, 27.6 and 55.2 kN/m^2 (1, 2, 4 and 8 psi) i.e. close to the scale factor of 9.3:1. The 19 mm - 6 mm gravel was strained at 0.15 mm/min (0.06 in/min) and in model materials at 0.12 mm/min (0.048 in/min) and 0.04 mm/min (0.016 in/min). The results of the tests are given in Table 3. It was noted that over the ranges of stresses examined the angle of internal friction was essentially independent of normal stress and that there was negligible cohesion. Although the initial tests showed remarkable consistency and linearity with variation of normal stress and bulk density, subsequent tests carried out on nominally identical samples at recommended bulk densities showed considerable variation between testing laboratories. Fig.8 and Table 3 show the variability which occurred with Weeford sand, presumably the result of its greater angularity and the multi-farious interlocking arrangement which could occur compared with the more rounded Ardleigh particles.

The results of the shear box tests were plotted as bands showing the relationship of tangent of angle internal friction to bulk density for each material (Fig.8). Model material was selected as that having the band closest to that of the full scale gravel. As stated in the main text incorrect values of density were originally calculated for the full scale material leading to a selection of Weeford sand as the most appropriate model sand. It will be noted that the shear box test re-affirmed the previous evidence of low friction for the Ardleigh sand.

As an extension of the flow tests reported in Appendix C shear box tests were also conducted on a mixture of 67% Ardleigh and 33% Weeford material. Tests were conducted by two laboratories at specified densities. Both reported reductions in shearing resistance below those of either parent material (Table 3). This rather surprising result was without complete explanation. It is possible that at this particular mixture ratio only sufficient angular Weeford particles were present to assist with intergranular sliding. On this evidence of unpredictability there was no incentive to proceed further with mixtures and the work was terminated.

Appendix C

FLOW AND LOOSE BULK DENSITY TESTS

From the outset it was realised that conventional soil testing apparatus was very limited in the range of shear rates that they could apply to soil samples. It was not known in what way high shear rates would effect the soil properties (i.e. friction, cohesion) or whether these conventional soil parameters would still be meaningful in comparing two materials at these higher rates. Various methods for dynamic testing of soils were considered but most were impractical when considering application to the full scale gravel. Observations of high speed film of the full scale and model experiments showed the arresting material to behave very much as a fluid. It was decided, therefore, to carry out a pilot investigation of a flow rate test in which material was allowed to flow through an orifice under the influence of gravity. Similar experiments had previously been conducted by a number of workers, in particular Hughes and Bahramian[7], as a means of comparing the angularity of aggregates with the same particle size distribution. These experiments had consisted of measuring the time taken for a known volume of material to flow through an orifice and comparing that with the time taken for an equal volume of glass spheres of the same size; the ratio being termed the angularity number. A supplementary experiment had also been carried out in which the solids ratio (ratio of solid volume to total volume) of the aggregate have been measured after falling from the orifice through a fixed distance into a container below. Comparisons were again made with the solids ratio achieved for glass spheres of the same size. Although the flow rates were still relatively low the movements of the particles were more realistic than those in shear box and triaxial tests, and it was thought that the method might be better and quicker for selecting model materials. It was considered that such tests would take account of particle shape, surface texture and size. By using linearly scaled hoppers and containers the flow times for equivalent volumes were expected to be related by the time scale factor $1:9.3^{\frac{1}{2}}$.

A schematic diagram of the apparatus used is shown in Fig.17. The volumes of the hoppers and containers were determined by considering the mass of full scale gravel which could be handled reasonably and the orifice size by the need for a long enough flow time for the model material to allow sensible accuracy from a hand-operated stop-watch. Consideration was also given to the ratio of orifice size to particle size. In Ref.7 ratios greater than 10:1 had been used which would have given very short flow times for the model materials. Bishop[10], on the other hand, quotes a ratio of 4 or 6:1 for triaxial test specimens. It was decided, therefore, to use an orifice of 100 mm (4 in) diameter for the full scale material and 11 mm (0.43 in) for the model materials.

Tests were conducted with materials loosely and densely packed in the hopper. Five tests were carried out with each sample at each density. All materials were tested dry with an additional set of wet tests on the gravel. Materials tested were 19 mm - 6 mm Thames Valley gravel, Ardleigh, Weeford, Carnforth and South Cerney sands (all -7 +14 BS sieve), and 20 mm and 2 mm glass spheres. Tests were also conducted on mixtures made up in varying proportions of Weeford and Ardleigh sands. Table 4 gives the results of all these tests. Examination of the results showed that in general the volume of particles flowing per unit time was almost independent of the packing state in the hopper, and that the effect of water on the Thames Valley gravel was to increase the flow rate by approximately 10%, presumably by reducing intergranular surface friction. It was also evident that flow times could not be compared directly. The figures shown in parenthesis in column 4 are the flow times that should have been recorded for a suitable scaled material. It will be noted that none of the times recorded for sands are short enough; Ardleigh being closest. To eliminate the effect of differing particle density and packing density in the hopper, the particle volume flowing per second was calculated. These are given in column 5 where figures have been divided by the hopper volume to keep the full scale and model numbers of the same order. Again figures in parenthesis show equivalent model values. From these it will be noted that none of the model materials is again correct: Ardleigh and Sourth Cerney being closest. The glass spheres appear to be correctly related to within 2 or 3% despite considerable differences in particle density. A mean particle volume flow ratio is calculated by dividing the figures obtained for the sands and gravel into those for the 2 mm and 20 mm glass spheres respectively (column 6). These results reflect those of column 5.

From the loose bulk density tests it was noted that the effect of pouring from loosely and densely packed hoppers was negligible. Comparison of loose bulk densities showed South Cerney, 67%/33% and 40%/60% Ardleigh/Weeford mixtures as most favourable (column 7). Column 8 lists the solids ratios which show South Cerney, Carnforth and Ardleigh sands as most closely related to the full scale gravel. There was, however, a greater discrepancy between the solids ratio for 2 mm and 20 mm glass spheres (approximately 6%) than had been recorded for the flow tests. An angularity number was calculated by dividing the solids ratio for the glass spheres by that of the respective sands and gravel (column 10). 60%/40%, 72%/28%, 67%/33% Ardleigh/Weeford mixtures looked best on this basis.

Considering the parameters thought to be of greatest importance, i.e. particle density, loose bulk density and particle volume flow, the above results would suggest selection of South Cerney sand for the model experiments. This was in line with conclusions reached from the revised tan ϕ versus bulk density results (Fig.8).

However, the results were not considered conclusive enough to recommend this method, in the form used here, for the purposes of selecting scaled model materials in preference to more conventional methods such as shear box testing.

Table 1

PRINCIPAL AIRCRAFT AND MODEL DIMENSIONS AND WEIGHTS

Aircraft parameter	Lightning		Canberra	
	Prototype	Model	Prototype	Model
Mass (kg) Weight (lb)	11804 26000	14.64 32.24	12440 27400	15.43 33.98
Radius of gyration in pitch (m) (ft)	3.75 12.3	0.40 1.32	2.87 9.4	0.31 1.01
cg height above main wheel axles (m) (ft)	1.62 5.3	0.17 0.57	1.34 4.4	0.14 0.47
cg position forward of main wheel axles (m) (ft)	0.43 1.4	0.046 0.15	0.25 0.82	0.27 0.088
Wheelbase (m) (ft)	5.46 17.9	0.59 1.92	4.30 14.1	0.46 1.52
Track (m) (ft)	3.90 12.8	0.42 1.38	4.82 15.8	0.52 1.70
Main wheel tyre size (in)	33 × 6.75 - 20	3.55 × 0.73 - 2.1	43 × 13.5 - 19	4.62 × 1.45 - 2.0
Main wheel tyre pressure (kN/m^2) (psi)	1793 260	193 28	758 110	81 11.8
Nose wheel tyre size (in)	22 × 5.50 - 12	2.36 × 0.59 - 1.3	26 × 6.50 - 14	2.80 × 0.70 - 1.5
Nose wheel tyre pressure (N/m^2) (psi)	NOT SCALED			
Nose wheel spacing C_L to C_L (m) (ft)			0.38 1.25	0.04 0.13

Table 2

RESULTS OF TRIAXIAL COMPRESSION TESTS

Material	19 mm - 6 mm ($\frac{3}{4}$" - $\frac{1}{4}$") Thames Valley gravel					Ardleigh sand -7 +14			
Cell (lb/in^2) pressure σ'_3 (kN/m^2)	10 69	10 69	20 138	40 276	80 552	10 69	20 138	40 276	80 552
Friction angle ϕ_F	46.8	54.0	46.5	43.9	41.0	36.2		37.3	36.5
Density (lb/ft^3) (start) (kg/m^3)	94.8 1519	94.5 1514	97.3 1559	95.7 1533	98.2 1573	102.9 1648		100.0 1602	98.8 1583
Density (lb/ft^3) (failure) (kg/m^3)	92.8 1487	93.4 1496	95.4 1528	95.8 1535	100.3 1607	98.4 1576		100.8 1615	99.7 1597

Table 3

RESULTS OF SHEAR BOX TESTS

Material	Density		Strain rate		ϕ_F (°)	
	kg/m^3	lb/ft^3	cm/min	in/min		
Thames Valley gravel 19 mm - 6 mm	1341	83.7	0.152	0.06	46	
	1486	92.8	0.152	0.06	54	
Ardleigh sand -7 +14 BS sieve	1434	89.5	0.0406	0.016	35	
	1434	89.5	0.122	0.048	36	
	1565	97.7	0.0406	0.016	47	
	1565	97.7	0.122	0.048	47	
South Cerney sand -7 +14 BS sieve	1349	84.2	0.0406	0.016	41	
	1349	84.2	0.122	0.048	41	
	1522	95.0	0.0406	0.016	56	
	1522	95.0	0.122	0.048	57	
Carnforth sand -7 +14 BS sieve	1405	87.7	0.0406	0.016	42	
	1405	87.7	0.122	0.048	40	
	1578	98.5	0.0406	0.016	54	
	1578	98.5	0.122	0.048	57	
Weeford sand -7 +14 BS sieve	1195	74.6	0.0406	0.016	40	
	1195	74.6	0.122	0.048	40	
	1389	86.6	0.0406	0.016	52	
	1389	86.6	0.112	0.048	52	
Ardleigh sand -7 +14 BS sieve	1426	89.0	0.122	0.048	36	*
	1426	89.0	0.122	0.048	36	**
	1586	99.0	0.122	0.048	49	*
	1583	98.8	0.122	0.048	46.5	**
Weeford sand -7 +14 BS sieve	1265	79.0	0.122	0.048	37	*
	1265	79.0	0.122	0.048	40	**
	1442	90.0	0.122	0.048	52	*
	1442	90.0	0.122	0.048	44	**
67% Ardleigh +33% Weeford -7 +14 BS sieve	1346	84.0	0.122	0.048	34	*
	1346	84.0	0.122	0.048	29	**
	1522	95.0	0.122	0.048	40	*
	1522	95.0	0.122	0.048	41	**

