Design and Development of Fighting Tanks

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By T. L. H. Butterfield*

HISTORY

THE HISTORY OF THE TANK and its role in battle goes back to World War I. It was the answer to the stalemate of trench warfare when opposing armies were pinned down by machine-gun fire.

The origin of the tank seems to be shrouded in a little mystery. In his book *Eyewitness* Lt Col Swinton claims not only to be the originator of the idea but also that his idea triggered off the development of tanks in Britain. Ogorkiewicz, who has obviously carried out a considerable amount of research in this field and quoting such authorities as Liddell Hart, contests these claims in an article in *Armor* (July–August 1965), denouncing them as pretentious. He points out that Swinton's idea was certainly not original and that Capt. Levavasseur of the French Artillery put forward a suggestion for a tracked armoured vehicle as early as 1903, as also did Capt. Burstyn of the Austro-Hungarian Army in 1911 and L. E. de Mole, an Australian civil engineer in 1912.

Nevertheless, it appears that Swinton may have been the first in Britain to propose a tracked vehicle after the commencement of World War I and that his ideas led to the sending of a Memorandum by Col. M. Hankey, the Secretary of the Imperial Defence Committee, with whom Swinton had discussed his ideas, to Winston S. Churchill and others but that the proposals may well have been partly due to Hankey himself.

In fact, Churchill was already considering some ideas for a tracked fighting vehicle put to him by the officers of the Armoured Car Division of the Royal Naval Air Service and his decision to set up an Admiralty Landships Committee in February 1915, which led to the development of the first tank, may have been to some extent strengthened by Hankey's Memorandum.

The idea of the tank was simultaneously exploited by the British and French. However, the British combined effort by the War Office and the Admiralty produced the prototype 'Little Willie' in September 1915, and later 'Big Willie', the famous Mk 1, known also as 'Mother', in January 1916. The Mk 1 came in two models, one armed with a six pounder and four machine-guns, Fig. 1, whilst the other carried six machine guns. It weighed 28 tons, was 32 ft 6 in long and 13 ft 9 in wide and had a maximum speed of 3·7 mile/h. The French Schneider tank which followed shortly afterwards weighed 15 tons, was armed with a short 75 mm gun and two machine guns and developed a maximum speed of 5 mile/h. Throughout the war many new marks of British tanks appeared and names which loomed large in the designing of them were those of Sir William Tritton, of Messrs William Foster and Co., and Major C. G. Wilson.

The first appearance of the tank at the battle of the Somme in 1916 produced an enormous psychological impact but apart from this, its performance was unimpressive. The records show that of the 49 tanks which took part in the engagement, 17 broke down before they reached the front line, 9 more broke down at the front line and 5 got bogged down during the attack. However, its invulnerability to small arms fire rather established the tank as a sort of perambulating fortress with the accent on armour protection rather than on mobility. Tanks were mainly used for subduing machine gun fire and crushing barbed wire and generally for opening the way for an infantry attack. Tactical surprise, however, was completely lost since their use was generally preceded by an Artillery barrage. When anti-tank defences appeared, commanders tended to regard the tank as a rather specialized piece of equipment which had to be carefully nursed.

Not until 1917, at the battle of Cambrai, did tanks become a real factor in battle. They were used in large numbers without the usual artillery bombardment and the massed, surprise assault achieved a spectacular breakthrough.

Towards the end of World War I, improved engine designs led to the development of faster tanks. It seemed that the Allies at last had the answer to the problem of strategic penetration following a break-through. In point of fact, this was never proven because the war came to an end before a plan formulated by the British Tank Corps to use 10 000 tanks in an independent mass assault could

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be put into effect. It was left to the German Panzer divisions in World War II to show how effective this could be.

Although by the end of World War I the tank had established itself in assault, its value as a mobile weapon, capable of carrying out a sustained drive, was not proven. The period between the wars saw the development of specialist tanks to meet the different tactical needs in the manner of the fighting ships. The light tank carried out reconnaissance roles, the cruiser tanks were the mobile fighting machines, and at a later stage came the heavier infantry tanks such as 'Matilda', Fig. 2, known as the infantry tank Mk 2, and 'Valentine', Fig. 3, the infantry tank Mk 3. These latter tanks were immune to the 37 mm anti-tank guns and were only required to move at infantry pace. Tanks were therefore not yet regarded as versatile equipments able to carry out all the different roles (see Table 1).

Fig. 1. The Mk 1 tank 'Big Willie'

Fig. 2. Infantry tank Mk 2 'Matilda'

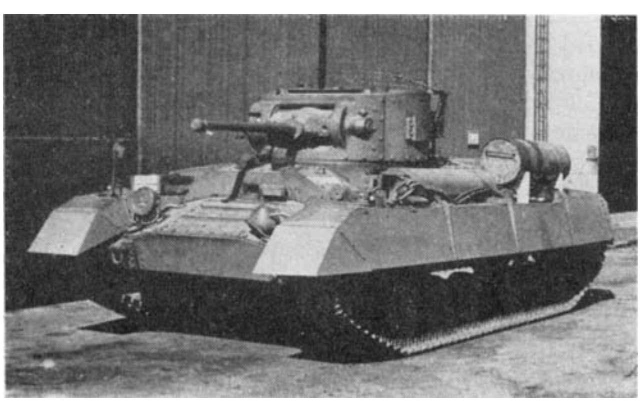


Fig. 3. Infantry tank Mk 3 'Valentine'

The German Panzer Divisions of World War II began to set the modern tactical philosophy. They were organized both for striking power as well as for exploitation. Tanks in balanced combination with mounted armoured infantry and artillery formed the spearhead of the attack and were able to smash the opposition as well as outflank it. The Allied tanks, hampered by their strict adherence to cavalry and infantry roles, were overwhelmed, and not always by weight of numbers. This necessitated some reorganization in the Allied exploitation of tanks which resulted in the formation of the armoured divisions in which tanks were exploited in a much more versatile fashion.

The general trend has been for tanks to get heavier. Since World War II, Britain has developed the 50-ton 'Centurion', Fig. 4, and the 65-ton 'Conqueror', Fig. 5. They appear together in the armoured squadrons with Centurion providing the medium tank role and Conqueror, with its 120 mm gun, the heavy anti-tank capability. These tanks possess considerable sophistication compared

Fig. 4. The 'Centurion'

Fig. 5. The 'Conqueror'

Fig. 6. The 'Chieftain'

with their predecessors. Centurion with its stabilized gun is able to fire accurately on the move across rough country.

The 'Chieftain', weighing 50 tons and now about to enter service, marks a new line in tanks, Fig. 6. Termed a battle tank it combines the capabilities of the medium and heavy tanks and is probably the most powerful fighting tank in existence. It has a formidable gun, heavy armour protection and very adequate mobility. It also is able to fire on the move and has many improvements over Centurion.

This historical survey shows how the battle tank of today has come to acquire its present role and the extent to which it has increased its battle effectiveness. It is now regarded as the spearhead of the attack in armoured formations. It must be able both to create and exploit a break-through. It must be capable of defeating and outmanoeuvring enemy tanks and of giving supporting fire of various types to the infantry. It is required to fire on the move, fight both by night and by day, and be able to survive on the future battlefield. It must have mobility to enable it to cross all types of terrain and negotiate obstacles, including water obstacles. Most countries are agreed that the tank must be characterized primarily by its fire power and that next in importance comes armour protection and mobility. Opinions, however, differ as to the order of priority of protection and mobility, although the majority of countries give preference to mobility. At the present time, the U.K. rates protection higher than mobility. Nevertheless, the priorities must always come under review in the light of new technological advances and tactical doctrines.

It will be seen, therefore, that the three principal characteristics of the tank are regarded as being fire power, armour protection and mobility. Ideally, of course, every tank soldier would like to see all these characteristics catered for to a maximum degree. He would like fire power capable of defeating any tank which the potential enemy could put into the field, armour protection capable of resisting all enemy anti-tank fire and superior mobility to enable him to outflank and outmanoeuvre the enemy's armoured formations.

Each of these characteristics can individually be fairly precisely defined and it should not, therefore, be impossible to design a tank possessing all these virtues provided that there is no restriction on weight or dimensions which would prevent the designers achieving these aims. Unfortunately, weight and dimensional restrictions are always imposed for both logistical and operational reasons. The tank must conform to rail gauge requirements and to bridge classifications. Its fuel economy must be good and it must possess a low silhouette both for the sake of concealment and to reduce the size of the target presented to enemy fire. Thus, fire power, armour protection and mobility which all make demands on weight and space become conflicting requirements. It is, therefore, not necessarily possible to design a tank which is superior in all departments to the enemy's tank.

In formulating his requirements, the user must, after due consideration of the enemy threat and the tactical roles required of his tank, state his priorities and, in particular, the priority to be given to the principal characteristics. He must accept that overall superiority over the enemy's tanks may have to be achieved by a correctly proportioned balance of the characteristics rather than by superiority in all departments. He must be prepared also to relax, within reason, any restrictive requirements which prevent a satisfactory balance from being achieved.

FORMULATION OF USER REQUIREMENTS

A prerequisite to the development of a fighting vehicle is a requirement. The processes by which this is formulated are worth studying since it will show the start of the user/designer relationship which must be maintained at all stages of the development in order to ensure a design of well balanced characteristics.

In the U.K. the requirement first appears as a General Staff Target (G.S.T.). This is a broad statement by the sponsoring user of the type of fighting vehicle he considers necessary to enable him to fulfil the tasks envisaged by the long term strategic and tactical planning.

The G.S.T. will outline the role of the vehicle and the conditions in which it must operate. It will normally limit itself to the operational and functional duties but will include limiting weights and dimensions. The draft G.S.T. will previously have been vetted by all concerned, including the Research and Development (R & D) Establishment responsible for the design and development. In the case of fighting vehicles, this is the Fighting Vehicle Research and Development Establishment (F.V.R.D.E.) who are thus given a chance to comment even at this early stage.

Feasibility studies are then carried out by F.V.R.D.E. in collaboration with other R & D Establishments involved. One of the objects of the feasibility study is to establish the general parameters of the design and to see how far it is possible to meet the user requirements in full, and, if this is not possible, to suggest the best 'trade offs' in order to effect the most suitable compromise of the main characteristics—fire power, armour protection and mobility.

Because the relationship and interaction of these

Table 1

DEVELOPMENT OF BRITISH TANKS

Date	Tank	Armament	Armour, mm	Weight, ton	Length, ft in	Width, ft in	Height, ft in	Engine	B.h.p.	Road speed, mile/h	Other features
1916 to 1918	Mks I to IV Male Female	Two 6 pdr sponson-mounted Four Hotchkiss M/G's One Hotchkiss M/G Four Vickers M/G's	12 max. 12 max.	28 27	26 5	13 9	8 0½	Daimler 6-cycle sleeve valve	105	3·7	Unsprung roller suspension. Steering tail. Also by differential and secondary gears to each track assisted by brake for skid turns
	Whippet (Mk A)	Four Hotchkiss M/G's	14	14	20 0	8 7	9 0	Two Tyler JB.4's	45 each	8·3	Separately driven tracks. Final drive shafts locked together for straight ahead
	Medium (Mk C) Male Female	One 6 pdr in fixed turret Three Hotchkiss M/G's Four Hotchkiss M/G's in fixed turret	12 max.	19½	25 10	8 10	9 7½	Ricardo 6-cycle	150	7·9	Steering by differential and secondary epicyclic gears to each track
1924	Medium Mk 1 Mk 2	One 3 pdr gun in rotating turret Four Hotchkiss M/G's As for Mk 1	8 8	12 16	17 6	9 1½	9 3	Armstrong Siddeley V8	90	15·2 14·0	Sprung suspension bogies, clutch and brake steering. Epicyclic gears—8 gears
1929 to 1936	*Light tanks* Mk I to V Mk VI	One Vickers M/G mounted in rotating turret One 15 mm and one 7·92 mm BESA M/G's in twin mounting	14 or 12 max.	4¼				Meadows, later Rolls-Royce	58 66	30 to 36	Clutch and brake steering. Horstmann suspension
	Tetrach	One 2 pdr gun in turret One 7·92 mm BESA (Co-ax)	16 basis	7½				Meadows	165	37	Independently sprung wheels. Clutch and brake steer also by pivoting wheels for larger radii turns
1937	*Cruiser tanks* Covenanter Crusader Mk 1 Mk 2 Mk 3	One 2 pdr gun in turret One co-ax. M/G One 2 pdr gun in turret Two BESA A/A As for Mk 2 One 6 pdr in turret One BESA, one Bren	 40 50 52	18 18¾ 19 19¾				Meadows Liberty Liberty Liberty	300 340 340 340	31 27 27 27½	Christie suspension steering by two Wilson air-operated steering units, one on each side of gearbox

Date	Tank	Armament	Armour, mm	Weight, ton	Length, ft in	Width, ft in	Height, ft in	Engine	B.h.p.	Road speed, mile/h	Other features
1939	*Infantry tanks* Mk 2 Matilda	One 2 pdr gun in turret One 7·92 mm BESA (Co-ax) Bren A/A	78 max.	26$\frac{1}{2}$	19 5	8 3	7 10	2-A.E.C. diesel or 2-Leyland	174 each 190 each	15 15	10 bogies—bell crank suspension arms with coiled springs. Wilson epicyclic gearbox with air servos. Rackham steering clutches
1940	Mk 3 Valentine (Mks 1 to 11)	One 2 pdr gun in turret One 7·92 mm BESA (Co-ax) Bren A/A	65 max.	17	17 11	8 9	7 6	A.E.C. and G.M.C.	131 to 137	15	Clutch and brake steering
1940 to 1945	Churchill Mks I and II	One 2 pdr gun in turret Medium BESA (Co-ax) M/G No. 6, Mk I									David Brown Tractors Type 301C or Type H4 transmission with Merritt-Brown controlled differential steering
	Mks III and IV	One 6 pdr gun in turret Medium BESA (Co-ax) M/G No. 1, Mk I	4 in max.	38·5	24 1$\frac{3}{8}$	10 8	8 2	Bedford Twin 6	325	17·3	
	Mk V	One 95 mm How. 7·92 mm BESA (Co-ax) M/G No. 1, Mk I									
	Mk VI	One 75 mm gun Medium BESA (Co-ax) M/G No. 1, Mk 1									
	Mk VIII	One 75 mm gun 7·92 mm BESA (Co-ax)	6 in max	39·5	24 2	10 10$\frac{5}{8}$	8 7	Bedford Twin 6	325	13·5	
1941	*Cruiser tanks* A24 Cavalier	One 6 pdr gun in turret One 7·92 mm BESA (Co-ax) Hull M/G	3 in max.	26				Liberty V.12	360	24	Christie suspension. Steering as for Crusader
1942	A27 Centaur Mk 1	As Cavalier	3 in max.	26				Liberty	380	27	Christie suspension. Merritt–Brown controlled differential steering
	Mk 3	One 75 mm Mk 5 gun One 7·92 mm BESA (Co-ax) Hull M/G	3 in max.	26				Liberty	405	29	
1943	Cromwell Mks 1 to 8	One 6 pdr or 75 mm or 95 mm how. in turret One 7·92 mm BESA (Co-ax)	3 in max.	28				Rolls Meteor	600	40 but reduced to 32	As Centaur
1944	Comet	One 77 mm Mk 2 One 7·92 mm BESA (Co-ax)									
1945	Centurion (various Mks)	Centurion Mk 1 had 17 pdr gun. Later Mks were up-gunned to 20 pdr gun and later to 105 mm gun	—	51	25 8 ex- cluding gun	11 1$\frac{1}{2}$	9 9	Meteor Mk 4B	635	21·5	Sprung bogie suspension. Merritt-Brown Z5R transmission

characteristics is complex, no precise mathematical assessment can be carried out in order to integrate them into a correctly balanced fighting unit. The solution involves personal opinions and subjective judgements by users and designers alike based respectively on their battle experience and design skills. Ogorkiewicz in a contribution to the September/October 1965 issue of the U.S. Journal *Armor* suggests an approach similar to that already used for evaluating fire control systems in which the effectiveness of the tank is determined by a quantitative assessment of the overall probability that it will successfully accomplish its mission. Since the defeat of enemy tanks is its most difficult mission, he accepts that its ability to destroy or kill enemy tanks is the criterion for tactical effectiveness.

