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AGARDograph

OPERATIONS FROM UNPREPARED & SEMI-PREPARED AIRFIELDS

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AGARDograph 45

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OPERATIONS FROM UNPREPARED AND SEMI-PREPARED AIRFIELDS

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SUMMARY

The problem of operating aircraft from unprepared and semi-prepared airfields is treated in three parts.

The first part deals with unprepared landing areas, their classification, and temporary stabilization. Various possible types of soil are discussed. The surface characteristics, vegetation, and likely obstacles are classified. Tested methods suitable for temporary soil stabilization are presented.

In the second part are discussed the design criteria for landing gears which have been developed for operation from unprepared areas having various characteristics. Experience obtained with such landing gears is described.

In the third part an attempt is made to classify aircraft suitable for take-off and landing on unprepared airfields, in order to determine the operational possibilities of a given type of aircraft from a particular airfield, by simply comparing corresponding parameters of the two classification systems.

SOMMAIRE

Cette étude, qui traite des problèmes posés par les opérations de décollage et d'atterrissage sur terrains non aménagés ou partiellement aménagés, se divise en trois parties.

Au cours de la première partie sont étudiées les aires d'atterrissage non aménagées, leur classification et leur stabilisation provisoire. Les différentes natures de sol sont passées en revue. Les caractéristiques présentées par la surface, la végétation et les obstacles possibles sont classées. Les méthodes de stabilisation provisoire du sol expérimentées jusqu'à présent sont exposées.

La deuxième partie traite des caractéristiques des atterrisseurs adaptés aux opérations de décollage et d'atterrissage sur terrains non aménagés de diverses natures. Les expériences effectuées avec ces atterrisseurs sont décrites.

La troisième partie est consacrée à un essai de classification des appareils utilisables sur ces terrains. Cette classification est destiné à déterminer les possibilités d'utilisation d'un type d'avion donné sur un terrain déterminé grâce à une simple comparaison des paramètres correspondants dans les deux systèmes de classification.

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OPERATIONS FROM UNPREPARED, AND SEMI-PREPARED AIRFIELDS

Prof. Dr.-Ing. G. Bock*

1. INTRODUCTION

1.1 General Considerations

Airfields with concrete runways built in peace time will mostly be known to the enemy. Therefore it has to be taken into account that the enemy will already have destroyed the prepared airfields during the first days of a war if they are situated only some hundred miles behind the combat line. So, in many cases, airplanes must be able to operate from unprepared landing areas. Sometimes it will be possible to improve such airfields by auxiliary measures, and to make them semi-prepared.

Take-off and landing from unprepared and semi-prepared fields impose special requirements on the aircraft also. In recent years, these requirements have led to a special type of aircraft designated STOL and VTOL aircraft. However, for the time being the development of these aircraft is not sufficiently advanced to give a useful survey of the actual techniques in this field.

The possibilities for take-off and landing of aircraft of the conventional type on unprepared or semi-prepared fields are often limited by the type of landing gear. Therefore, the kind of airfield from which the airplane will be operated also has to be taken into account in the design of the landing gear. It seemed desirable, therefore, to make a compilation of existing topics on the design of such landing gears, and to report on the experiences obtained with landing gear types developed for this special purpose.

As a consequence of the above considerations, the AGARDograph is divided into two main parts. The first main part deals with unprepared landing areas, their classification, and temporary stabilization. It has been compiled by Dr. C.E. Gerlach, a well known German authority on airfield establishment and development. The second main part deals with the design of landing gears which have been specially developed for take-off and landing on unprepared areas. The author of this part is Dr. E. Tönnies, who is one of the specialists in this field in Germany. In addition, an attempt is made in a third, short, part to classify aircraft suitable for take-off and landing on unprepared airfields. This part was compiled by Mr. Beauvais, who is head of the department for manned aircraft in the Flight Test Centre of the German Air Force.

References are included in the various sections in order to enable the reader to study in more detail the problems treated in the AGARDograph.

1.2 Landing Areas

In order to know which unprepared airfields are usable for different types of aircraft in case of war, it is necessary to have these fields already classified in peace time.