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** Department of the Environment (Soils Laboratory, Cardington)

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Table 4 - SUMMARY OF FLOW AND LOOSE BULK DENSITY TESTS

Material	Mean § particle specific gravity	Flow tests				Loose bulk density tests		
		Bulk density in hopper (kg/m^3)	Flow time from hopper (sec)	Ratio particle to total volume flowing/sec (sec^{-1})	Mean vol. flow ratio	Loose bulk density after pouring (kg/m^3)	Solids ratio	Mean angularity number
19 mm - 6 mm Thames Valley gravel (wet)	2.43	1398 1575	25.4 (8.33) 28.6 (9.38)	0.0227 (0.0692) 0.0226 (0.0692)	1.110	1341 1373	0.552 0.565	1.075
19 mm - 6 mm Thames Valley gravel (dry)	2.43	1336 1519	27.1 (8.89) 29.4 (9.64)	0.0203 (0.0619) 0.0213 (0.0650)	1.211	1317 1322	0.542 0.544	1.105
100% Ardleigh -7 +14 BS sieve	2.65	1414 1586	8.94 10.06	0.0597 0.0595	1.252	1418 1422	0.535 0.537	1.055
87.5% Ardleigh 12.5% Weeford	2.64	1371 1551	9.02 10.03	0.0577 0.0572	1.305	1365 1368	0.518 0.519	1.088
72% Ardleigh 28% Weeford	2.62	1336 1512	9.22 10.58	0.0554 0.0547	1.365	1355 1352	0.518 0.517	1.092
67% Ardleigh 33% Weeford	2.62	1352 1511	9.08 10.20	0.0569 0.0565	1.324	1360 1362	0.519 0.520	1.088
67% Ardleigh* 33% Weeford	2.62	1352 1531	9.46 10.56	0.0532 0.0537	1.403	1325 1325	0.506 0.506	1.117
60% Ardleigh 40% Weeford	2.61	1320 1493	9.06 10.40	0.0559 0.0551	1.352	1341 1341	0.515 0.515	1.098
40% Ardleigh 60% Weeford	2.60	1291 1475	9.48 11.08	0.0525 0.0513	1.446	1299 1299	0.500 0.500	1.130
100% Weeford -7 +14 BS sieve	2.56	1241 1446	9.82 11.14	0.0495 0.0497	1.513	1257 1264	0.492 0.495	1.145
South Cerney -7 +14 BS sieve	2.44	1328 1512	9.36 10.58	0.0583 0.0587	1.283	1325 1322	0.544 0.543	1.040
Carnforth -7 +14 BS sieve	2.56	1410 1573	10.08 11.56	0.0547 0.0533	1.390	1392 1395	0.545 0.546	1.037
20 mm nominal soda glass spheres	2.50	1514	24.0 (7.87)	0.0252 (0.0769)	1.000	1495	0.600	1.000
2 mm nominal lead glass spheres	3.05	1690 1792	7.30 7.90	0.0757 0.0745	1.000	1719 1719	0.565 0.565	1.000

NOTE: All mixtures by weight

* Second mixture made up at later date for shear box testing

§ calculated where necessary from $\rho_{mix} = \rho_A \rho_W \Big/ \left[\frac{n}{100} \rho_W + \left(1 - \frac{n}{100}\right) \rho_A\right]$

where: ρ_{mix} = mixture particle density, ρ_N = Weeford particle density

ρ_A = Ardleigh particle density n = percentage Ardleigh included

Figures in parenthesis are scaled to model values.

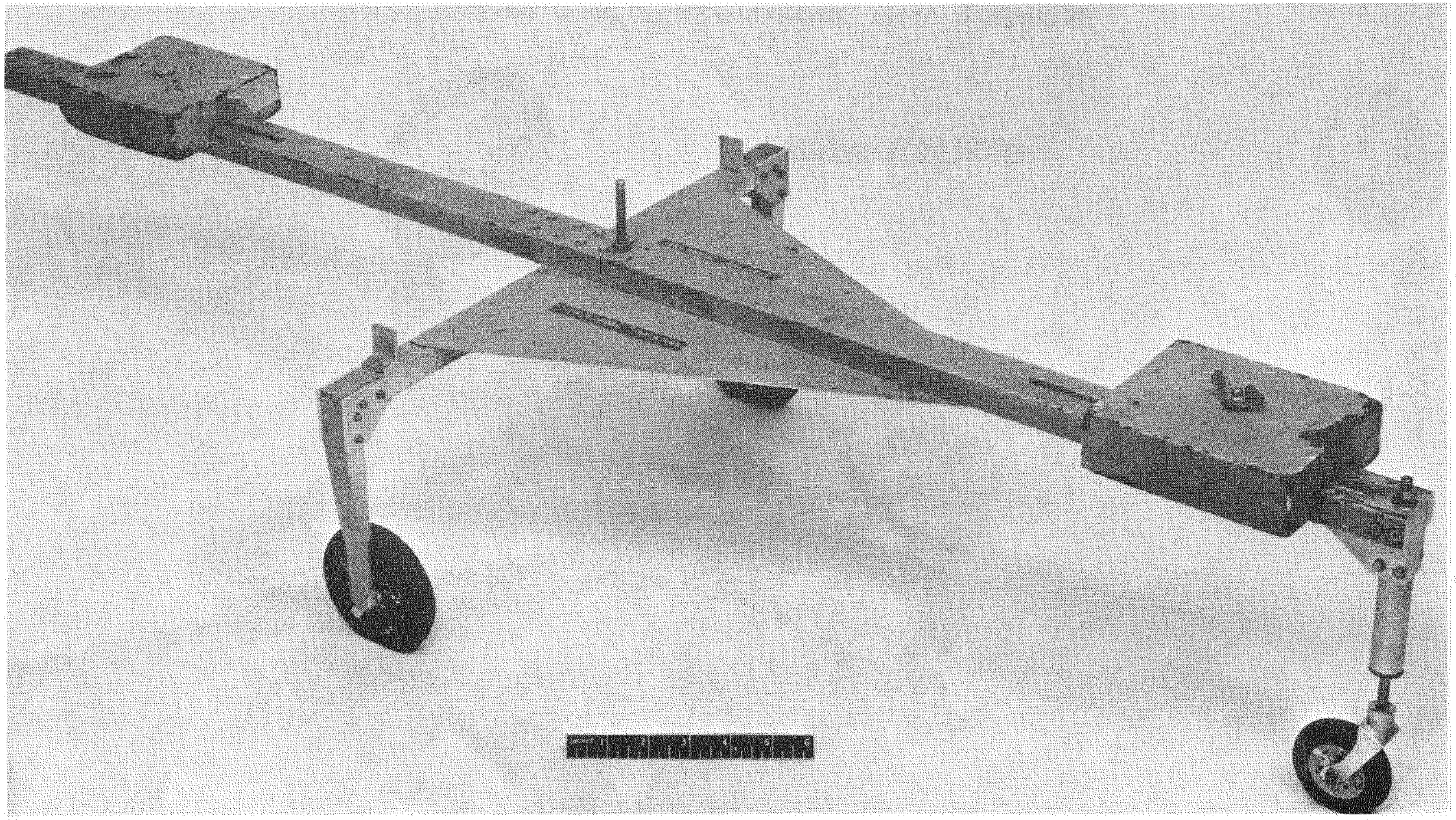


Fig.1 1:9.3 scale model of Lightning aircraft 11804 kg (26000 lb)

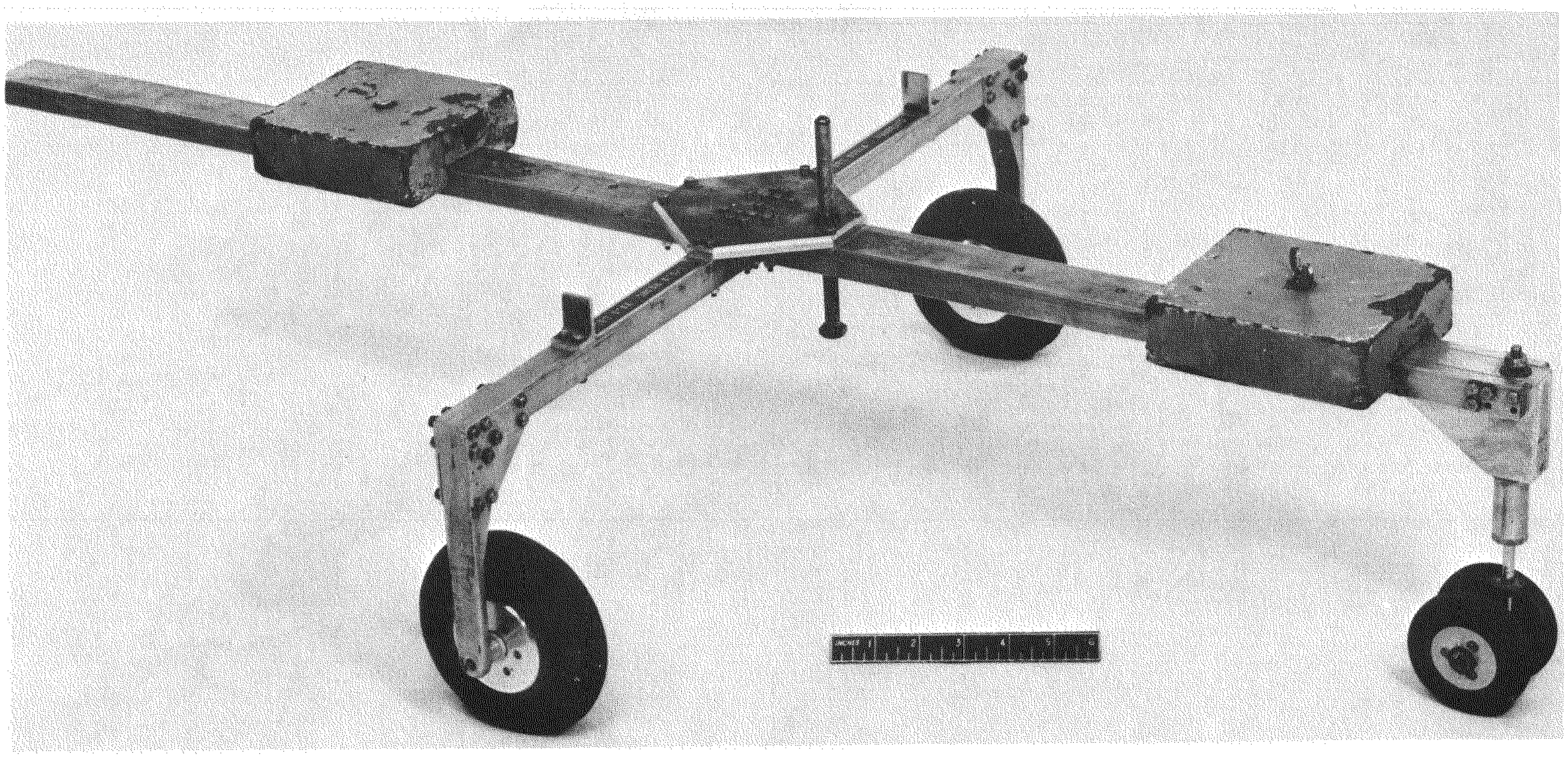


Fig.2 1:9.3 scale model of Canberra aircraft 12440 kg (27400 lb)

