Off-the-Road Locomotion

By R. M. OGORKIEWICZ, M.Sc. (Eng.), A.M.I.Mech.E.

No. III—(*Concluded from page 62, July 14*)

The First International Conference on the Mechanics of Soil-Vehicle Systems held last month in Italy covered a wide range of subjects related to land locomotion. Several of its papers were reviewed in the first two parts of this series, and the concluding part of the review, which follows, is concerned chiefly with new vehicles and components.

SEVERAL of the papers presented at the Conference on the Mechanics of Soil-Vehicle Systems dealt specifically with problems related to wheels and tyres. Those of particular interest referred to measurements of forces and deformations which occur when wheels roll over soft surfaces. A considerable amount of work has already been done in this field but much more remains to be done, particularly on the important problem of stress distribution at the tyre-ground interface, and on systematising the information obtained about the interaction between wheels or tyres and the soil.

Apart from the paper by Janosi, mentioned in the second part of this review,* which outlined the work accomplished at the Land Locomotion Laboratory of the U.S. Army Ordnance Tank Automotive Command, other interesting work in this field was reported, among others, by E. T. Vincent, of the University of Michigan, in "Pressure Distribution on and Flow of of the wheel, forming a bow wave, and then falling into the rut behind the wheel. Thus, the motion of a wheel in sand is accompanied by a flow process, as well as compaction, which alone is insufficient to account for the sinkage of a wheel in sand.

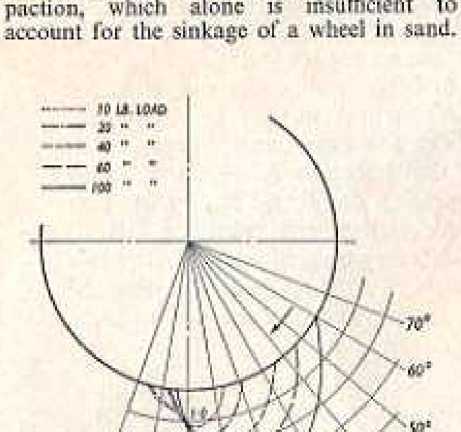


Fig. 1—Variation of loaded area and pressure under centre of wheel, 12·5in outside diameter and 6·5in wide.

In fact, he concluded that, except for lightly loaded wheels with small sinkage, compaction effects were small and the sand flow predominated. Work which led to this conclusion included measurements of pressures at the wheel-sand interface by means of a small pressure transducer consisting of a ¼in diameter plunger fitted into the surface of the wheel and attached to a differential transformer with appropriate circuit whose output gave a trace proportional to the variation of the load on the plunger. Results obtained at the face centre of a 12½in diameter, 6½in wide wheel are shown in Fig. 1; they illustrate a change in the stress pattern between the light, 10 lb and 20 lb loads, when the soil might be considered to behave as an elastic medium, and the heavier loads when the soil no longer appears elastic to any great extent.

Behaviour of wheels in purely cohesive soil was reported by F. L. Uffelmann, of the Fighting Vehicles Research and Development Establishment. In this case a simple compaction theory based on plastic deformation without recovery, i.e. rut formation equal to the instantaneous sinkage, and uniform normal pressure over the arc of wheel-soil contact, gave reasonable agreement with experimental observations at small sinkage. Simple theory also gave acceptable results for the traction available from the wheel rim 18in and 24in wide and the results suggested the possibility of a 5ft diameter wheel with a rigid 1½ft wide rim, ridged side plates and self-injecting spuds which would be capable of carrying a load of 3 tons to 5 tons off the road. Such a wheel would be resilient by means of rubber pads between the rim and the hub and would have cavity cushion tyres in segments around the rim for hard ground running.