Thus he shows that the overall probability that a tank will accomplish its mission, Pss, is given by the product of the probability of its being available at the right place at the right time, Pa, the probability of survival when within range of its target, Ps, and the kill probability, Pk, i.e. $Pss = Pa \times Ps \times Pk$.

To obtain each of these probability factors he breaks them down in turn into component events and takes the product of the probability of occurrence of each event.

The approach appears to be an oversimplification of the problem. For instance, speed of engagement and rate of fire are obviously important factors in tank effectiveness but do not appear anywhere in his breakdown. The determination of probability of availability would also present problems since it involves functional reliability which, in the feasibility stage of the design of the tank, would be impossible to forecast. A tank's ability to perform its other various supporting roles also cannot be neglected in evaluating its battle effectiveness. The support of infantry is still probably its major function.

Nevertheless, this approach is worth examining further to see whether a satisfactory method can be devised.

The playing of war games in slow motion, in different tactical situations in which the many complex characteristics and factors may be fed in and the significance of each move examined in detail, may well provide the answer when the techniques have been developed to a suitable degree.

On completion of the feasibility studies a presentation of preferred concepts will be made to the General Staff for acceptance. The design at this stage is largely in a schematic form and a minimum of detailing is done.

A General Staff Requirement (G.S.R.) is then prepared which will be largely guided by the findings of the feasibility study. This will be a more detailed statement of the requirement and will cover all aspects of the tank. It will, if necessary, state the priorities of the requirements and also give the in-Service date.

F.V.R.D.E. then carry out a detailed project study of the preferred design to establish with absolute certainty, the feasibility, the range of components to be used and the areas of development to be carried out. Other points which must emerge from the project study are a clear indication as to how far the user requirements can be met, a realistic weight analysis showing the allocation of weight to the various component assemblies, a cost analysis indicating both development and production costs and a programme showing the target dates for the various stages of development.

A presentation of the project study is then made to the General Staff, and, if accepted, financial approval is sought from the Treasury for design and development to proceed.

Before describing the design and development stage it is worth discussing some of the processes by which the concept design is evolved during the feasibility and project studies.

CONCEPT DESIGNS

Concept design studies, based on a G.S.T. or a G.S.R., are so much of an art that it is very difficult to set down on paper the mental processes and the design procedures. A colleague claimed his own technique was as follows.

Having studied his requirement he then passes through a period of contemplation during which he tries to get a clear idea of what the user intends and guided by an acquired instinct, he begins to break down the problems one by one. His theme may well be centred around some new and unconventional approach which he feels may present some dividends, e.g. around an automatic loader or around components of advanced design, in the fields of protection, mobility, etc. He looks particularly for any approach that will help him to reduce the weight, for weight is always something which is predominant in his mind. He knows that he must produce a better tank than ever before for less weight than he was previously permitted. The size and silhouette of his vehicle must be compact and every component must be pared down to the minimum weight consistent with good performance and adequate reliability.

Piece by piece he builds up his mental picture until one day he is ready to set down some lines on paper. He starts with the usual datum lines—the ground line, the centre line of his fighting compartment and certain limiting dimensions which are dictated by the specification and the rail gauge. Since he knows his ground clearance he can also draw in a line representing the bottom of the hull. He then establishes in space the centre line of the gun trunnions, a position which will allow the recoiling breech to just clear the floor when the gun is at maximum elevation and also provide a maximum of operating space in the fighting compartment.

Around this key datum he is able to sketch his ancillary gear and surround it with the armoured envelope of the hull and turret which must be closely integrated. The shape of the hull and turret will largely be dictated by the sloping of the armour which must conform to the ballistic performance curves for the attack under consideration. Since armour accounts for a considerable proportion of the total weight of the vehicle, careful attention must be given to minimizing the volume and optimizing the shape, both to be compatible with the protection requirements and for housing the crew and the large amount of control gear, electrical items and ammunition, etc., which must be stowed inside. The hull must also be as short as possible and this may involve experiments with various driving positions involving seated, reclining or even prone drivers.

When laying out the engine compartment, the design team and relevant specialist branches will have made a thorough review of the available engines and transmissions to see whether any of these lend themselves to a compact vehicle design and provide the necessary power. If no suitable engine is available it will, of course, be necessary to develop one together with a transmission of the right size and shape dictated by the design and to integrate these into a compact and easily serviced power package. The types of suspension are reviewed to see which type is most suitable for the concept. The hull itself must be adapted to carry the selected suspension and to provide the necessary wheel movement. Wheel stations must be positioned to give the best possible load distribution and a suitable length of track on ground.

Finally, he fixes his track width and length in accordance with the ground pressure he desires but later he may find it necessary to adjust these for weight reasons or in order not to exceed the permissible overall width of the vehicle.

Should the weight analysis of the vehicle show that he is badly in error he will have to begin all over again and make the necessary compromises and adjustments, or even change his approach completely in order to try and achieve a satisfactory solution. He may have to repeat this process many times before he eventually finds a solution which he feels may be acceptable. Alternatively, he will have established that the goal is not attainable and that the user must vary his requirements to some extent. During this period, unofficial discussions with user representatives are held and advice and collaboration is sought from Specialist Branches on component design and from the Research Division of the Establishment who may be producing new ideas that could, with advantage, be fed into the design.

SELECTION OF COMPONENTS

During the project study phase, particular attention must be given to the selection of components. The factors guiding the method of selection of some of the principal automotive components are discussed. It is not proposed to go into fighting equipment in detail both to avoid security problems and because details of this type of equipment are probably of less interest to the members of this Institution.

Engines

There are various forms of engine from which to select the engine for a tank. These include diesel engines, gasoline engines, blown and unblown, carburetted or fuel injected, in various cylinder configurations and overall shapes. Not all of them will be suitable for one reason or another. The tank engine must simultaneously fulfil the functions of a low speed, high torque engine for superior movement across difficult country and a high speed automotive engine which will produce high vehicle speeds on the roads. It must operate in ambient temperatures up to 125°F, without overheating, when installed in a confined armoured box with a limited louvre opening for cooling purposes. In addition, it must be robust and require a minimum of maintenance. Most of these are conflicting requirements and none can be optimized except at the expense of others. Thus the best low speed performance can only be obtained at some expense of power and fuel economy at top speed. On the other hand, a compact size, coupled with a high specific output, necessitates high maximum speeds. Robustness and mechanical reliability usually involve heavy scantings and require additional weight, whereas compactness is not normally compatible with ease of maintenance. Thus tank engine design involves a series of compromises between these desirable requirements. Today, the field is narrowed by the fuel policy adopted, not only by the British Army, but also by the armies of most other countries, which is that a military engine in future must be capable of multi-fuel operation. This means the virtual elimination of the straight gasoline engines since the multi-fuel capability, at the present state of the art, is obtained from engines operating on a diesel cycle. Although most diesel engines can be adapted for multi-fuel operation, to date, multi-fuel versions are not used commercially to any significant degree. Engines suitable for tank design are, therefore, very limited and would normally have to be specially developed for new tank requirements, particularly as the demand now seems to be in favour of greater horsepowers than ever before.

A 700 b.h.p. multi-fuel engine of a novel form was developed for the Chieftain tank and will be of interest. This engine, known as the L.60, was jointly developed by Leyland Motors and the F.V.R.D.E. It is an opposed piston, two-stroke engine operating on a diesel cycle. Fig. 7*a* shows a sectional view of this vertical, water-cooled engine which has six cylinders each with two opposed pistons. The upper crankshaft is ganged to the lower by a train of gears and the engine output shaft and starter ring are driven from one of the intermediate gears of this train. Also driven from the auxiliary gear train are a Roots type scavenge blower for scavenging exhaust gases from the cylinders, an in-line, 12 element fuel pump and hydraulic speed governor, and a gear pump which pressure lubricates the engine from a separate oil tank. The L.60 has proved to be a rugged tank engine and reliability trials have shown that it is capable of producing life milages in excess of 6000 miles. The multi-fuel characteristics enable it to operate on diesel fuel, gas turbine fuel, MT gasolines of 74 or 80 octane rating, premium grade motor spirits or a mixture of any of these.

Performance data for this engine are shown in Fig. 8. It will be seen that this engine has all the requisites of a good tank engine as regards high torque, at both low and

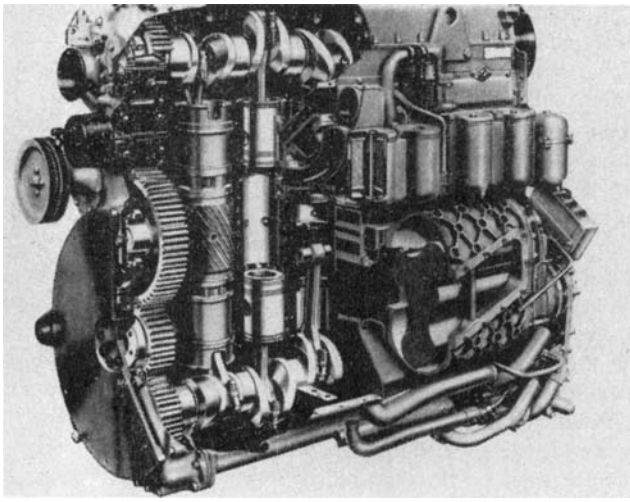


Fig. 7a. The L.60 multi-fuel engine

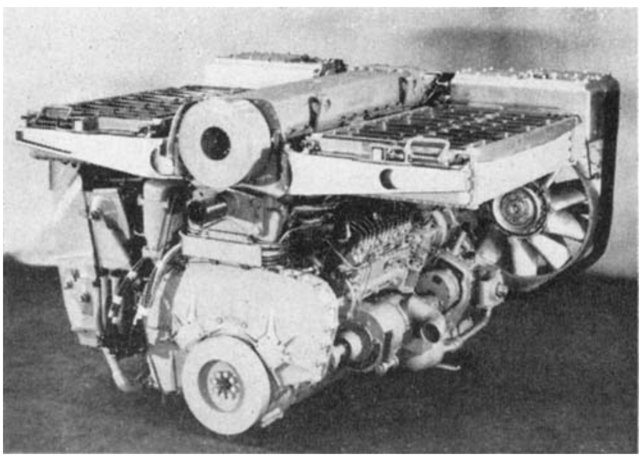
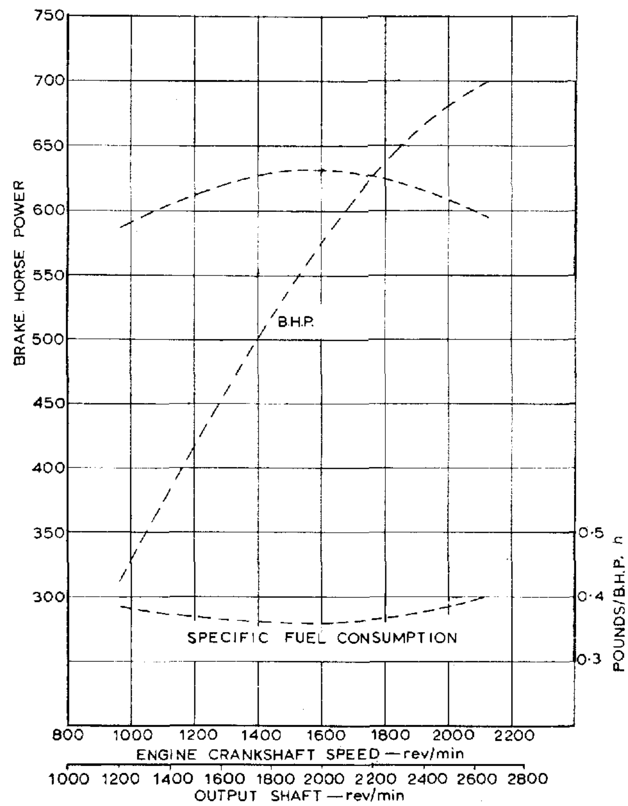


Fig. 7b. The Chieftain L.60 power pack



Six-cylinder opposed piston two-stroke

Bore	4·65 in	117·5 mm
Stroke	5·750 in × 2	146 mm × 2
Swept volume	1160 in^3	19 litre
Fuel	Diesel	

Fig. 8. L.60 engine performance curves

high speeds, and has low fuel consumption relative to a spark ignition engine.

For tank installation, an engine should ideally be compact in all dimensions and particularly in height, since this is reflected in the height silhouette of the vehicle. A short length is also very desirable, since any increase in hull length may well result in the need to have additional suspension stations and road wheels which can have a serious effect on the weight increase of the vehicle. With the engine ancillary components mounted, it should be capable of being made up into a neat and compact power package capable of delivering the maximum power per cubic foot of space occupied. Several common engine cylinder configurations are shown in Fig. 9. The in-line engine is poorly adapted for tank use because its length becomes excessive at outputs suitable for tanks. The Vee-engine is much more efficient in the utilization of space than the in-line engine. The length is reduced approximately by half and the height and width are effectively compromised. The air flow path lends itself to air cooling and because crankshafts and crankcases are shorter than in an in-line engine, the design can be made very rigid. The horizontally opposed engine is also short in length and minimizes the height but the width is greater and if it is located in the bottom of the tank, air flow for cooling is not ideal. Radial engines and 'X'-engines minimize length but tend to be excessively high and wide and are therefore not very suited for tank engines.