Darmstadt, Germany

For this classification it is practical to consider atmospheric and terrain parameters. Atmospheric parameters are, e.g., air temperature and its changes in the course of the day and year, wind velocity and direction, rain, fog and haze. It is desirable to know for each airfield what are the values of these parameters in different seasons, and the probable frequency of extremes which reduce flight operations from these fields (see Section 2.1).

The following terrain parameters must be considered for the establishment of airfields: area elevation, dimensions (length, width), area slope (in both directions), undulation, surface roughness, approach and climb-out obstacles, soils. The nature of the soil and its suitability for flight operations depends highly upon the weather characteristics. The possibility of snow and ice on the airfields must also be taken into account (see Section 2.2).

In order to comprehend the terrain parameters systematically, A.R. Bredahl and E.P. Kiefer have proposed a classification system which is dealt with in detail in the AGARDograph. Then some critical remarks follow as to the feasibility of such a system, as well as some proposals concerning further work on improvement (see Sections 2.3 and 2.4).

The question of preparation of semi-prepared airfields was considered very thoroughly in Germany during the last war. Essentially, the following methods were used:

(a) Cement-Soil Stabilization

(b) Bituminous Sand Course

(c) Bituminous Soil Stabilization

(d) Soil Stabilization by Special Granulometry

(e) Surfacing by Metal Sheets, Grates and Mats

(f) Surfacing by Concrete Grates.

These methods, and the improvements achieved in recent years, are discussed in detail. Furthermore, the prerequisites to the feasibility of the different methods are treated (see Section 2.5).

1.3 Aircraft and Landing Gears

Aircraft operating from unprepared or semi-prepared areas are mostly equipped with wheel-type landing gears. Their suitability on unprepared areas, especially on soft ground, depends on the specific ground load (wheel dimensions, tire pressure) and on the arrangement of the wheels (e.g., twin-wheel units). The design of the landing gear and the nature of the soil further influence the rolling resistance and the braking effect. Test results are presented for these topics. After that are described several landing gears specially designed for aircraft built for operation from unprepared areas (see Section 3.2).

In recent years, tandem landing gears have often been used on aircraft of high gross weight. The main advantage of these landing gears is the possibility of using wheels of smaller diameter, and maintaining the same specific ground load. So, weight can be saved. Their disadvantage is the occurrence of high side forces on the wheels when taxiing in a circle. Hereby the manoeuvrability on the ground is reduced, especially on soft soil. The influence of the varied constructional parameters on the characteristics of such landing gears has been dealt with in detail.

In order to improve the use of landing gears on nearly impassable terrains, various special constructions have been designed and tested. Such constructions are, e.g., landing gears with skids, wheel-skid combinations, and caterpillar track gears. Some descriptions of such designs and test results are presented in the AGARDograph (see Sections 3.3 - 3.6).

In the third, short, section an effort has been made to classify aircraft suitable for take-off and landing on unprepared fields.

In spite of the authors' efforts it could not entirely be avoided that the close relations between the three parts should lead to some overlap.

1.4 Special Remarks

According to the problem under consideration, a number of questions had to be dealt with in the AGARDograph for which no definite solution is known. Therefore the AGARDograph cannot present more than the state of the art in this field, as known in 1959. In addition, regard has probably not been paid to some publications on the problems under consideration since they were not known to the authors. Besides this, the original text was written in German, and the translation may not be quite correct in some points. So, after some time, it will be necessary to rewrite the AGARDograph corresponding to the progress of development. The authors will be very grateful to the readers of the AGARDograph if they could forward proposals for its improvement and completion.

2. UNPREPARED LANDING AREAS*

In order to create a system of classification of unprepared landing areas, it is necessary to determine the most important parameters influencing flight operations. It seems to be suitable to distinguish two fundamental groups of parameters, namely atmospheric parameters and terrain parameters.

2.1 Atmospheric Parameters

Atmospheric parameters are dealt with first, because of their fundamental importance to flight operations. Contrary to terrain parameters, it is hard to put them in a fixed system of classification as they change frequently; but it is of great importance to have data on the atmospheric conditions of the landing area before starting flight operations.

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2.1.1 Air Temperature

Data on air temperature, duration and series of extremes in the course of the day, month and year are of importance as they influence engine performance, and take-off and landing qualities.