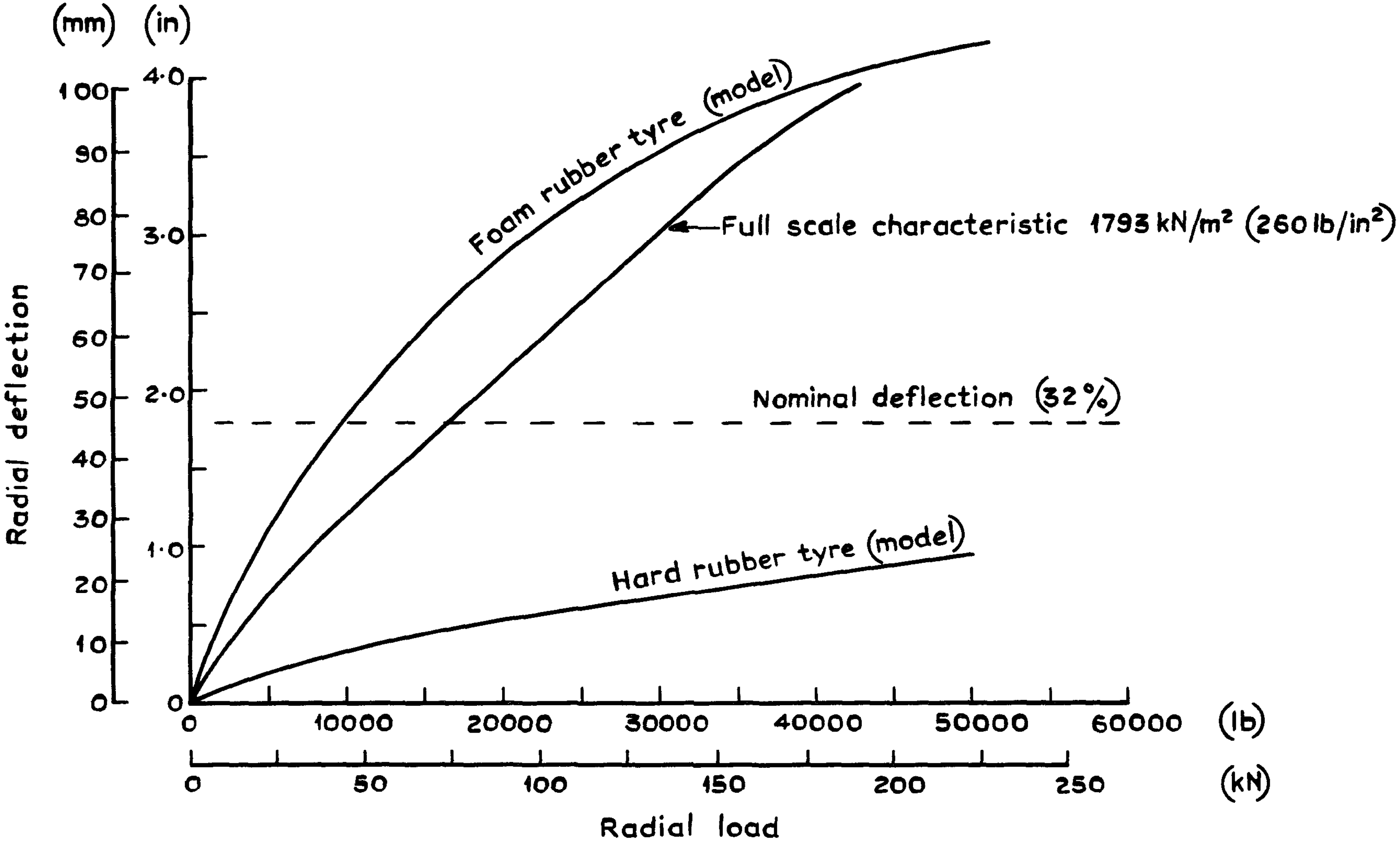


Fig.3 Load / deflection curves for full scale and model Lightning main wheel tyres