A related development of a "Forced-Slip Wheel and Track Tester" was described by A. R. Reece and B. M. D. Willis, of King's College, University of Durham. This is a special purpose machine for field measurements of tractive effort, rolling resistance and slip based on the forced slip principle, in which the test wheel, or track, is obliged to rotate at a controlled slip by the unwinding of a rope from a drum which is geared to the wheel under test. The input torque and output thrust are simply measured as they are a function of the forces exerted by the towing tractor and the cable, which is anchored to the ground, and the whole apparatus has the virtue of simplicity and low cost.

At the other extreme in elaboration one may place the test equipment available at the U.S. Army Engineer Waterways Experiment Station and described by W. J. Turbull and D.R. Freitag in "Influence of Soil Factors and Tyre Geometry on the Performance of Pneumatic Tyres in Sand." The equipment is based on a soil bin, which can be built up to a length of 165ft, and a dynamometer carriage which travels on carefully aligned rails and which is linked to the wheel under test. The attachment is such that the wheel can be loaded and powered and yet be free to move up or down as the soil conditions dictate; vertical loads of up to 3000 lb may be applied and the dimensions of the apparatus permit the testing of wheels up to 32in diameter and 16in wide. Normal test procedure consists of towing the carriage, and with it the wheel which is being tested, at a velocity which increases linearly to a maximum at the mid-distance along the soil bin and then decreases, while the speed of rotation of the wheel is held constant. In this way a complete drawbar pull *v* slip curve is obtained in each pass. Typical curves of drawbar pull and torque *v* slip are shown in Fig. 2, where three points of

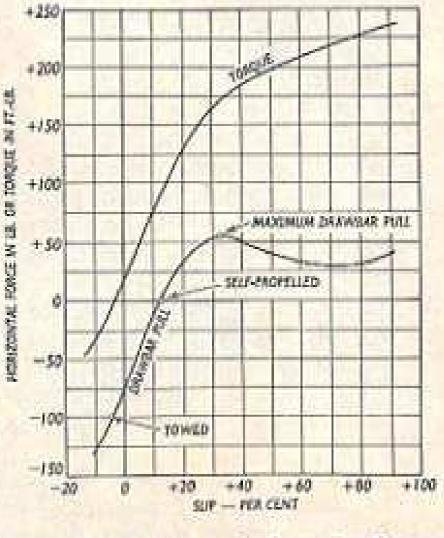


Fig. 2—Typical curves of drawbar pull and torque *v* slip

pull or self-propelled point, and the maximum drawbar pull point.

Initial tests had been performed with three different sizes of tyres of approximately the same overall diameter and without a tread, to eliminate the effect of tread pattern which is to be studied later. Test results, based largely on 4·50–18 tyres, indicated that the various aspects of tyre performance can be related to tyre sinkage but the authors stated that none of the existing methods of predicting sinkage was satisfactory. The last comment seems a little surprising in view of the success in predicting wheel performance achieved at the Land Locomotion Laboratory and the University of Michigan, unless an exceptionally high degree of accuracy is expected. There is no doubt, however, that the authors' well instrumented laboratory should produce valuable experimental data on wheel and tyre performance and it is only to be hoped that at some future date they will be able to synthesise their results.

Extensive testing facilities are also available at the National Tillage Laboratory of the U.S. Department of Agriculture, at Auburn, Alabama. They include soil bins 20ft wide and 250ft long and well instrumented dynamometer carriages, which were outlined by G. E. Vandenberg, I. F. Reed and A. W. Cooper in "Evaluating and Improving Performance of Traction Devices." Unfortunately, no results obtained with these elaborate facilities were given, in spite of nearly twenty-five years' experience to which the authors themselves refer.