2.1.2 Wind Velocity and Direction

Wind velocity and direction influence the direction of the take-off and landing strip. The degree of cross-wind sensitiveness of the operated airplane is decisive for use and operational value of a landing strip. Its direction depends more or less upon the main wind direction or the direction of the maximum wind velocity.

2.1.3 Weather Variations

All other variants of weather like rain, hail, fog, haze, smoke, etc., are partly of direct, partly of indirect influence on the possibility of operating an airplane from a special landing area.

Early and thorough information about the atmospheric conditions of the terrain is absolutely necessary for the evaluation of a landing area the terrain parameters of which are known.

2.2 Terrain Parameters

Terrain parameters are more easily determined than atmospheric parameters are. Therefore they are grouped without difficulties in a system of classification[1*] of landing areas. The great number of terrain parameters involved will be discussed subsequently, in detail.

2.2.1 Area Location

The position of the landing area in question can be taken generally from a map, where the degrees of longitude and latitude can be found. In any case, one has to mark all possible landing areas on a map when examining a larger terrain.

Once the position of a landing area is known, it is desirable to know the direction of the largest extension. As mentioned at the beginning, it is not possible to use a certain landing strip, or its use is restricted, if its direction differs considerably from the direction of the prevailing winds. In most cases the analysed terrain is not so large that it can be adapted to direction and force of the prevailing wind.

The position of a terrain close to populated areas, especially agricultural ones, includes the possibility of obstacles put on the fields in the course of the year, e.g., during the harvest. As to the following parameters, an area may be of use, but cannot be used all through the year.

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*See references - Section 2.6

2.2.2 *Area Elevation*

The elevation of the landing area is most important. The engine performance decreases at higher elevation with decreasing air density; longer runways are required.

2.2.3 *Area Size*

The parameters of the dimensions of a landing area are generally referred to length and width. The largest rectangle which fits into the area in question is decisive for its useful dimensions.

2.2.4 *Area Slopes*

The largest slopes of the landing area must be determined in both dimensions, and must be defined by a parameter.

2.2.5 *Configuration*

As to the shape of the surface, larger and smaller undulations, lumps in the ground, ripples, etc., are of importance. Undulations are determined by height, center-to-center distance, slope, direction and distribution. One distinguishes primary and secondary undulations.

2.2.6 *Surface Roughness (Obstacles)*

In defining the surface roughness with reference to obstacles, the nature of the obstacles, height, distance, position, resistance and slope are of importance. Also distribution, age and kind of obstacles - natural or man-made obstacles - are important.

The position of obstacles on the landing area could be determined exactly, if reference points could be fixed. As most unprepared landing areas are not real rectangles it will be practical to examine the field by steps, both in longitudinal and cross sections.

An airplane built for operation from unprepared areas is probably capable of running over the obstacles of smaller size without damage, regardless of their position. If there are bigger obstacles, this is no longer possible, and their position must be known.

If necessary, this problem can be solved as proposed in Figures 1 and 2 without exact specifications of the position of obstacles.

In Figure 1 a number of larger areas are marked inside an area usable for flight operations. This area has to be classified with reference to length and width. The location of trees must be marked, thus indicating that the given width is not usable over the total length. Therefore it would be suitable to divide the area into two landing strips the dimensions of which can be classified according to Figure 2. The classifications resulting from the division of the area do not indicate that the two landing strips touch. The area between the landing strips could be classified as an area of obstructions. On the other hand it is to be expected that a pilot approaching an unprepared landing strip will do one circuit at least. So he will find and avoid large restricting obstacles on the ground.

The resistance of an obstacle, i.e. its shock resistance, is most important when moving the airplane fast on the ground. Small bushes or shrubs of a certain height and spacing are entirely different from rocks of the same dimensions and spacing. In any case, it is necessary to mark as well the nature of the obstacles. Many kinds of obstacles have the same influence on taxiing airplanes, e.g., tree stumps and rocks of the same size and distribution. It is of special interest to know the dimensions of very compact obstacles. As to less rigid obstacles, dimensions and shock resistance are important. Therefore a number of explanatory letters are to be added to the classification system[1] described subsequently.