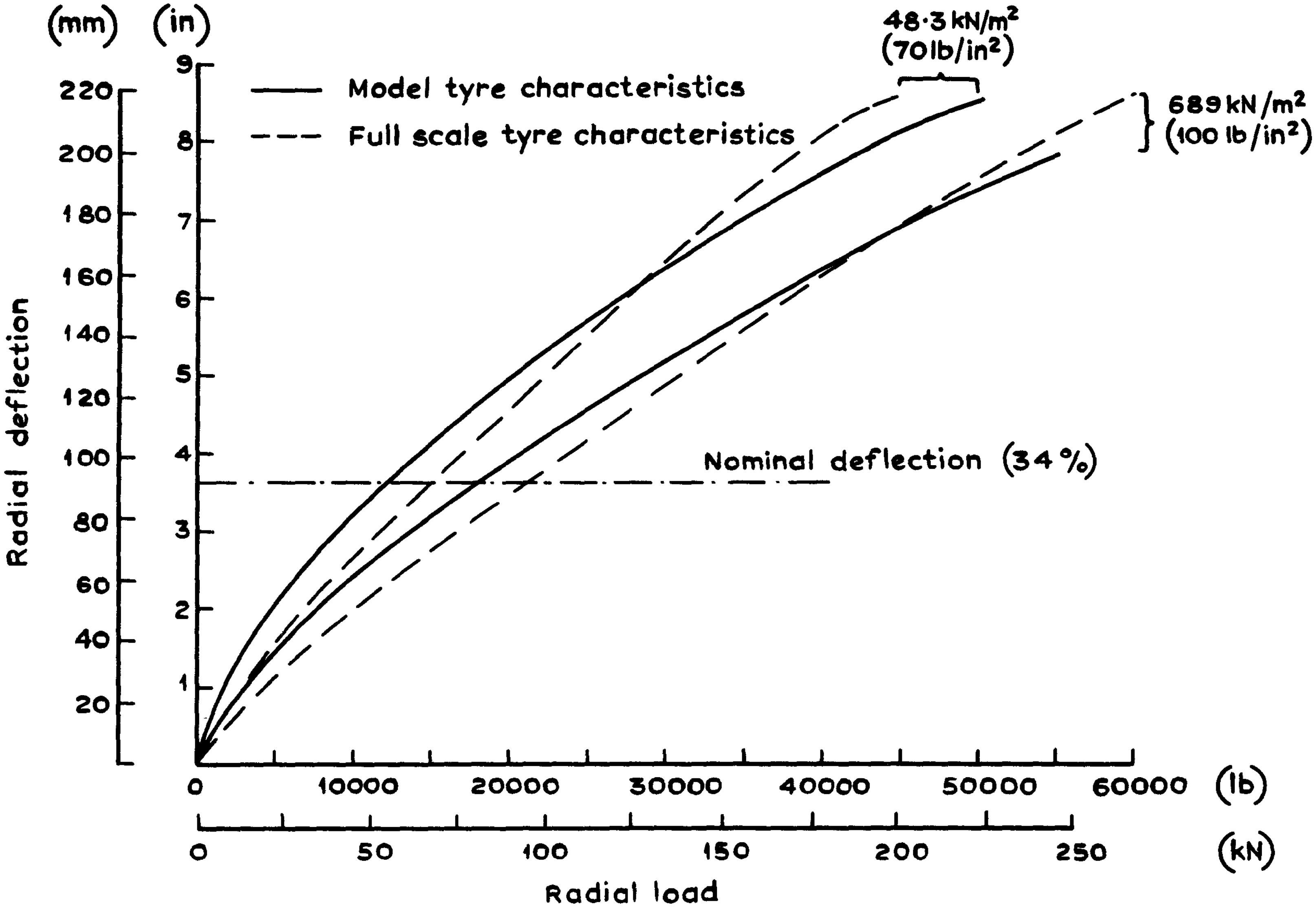


Fig.4 Load/deflection curves for full scale and model Canberra main wheel tyres

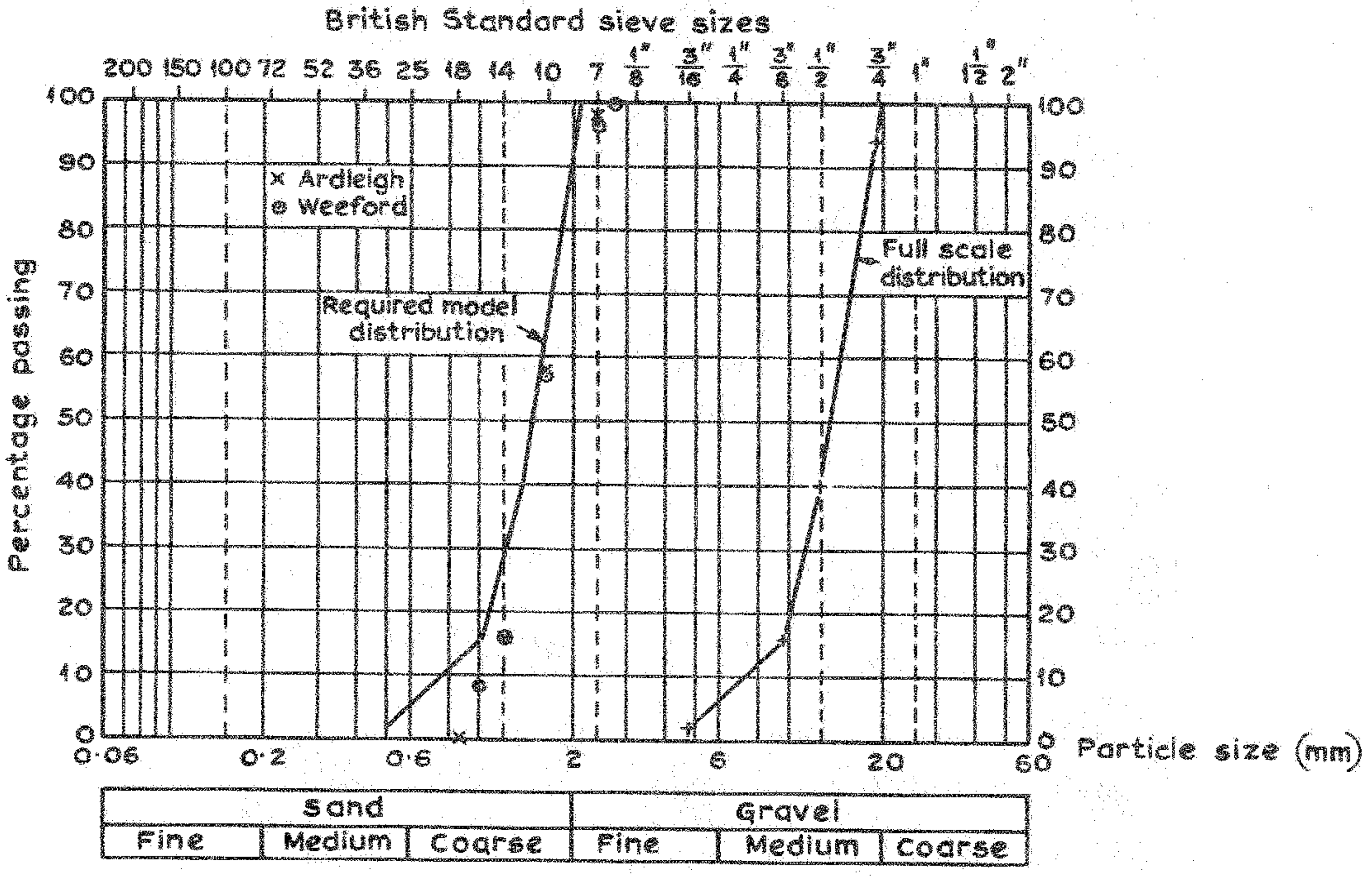


Fig.5 Sieve analyses of full scale gravel and two model sands

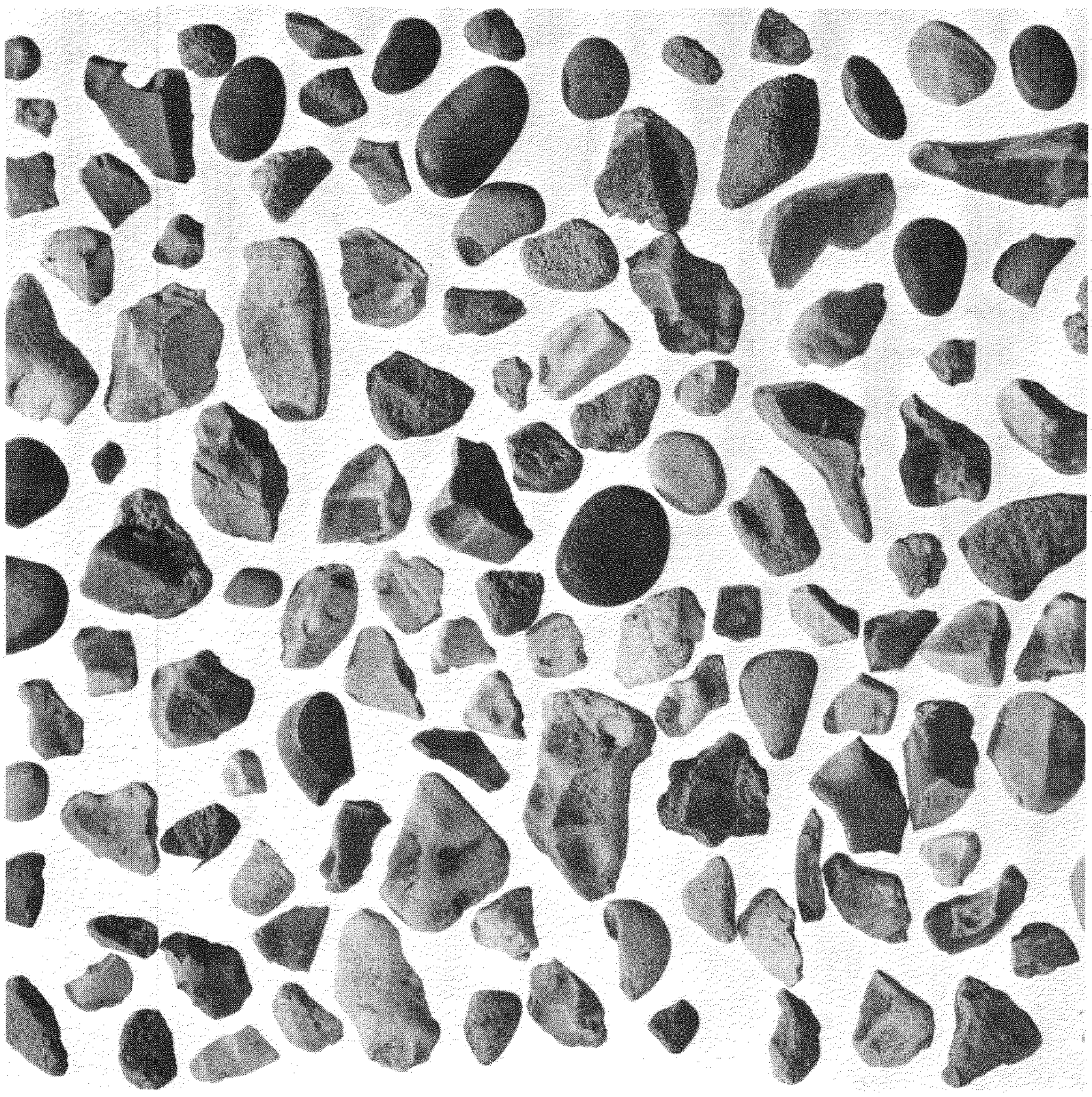
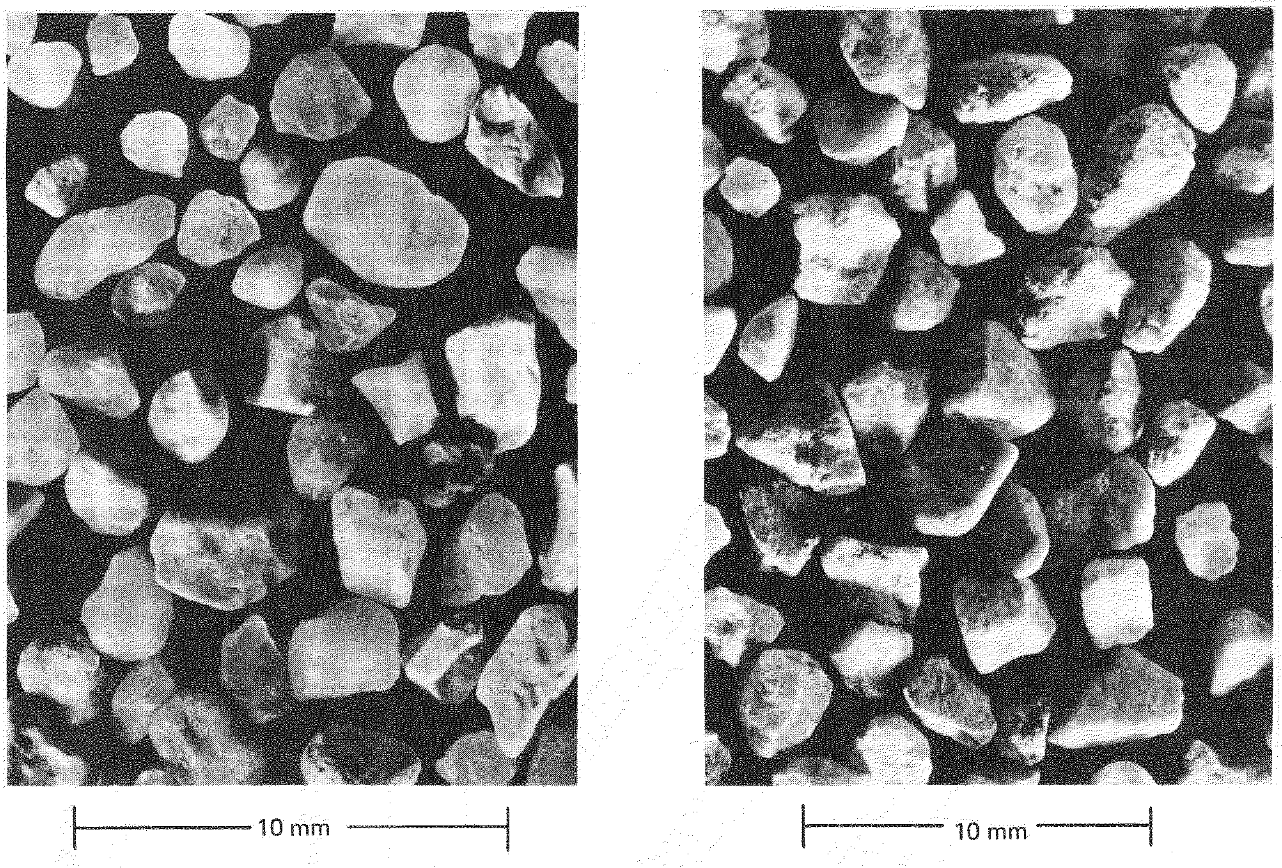
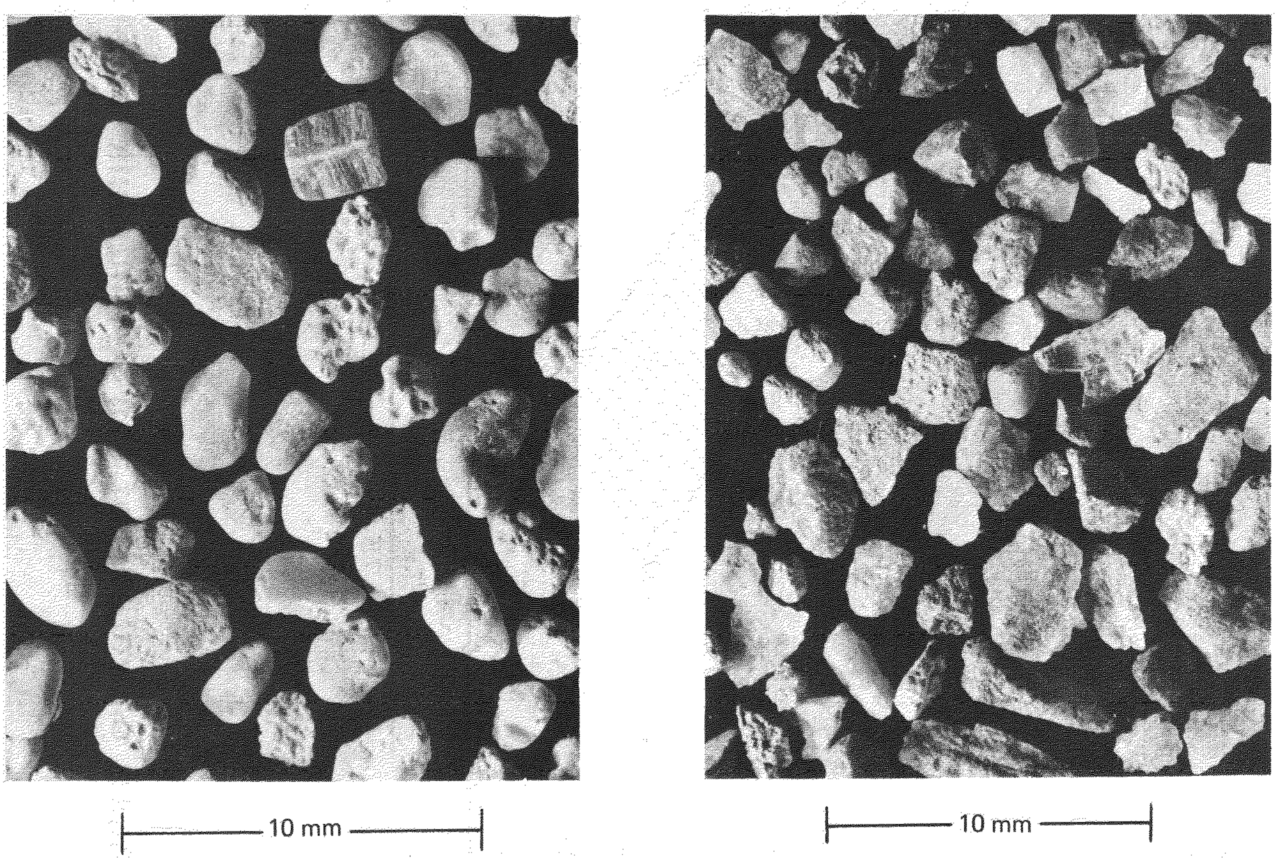