WALKING MACHINES

Walking machines have long existed in science-fiction but more recently they have also attracted more serious interest, aroused partly by the hope that under some conditions

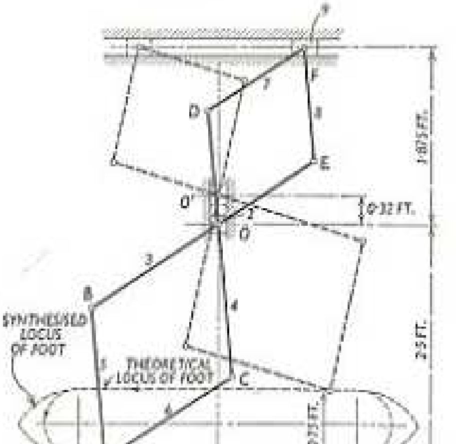
---

* THE ENGINEER, Vol. 212, July 13, 1961, page 59.

their performance might be superior to that of wheeled or tracked vehicles. A consequent investigation sponsored by the Land Locomotion Laboratory was described by J. E. Shigley, of the University of Michigan, in "The Mechanics of Walking Machines." Starting with the requirements of an ideal walking machine, the author established what he considered the most promising locus of the foot as it moves relative to the vehicle. This consists of parallel, horizontal stride and return parts of the cycle, relatively long compared with the height of the step, joined by a semi-circular lift phase and a similar phase during which the foot is lowered. The proposed locus promised to give minimum acceleration and offered the possibility of balancing the inertia forces and torques by properly phasing a number of walking mechanisms on like paths. To make inertia torque reactions on the vehicle small, the author considered that a minimum of sixteen legs was necessary, four at each corner of the vehicle.

Synthesis of a possible mechanical linkage driven by a rotating source of power was based on the Hrones-Nelson method†. It revealed that only a few linkages will generate a path approximating to the desired locus and, in general, the author concluded that none of the walking mechanisms driven by a rotating crank was very satisfactory. None fulfilled the requirement of uniform velocity, unless pairs of non-circular driving gears were used, and none gave a stride which was long compared with the total space required by the mechanism. Moreover, further analysis revealed that, while it was possible in several cases to balance the inertia torques, it was not possible to balance the inertia forces. possible solutions, the author did not rule out the possibility of finding a mechanism which could be balanced.

In the meantime, the limitations of mechanically operated machines led him to consider hydraulic operation with two cylinders per leg. One of the two hydraulic cylinders would be used for driving and the other for lifting, and by suitably programming the flow to them the foot could be made to generate the desired locus. Further, to make the lift and driving motions independent of each other, a pantograph mechanism shown in Fig. 3 was adopted in which the centre O was driven up and down by the lift cylinder while a second cylinder drove the slider 9 in the horizontal direction. With this arrangement a single flow programme is sufficient for each cylinder, regardless of the values set for stride or lift, and using a minimum of sixteen legs it is possible to balance the inertia forces and torques.



AB = AC = BO = CO = 1·625"; DO = EO = DF = EF = 1·22".

Fig. 3—The pantograph mechanism for a walking machine.

A similar if less searching investigation has been carried out in Italy by S. Muratori, with the object of devising a mechanical horse which could be used in undeveloped areas on trails or mountain paths. In this case a four-legged machine was considered feasible, possibly because only slow speed operation was envisaged, but it is interesting to note that, as in the above-mentioned paper, hydraulic actuation of the leg in stride was also suggested, with hydraulic or mechanical control of foot lift.

Another scheme has been investigated at the Munich Technical College and reported by H. von Sybel and F. Grose-Scharman in their paper "On Increasing the Tractive Effort of Off-the-Road Vehicles." In this case the vehicle was wheeled but the wheels were mounted on arms which could be swung to and fro about their pivots, as indicated in Fig. 4, which shows a six-wheeled version.

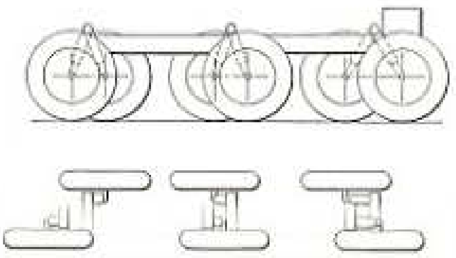


Fig. 4—Diagrammatic arrangement of a six-wheeled walking machine.