Finally, the opposed piston engine is of reasonable length and is narrow. It is, however, the tallest of all the forms of engine and is not, for that reason, a good form of configuration for tank installation, although the L.60 in the Chieftain is, in many ways, ideal for that tank. To begin with, it is, in accordance with U.K. practice, a water-cooled engine and because of its narrow width, even with ancillaries mounted, it allows space on either side for the large cooling radiators with convenient space underneath for mounting a large auxiliary engine and generator necessitated by the electrical demands of the fighting compartment. Together with radiators, fans, engine ancillaries, air cleaners, oil tanks, etc., it forms an extremely neat and easily removable power package and with the transmission occupies every inch of available space in the engine compartment, Fig. 7b. Air-cooled

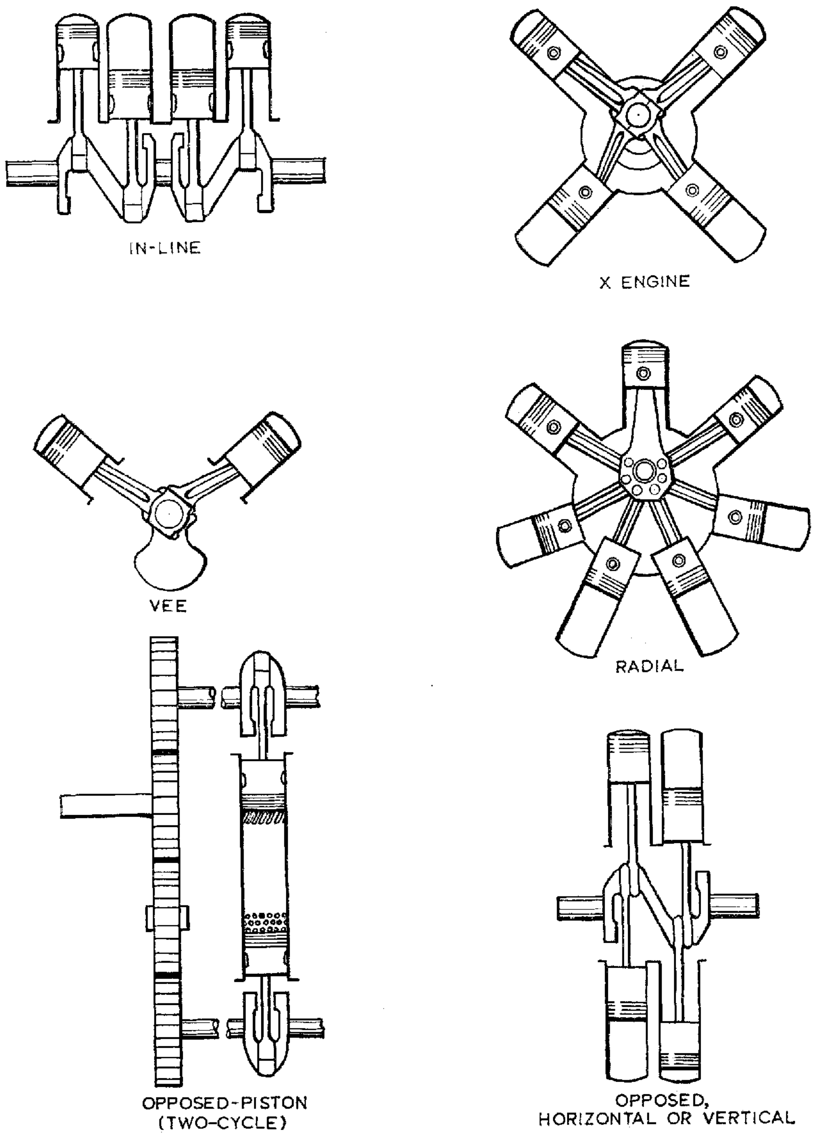


Fig. 9. Cylinder arrangements for reciprocating engines

engines used widely in the U.S.A. must also be considered since they usually require less space for the combined engine and cooling system, mainly because they require no large radiators or header tanks. They operate on higher differential air temperatures than liquid-cooled engines, where the temperature is limited by the boiling point of a coolant in a pressurized system. They thus require a smaller quantity of air to effect a given amount of cooling and hence fans are smaller and absorb less power.

Gas turbines are also receiving attention as possible tank engines because of their high specific horsepower output both on a volume and weight basis, their easy adaptation to multi-fuel operation, their inherent torque multiplication and their mechanical simplicity with no reciprocating parts or unbalanced forces.

Their principal drawback is low thermal efficiency resulting in high specific fuel consumption; apart from this they require large volumes of air which aggravate air-filtering problems.

Transmissions and steering systems

The function of the transmission is to extend the range of torque given by the engine by transforming the power from one combination of speed and torque to another according to the duty required. Not only must a tank transmission be able to vary the ratio between the engine torque and the torque at the driving sprockets, but it must do this at the most economical engine speed possible.

During cross-country movement vehicle speed may be restricted by considerations of crew comfort and by the limitations of the suspension rather than by lack of torque at the sprockets. In such circumstances the transmission acts principally as a speed change maintaining the speed of the prime mover above its stalling speed even though the torque requirement could readily be met by less speed reduction in the transmission.

Since, also, the output shaft of the prime mover is unidirectional, the transmission must provide the means for reversing the direction of rotation of the sprocket.

Tank transmissions must be able to provide a variety of torque ratios permitting the tank to operate at high speeds on roads and across rough country, to climb steep slopes, to cross a variety of obstacles and in combination with a steering unit to accomplish turns of varying radii including slewed turns. This variation could be provided in a limited number of finite steps or in infinite variation by automatic means requiring no judgement on the part of the operator.

Transmissions must be efficient and simple to operate, requiring a minimum of skill and effort on the part of the driver in changing from one ratio to another.

The cost must preferably be small and the size and weight as low as possible so as not to compromise unduly the weight of the vehicle itself.

Finally, tank transmissions must be capable of operating in a variety of environmental conditions ranging from -60°F to 125°F.

The steering of a tracked vehicle is accomplished by controlling the relative speed of the tracks and at the same time supplying the necessary power to overcome the steering losses resulting from the skidding of the tracks both laterally and longitudinally.

Steering systems that have been employed for tanks range from simple clutch-brake steering and controlled differential steering to more complex systems such as the Merritt triple differential steering.

The clutch-brake system provides good stability straight ahead and enables pivot turns to be accomplished about either track. It is, however, only suitable for low speed track-laying vehicles because the power of the inner track has to be entirely wasted. At high speeds the steering losses become too great and a regenerative form of steering becomes necessary.

Controlled differential steering produces a geared turn of fixed ratio. A high ratio is normally required by the need to turn sharply in confined spaces and, since this gives a sharper turn than is required at high speeds, intermittent application of the steering brakes is necessary, therefore, so that the turn can be made by a succession of short sharp turns, or the brake has to be slipped. Pivot turns cannot be made with the controlled differential steering system and steering straight ahead is somewhat unstable during deceleration, particularly at high aspect (C/L)* ratios. Power losses are higher than for the Merritt triple differential system.

The Merritt–Brown steering system is a divided torque system combining the steering system with the speed change. It is a regenerative system which has been used for a number of years on British tanks including the Centurion and is described later in greater detail.

* *C = Distance between track centres.*
L = Length of track on ground.

Various forms of tank transmission in combination with steering systems are discussed as follows.

Synchromesh transmissions

Synchromesh transmissions have a very high efficiency relative to other forms, particularly in high gear. Even in the lower gears, the efficiencies range between 85 and 95 per cent. They are normally used in combination with a mechanical friction clutch and controlled differential or triple differential steering.

Efficient use of the transmission, however, as with spur gear transmissions, depends on driver skill and a considerable amount of effort must be expended in operating heavy clutches. Since the ratios are varied only in a limited number of steps, the engine is not always operated at the maximum fuel economy for the horsepower required.

Hydramatic transmission

Although used on a number of World War II light tanks, synchromesh transmissions are generally unsuited for heavier tanks since the rotational inertias involved result in excessively large synchro-cones to transmit the torque.

Driver skill and effort are reduced considerably by the Hydramatic transmission which has been used in some of the American tanks since World War II. This form of transmission combines a fluid coupling with an automatic planetary gear transmission. The U.S. transmission has four forward speeds and one reverse. Speed range selection is made through manually operated hydraulic valves and gear ratios are automatically changed by hydraulically operated multiple disc clutches and friction bands. A split torque drive produces a combination of mechanical and hydraulic drive and reduces the slip of the fluid coupling at high speed, thus increasing the efficiency.

Torqmatic transmissions

Torqmatic transmissions consist of a hydraulic torque converter connected to a multiple speed and reverse planetary gear transmission. The operation is similar to that of the hydramatic transmission except that the torque converter provides torque multiplication in the various speed ranges.

Merritt–Brown transmission

The Merritt–Brown (1)† transmission, so called because it was evolved by Dr H. E. Merritt and built by David Brown Tractors, has been referred to previously as having been fitted to British tanks over a number of years.

It combines the functions of both transmission and steering unit in one lightweight unit and is, at the same time, easy to construct and very efficient. It is in many ways admirably suited for a tank transmission and deserves description.

Referring to Fig. 10, the input from the engine is divided, one path being channelled through a spur-gear, change speed gearing to the ring gears of the output

† *References are given in the Appendix.*

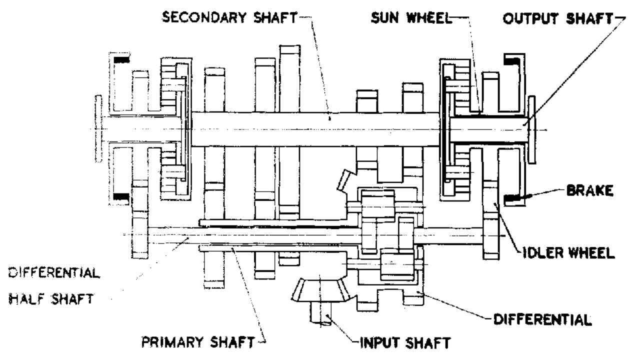


Fig. 10. Merritt-Brown type Z5 transmission

planetaries, and the other, via a differential and half shafts, to the sun gears of the same output planetaries where the power paths are combined and react on the output shafts which are directly connected to the planet carriers. It will be noted that idler gears are interposed between the half shafts and the sun wheels. This arrangement results in the sun wheels of the output planets rotating in the opposite direction to that of the ring gears when in forward drive. The effect of this is to increase the overall ratio spread of the transmission as a whole compared with that given by the change speed gearing alone. In order to steer, one or other of the steering brakes is applied to arrest the appropriate sun wheel, thus speeding up the output shaft on the brake side and slowing down the opposite output shaft by a slight amount. The change speed gearing has 5 forward and 2 reverse ratios, the minimum turning circle being different in each gear with the largest radius of turn being obtained in the highest gear and the smallest in the lowest gear. When in neutral a pivot turn can be made about the central axis of the vehicle.

The system provides completely regenerative steering and, because of the high efficiency, the transmission requires no additional cooling other than the airstream from the engine fans blowing over the casing. One of the main disadvantages of the system is the fact that it is used in conjunction with a large manually operated mechanical clutch which requires considerable effort on the part of the driver. This was not acceptable for the Chieftain in which the driver adopts a reclining posture when closed down for action. In this attitude he is incapable of exerting large efforts with his legs.

An easy change transmission of the 'hot shift' type was, therefore, specially designed for this tank and is described as follows:

Chieftain 'hot shift' tank transmission—TN.12

The Chieftain TN.12 transmission, Fig. 11, combines the Merritt steering system with a Wilson epicyclic type of gear change in which the various gear ratios are selected by the application of brake bands to the appropriate reaction members of the epicyclic train. These brake bands are actuated by hydraulic cylinders which are supplied with hydraulic pressure from pumps incorporated in the transmission.

The driver's gearshift control is a foot-operated ratchet switch which energizes the solenoid operated valves supplying hydraulic pressure to the cylinders. In this way he changes up or down, one gear at a time, simply by lifting or depressing the switch with his toe. There is no clutch pedal for him to operate since the drive from the engine is taken up by a centrifugal clutch.

Thus, various factors affect the choice of type of transmission for a particular design of vehicle. Apart from operating efficiency, the weight, size and general configuration are important considerations. Ease of operation and a reduced tendency to cause driver fatigue can also have an important bearing on choice as in the case of the Chieftain tank.