Fig.6 Full scale material – 19 mm–6 mm (¾ in–¼ in) Thames Valley gravel (flint)



(a) Ardleigh
(flint)

(b) Carnforth
(carboniferous limestone)



(c) South Cerney
(jurassic limestone)

(d) Weeford
(quartzite)

Fig.7 Model sands considered – all graded –7 +14 BS sieve

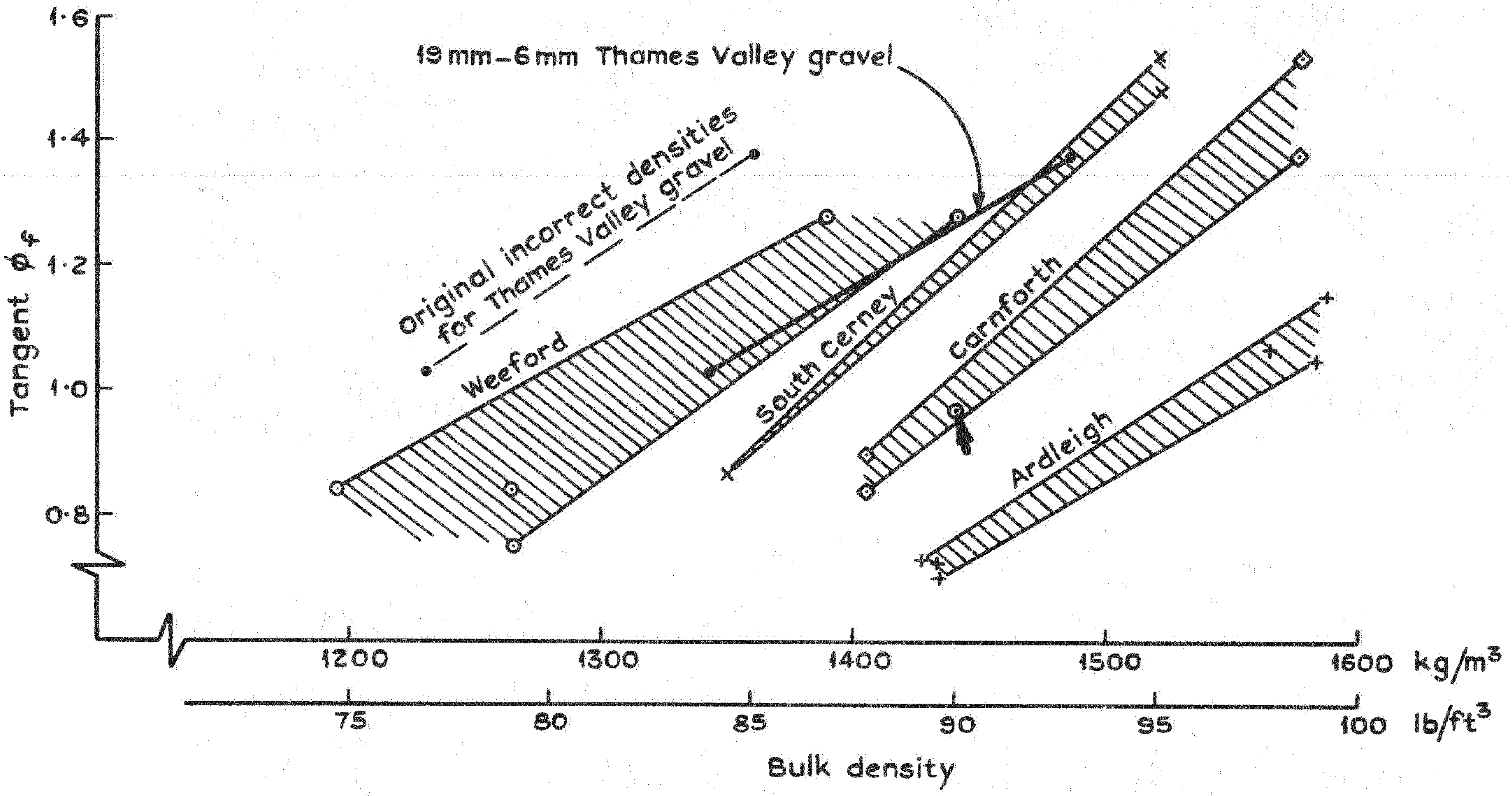


Fig.8 Ranges of values of tan ϕ_F and bulk density for full scale gravel and model sands (as determined by shear box tests)