Poussée

With such an arrangement motion of the vehicle could be obtained by alternately braking some of the wheels and pushing the vehicle against them by means of a suitable hydraulic mechanism while other wheels rolled forward under little or no load. In this way advantage could be taken of the fact that greater thrust can be obtained with a stationary wheel than a rotating one, and the system was suggested for use under particularly difficult terrain conditions.

All three investigations indicated that any walking machine would be relatively complex and none showed to what extent their overall performance would be better than that of other vehicles. It is difficult, therefore, to assess whether the investigations point to useful vehicles or whether they are merely an exercise in the theory of machines.

PNEUMATIC TRACKS

In addition to the technical sessions, one practical demonstration also took place during the course of the Conference at the Regional Airport of Aosta. Its subjects were an aircraft with pneumatic tracked landing gear and tractors fitted with pneumatic and roller tracks, all developed in Italy by G. Bonmartini.

The pneumatic tubular track has been under development since 1949, when the first one was made by Bonmartini in collaboration with the Superga company of the Pirelli group. Its first aircraft application was in a Piper light aircraft and the subsequent use of the Bonmartini 2-550-III pneumatic track landing gear in the more modern Piper 18A gained for it in 1959 the approval of the Registro Aeronautico Italiano, the Italian air registration authority. During the trials which led to the approval certificate, the aircraft executed 147 take-offs and landings on grounds such as meadows with ditches up to 12in or 16in wide, cultivated fields with surface depressions not more than 6in deep and 20in wide, and sandy beaches. The same type of aircraft, used for agricultural insecticide spraying and shown in Fig. 5, was demonstrated at the Aosta airfield where it too successfully crossed small ditches which would have been disastrous for aircraft with the normal single wheel landing gear.

The pneumatic track itself is essentially an the tube. The plies are placed at 85 deg. to the cables and a natural rubber compound is used for the side walls and the tread. The track is made in two sizes, 150×3740 and 110×3130 with nylon and rayon plies respectively, the weight of one track of the first kind being around 24 lb to 26 lb and of the second 15 lb to 17 lb; in both cases the operating pressure is 35·5 lb per square inch. The track is intended to be used with bogie wheels having a diameter three times its own and so shaped that the bead cables run very close to the wheel rim, as illustrated in Fig. 6, which shows the two-wheel 2-550-III landing gear used with the Piper 18A aircraft. The inner surface of the track is lubricated with castor oil by means of a small pump driven off one of the wheels, and the track gear has been designed for a static load of 1100 lb to 1300 lb. During the rough ground approval trials the total

Fig. 5—Piper light aircraft with the Bonmartini track taxying across a ploughed field

---

† Hrones, J. A., and Nelson, G. L., "*Analysis of the Four-Bar Linkage*," Wiley, New York, 1951.

Fig. 6—Aircraft landing gear with the Bonmartini pneumatic track

weight of the Piper aircraft was 1800 lb and maximum vertical and horizontal accelerations of 2·5g and 2g respectively were recorded. The heaviest aircraft in which this type of landing gear has been tried so far appears to be the Dornier Do. 27, which weighed 3340 lb when tested in 1958.

The attractions of the pneumatic track landing gear for aircraft which have to operate off unprepared grounds are fairly obvious, for it can distribute their weight over a larger area and thus enable them to traverse soft surfaces. In connection with this, it is said that the track gear can be used where a surface pressure of 5¼ lb per square inch does not produce a penetration of more than 2in to 2½in, i.e. not more than the radius of the track tube. This type of landing gear has the advantage of reduced frontal area, and consequently lower drag in the air and smaller bulldozing resistance on the ground, over the wide single low-pressure tyre type of landing gear tried on some light aircraft for soft ground operation. ditches and similar obstacles, as already indicated. At the same time, it has the advantage of far greater resilience over the endless-rubber-band track used experimentally on some heavy aircraft.

Application of the pneumatic track has now been extended to tractors, as indicated in Fig. 7, which shows a Lombardini Castoro light tractor demonstrated at Aosta. The track drive of this experimental vehicle relies on friction between bars connecting the flanges of the rear driving wheels, which imposes limitations on traction, but the pneumatic track has undoubted agricultural possibilities, particularly where a minimum disturbance of the soil is important; in addition to tractor applications, it could also be used to advantage in some cases with trailers.