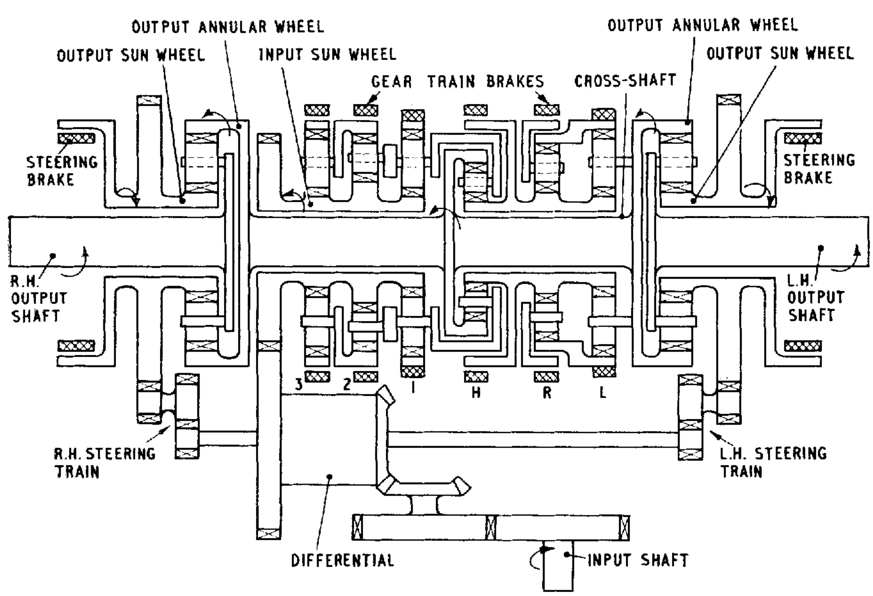


Fig. 11. TN.12 transmission

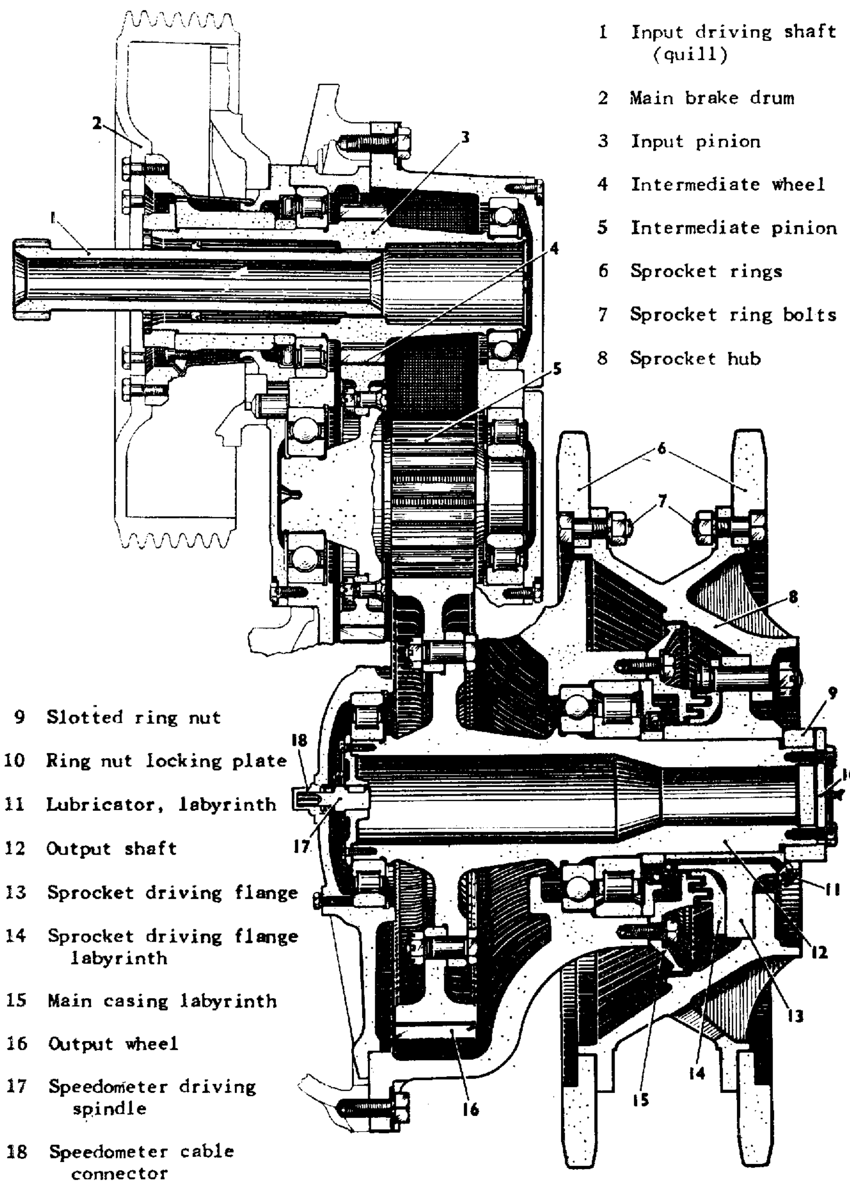


Fig. 12. Centurion final drive

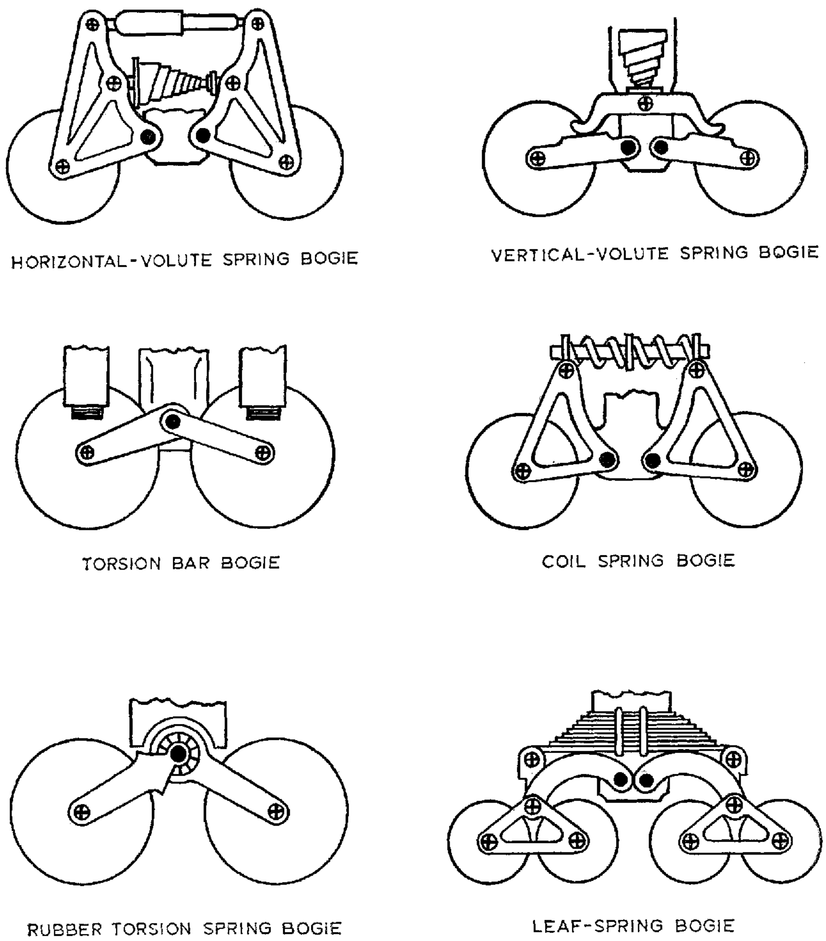
Final drives

We now move outside the tank to the final drive assemblies which are normally bolted on to the hull. They contain the final reduction gearing which drives the sprockets that engage with the tracks. When used with regenerative forms of steering, which involve the transference of torque from one side of the transmission output to the other, they have to cope with power in excess of that being delivered by the engine. Gears and bearings must, therefore, be designed for this duty and additionally must be capable of coping with the superimposed loads from excessive tension in over-tightened tracks, etc.

Both straight spur gear reductions and planetary gearing have been employed in final drive designs. Fig. 12 shows the final drive for Centurion.

Suspensions

The speed of the tank across rough country may be seriously limited by the inability of the crew and the more delicate components and instruments to stand the rough ride. The operational requirements of today demand far greater power/weight ratios for tanks than previously in order to achieve greater speeds and accelerations. It is quite obvious, therefore, that the suspension characteristics must be able to match the tank's performance and produce as smooth a ride as possible in order to use the available power to the best advantage. A smooth ride also provides an enormous tactical advantage in enabling the main armament to be served and, with the aid of stabilizers, to be fired on the move with greater accuracy.



● Fixed pivot. ⊕ Movable pivot.

Fig. 13. Various bogie type suspensions

The suspensions themselves and the road wheels must be extremely rugged to withstand the severe duty to which they are thus subjected and at the same time their weight must not be excessive if they are not to add considerable weight to the vehicle.

The number of different types of suspension used in tank design have been legion. They fall, however, into two main categories:

(1) Bogie type suspensions in which two or more wheels are mounted on pivoted axle arms in one unit and linked through an interconnecting spring, Fig. 13.

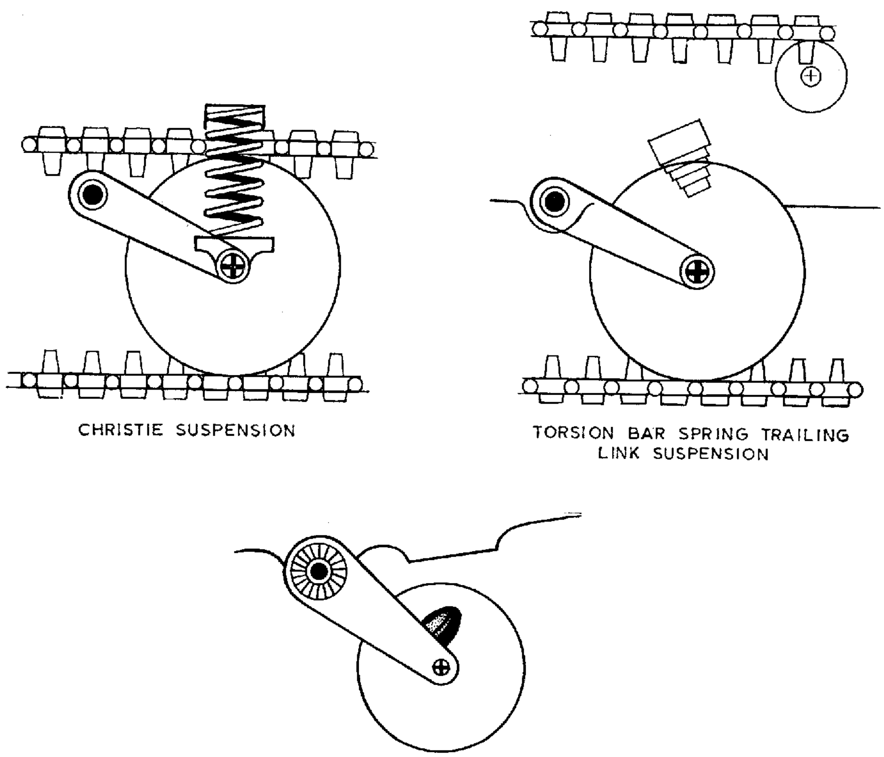
(2) Independent pivoted arm suspensions in which the independently sprung wheels are free to move up and down without reacting on the other wheels, Fig. 14.

The springing of these suspensions has been effected by volute springs, leaf springs, coiled springs, torsion bars, rubber torsion springs and hydro-pneumatic spring systems. Variations in spring rate characteristics can be produced by the compounding of springs to give any desired effect and resilient bump stops may be used to give a rapid spring rate at the extreme deflections and to limit the lifting of the road wheels and the loading of the spring system.

The compression of suspension springs can be regulated by the use of shock absorbers and both single-acting types which damp rebound only and double-acting types which check the compression as well may be used. The two principal types of shock absorbers in use are hydraulic types and friction types. Both produce their damping action by the conversion of mechanical energy to heat energy.

Generally speaking, hydraulic shock absorbers tend towards overheating and the leaking of seals due to the increase of viscous damping with increase of the speed of oscillation. By virtue of this same characteristic, however, they tend to adjust automatically their damping action to the speed of oscillation and are therefore equally effective at both low- and high-speed travel.

Friction dampers on the other hand produce a constant rate of damping irrespective of speed. If adjusted to suit high speed they are too harsh for lower speeds and vice versa. They have, however, been used effectively on



● Fixed pivot. ⊕ Movable pivot.

Fig. 14. Independent trailing-arm suspensions

vehicles where the speed range is limited and tend to have a relatively good life.

The characteristics of a good suspension system are:

(1) Adequate wheel lift.
(2) A good spring rate characteristic.
(3) Good damping characteristics over a wide speed range.
(4) Low weight and good ratio of sprung weight to unsprung weight.
(5) Good fatigue life and wear and abrasion resistance.

Torsion bar suspensions (Fig. 15*a*) of the independent trailing arm type have been widely used for fighting vehicles. Their main virtue lies in the fact that they have a relatively high energy storing capacity per unit weight. Since the torsion bars are housed inside the vehicle they are protected to a greater extent from ballistic attack and, if properly made from the right materials, have a reasonably good life. The main disadvantage is that the internal space they occupy can increase the height of the hull unless they are skilfully integrated into the hull design to avoid this. Further, if the hull is distorted due to mine attack they may prove difficult to remove and replace in the field.

Fig. 15*b* shows the design of the Centurion's suspension which is typical of that used on the more recent British tanks. It is a bogie type suspension in which the two road wheels are mounted on pivoted arms, one trailing and the other leading, and linked by a helical spring, the thrust of the spring being taken on knife edges. Since the complete suspension is mounted on the outside it is easier, generally speaking, to remove and replace when damaged.

Tracks

The purpose of the tracks is to lay a smooth continuous path over the ground for the road wheels and to transmit the tractive effort to the ground. Under conditions of soft going it acts as a load-spreader and provides the necessary flotation.

These functions are best performed in a tank by a continuous arrangement of linked plates or shoes, the outer surfaces of which provide the necessary grouser action for traction with the inner surfaces providing the smooth wheel path and carrying the necessary guide horns to prevent the track from being thrown off the suspension. The track must also be provided with the means for engaging the driving sprockets.

Tracks must be strong and resistant to wear and abrasion. At the same time, they must be as light and flexible as possible if the power lost to the tracks is to be kept to a minimum. Cleare (**2**) points out that of the total power lost to the track and suspension system in rotating the tracks about 60 to 70 per cent is lost to the track itself depending on the tightness of the track. He indicates also that losses

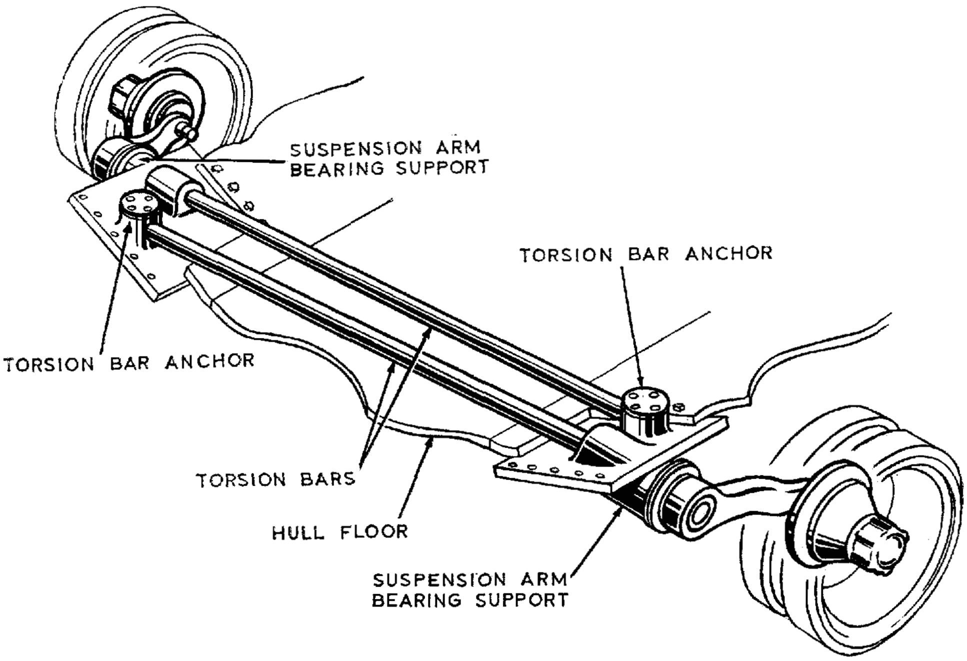


Fig. 15a. Torsion bar suspension system

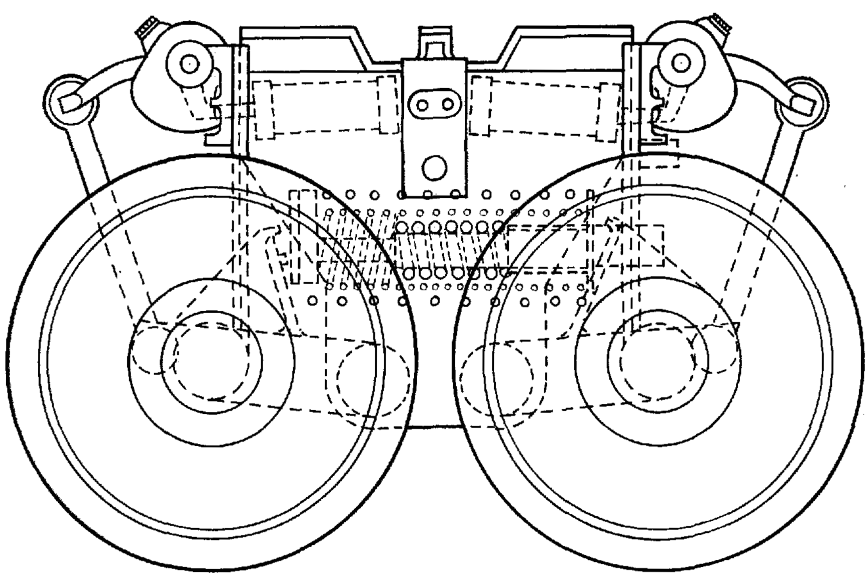


Fig. 15b. Centurion 7 and 8 suspension

in tracks having rubber bushed hinge pins are less than those in dry pin tracks. Many different track forms have been used in tank designs and these have included all-metal dry pin tracks, rubber padded metal tracks, metal tracks with rubber bushed pins and metal tracks which are both rubber padded and have rubber bushed pins.

A considerable amount of development effort is involved in producing a new track of low weight, low rolling resistance and long life. Tracks must be tested and compared with alternative designs under actual running conditions over various types of ground and this may involve many thousands of miles of running.

An essential requirement of the tank is that it should be able to negotiate bogs, swamps and other forms of low strength soil which exist on many parts of the earth's surface, particularly in the wet season. Two of the most important functions of the track, therefore, are to provide adequate flotation and adhesion on weak soils both to prevent road wheels from sinking in too far and to enable the tank to climb slippery slopes.

Excessive sinkage can so increase the rolling resistance that the weak soil cannot support the tractive effort required to propel the tank. This allows the tracks to slip with consequent loss of traction, however good the grouser action may be.

To prevent this, a low nominal ground pressure is necessary. This is the ratio of the weight of the tank to the area of the track in contact with the ground and is usually expressed in pounds per square inch. Research in the field of soil mechanics and practical experience has shown that most of the low strength soils likely to be encountered by tanks can be negotiated if the ground pressures do not exceed 6–8 lb/in^2.

The attainment of this desirable goal becomes more and more remote as the density of the battle tank increases. Since the tanks of today are required to be smaller and to carry larger weapons and more armour than previously, their density is high and this must reflect in the ground pressure.

The limitation on the overall width of the tank and the minimum hull width permitted by the design dictates the maximum track width, whereas the need to maintain a reasonable aspect ratio, C/L, limits the length of track on the ground.

Thus the designers must, as usual, make the best compromise possible between hull and track width and between the length of track and the steering characteristics of the vehicle. Other than that a substantial weight reduction must be made which may involve some compromise on armour protection.

FIGHTING EQUIPMENT

It is not intended to say a great deal on fighting equipment except to point out, generally, that a vast amount of gun control equipment, fire control equipment, vision devices, electrical equipment, ammunition and various other items must be housed in and about the vehicle.