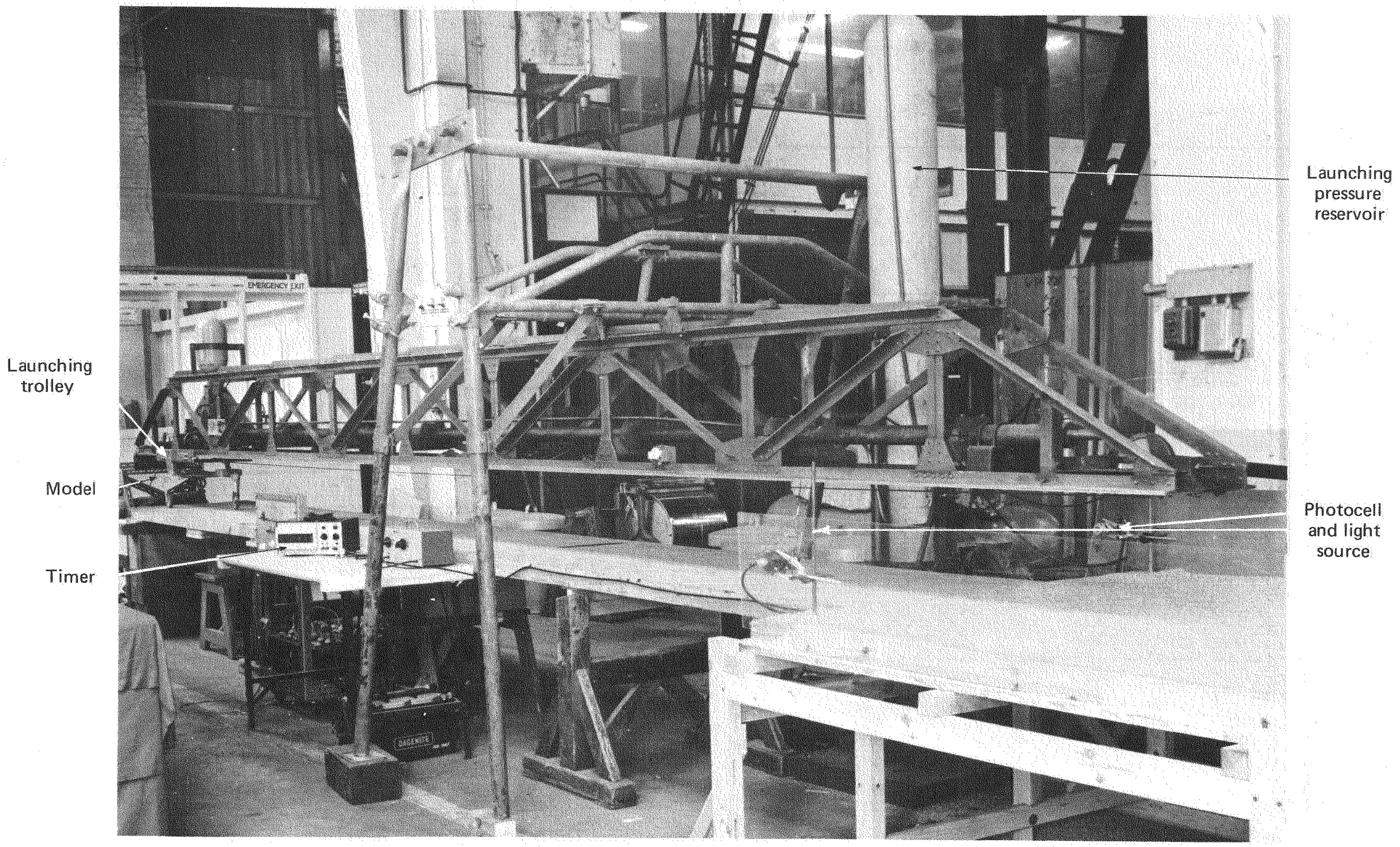
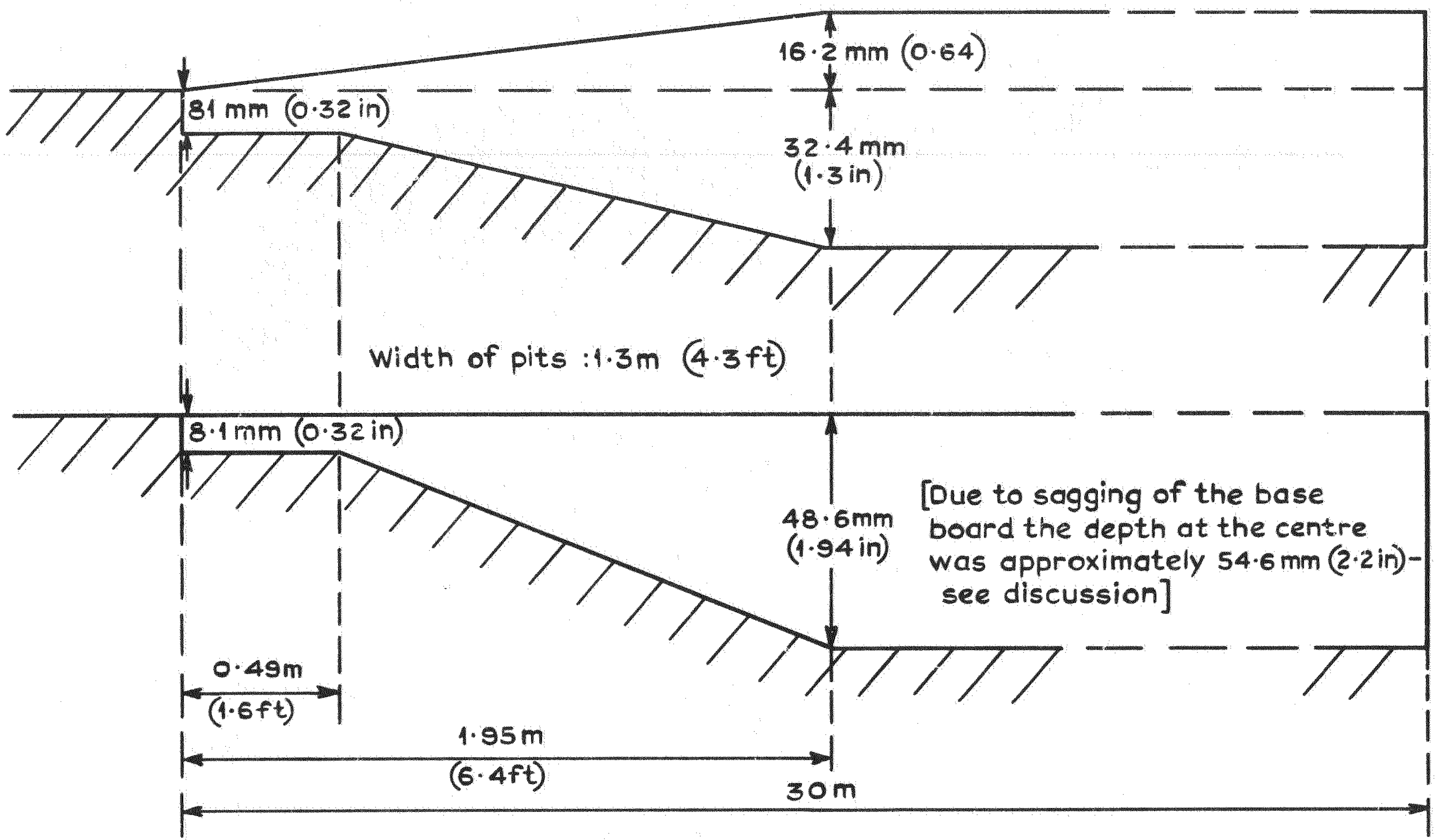


Fig.9 General view of pneumatic catapult showing location of model and speed measuring equipment

a Scaled pit geometry as used for majority of experiments



b Modified pit geometry

Fig.10 a & b Model pit geometries

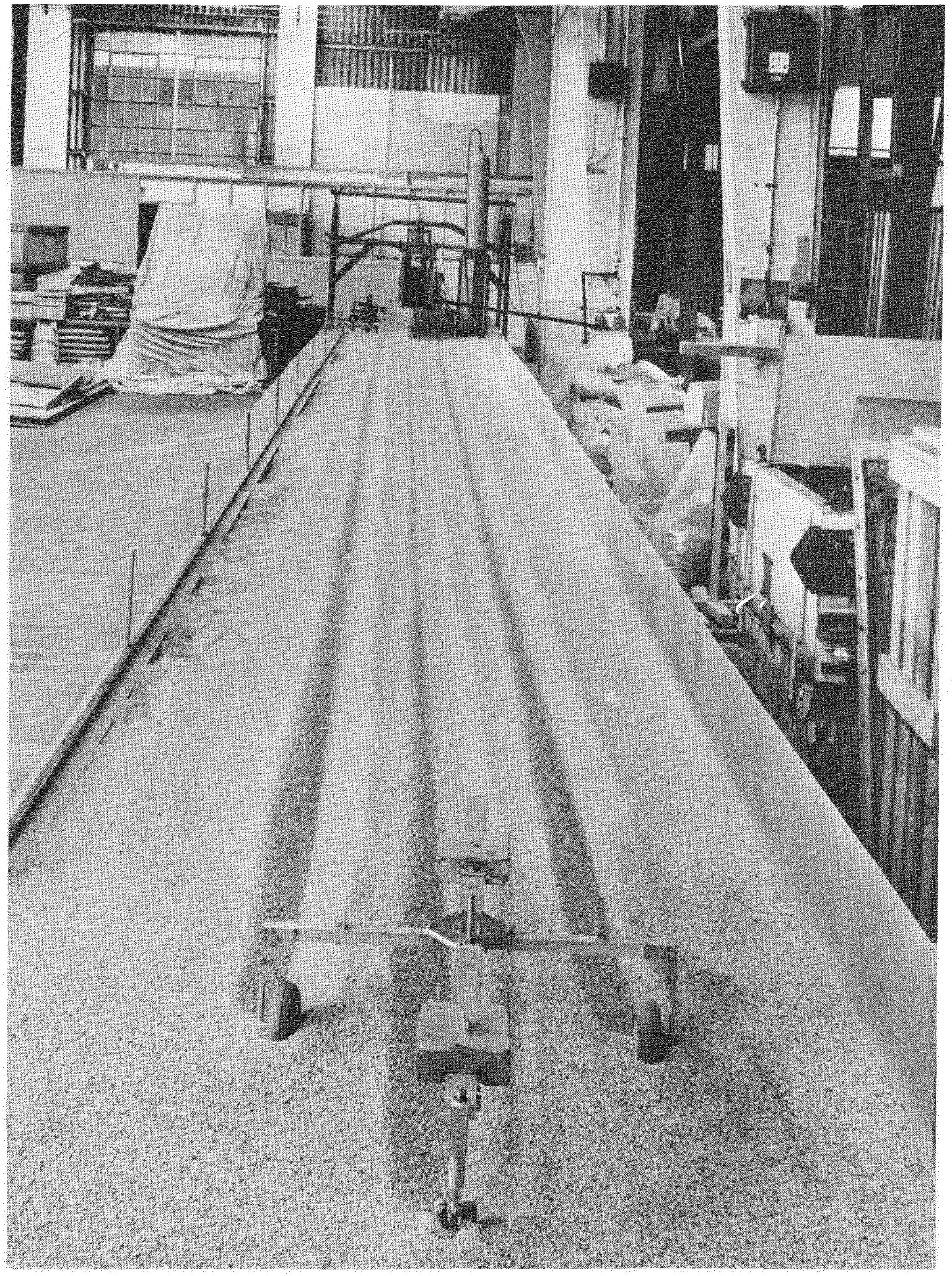


Fig.11 Canberra model in pit illustrating directional stability

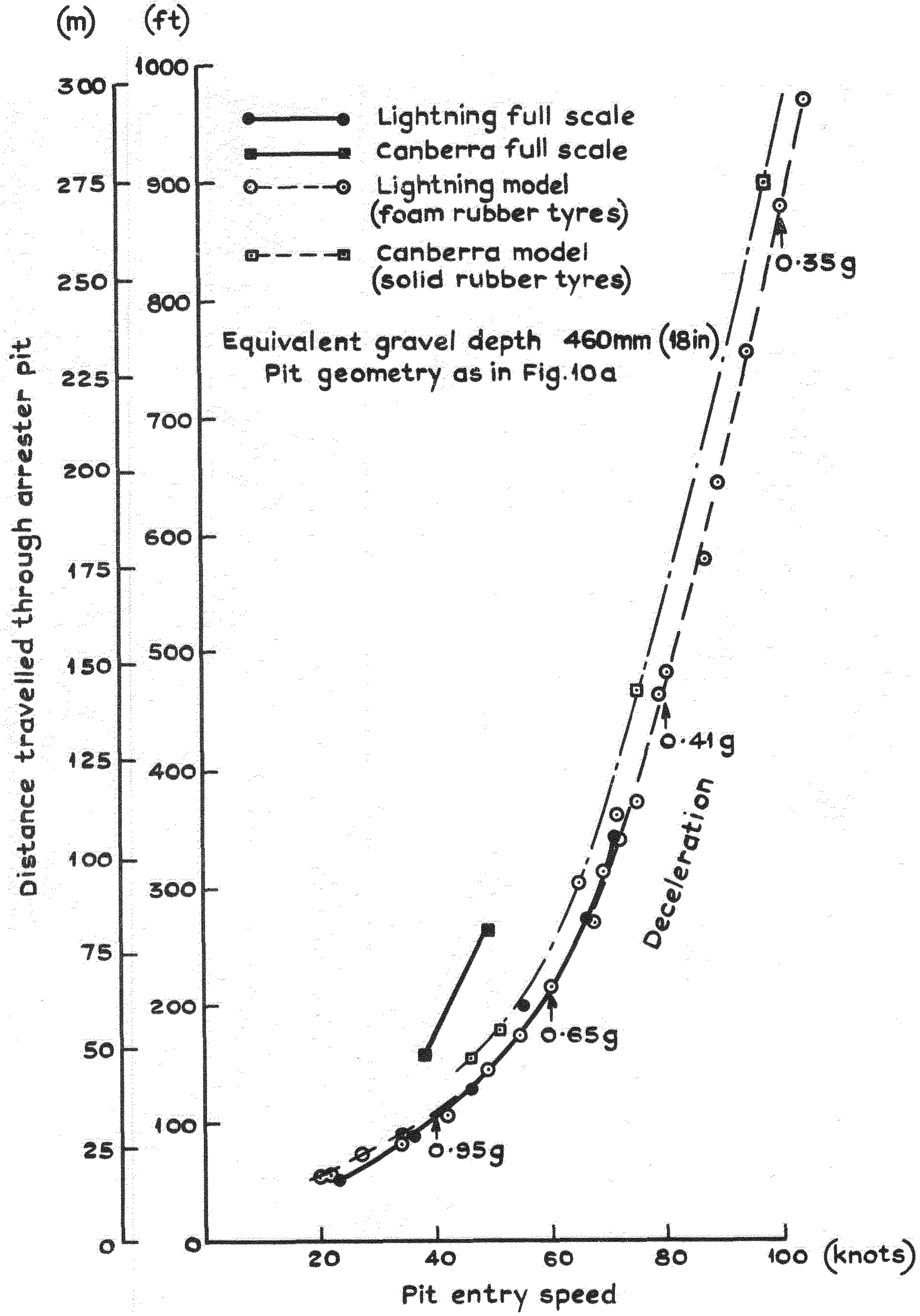


Fig. 12 Comparative performance of full scale aircraft and models in equivalent 460 mm (18 in) gravel – Ardleigh sand