Bonmartini has also developed another and entirely different type of track for tractors and tracked trailers, shown in Fig. 8. This is more conventional in that it consists of pin-jointed track links, but each link has two rubber-faced rollers free to rotate about pins set in the links at a small angle to the longitudinal axis of the vehicle. As a result, resistance to lateral track movement is greatly reduced and a smaller moment is necessary to turn the tractor, on hard surfaces at any rate. On soft ground, however, where considerable track sinkage takes place, the rollers lose their advantage and the track could not be used to design vehicles with a greater length to width ratio because they would be as unsteerable in soft ground as similar vehicles with conventional tracks. The most fruitful field of application of the roller track would appear to be in tractors which have to operate frequently on roads and which they could then do without the usual tearing up of the road surfaces when steering.

ARTICULATED TRACKLAYERS

Limitations imposed on the length-to-width ratio of tracked vehicles by conventional steering methods have led to a significant revival of interest in articulated track vehicles, particularly in the United States and Canada. The consequent developments were outlined in *The Steering of Tracked Vehicles by Articulation*, by C. J. Nuttall, of Wilson, Nuttall, Raimond Engineers, Inc., a company which has constructed several such vehicles since the mid-fifties. As the author pointed out, with conven- by reducing the net longitudinal thrust of one track and, if possible, increasing that of the other. Where the soil is already stressed close to failure, an increase in thrust is not possible and steering is accompanied by a reduction in the total forward thrust. In soft soil this may lead to a complete immobilisation of the vehicle, and it is interesting to note that the Ministry of Supply committee which investigated the bogging down of tanks at the end of the 1939–45 war reported that this occurred most frequently when tanks were attempting to steer.

Difficulties associated with conventional steering methods may be eliminated by using articulated vehicles, which may be made to follow a curved path by changing the attitude of one half of the vehicle relative to the other in the steering plane. Three main types of articulated vehicle configurations, which are in use today, are shown diagrammatically in Fig. 9; the fourth, which is attributed to Bekker, has not been tried so loading. Instead, he suggested that the third type fitted with a heavy damper across the joint in the pitching plane offered a more promising compromise.