Fig. 16 shows an array of gun control equipment and turret electrical items used in the Chieftain tank. All this complex equipment is necessary in order to fight the gun when the tank is static, to stabilize it when the tank is on the move and to give it a high chance of hitting and killing its target. Their accommodation in the tank is nevertheless

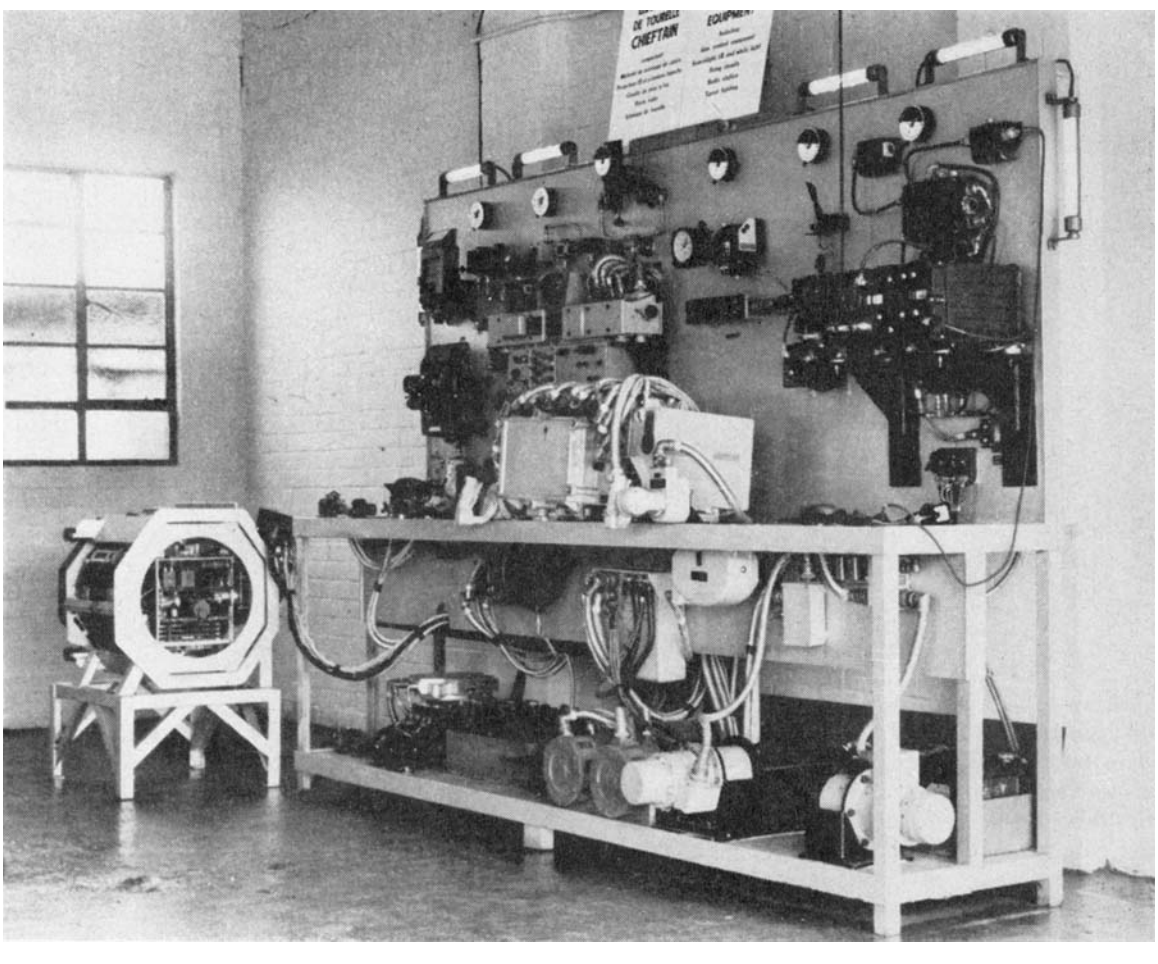


Fig. 16. Gun control equipment and other turret electrical items used in the Chieftain tank

a nightmare for the designers. Much effort must, therefore, be devoted to the miniaturizing of components and to the integration of their shapes to give a compact layout. Equipment and controls must be conveniently positioned for the members of the crew who have to use them. At the same time, they must not obstruct movement or cause injury when the tank lurches.

DESIGN AND DEVELOPMENT

Again, space permits only a very superficial treatment of this phase of development. On the completion of the project study and the granting of the necessary financial sanction, contractors are selected by tender to engineer the design, produce manufacturing drawings and construct prototypes for development testing. A main contractor will cover the design of the vehicle as a whole, but various other contractors, specialists in various fields, will be involved in the development of components.

It has been the practice that most of these firms are under direct contract to F.V.R.D.E. rather than to the main contractor as this arrangement shortens the link of technical liaison between firms and the Establishment who are required to feed in the necessary specialist expertise relating to tank design which does not necessarily exist in industry.

The Establishment is well organized to cope with this method of working. It has a hardcore of engineers, scientists and other technical grades who are formed into three divisions. The tracked division, the wheeled division and the research division who control the development of the research work of the Establishment. The former have co-ordination branches whose function is to provide project officers to run the project and supervise the technical and financial control with the aid of a planning and financial branch. They maintain liaison with the firms and introduce assistance from the specialist branches as required. The specialist branches deal respectively in power plant, running gear, turrets and sighting and electrics. In addition, regular design and progress meetings are held which are attended by all concerned, including contractors. A project management system is proposed for future major projects which need not be discussed at this juncture. When the prototypes of vehicles and components arrive, an intensive programme of development testing is put in hand. Whenever possible, and the time factor permits, components, etc., are bench tested or rig tested under simulated environmental conditions to reveal defective designs or other defects before being tried out in vehicles. There is a growing realization that this form of testing, provided that it is sufficiently realistic in representing actual conditions, can do much towards 'debugging' components of their weaknesses and defects before they are run in actual vehicles, thus saving much valuable time and money. This applies particularly to automotive or electrical components where successive failures of such components during development running of vehicles can cause frequent stoppages and delays in the development of other components.

The Establishment has a modern and well equipped engineering test laboratory for the performance testing of components and assemblies such as gearboxes, engines, air cleaners, fans, suspension units, tyres, etc. Facilities include a fully instrumented low temperature chamber big enough to accommodate a tank for cold starting and other trials, in which temperatures down to $-60°F$ (100° of frost) can be achieved. There is also a tropic chamber and a comprehensive range of dynamometers for testing engines and transmission systems. There is a need, however, to increase these facilities, particularly with regard to the provision of environmental test beds, which will allow automotive components and even complete vehicles to be tested under faithfully simulated running conditions. A comprehensive plan is being put into effect and will undoubtedly pay dividends in the years to come.

Although laboratory and engineering testing play an extremely important part in component development, the ultimate proving of components must be carried out on the vehicles themselves, since it would be impracticable to simulate every environmental condition on a test bed. The Establishment places great importance on such trials and prototype and production vehicles are subjected to many thousands of miles of running on roads and cross country going of all types in varying soil conditions. They are also required to be driven over a number of different suspension courses which are a severe test of the vehicle's suspension and running gear and their ability to provide a smooth ride.

Towed cooling trials at maximum engine torque and horsepower are always carried out to test the effectiveness of the engine compartment cooling system and supply data which will enable the behaviour of the vehicle at the specified limiting ambients to be determined by extrapolation. Climatic trials with tanks are usually carried out at a later stage to confirm these results. The running trials are normally planned and scheduled by the co-ordinating and specialist branches and carried out by the trials sections under military officers who are able to introduce something of the user element into the trials.

The Establishment has well equipped test tracks with a 2-mile road circuit with banked curves, various suspension courses, test slopes, a skid pan, suspension ramps, a wading pit and other facilities for vehicle testing.

In the course of intensive development running many defects come to light and immediate action is taken to redesign or modify components. They must then be retested with as little interruption as possible to the running of prototype vehicles, although inevitable delays do occur.

The Establishment is fortunate in having well equipped workshops for maintaining and modifying project vehicles. They play an essential part in the development.

Experience has shown that, in spite of the fact that everything is done to subject vehicles to rigorous testing, the development trials do not bring to light many defects which tend to occur when the vehicle is in user hands. This is generally thought to be because the F.V.R.D.E.

drivers and crews become very skilled and are far less likely to abuse the vehicles as much as the less skilled service crews.

Much importance is, therefore, placed in the carrying out of user trials under operational conditions. In the course of these trials many new defects come to light and the user has the opportunity to assess the vehicle for service use and request modifications to improve it from this point of view. Due to telescoping of the development programme, development trials and user trials often overlap. This increases the difficulty of modifying user trials vehicles with the modifications found to be essential from the development trials. Thus users must have relatively undeveloped vehicles and experience many failures, which can cause distrust in the vehicles and a reluctance to believe that they can be made acceptable in due course. Against this, the early discovery of new defects does tend to accelerate the introduction of modifications into the production design with obvious benefit to the user.

Acceptance of the vehicle for service use is normally made on completion of the user trials and is usually conditional upon the introduction of modifications requested by the user.

Authorization is then given for the vehicle to go into production and be manufactured to an agreed specification.

ACKNOWLEDGEMENTS

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APPENDIX

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(2) CLEARE, G. V. 'Factors affecting the performance of high-speed track layers', *Proc. Auto. Div. Instn mech. Engrs* 1964 **178**, 51.

Discussion

Mr R. M. Ogorkiewicz, M.Sc. (Eng.) (*Associate Member*) —In the historical section of the paper I note that the author does not accept the widespread myth about Sir Ernest Swinton being the 'originator' of the tank. As I have already tried to show elsewhere*, Swinton's contribution to the development of the first British tank was negligible and the credit for it must be given to others.

When he comes to present-day problems, it is a pity that the author says so little about armament and protection. I appreciate his concern for security but there is no lack of unclassified information and no discussion of tank design can be complete without taking armament and protection into account, if only in general terms. Moreover, I would suggest that the integration of armament, protection and automotive components into an effective weapon system represents a more important and interesting problem than the development of any one component.

It was the need ultimately to proceed beyond analyses of individual components and to consider the tank as a system of interacting elements which made me put forward the method of evaluating tanks referred to by the author†. I am glad that he considers it worth examining further and I see no reason why it should not be elaborated to include the additional factors which he mentions. For instance, the rate of fire can be brought in by considering the kill rate instead of the single shot kill probability. Reliability is already taken into account in comparisons of different tank armament systems and it could be introduced in a similar way into the evaluation of tanks as vehicles.

I must admit that I have not so far developed the proposed method of evaluation to cover all these additional factors but I can only devote to tanks what time I can spare from earning a living in other fields of engineering. Others, who are better off in this respect, should be able to improve on my original mathematical model.

Finally, I would like to ask a question connected with the automotive components to which the author has devoted most of his attention. How attractive does he consider the hydro-mechanical steering systems with a hydrostatic unit in the steering drive and the hydropneumatic suspensions which have appeared on some foreign tanks?

* Ogorkiewicz, R. M. 'The first tracked armoured vehicle', *Armor* 1965 **LXXIV** (4, July–Aug.), 46.

† Ogorkiewicz, R. M. 'A method of evaluating tank designs', *Armor* 1965 **LXXIV** (5, Sept.–Oct.), 54.

Mr G. V. Cleare (*Member*)—I have played some part in the development of practically all the vehicles listed in the paper during the 34 years I have spent on the design and development of fighting vehicles. Even the Mk V and Medium C tanks of the first world war were regularly run in the course of demonstrations staged by the pre-1940 Establishments, which were the foundations on which the present Fighting Vehicles Research and Development Establishment was built. There is a great deal in the paper on which one could comment but time will only permit of reference to one or two points.

This type of vehicle is inevitably a compromise and the strains and stresses within F.V.R.D.E. when a concept is being forged into a realistic vehicle design must be experienced to be believed. Each Specialist Branch naturally strives to provide the best performance and reliability from the components for which it is responsible and the resulting compromise should be an optimization of what is possible within the framework of the overall concept.

The author has referred to the limitations of the clutch/brake steering system when applied to tanks. This became apparent at a relatively early stage in the development of tanks in Britain, and other forms of steering mechanism were being actively developed more than 35 years ago. It is perhaps worth recalling that Dr Merritt was Superintendent of Design in the Tank Design Department at Woolwich Arsenal when the steering mechanism associated with his name was evolved. This was his very successful contribution to the search which had been in hand for a long while for a mechanism to improve the efficiency of the steering of high-speed track-layers.

The author has commented on the three principal characteristics of the tank—fire power, armour protection and mobility. Those who engage in tank philosophy often argue about the order of importance of these characteristics. In this connection, it is perhaps worth looking at the relation between gross power/weight ratio of tanks and their speed on cross-country terrain as represented by the Long Valley at Aldershot. I have plotted some points, Fig. 17, derived from actual vehicle tests on a number of vehicles, the gross power/weight ratios of which vary from 8·8 to 21·6 hp/ton.

There is necessarily some degree of scatter in the results due largely to variations in ground conditions, but as one would expect it is virtually a straight line relationship. The first point which I think is worth making is that the

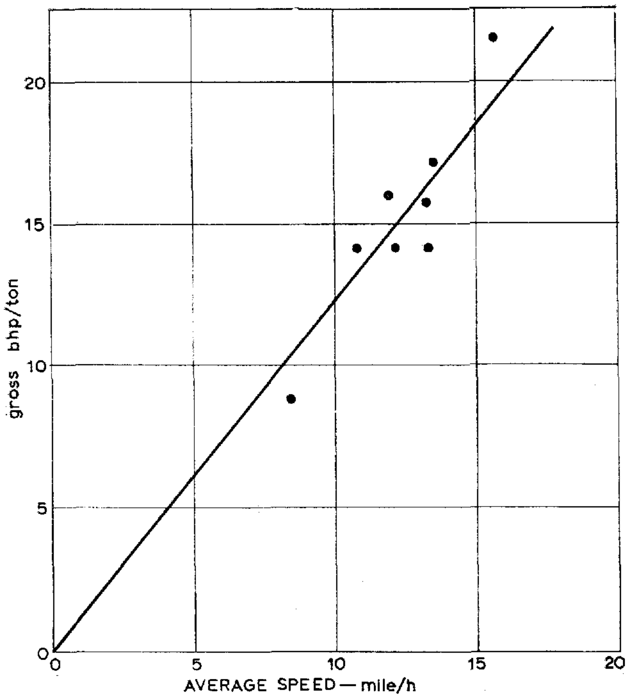

Fig. 17

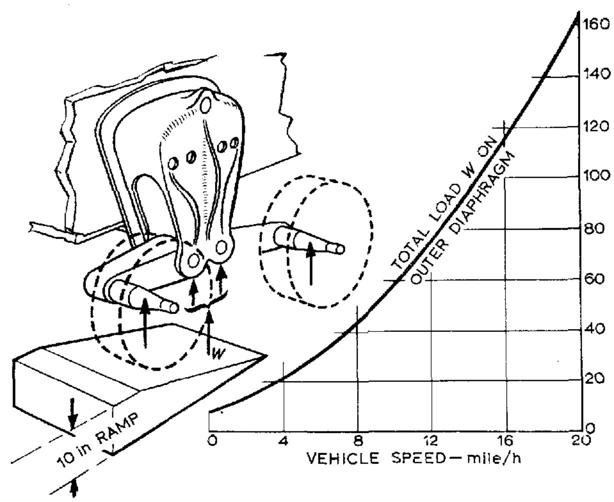

Fig. 18

difference in average speed for vehicles of, say, 12 and 20 b.h.p./ton is around 6 mile/h or 8·8 ft/s. There may be reason to doubt whether this is likely to give much extra protection from a high velocity gun.