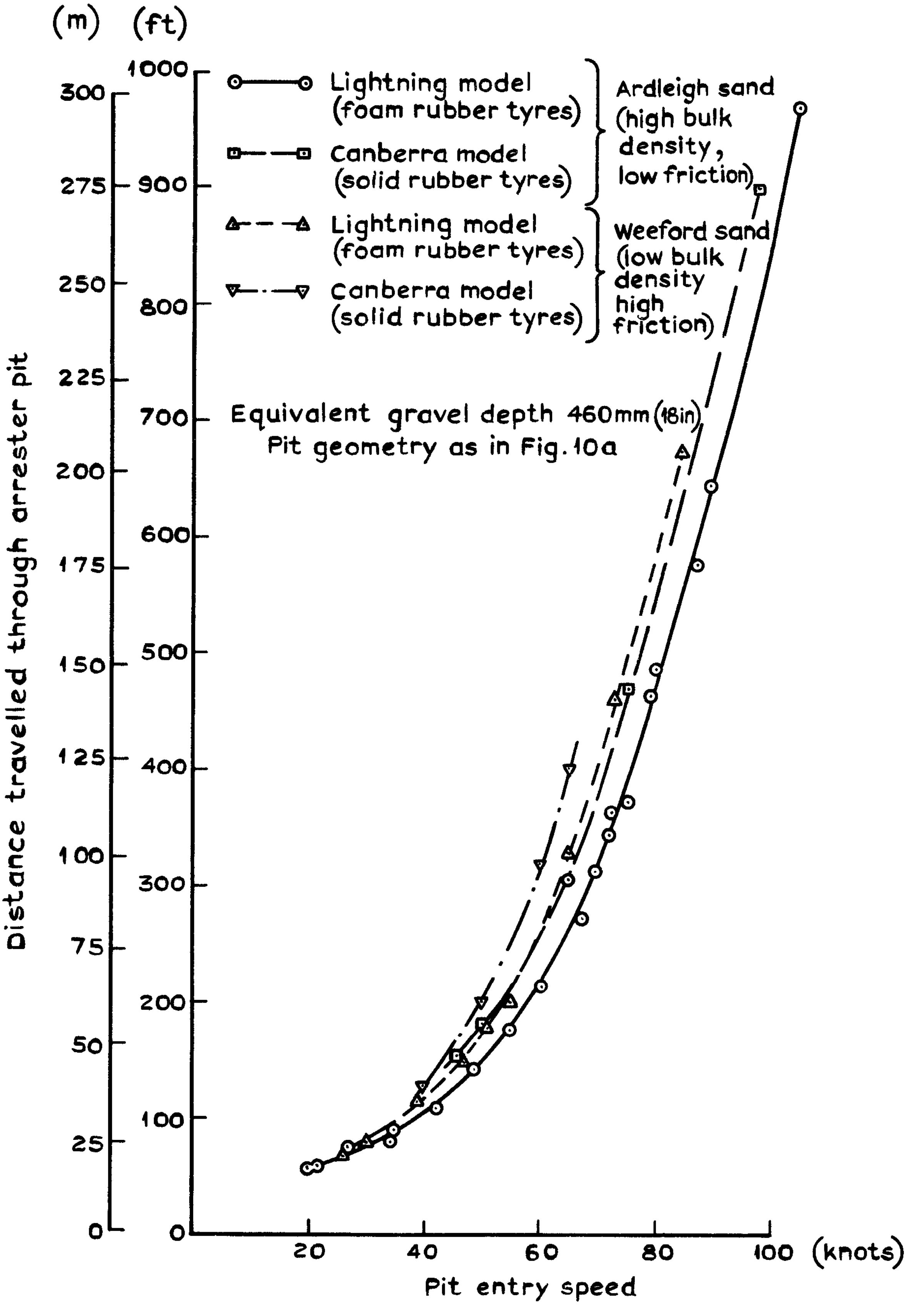


Fig. 13 Comparative performance of Lightning and Canberra models in Ardleigh and Weeford Sands