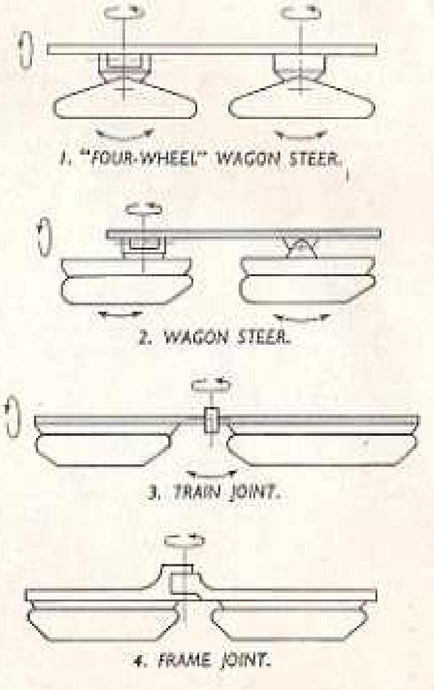
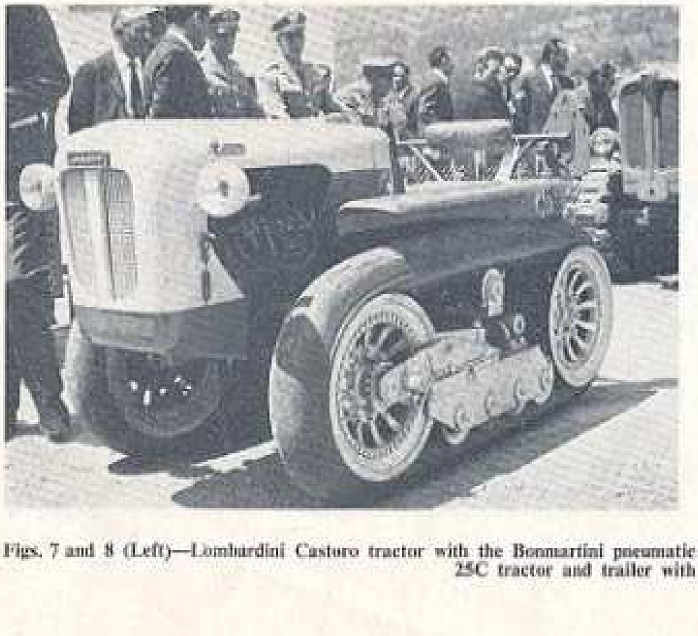
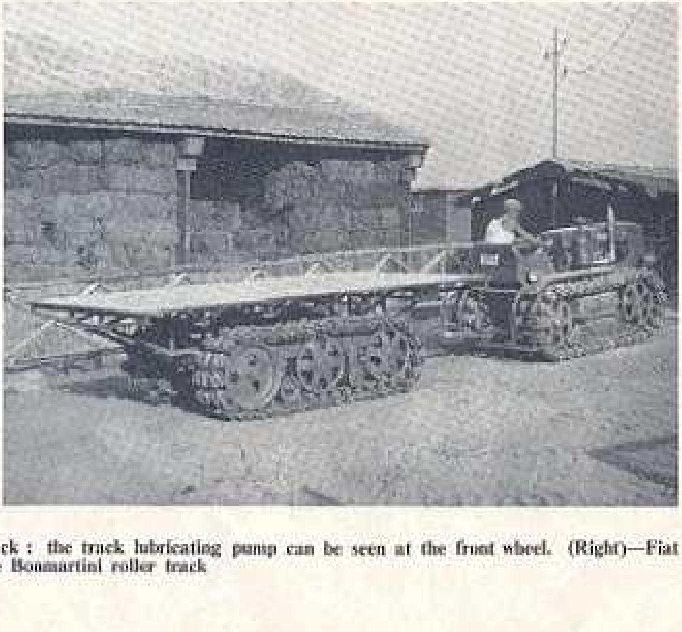


Fig. 9—Main types of articulated vehicle configurations

Judging by his review of developments which preceded present-day vehicles, the author knew of B. J. Diplock, who pioneered articulated tracked vehicles in this country shortly before the 1914–18 war, but appeared unaware of experiments made during the conflict and again during the early 'thirties. In view of the ignorance about the early history of articulated vehicles, even among those who have studied them for many years, it may be worth noting that Diplock's first articulated tracked vehicle was exhibited at Olympia in 1913 and was fully described





Figs. 7 and 8 (Left)—Lombardini Castoro tractor with the Bonmartini pneumatic track: the track lubricating pump can be seen at the front wheel. (Right)—Fiat 25C tractor and trailer with the Bonmartini roller track on these pages at the time.‡ The present revival of interest started, as described by the author, during the late 'forties with the construction of the Tucker "Sno-Cat" and Bekker's work on models. The four-track "Sno-Cat" was evolved from experience with several small half-track and half-ski machines and has been used since on some scale for over-snow operation. Among others, four "Sno-Cats" were used by the 1957–58 British Trans-Antarctic Expedition. Another pioneer vehicle was the small belly-less "Rat" evolved by the Canadian Directorate of Vehicle Development in 1955–56. Leading particulars of these and other more recent vehicles are listed in the following table.