Secondly, the straight line relationship indicates that on the vehicles built to date the suspension has not proved to be a limiting feature.

The author has mentioned the severity of the duty to which suspension components are subjected and it is perhaps useful to attempt to convey some idea of the magnitude of the loads involved. We have, from time to time, endeavoured to measure suspension loading by means of strain gauge techniques. A typical example is shown in Fig. 18 which shows the impact load on the leading bogie brackets of the Conqueror tank after negotiating a 10 in ramp at various speeds. It will be seen that at 20 mile/h the load on the bogie bracket was 160 tons, which, expressed in static terms, is equivalent to $2\frac{1}{2}$ times the entire weight of the tank on one bogie. This gives some idea of the magnitude of the loads with which the suspension units must be designed to cope and explains why the suspension systems on high-speed track-laying vehicles accounts, on average, for some 15 per cent of the vehicle weight.

The author has referred to synchromesh transmissions but it should be noted that the conventional form of synchromesh gearbox is not suitable for heavy tanks. It is not possible to accommodate synchro-cones of sufficient size to cope with the rotational inertias involved. A commercial type of synchromesh gearbox was used successfully in the 16-ton Valentine tank. The U.S. Sherman tank gearbox also contained synchro-cones but in this heavier vehicle they frequently gave trouble.

I am not aware of the hydramatic transmission being used in any U.S. tank since World War II. The term 'hydramatic' denotes a particular gearbox designed originally for motor cars. It was used in certain war-time vehicles embodying dual power units and has been used both in America and Britain in some light-tracked vehicles since the war.

Likewise, the term 'torqmatic' is also a registered name for certain transmissions produced by the Allison Division of General Motors Corporation and is not applicable to all transmissions embodying hydraulic torque convertors and compound epicyclic range change gears.

In my experience the principal problem of the hydraulic shock absorber, if it is of the telescopic type, is that since it 'sucks and blows' it also tends to inhale abrasive material. This causes its performance to deteriorate very quickly. Where hydraulic shock absorbers are well designed, and we have a very good one on the Centurion tank, they are virtually trouble-free; but with the exposed telescopic type we have had little success because of the particularly dirty conditions in which we have to operate.

Mr E. T. J. Tapp, M.B.E. (*Member*)—The author has given us a most informative survey covering the recent history of the tank leading up to the tanks of today. The survey shows a general tendency for increasing weight but the competition for importance between armament, armour, speed and range increases in proportion as the weight goes up.

The author mentions a desirable track weight spread of 8–9 lb/in^2, but do any of the machines he has shown come anywhere near this figure? Does he not agree that there seems a need for an intermediate machine between the full size tank capable of long range action and the infantryman—something approaching a mechanized infantryman in fact? Some exploratory work was done on such a machine at the end of World War I but the idea was shelved until 1936 when World War II seemed inevitable. Preliminary designs were prepared of a one-man machine, the War Office was contacted and the construction of an experimental machine privately undertaken with their approval.

Permission was given by General Sir Bernard Paget, Commandant, to test the machine at Minley, Sandhurst, and on seeing the machine he said that, if successful, this machine was the answer to an urgent need.

The machine was criticized in certain aspects, particularly in that only one man could be carried. Nevertheless, all were in favour of further development and we were authorized by the General Staff to prepare with all possible speed a design for a two-man machine with similar characteristics.

Setting all other projects aside in order to comply, drawings were completed and despatched to the War Office in December, 1939, but no acknowledgement was received until 22nd January 1940, when an order arrived from the Ministry of Supply forbidding all further work on the project.

Over nineteen months later we again received a request for demonstration before representatives of the General Staff and members of the Department of Tank Design. They reached the same conclusion as two years before and work proceeded, but the project was shut down in 1944. I wish to record my appreciation for the encouragement and assistance of various personnel in the Department of Tank Design and the Army at that time, but nevertheless the frustration arising from the delays in times of national peril bore heavily on the originators.

The two-man machine was eventually built and was christened the 'Praying Mantis' by General Richardson because of its similarity of movement and appearance to that creature and has been known as that ever since, but it has also been referred to as a possible submarine of the battlefield. The leading particulars of this machine are: Weight—5 ton, height ground to gun barrel, fully elevated—12 ft. Speed—35 mile/h, fire power—periscope sighted twin Bren guns.

The Praying Mantis can go anywhere that an infantryman can walk and was originally designed to pass through water 10 feet deep with the helmet raised to full height, although this characteristic was not incorporated in the first test machine.

The design of the driving controls was difficult as automatic transmissions, which would have solved a number of problems, were not then available.

Although further development does not seem to have taken place I feel sure that a machine with such characteristics must have a future.

Brig. P. G. Palmer, M.B.E., B.Eng. (*Member*)—I am Deputy to the Director of Electrical and Mechanical Engineering in the Ministry of Defence. As you know it is the Corps of the Royal Electrical and Mechanical Engineers that has to repair the tanks when they break down or are damaged, so we have an interest in two vital aspects, reliability and maintainability. I was disappointed to see that neither aspect was given more than passing reference in the paper; both are vital to the success of the tank on the battlefield, and in fact are placed very high in the order of priority in setting the essential characteristics.

I therefore make no apologies for stressing their importance in commenting on a paper dealing specifically with mechanical design.

It is vital that a tank is both reliable and maintainable, as when it breaks down it becomes an intolerable liability. In a modern army technical manpower is scarce and can only be provided at the expense of fighting troops. Thus, as equipment becomes more complicated, and engine compartments become more congested, ever-increasing importance is being given to these two characteristics. REME has an important part to play in the development cycle Mr Butterfield described and we participate at all stages. We advise the General Staff on the reliability and maintainability requirements during the formulation of General Staff Targets and General Staff Requirements. We endeavour to watch the whole process of design and advise and check on maintainability. There is a small team of officers and warrant officers with experience of maintaining and repairing tanks under field conditions, who live in the design establishment and pay great attention to all aspects which might complicate the REME task.

There will be teething troubles in the early stages of service and these are probably inevitable with such a complicated piece of equipment such as the tank. When these troubles become serious or numerous, it throws considerable strain on the limited resources of the Corps. This only emphasizes the vital necessity of a clear definition of reliability, good design and adequate testing to achieve it, and a high degree of maintainability under field conditions when the inevitable failure occurs.

Mr H. A. Dean (*Member*)—One aspect of the paper that interested me tremendously was that although very different in size and purpose from passenger cars, the principles, and to a certain extent the methods of design and development, are remarkably similar. For example, the design has to be acceptable to the customer. The designer has to work to minimum weight standards. He has to evolve the most economical design of vehicle. The development engineer goes through prototype testing, rig shop testing of components, track testing, cold room work, towed cooling trials. Similarly, too, the manufacturer's development trials do not show up all the snags, some are only brought to light by the user.

After carefully reading the paper and studying Table 1, I was more than surprised to find that the author had omitted any mention of the World War II Churchill tank. The author did to some extent rectify this omission by referring to the Churchill during the presentation of the paper, but it is unfortunate that the reference does not appear in print.

The Churchill, Fig. 19, was designed and built as a result of an urgent demand for a heavily armoured infantry tank. It weighed around 35 ton and had a maximum speed of 12–14 mile/h. Although the biggest and

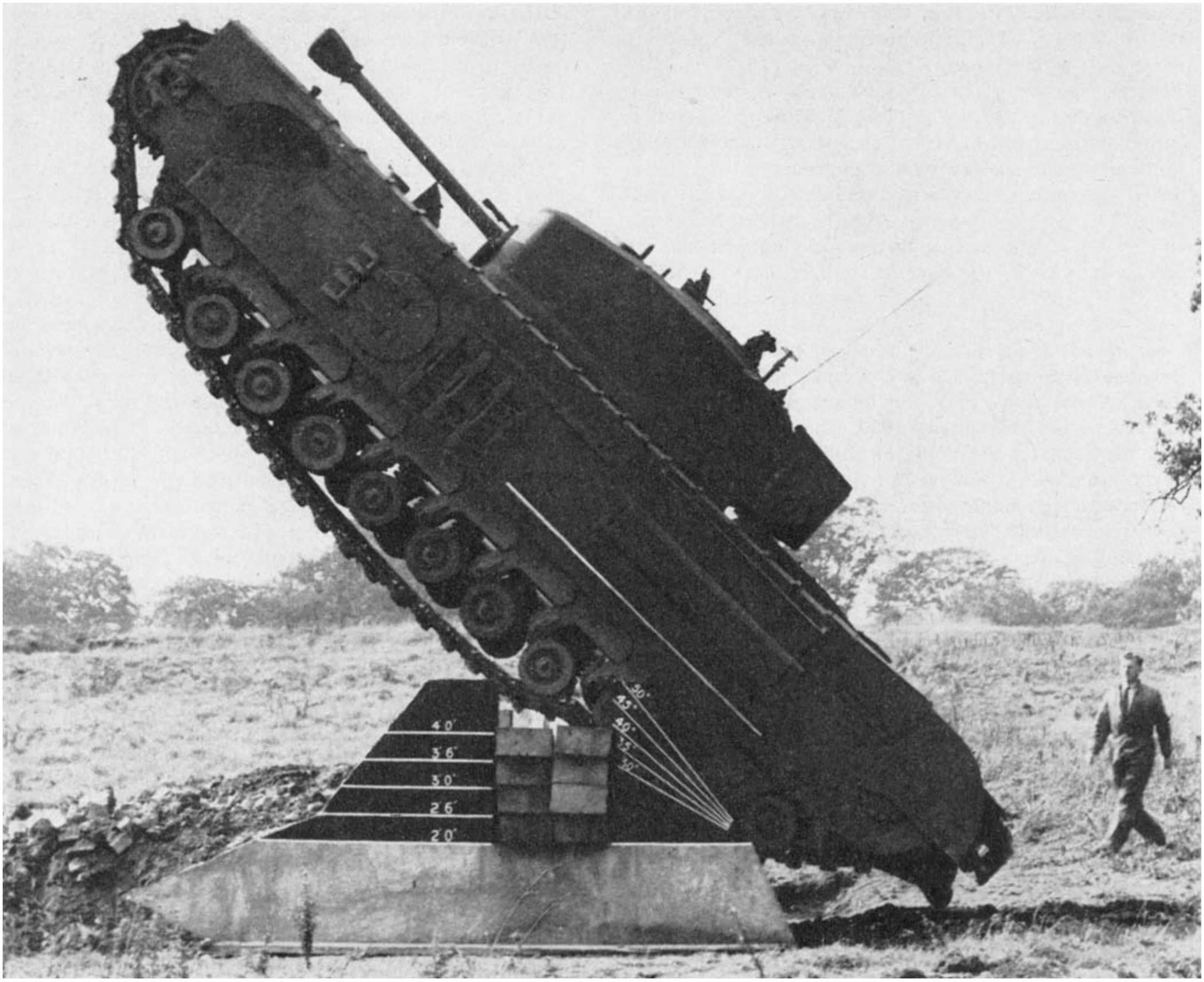

Fig. 19

heaviest tank at that time, its ground pressure was low, with the result that its flotation was good and it handled well on soft ground or thick mud. It was used in a wide variety of roles, as a flame-thrower known as the Crocodile, as a bridging device and for towing heavy guns. One of the features which contributed to its manoeuvrability was its Merritt–Brown gearbox and steering, referred to by the author in connection with later tanks. It is interesting to note that this type of differential steering gear, where the speed of one track has a geared relationship to that of the other, is still looked upon favourably 25 years later. It was also intriguing to me that the latest box is combined with Major Wilson's epicyclic gearbox principle, to lighten the clutch load.

Although through force of circumstances, mainly the threat of invasion, the Churchill tank was designed and put into production almost straight from the drawing board, thereby suffering the teething troubles always associated with an insufficient development period, we were most encouraged by the tremendously favourable comments we received.

Returning to the paper, I would like to ask the author for a fuller explanation of his comments on hydraulic shock absorbers, 'Generally speaking, hydraulic shock absorbers tend towards overheating and the leaking of seals due to the increase of viscous damping with increase of the speed of oscillation'. As I see it, while it is true that with a simple orifice type hydraulic damper viscous damping would increase with speed of oscillation, this surely does not follow to the same extent with a valve-type orifice. Surely the question of overheating is more related to the work done and heat dissipation properties, rather than whether the shock absorber is hydraulic or friction type?

Capt. W. G. V. Kenney, B.A., REME (*Graduate*)—I served in Kuwait with an armoured regiment equipped with Centurions. The temperature in the shade was about 125° and in the sun reached 170°. With the hatches open, the temperature inside a Centurion was about 140°.

With the hatches closed, firing the main armament and co-axial machine gun, both producing hot fumes, the temperature rose above 140°. There are men in a confined space tying to load 20 pounder ammunition, which weighs more than 20 lb, into the main armament. These conditions mean the crew are at or near a state of collapse in about three hours. This is a realistic figure.

I would like to ask Mr Butterfield how a tank was produced with these limitations? I feel far too much tank design is geared to North-west Europe. Also what has been done to obviate these deficiencies on current developments?

Communications

Professor A. D. S. Carter, B.Sc. (*Member*)—I have been involved in comparing vehicles of radically different design. Although these were not tanks the comparison emphasized the need for a rational quantitative approach tied closely to the objective. I suspect the same consideration would apply to tanks. On this score I would agree that Ogorkiewicz's approach is worth a re-examination. It is a quantitative method though additional factors will have to be introduced, as suggested by the author, if it is to yield worthwhile results. There should be no difficulty in doing this. My worry is that when fully developed the method will conceal more than it will reveal. It should be most powerful when dealing with small changes in design or in the development phase, but will probably be too detailed when substantial design changes are being contemplated. Substantial changes are bound up very closely with component design and performance. To deal with components a much more simplified method is necessary. The cost per payload ton/mile has been used as a criterion in some analyses involving vehicles of different design. The capital costs can be expressed in approximate technical terms as the ratio of all-up weight to payload weight and the running costs as the fuel consumed per payload ton mile. If the payload is interpreted as shells landing on the target it would seem that we are back to Ogorkiewicz's analysis, but a more liberal treatment in which the layload can be treated as the gun plus the ammunition plus gun crew plus associated armour may offer a simplified approach. The engine, transmission, traction, and their associated armour can then be treated separately.

I cannot agree that weight is a suitable simplified criterion. Even if overall weight is considered a prime factor, component weight may not be significant. This can be illustrated by reference to the component in which I am particularly interested, that is the engine. Taking a long term view the designer might have to chose between the diesel, supercharged diesel, compound diesel and gas turbine, the straight gas turbine, the diesel Wankel engine, and so on as a power plant for tanks. I cannot believe that weight of engine or even weight of engine plus fuel is the criterion by which the most promising of these engines could be selected. However, in the case of the tank, the weight of the armour associated with the engine compartment is likely to be far greater than that of the engine itself, and must be debited to the engine. This has led some workers to select engine volume plus the volume of fuel used in a typical mission as a criterion of engine effectiveness. Perhaps surface area of engine plus tanked fuel would be a better criterion though less easily evaluated at an early assessment stage. While appreciating that this does neglect such problems as installation, maintenance, reliability, cost and so on, it does enable a single figure of merit to be worked out for each system.

I would like to hear any observations Mr Butterfield may have on such simplified criteria and if he could suggest any other design criterion which would help component designers in the first optimization process.

Mr F. Robinson, B.Sc., Wh.Sch. (*Associate Member*)—The author has covered such a wide field that it is inevitable that certain parts lack detailed consideration. In particular the topic of suspension systems has been unduly curtailed.