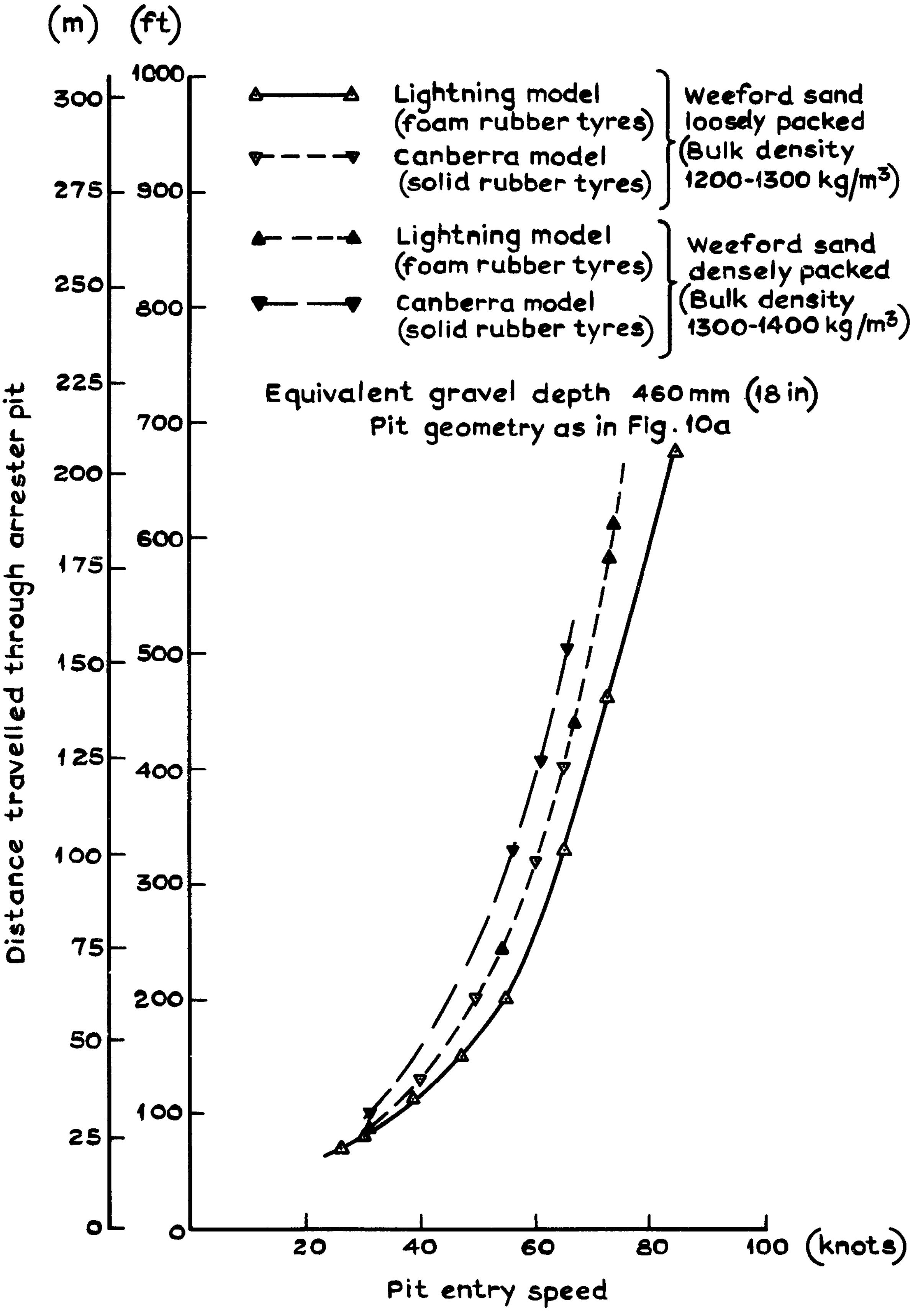


Fig. 14 Curves showing the effect of increasing bulk density of Weeford sand

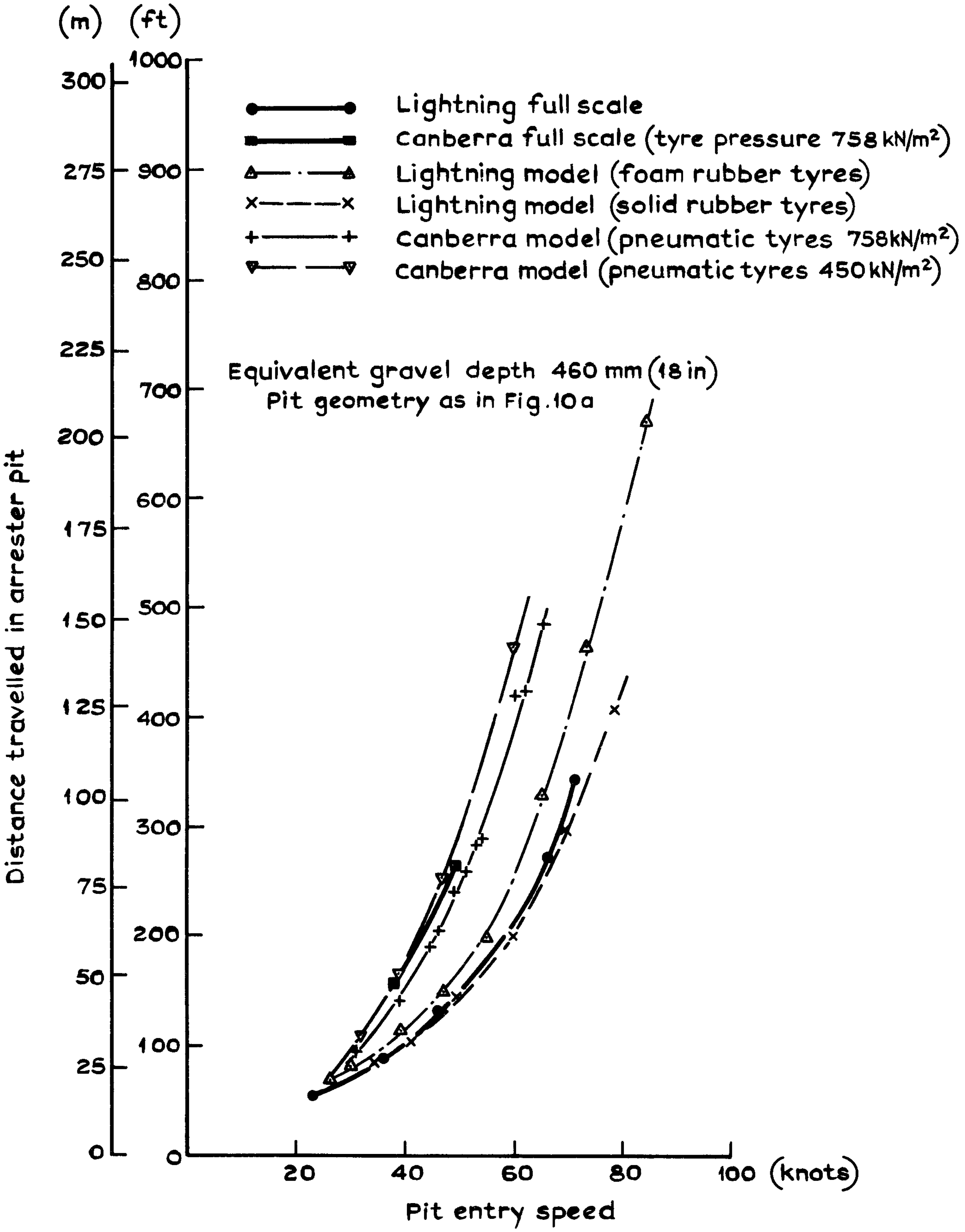


Fig.15 Curves showing the separation between models achieved using pneumatic tyres on Canberra model — Weeford sand

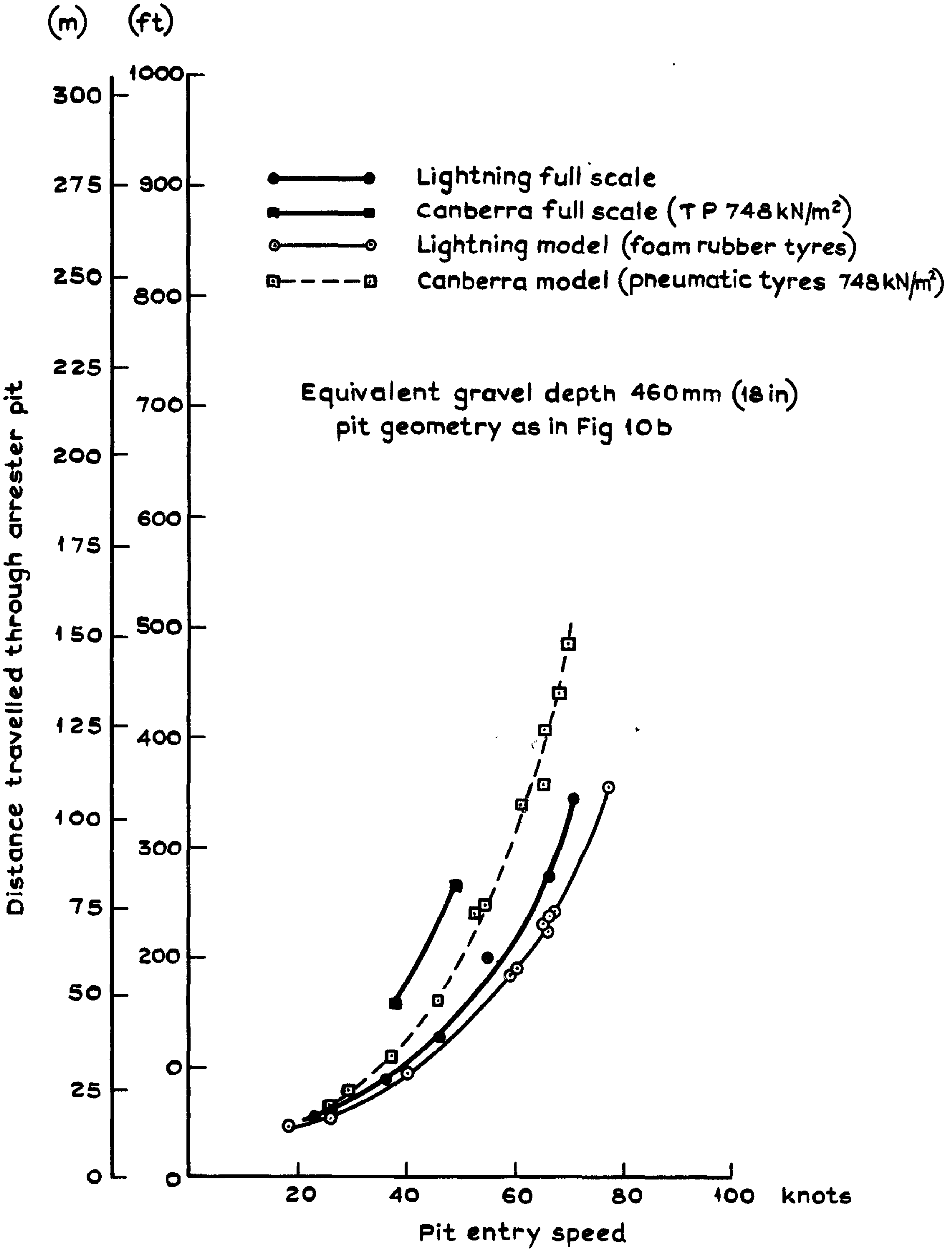
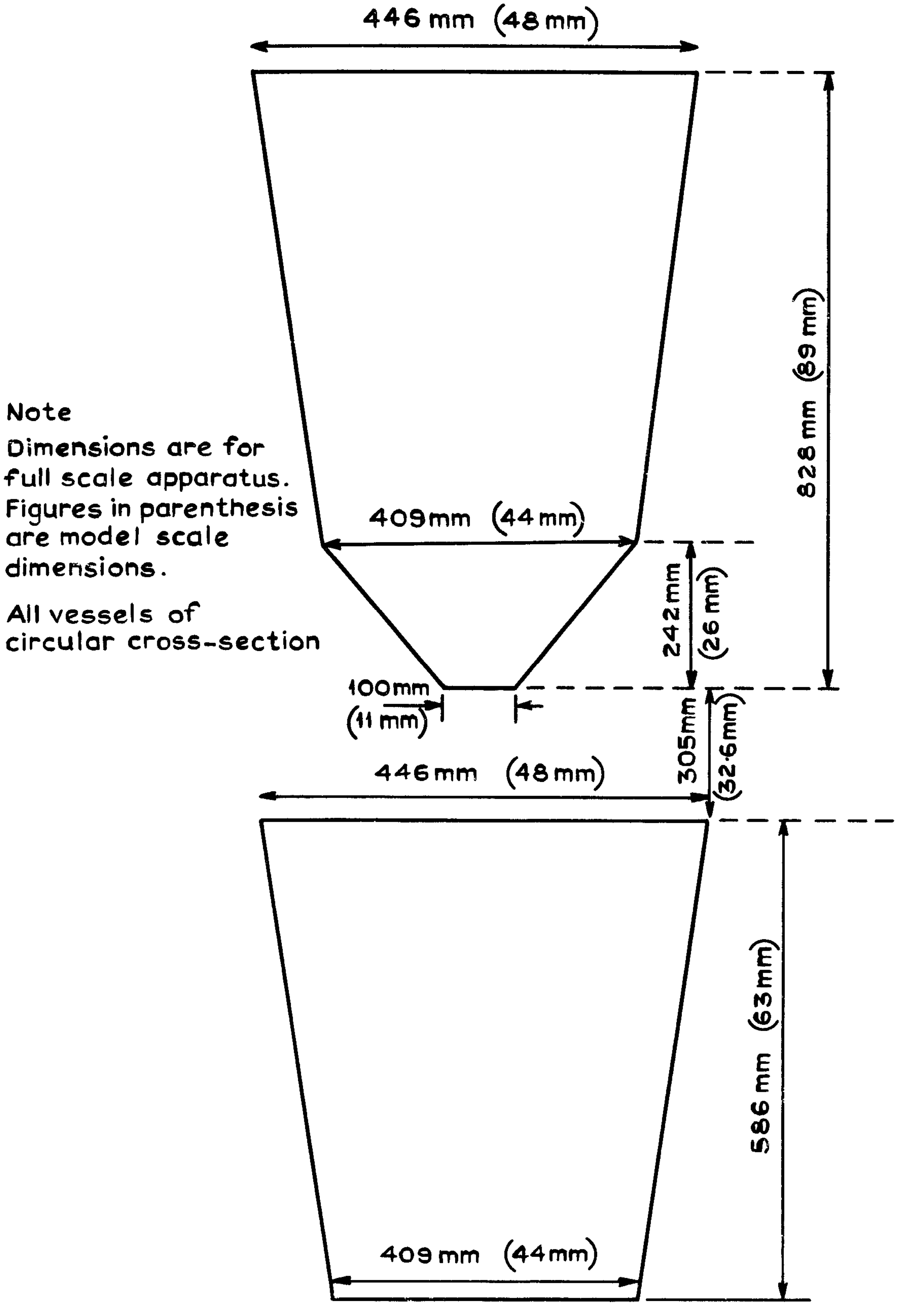


Fig. 16 Curves showing separation between models maintained in Ardleigh sand



Note
Dimensions are for full scale apparatus. Figures in parenthesis are model scale dimensions.

All vessels of circular cross-section

Fig. 17 Schematic diagram of apparatus used in flow rate and loose bulk density tests

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