General Characteristics of Current Articulated Tracked Vehicles

Vehicle	Manufacturer	Date of introduction	Type of layout[1]	Gross vehicle weight lb	Net payload lb	Payload to vehicle weight ratio	Overall length, ft	Overall width, ft	Installed horse-power	Maximum speed m.p.h.	Nominal ground pressure, lb/in²
"Sno-Cat"	Tucker	1949	1	8,400	2,000	0·24	20·0	7·8	140	12	0·9
"Rat"	Canadair	1955	3	2,000	600	0·30	14·5	3·7	35	10	0·5
"Polecat"	WRNE[2]	1957	3	12,000	4,000	0·33	24·4	5·5	140	27	1·9
Transporter	Nodwell	1958	2	57,000	20,000	0·35	39·5	10·0	300	12	2·0
"Musk-Ox"	WRNE	1959	3	90,000	40,000	0·44	48·6	10·0	375	14	3·1
"Cobra"	WRNE	1960	3[3]	27,000	8,000	0·30	42·7	6·6	200	20	2·1[5]
"Polecat" Mk. II ...	WRNE	1960	3[4]	29,000	10,000	0·35	37·5	8·5	195	27	2·3

[1] See Fig. 9.
[2] WRNE—Wilson Nuttall Raimond Engineers.
[3] Three unit vehicle.
[4] With heavy damper in pitching plane.
[5] Spaced-link track.

In general, the performance of articulated tracked vehicles built so far has shown that by abandoning conventional steering methods it is possible to develop longer, narrower vehicles with very low ground pressures, lower resistance to motion, higher drawbar pull to weight ratios and better ride. Some by the original "Polecat" built in 1957. This vehicle was built by coupling two M29 "Weasel" cargo carriers, which had been the U.S. Army's principal over-snow vehicles, and on trials it produced a drawbar pull equal to 240 per cent that of the "Weasel" and a 40 to 50 per cent increase in the average operating speed. At the same time, the life of the running gear was extended, which the author attributed partly to the elimination of track tension reversals accompanying normal skid-steering. Apart from higher first cost, a disadvantage of the articulated tracked vehicles is their inability to make very sharp or pivot turns, but this is not of paramount importance in several fields of application. One of the latest vehicles, the "Cobra" built between 1958 and 1960 for the U.S. Army Ordnance Tank Automotive Command, has extended the principle of articulated construction from two to three units and there will, in all probability, be considerable further development of this promising class of vehicles.

LUNAR SOIL

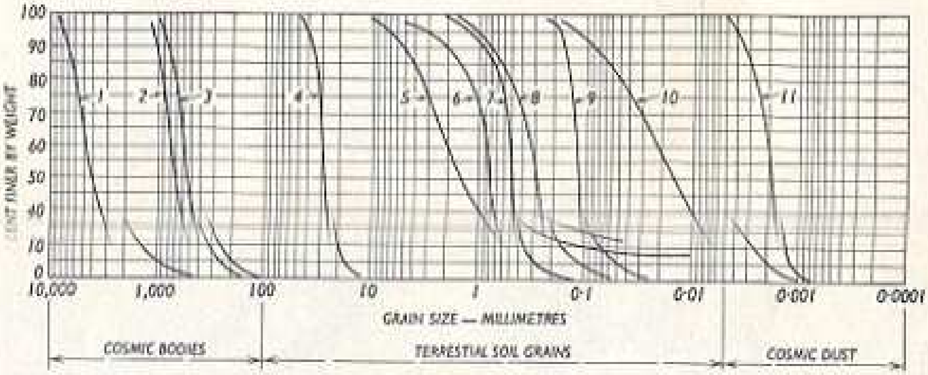
Progress towards exploratory landings on the moon makes it increasingly important to try and predict possible characteristics of the lunar soil, to be able to anticipate some of the problems which might arise. It was particularly interesting, therefore, that the papers presented at the conference included two on lunar soil.