It is begging the question to say that the characteristics of a good suspension are:

(1) Adequate wheel lift.
(2) A good spring rate characteristic.
(3) Good damping characteristics over a wide speed range.
(4) Low weight and a good ratio of sprung weight to unsprung weight.
(5) Good fatigue life and wear and abrasion resistance.

Given a particular class of vehicle and the ground characteristics on which it is to operate, what are the fundamental criteria from which adequate wheel lift and the optimum spring rate can be found?

What are good damping characteristics? Should damper forces be constant, proportional to velocity or to velocity squared or some other law? Is there a preferred value for the damping ratio and is there an optimum ratio of bump damping to rebound damping?

Low weight of unsprung masses would appear very desirable; is there any phenomena which would call for a specific ratio of sprung mass to unsprung mass as is suggested in the paper?

Mr A. E. F. Chambers (Shrivenham)—In the transmission and steering systems section the author lists two hydrokinetic forms of transmission, whose fundamental difference is mainly in the distinction between a fluid coupling and a torque convertor, the former fitted in the M.24 Chaffee, and the latter in the M.26 Pershing; both are presumably satisfactory to a degree. In the automobile field the present trend appears to be to use a torque convertor of relatively low torque multiplication as a clutch in the transmission assembly. I should be grateful if Mr Butterfield would say if the possibility of using such a transmission has been investigated, as it would appear to possess some of the qualities stated in the opening paragraph of this section.

With regard to the use of a torsion bar as a suspension spring I venture to suggest that there is little to choose between this and the coil spring, provided that the occupied volume of the coil spring is taken into account, and this volume, generally being situated outside the hull, in no way detracts from the useful internal volume. An additional advantage of the bolt-on type of bogie suspension unit is the fact that this will no doubt eliminate the necessity of carefully controlled and hence costly machining operations on the hull side plates required for transverse torsion bar assemblies. Transverse torsion bars will also make the escape of crew members via a belly hatch somewhat difficult.

Mr W. A. Robotham (*Member*)—I have a particular interest in power units for armoured vehicles, since for a short time during the last war I worked under Lord Beaverbrook. During my sojourn at the Ministry and subsequently, the Meteor tank engine and the B-range of vehicle engines were developed by Rolls-Royce with the co-operation of F.V.D.E., and put into production. I believe it is correct to say that these remained the British Army standard engines for armoured fighting vehicles for about 20 years, and that many have been successfully exported.

During the last few years the Meteor 4-stroke petrol engine has been superseded by the opposed piston, 2-stroke, multi-fuel, compression ignition L.60 engine. Mr Butterfield points out that the main reason the opposed piston 2-stroke configuration was adopted was the demand for multi-fuel operation. I suggest that it would be useful now to make a critical evaluation as to what handicaps, if any, in tank performance and durability have been imposed on the designer by the type of engine brought into being by the multi-fuel requirement.

From 1950 to 1962 I was heading an organization engaged on the design, development, manufacture and export of a range of 4-stroke diesel engines, having a common bore and stroke of $5\frac{1}{8}$ in × 6 in. As we finished up operating in over a hundred countries, from the tropics to the Arctic, and covered a range from 100 to 350 b.h.p. in a very large number of applications, we got to know a great deal about the operational problems of diesel engines round about this size, not only our own problems, but those of our competitors.

Table 2

Source of information	G.M. diesel catalogue 35 A 90	*Diesel progress* October 1961
Type of engine	General Motors 2-stroke V6 6·9 litres	Cummins 4-stroke V6 9·631 litres
Details of performance		
Rated hp	210	200
Length, fan to flywheel	41 in	35·282 in
Weight, lb	1855	1475
Weight per hp	8·83 lb	7·35 lb

I do not think it is by chance that only about 16 per cent of the 100 to 300 b.h.p. diesel engines in operation in the world today are 2-strokes, and probably less than 1 per cent are opposed piston 2-strokes, in spite of the fact that, far from being novel, the opposed piston diesel has been in existence since the last century. Table 2 shows how the latest 2-stroke and 4-stroke engines from the two premier manufacturers of the types compare for weight and bulk. It will be noted that in this particular comparison the 2-stroke is having to produce about 45 per cent more hp from every litre of cylinder in order to achieve an 18 per cent worse power/weight ratio than the 4-stroke. In my experience the life of a highly rated diesel engine is very sensitive to the specific output of the cylinder, and this is particularly true if the cooling is marginal, which, as Mr Butterfield points out, it is always likely to be in desert conditions in a tank engine compartment. It is even more vulnerable if the air is contaminated with abrasive dust. Furthermore, under these conditions, I would suggest that piston rings running over exhaust ports do not make for durability. This is a feature of the L.60 but not of the majority of 2-stroke diesels in commercial use.

Mr Butterfield lists the principal characteristics required from a tank as fire power, armoured protection and mobility. I would personally, however, add one word to the last requirement, and that is I would demand reliable mobility.

Because reliability is never absolute, it is most difficult to determine under all conditions and it seems to be rather taken for granted when considering new concepts for armoured fighting vehicles.

The sort of situation one had to face in the early part of the last war was a specification of minimum performance, fire power and protection, the engineering department being left to achieve the necessary reliability in a relatively short time by unspecified means. In the struggle to achieve reliability in 1941 and 1942 it became clear that field testing was a prohibitively slow means of locating and rectifying troubles. Rig testing was therefore instituted whereby every unit of the transmission, track, steering, suspension and cooling system could be tested in isolation in the workshop. The conditions of test were generally established by instrumentation on the running tank on the proving ground.

Ideally it should be possible to operate these test rigs under extremes of atmospheric temperature, simulating the whole potential range of tank operation, i.e. from +125°F to −40°F, but temperature is only likely to affect the majority of tank components to a limited extent.

In the case of the engine, however, extremely low starting temperatures after which the engine is immediately run at full torque or power at the same ambient, or alternatively high ambients where the cooling system is functioning near the limit of its capacity, can induce complete failures of catastropic magnitude.

I believe that a normal clean air test bed endurance run on an engine at 15°C, or a few thousand miles in a tank on a test track in a temperate climate will give little indication of the merits of the power unit under operational conditions in the Western desert. I would recommend that the type test of the future should be carried out on the complete engine installation in a mock-up of the tank hull, after the radiator fans and air cleaner have had a few hundred tank hours endurance running under conditions to simulate the deterioration in efficiency which will inevitably occur. I would suggest that the type test should be run at the maximum ambient temperature likely to be encountered under desert warfare—the paper suggests 125°F—with an atmosphere suitably contaminated with abrasive particles, similar in quality and quantity to those that might be encountered during a mass tank operation in Libya.

I am also of the opinion that the complete engine installation should not only be subjected to starting tests at −20°F but that after starting, facilities should be available immediately to subject it to full torque and/or full power for a short time to assess its ability to withstand such abuse. I believe that under conditions such as these, there would be an astonishing variation in the life of different types of engine operating at similar power/bulk ratings, and that the 2-stroke would rate moderately for durability. I would ask Mr Butterfield if tests of this kind have ever been carried out on the L.60, and if so, how the results compared with the Meteor figures?

If it is seriously considered that an armoured division will have to run on MT 80 octane fuel for extended periods, then of course its effect on the engine under the suggested revised type conditions should be established, because I think that the effect of this fuel might be quite spectacular on the durability of a highly rated 2-stroke compression ignition engine, and having once deteriorated the performance might not recover after reverting to diesel fuel.

One final question, since the *raison d'être* of the L.60 engine is its multi-fuel ability... Why is the power curve shown in the paper run on diesel fuel? Would it be correct to assume that this engine will produce the same power reliably on MT 80 octane petrol? If not, could we have the relative power curves based on 125° ambient, and 500 hours' endurance reliability.

Mr H. E. Milburn (*Member*)—I must point out that the author is wrong in his history.

There were three Battles of the Somme in 1916, 1st July, 14th July and 18th September. One tank only was used on 18th September. It was a curiosity and should not have been used as its surprise value was lost for later use.

There were two Battles of Cambrai in 1917 and no tanks got through during the first battle on 3rd May.

Why does the author ignore the Churchill which really taught us how to design and build a heavy tank?

Mr D. M. F. Sheryer (*Member*)—At the concept stage it would be interesting to know whether any use is made of scale models of fighting and machinery compartments.

As to propelling machinery, it is substantially true that, between the two wars, with one notable exception (Medium Mk 1—1924), tank designers were restricted to commercial engines as a matter of official policy and their limitations were apparent. Not until the rearmament period from 1937 was attention again given to specialized power plants. These were, in the main, adaptations of aircraft engines; the Rolls-Royce Meteor is the classic example.

The L.60 is not an ideal shape for a tank on account of its height as the author points out. But the opposed piston 2-stroke diesel unit does offer some thermal advantages. Heat to coolant is low, enabling a compact cooling system, economical in fan power and radiator space. The greater proportion of waste heat is rejected through the exhaust but at moderate temperature. Heat to lubricant, however, may well be proportionately greater than in a conventional 4-stroke unit.

Perhaps the author would say whether the problems pertaining to the exhaust piston and exhaust belt of the cylinder liner have been satisfactorily surmounted in L.60 at prolonged full power. Do these components last the life of 6000 miles without disturbance?

The combination of the Wilson change speed gearbox with the Merritt steering in the TN.12 transmission is probably the best arrangement for a purely mechanical tank transmission so far conceived, but the incorporation of a centrifugal engine clutch raises some questions. For negotiating severe obstacles on unknown terrain, in battle, it is surely desirable that the engine should be capable of being locked to the transmission by a clutch under the driver's control. Under 'hot shift' conditions is there any disengagement of the centrifugal clutch or is drive take-up entirely on the Wilson brakes, leaving the centrifugal clutch for disconnecting the engine to start and move-off from rest.

In my experience, development of a new vehicle almost invarably has to be telescoped and, however much care is taken, the first issue of any new machine to troops will always bring fresh troubles in its train. From first receipt of a new requirement at F.V.R.D.E., what is the average lapse of time before the new vehicle is fit for issue to the Service.

Finally, to complete the record, Table 1, 1916–1918, should include the Mk V tank and its variants which formed the greater part of the tank fleet in 1918. There were also the Medium Mk B and the Liberty engined Mk VIII designed for inter-allied production. I do not recollect any Medium Mk C machines with 6 pounder guns, but believe they had only machine guns.

Mr D. C. Rodger (*Associate Member*)—It would seem that we are committed to one type of tank, and this in reducing numbers, although it is understood that private companies are developing light tanks which could presumably be air portable, a feature which the shrinking number of overseas bases makes all the more important if an early shock component is to be provided to our ground forces.

The Chieftain is probably the world's finest main battle tank available at present and is well worthy of replacing the popular Centurion. Whether it is an overweight orthodox progression or an economic/tactical compromise between it and the much heavier Conqueror is not known, but, unless it is produced in quantity and handled correctly, it will become a defensive weapon and as such will fail in its task. However, the real effect of new tanks, like nuclear weapons, can only be assessed under war conditions. Though comparing favourably with the Centurion, it seems regrettable that the Chieftain has not got a few more mile/h available under its decking; the lighter French and German tanks having about 60 per cent higher maximum speed.

The development of a suitable armoured hovercraft, with its excellent cross-country and water performance, would appear to be a future trend in design. It would certainly solve the problems associated with tracks and suspension and maybe eliminate the need for a rotating turret. The economic and logistic considerations would be immense to such a project.

Finally it is acknowledged that considerable attention has already been given to the reduction of time and effort spent in servicing and repair but anything which could further reduce this would be most welcome. A centralized system of lubrication, track re-tensioning assistance and a powered feed for re-fuelling tanks are examples in this direction.

Presumably all the foregoing points have already been debated upon in arriving at the solution but perhaps it may be possible for Mr Butterfield to comment on future trends.

Author's Reply

Mr T. L. H. Butterfield—I would welcome an opportunity to have further discussions with Mr Ogorkiewicz on this very complex subject of assessing the battle effectiveness of a tank. I know he himself admits that it is a very complex subject and would want a considerable amount of thought given to it.

We have, as yet, little or no experience with hydromechanical steering systems with hydrostatic steer on tracked vehicles. The advantage claimed for this type of steering is that it produces an infinitely variable radius of turn which would allow smooth continuous turns to be made as against other systems where turns must be accomplished by a fixed radius of turn or intermittently in a series of short, sharp turns or skids, or alternatively, by slipping the steering brakes. A further advantage is that the steering can be controlled from a small steering wheel or lever and the fact that it is power steered means that very little effort is required on the part of the driver. In other forms of steering, which incorporate manually operated steering brakes, the effort on the steering levers is relatively high, particularly in the lower gears. A big disadvantage is the size of the hydrostatic steering unit which, of course, must be designed to cope with the severest condition. In Chieftain, for instance, this would be a neutral turn which, as a rough estimate, would absorb about 500 hp A hydrostatic steering unit to cope with this sort of horsepower involves a sizeable unit which has to be grafted on to the mechanical part of the system. From an installation point of view, this could consume a considerable amount of room in the vehicle which would involve a substantial weight penalty. Apart from this, the components of the system are complicated and expensive and could add to the unreliability of the vehicle.

Hydro-pneumatic suspensions are being considered by a number of countries in an effort to obtain greatly improved ride characteristics in tracked vehicles to meet the greater cross-country speeds demanded today. It is claimed for this type of suspension system that the inherent damping that can be built-in, coupled with the readiness with which the spring rate and the damping can be adjusted, provides a system which can be readily optimized for the vehicle. It is too early for us, I think, to confirm or refute this view but it must be said that the primary requisite of a good cross-country suspension is that it should allow of adequate wheel movement without which no suspension would be effective. One of the chief problems with hydro-pneumatic suspensions is the sealing of the fluid under severe operating conditions and keeping out the mud and dirt.

I am grateful to Mr Cleare for producing his figures showing the relationship between average cross-country speed and gross power/weight ratio for conventional tanks which he has put forward by way of support for the United Kingdom philosophy which puts armour protection before mobility in the order of priority of the principal characteristics.

The protagonists for a high power/weight ratio argue that high speed and acceleration can reduce substantially the exposure time of a vehicle which has to move from one point of cover to another, and so reduce the chance of its being seen and engaged. Mr Cleare's figures show that the increase in speed, which comes from an increased power/weight ratio under going conditions pertaining to these particular trials, does not appear to pay sufficient dividends in terms of increased average speed to significantly make up for a lack in armour protection. This is particularly so in view of the high-velocity anti-tank weapons and sophisticated fire control systems which exist today.

What is somewhat surprising, on the face of it, is his observation that the straight-line relationship between speed and power/weight ratio 'indicates that on vehicles built to date the suspension has not proved to be a limiting factor'. I think this needs qualifying, particularly since I have made the point in the paper that under certain conditions of going, the suspension characteristics can limit the speed. The trials to which Mr Cleare's figures relate were all carried out on the Long Valley Course at Farnborough where constant running of vehicles over the same ground has made the going muddy and heavy and deeply cratered and ridged. Under these conditions, the rolling resistance is high and the vehicles are constantly having to climb in and out of deep holes and over steep ridges. It is not surprising, therefore, that the limiting factor in this case is the available horsepower and not the suspension, since, in any case, the speeds obtained are also fairly low and may not show up to any significant degree differences in suspension characteristics of the vehicles involved. In any case, the straight-line relationship is only an approximation. Could not the scatter in the results be partly accounted for by differences in the suspension characteristics? Under undulating cross-country conditions, where the going is firmer and higher speeds would be possible, the suspension characteristics could certainly have a limiting influence on the speed. What this all adds up to is that, if people want to have a very high power/weight ratio than the suspension ride characteristics must be a match for the higher speeds that will be possible across country.

Mr Cleare is, of course, quite right to point out that synchromesh transmissions are not suitable for heavier tanks because of the impracticability of accommodating synchro-cones of sufficient size to cope with the rotational inertias involved. If, however, the trend is for future tanks to become much smaller and lighter, there may well be an application for synchronous transmissions in the future.

I tried to find out for Mr Tapp why the 'Praying Mantis' was turned down. At the time it must have been a very exciting machine, and I am not surprised it caused such a lot of interest among the Generals. However, it is not always the Generals who decide what weapons an army is going to have. I am convinced also that it was not the Ministry of Supply who turned the machine down. They tested it and found certain mechanical faults which I am sure they realized could have been put right.

From the reports I read, I gather the machine was put aside because there was no requirement for it. In other words, the War Office did not appear to want this machine. Possibly, when they looked at it they could not visualize a use for it, but it seems to me the machine certainly did have possibilities, particularly as a reconnaissance machine. It seemed to me that the tower bucked rather a lot when the machine was going over rough ground and I was very sorry for the driver. Mr Tapp has personally experienced it, however, and says it is quite comfortable.

He is quite right about the unlikelihood of achieving ground pressure of $8\frac{1}{2}$ lb/in^2 in a tank, we get nowhere near that figure with present-day tanks. I merely mentioned this figure as a desirable goal if you want to achieve a high degree of ubiquity, at least in Europe. There are certain swamps that require even lower ground pressure if they are to be negotiated. It has, however, become almost impossible to achieve this goal in the sort of tanks everyone wants today; there are other tracked vehicles that do achieve these ground pressures and even lower ones.

Brigadier Palmer has pointed out that I have not devoted sufficient space in my paper to the question of reliability. Perhaps it was remiss of me not to have mentioned more on this question as it is obviously very important but time and space prevented me from covering this very wide aspect of tank development as fully as I would have liked to. However, I must confirm what Brigadier Palmer has said, that we do give a great deal of attention to reliability, and in this respect we are greatly helped by the REME cell which is located in the Establishment and gives us the benefit of its advice and experience on all matters affecting servicing, maintenance and reliability which are all related factors.

Reliability is something which we aim at all the time but do not always achieve from the beginning, particularly from the word 'go', especially when one is obliged, from weight considerations, to design to low engineering safety factors for operation in particularly hostile environments. Nevertheless, the whole pattern of development which continues throughout the Service life of the vehicle is aimed at improving its reliability. It starts during the design and development phases and continues during manufacture and inspection where great care and attention is given to producing good quality components whilst, during the Service life of the vehicle, the users and REME are geared with the system, giving their advice and reporting defects and bringing about the necessary modification actions. I thought I had shown this pattern in the paper but perhaps I did not stress sufficiently the great strain that unreliability places on REME.

Mr Dean has expressed surprise in finding no mention of the Churchill tank in the paper. In Table 1 of the paper I showed details of a number of tanks and in selecting them I was unable to show every tank that has been developed since there were far too many of them. However, I must admit that the Churchill certainly did deserve a mention in the paper. Not only was it an extremely good tank but it represented a milestone in tank development since it was the last of the infantry tanks. It was also the first of the all-welded tanks and I well remember the severe firing trials to which the tank was subjected in order to prove the ballistic and structural adequacy of the welding. I have therefore made amends and included details of various Marks of Churchills in Table 1.

On the question of hydraulic shock absorbers, my remarks do apply more to damping by means of a simple orifice. With port orifice control by means of a spring loaded valve or valves, of course, the viscous damping could be controlled to suit the speed of oscillation and consequently the tendency to overheat is correspondingly kept under control.

There is no doubt that aluminium has come to stay for the lighter and less heavily armoured vehicles and we are well aware of the particular material that Mr Willis has mentioned.

My paper was mainly concerned with battle tanks which are heavily armoured. Mr Willis mentioned that it requires about three times the thickness of aluminium as compared with steel armour. This being the case, the volume occupied by the armour would be out of all proportion to the available volume in the vehicle and would not make for an economical design. As far as lightly armoured vehicles are concerned, however, a number of advantages can be achieved by the use of aluminium, particularly where air-portability is required.

I am in complete agreement with Capt. Kenney's remarks about the intolerable conditions inside tanks when operating in ambient temperatures in the neighbourhood of 125°C. His estimate of 3 hours before a man collapses under such conditions ties up very closely with tests which we ourselves have carried out.

For a long time now we have tried to sell the idea of air-conditioned tanks to the Army. The idea has been hard to put across because of the high cost involved, the valuable space occupied and because the records show that such temperatures only occur very occasionally, even in the hottest parts of the earth. The Army also seems to have taken the view in the past that this is a luxury and that past experience of desert warfare has shown that they can take it.

However, I think the situation is now somewhat changed, tanks in the future may have to operate completely closed down for long periods and the need for refrigeration has been proved. We can now look forward to better conditions inside tanks and other armoured vehicles and we are, in fact, developing refrigeration and ventilation systems for this purpose.

There is, of course, a limit to what one can do. The amount of solar radiation which falls on a tank in places like the Middle East is very high indeed. To deal really effectively with this and the other heat sources in the vehicle requires an enormous amount of power for refrigeration which, when taken with the other electrical loads required for operating the vehicle, would make impossible demands on the vehicle's batteries and electrical supply. However, reasonable reductions in temperature can be effected which can reduce intolerable conditions to conditions which are just tolerable within the capabilities of the power supply system.

I agree substantially with the views Professor Carter has put forward with regard to a quantitative approach for the assessment of tanks and with his fear that, when fully developed, the method may conceal more than it will reveal. The proposal that cost per payload ton should be considered as a criterion is a novel one when related to a battle tank. I do not recall any requirement which has ever imposed a cost limitation on tank design. The low capital cost would seemingly have some bearing on the numbers of tanks which a country could afford and this, therefore, seems on the face of it, to be a powerful factor in support of using cost as a criterion. On the other hand, it is far more likely that man-power will limit the number of tanks that an army can field in which case it might even be undesirable to degrade the battle effectiveness in any way in order to reduce the cost. A limited tank force would almost certainly want the most effective tanks, irrespective of cost.

While concurring with much of what Professor Carter has to say in relation to the weight criterion, it is necessary to point out that the designer is always faced with an overall weight restriction which may or may not have been imposed for sound reasons and that this restriction may drive him to reduce the weight on some components beyond limits which he considers desirable. When faced with this eventuality, he must be prepared to make necessary adjustments or, alternatively, bargain with the user for some relaxation.

If the components are external to the armour, then the weight of the component could often dictate the choice. Where, however, the component must be surrounded by armour, then its volume becomes even more important than its weight and, as Professor Carter suggests, and as I explained in my paper, not only is volume a criterion but also the shape of the components and the way it integrates with other components into a compact installation. The engine, for instance, must not only be compact in size but it must be of a suitable shape to be capable of being integrated with other engine components, such as the cooling system, air cleaners, etc., and with the transmission components into an engine compartment which is optimized as regards its volume and weight. The selection of engine compartment components must be made, therefore, with reference to the complete engine compartment rather than in isolation.

Mr Robinson will, I am sure, appreciate that the purpose of my paper was not to show how to design a tank, this would have been a formidable undertaking, but to show the general pattern of tank design and development and to highlight the problems which beset tank designers. It is for this reason that I have not covered fundamental criteria for the design of suspensions and other components, nor would I consider myself an authority in this field. In any case, his question could not be adequately answered in a few words.

I can only refer him, therefore, to a Report, No. ST.12, published in December 1945, by the Running Gear Branch of the Fighting Vehicle Design Department. This is a translation of a lecture given by Dr Lehr of Aegsburg to the German Ministry of Armaments and War Production in January, 1944. In spite of its age, it is still regarded as an authoritative work on suspension design and probably answers all Mr Robinson's queries.

What he will find is that in the end he is still faced with a compromise. It is most unlikely that the various limiting factors of the design will allow him the wheel lift and wheel size that the ground characteristics dictate. He must therefore effect a compromise between wheel size and wheel lift (i.e. between the wheel life and the ride characteristics) based on past experience.

Mr Chambers asks whether it would be possible to use a torque convertor of relatively low torque multiplication in place of a clutch in a transmission assembly. Technically, there is no reason why this could not be done, provided that the transmission can provide the necessary range of torque and speed. In fact, the Chieftain transmission would be improved by substituting a torque convertor for the existing centrifugal clutch. The chief objection is that for a torque convertor to transmit a given amount of power it must necessarily be larger than a corresponding mechanical clutch and, in the case of the Chieftain, it means increasing the length of the hull by about 2 or 3 inches. This represents a substantial weight increase. Nevertheless, the matter is still under serious consideration.

Mr Chambers's remarks about the relative merits of torsion bar and coil spring suspensions are valid and are additional factors which can be taken into consideration in the selection of a suspension.

Mr Robotham has drawn attention to the 'Meteor' engine which was adapted from an aircraft engine for use as a successful tank engine. It did indeed reflect credit on all involved but it inherited certain features which were undesirable in the tank environment. For instance, the cooling system contained a large number of clipped hoses which were probably used for weight considerations. These were apparently quite satisfactory in the aircraft role but in the more hostile tank environment they were a constant source of coolant loss. Because of the light scantlings, the engine was very susceptible to overheating and defects such as coolant loss or choked radiators can soon give rise to catastrophic failures from overheating. Various measures, however, have been taken in latter years to offset this possibility and under normal Service conditions, an engine life of about 2000 miles can be realized. Under dusty desert conditions, however, this life will be more than halved.

Mr Robotham has launched a 'broadside' against the L.60 engine so I must rise to its defence and explain the reasons behind its choice. The change to a multi-fuel policy came when the Chieftain design was becoming fairly firm. Design studies had to be put in hand immediately to determine the best type of engine to meet this new requirement without unduly affecting the basic design of the tank. At that time some preliminary work on the multi-fuelling of 2-stroke and 4-stroke diesel engines was going on which included a commercially available Commer 2-stroke opposed piston engine. The indications were that the latter type of engine could be made to produce the best multi-fuel characteristics and this was attributed to the fact that the shape of the combustion chamber and its thermal characteristics appeared to be ideal for the purpose, particularly for the lower Cetane fuels.

Based on these findings and the fact that the rival Vee engine scheme did not properly materialize, it was decided that Leyland Motors should go ahead on the L.60 engine as it later came to be known. The slender form of the basic engine fitted well into the existing hull concept and enabled a compact engine compartment to be designed around it and this included the installation of a large auxiliary engine and generator unit which could be conveniently housed alongside. The hull height inevitably increased and further increases in the length of the hull had to be made during the development of the engine which resulted in a weight penalty of the order of 3000 lb. This was accepted as the price which had to be paid for the multi-fuel facility and the increase in the range of operation that would be achieved.

When developed, the engine proved to have a particularly good specific fuel consumption and it has since shown itself to be a rugged tank engine which has produced life milages of the order of 6000 miles. Furthermore, there remains considerable development potential in this engine and we can confidently expect higher horsepower from it in the future.

The comparative figures which Mr Robotham has submitted for a 2-stroke and 4-stroke engine are interesting and illustrate his point that the 2-stroke V6 engine has to produce about 45 per cent more horsepower for every litre of cylinder capacity in order to achieve an 18 per cent worse power/weight ratio than a 4-stroke V6. One of the reasons for selecting a 2-stroke engine was the very fact that more horsepower could be squeezed from each cylinder than with a 4-stroke engine. In relating his figures to the L.60 engine, however, Mr Robotham is not comparing like with like and he may be interested to have the comparable figures for the L.60.

Type of engine:

Leyland Motors L.60
2-stroke opposed piston
19 litres

Details of performance:

Rated hp	700
Weight	4250 lb
Weight/hp	6·0 lb

It should be pointed out that the engine weight does not include the fans and radiators which in a tank installation are not comparable with normal commercial cooling fans as regards weight and bulk since they have a far more difficult job to do.

As regards the piston rings which run over the exhaust ports, I can only add that this does not at present appear to be causing any reduction in the durability of the engine, nor can I see any particular association between this feature and the presence of abrasive dust in the atmosphere as Mr Robotham seems to suggest.

Making these claims, I would not wish to suggest that the L.60 is an ideal engine for future tanks which would have to be even more compact in size. In Chieftain, however, the L.60 is a good engine and I am sure that time will show it to be extremely reliable under operational conditions, which, as Mr Robotham rightly points out, is all important. In answer to Mr Robotham's query, we have carried out a number of low temperature trials to measure the starting torque of the engine and a limited number of low temperature starts have also been achieved. This work is proceeding. Unfortunately, facilities are not available in this country for running under full power or maximum torque conditions and we intend to do this when the vehicle is subjected to cold weather trials in Canada in the not-too-distant future.

I regret we are not in a position to publish performance figures with MT 80 octane fuel. This development has had to be put back pending the solution of more urgent problems when running on diesel fuel but no doubt the figures will be available in the course of time.

I am in no position to argue with Mr Milburn on the historical facts relating to the tank during World War I. I was not there as he was and I can only refer him to the historians from whom I got my information.

He will also note that I have now included some details of the Churchill. I do not see the point of his remark about the Churchill and Valentine being successful tanks, possibly because they were built by private industry. Let me remind him that industry has been involved in the design and construction of every tank that has ever been made in England. He must also recognize that the expertise in tank design exists at establishments such as F.V.R.D.E. and R.A.R.D.E. who are there to guide industry. F.V.R.D.E. are very much responsible for the design of the most successful tank to date, the Centurion, and they have now designed Chieftain which is coming into service and which, I am sure, will be a worthy successor to Centurion.

In reply to Mr Sheryer I would state that in the concept stage considerable use is made not only of scale models but also full-scale mock-ups to solve installation problems.

The problems pertaining to the exhaust piston and exhaust belt of the cylinder liner have been satisfactorily surmounted in the L.60 engine at the full power given at present by this engine. This has been demonstrated by prolonged bench testing and running in vehicles. These components will last the 6000 miles of engine life without disturbance.

No problems are experienced with the centrifugal clutch used in conjunction with the TN.12 transmission in the Chieftain tank when negotiating severe obstacles. Drivers normally drive on their instruments and the engine speed can easily be kept in the desirable ranges. With a 'hot-shift' gearbox this is not difficult to do. The clutch remains locked at speeds well below the normal operating speed range of the engine when the tank is in motion and is still solid at 1000 rev/min. Nevertheless, a safeguard is built into the system which has a speed sensing device that will automatically cause a down-shift if the clutch comes out of engagement due to an inadvertent drop in engine speed.

In the past, the pattern of development has been so different for each vehicle development that it is extremely difficult to say how long it normally takes to develop a new vehicle. I think the designers would like about 6 or 7 years from the placing of a firm specification but this is seldom allowed these days. Urgency normally dictates the design and development period of as little as 4 or 5 years.

In reply to Mr Rodger, Chieftain must not be regarded as a compromise between Centurion and Conqueror. Its battle effectiveness in terms of fire power and armour protection greatly exceed that of either of these two tanks so it can hardly be called a compromise. It was designed from scratch to a specification for a universal battle tank based on the requirements of today. It borrowed little or nothing from either tank. I believe it has all the speed it can usefully employ but there is scope for increasing the engine horsepower in the future if this is found to be desirable.

Many people now regard Chieftain as the ultimate development of the conventional tank and look for some completely revolutionary form of vehicle with outstanding technological advance to replace it. I think it is hardly likely that the technological jump will be a very drastic one but I feel that there is still scope for improving the battle effectiveness of the tank and particularly its ability to live on the battlefield against all the additional hazards which the tank will have to face in the future.