"Some Predictions as to the Possible Nature and Behaviour of the Lunar Soils" by J. A. Ryan, of the Douglas Aircraft Company, listed six environmental factors of importance in relation to the lunar surface. They were the absence of an atmosphere, surface gravitational force roughly one-sixth of that on earth, more extreme surface temperature changes, exposure to greater solar electromagnetic flux, direct exposure to corpuscular radiation, and the absence of protection against the impact of meteorites. So far as the current ideas on the nature of the lunar soil were concerned, there were two principal theories on the origin of the lunar features, namely meteoric impact and de-fluidisation and volcanic action. Lunar surface material was most likely in powder form and from both the volcanic and meteoric hypotheses the lunar soil would be expected contain much fine grained material or dust. There was, however, wide variance in ideas on the thickness of the soil layer, which has been estimated from 1m or 2m to as much as 1000m or more. In the light of the possible nature of the lunar soil and the environmental effects, the author concluded that lunar soil grains are generally of dust size, comparable to fine sand, and statistically more angular than in terrestial cohesionless soils. The internal friction of lunar soil may be greater or smaller depending on the porosity, which should be higher, and on the occurrence or otherwise of cementation. Porosity may be as great as 90 per cent, in which case there may be serious locomotion problems, but if it is not greater than in cohesionless terrestial soils there should be, in general, no locomotion problems.

The last comment is particularly interesting in relation to such projects as the instrumented exploration vehicles of the "Prospector" series planned by the U.S. National Aeronautics and Space Agency. However, it is probable that by the time such vehicles are landed some more definite information about lunar soil will be available from stationery instrument packages, such as the N.A.S.A. "Surveyor" series, landed on the moon.

N. A. Weil, of the Armour Research Foundation, in his paper on "Probable Soil Conditions on the Moon and Terrestial Planets," also concluded that the lunar surface would be covered by a layer of dust, except for the lunar highlands and crater rims, but considered that the thickness of the layer would vary from the order of centimetres in the marias to several strata kilometres deep in the lunar craters. Such considerations led him to the further conclusion that landings should be made in one of the lunar marias and that further exploration should be made from the marias by tracked vehicles. However, several of his assumptions were challenged by the author of the previous paper, and in view of the probable cohesionless character of the lunar soil one may also question the suggestion that tracked vehicles be used for surface exploration, which might well be done by wheeled vehicles.

An interesting contribution to the discussion was made by M. G. Bekker, who plotted the size distribution of cosmic bodies derived from the observations of H. Brown of the California Institute of Technology, together with grain size distribution of various terrestial soils and the particle size distribution of cosmic dust. The curves are shown in Fig. 10 and their similarity suggests a general law of particle size distribution which, if it could be established, might help to determine the particle size distribution of lunar soil.



1—Asteroids (H. Brown).
2—Iron meteorites (H. Brown).
3—Stone meteorites (H. Brown).
4—Cheril Bank gravel (England).
5—Hong Kong decomposed granite.
6—San Paolo sand (Brasil).
7—Cape Cod sand (U.S.A.).
8—Mason sand (Detroit, U.S.A.).
9—Pumice, grade 0, (U.S.A.).
10—Upper Silesia sand (Poland).
11—Cosmic dust.

Fig. 10—Grain size distribution diagram

P.T.F.E. PUMP.—A new pump introduced by Associated Electrical Industries, Ltd., has all its working parts made of p.t.f.e. The chemical inertness and imperviousness to corrosive action of p.t.f.e. adapt the pump for handling corrosive fluids or liquids. The pump is of diaphragm design and is self-priming. The diaphragm and all the other p.t.f.e. parts in contact with the liquid are housed in a cast aluminium body which is bolted directly to a capacitor-run a.c. geared motor. The motor gearbox provides a 7 : 1 step-down to give a diaphragm reciprocation speed of 200 cycles per minute. Pump delivery at a 1ft head is 2 litres per minute, and at the maximum working head of 15ft is 1·25 litres per minute; consumption is 50W. A coupler, developed for use with the pump, is of spring-loaded telescopic design and expands to grip the tubing inserted at each of its ends. It enables p.t.f.e. tubing to be joined so that only that material is exposed to fluids travelling in the tubes.

---

‡ "Commercial Motor Vehicle Exhibition," THE ENGINEER, Vol. 116, July 25, 1913, pages 97 and 99.