2.2.7 Approach and Climb-out Obstacles

Obstacles in the approach and climb-out zones are only of special importance for the classification of the landing area if they do not allow the airplane to fly safely over a 50-foot obstacle at the end of the landing strip as required generally for an airplane. As to flight operations, it seems, however, to be practical to mention the non-existence of obstacles in approach and climb-out zones and to add this fact to the length classification of the landing strip (Fig. 3), or to mark it in a plan view (Fig. 4).

2.2.8 Soils

Soil conditions are of great importance to the airplane designer as well as to flight operations, with reference to the trafficability of unprepared landing areas. The soil bearing capacity for smallest deformations ranks first. The bearing capacity influences especially the choice of tire dimensions, wheel loads and tire pressure, whilst the deformations produced are decisive for the number of passes the area may be used for. The moisture content of the soil is of great influence on its bearing capacity[2].

There exist several methods for determining the soil bearing capacity. In this report the CBR-method (California Bearing Ratio) is primarily referred to[3,4]. The so-called CBR-value represents the ratio of the percentage of the loads required to press a punch of certain dimensions first into a well compacted sample of soil and then into a standard sample of compacted gravels, to a depth of 0.1 inch.

In any case, it is necessary to classify the soil type with reference to the Unified Soil Classification System[4] as a test of the soil bearing capacity only with regard to the CBR-method does not give an exhaustive picture of its reaction to static and traffic loads, the influence of the moisture content being too varied. This system has been used by the Army Corps of Engineers for many tests of the bearing capacity of airfields.

An essential basis for the classification of soils is given by grain structure and plasticity qualities. The grain size of the soils is calibrated according to the U.S. standard screen (mesh) size. This allows for classification of grained soils (gravel-sand mixtures). The plasticity qualities refer to the physical properties of fine-grained soils (silts and clays) which pass even through the most close-meshed standard screen.

Nature and thickness of the soil layers are to be determined by diggings; in doing so, the lower layer also are to be examined with regard to a downwards constant, or increasing or decreasing bearing capacity.

Three general groups of soils are to be compared with regard to the influence of moisture content. The first group includes gravel-sand soils. Especially when humid they have a high bearing capacity, if there is no high percentage of clay or silt. The second group includes plastic clays the bearing capacity of which decreases considerably with increasing humidity[5]. We call them sandy or gravelly clays, the percentage of sand or gravel being low. The third group includes clays and silts. They are very hard when dry, but lose their bearing capacity at a relatively low moisture content.

As to the consistence and plasticity of the soil, slipperiness and stickiness also are of importance, especially when considering fine-grained soils of small bearing capacity. Sticky soils can stick to the tires, thus increasing the rolling friction. Generally slipperiness results from a layer of slippery soil on hard ground; this can cause difficulties in manoeuvring the airplane on the ground.

The permeability of the soil plays an important role in its ventilation, and in circulation and draining of water.

The question of depth of deformations and compaction has been dealt with by interesting tests of the Waterways Experiment Station. In practice an experimental value of ¾ inch of permanent deformation is considered as an acceptable basis for flight operations[6].

The compaction of soils and the use of practical compaction devices dependent on the nature of the soil and its moisture content are of special importance with regard to a possible improvement of the bearing capacity.

Another problem in using unprepared landing areas is the raising of dust caused by the airplanes, which makes flight operations considerably more difficult or even dangerous. Very fine-grained soils tend most easily to the raising of dust by intense air traffic in dry weather, especially if there is no vegetation. In general, a slight cross wind is sufficient to moderate somewhat the disturbing effects of dust[19].

Certain kinds of vegetation are inflammable; so the possibility of burning bushes or grass, etc., is to be considered when using jet power plants.

From the soil classification it follows, possibly with the criterion by Casagrande, to what extent frost is dangerous. Generally disturbing effects of frost do not exist, except when the upper layers thaw whilst the lower ones are still frozen so that no draining of water is possible from the upper layers. In this case, most cohesive soils form a more or less deep, slippery layer on the surface which can hinder the use of the landing strip or even make any flight operations impossible.

2.2.9 *Snow*

Contrary to comprehensive studies and experiences concerning the reactions of soils to traffic loads, our practical knowledge of the reaction of snow is still slight[7].

The connexion between the continuously changing qualities of snow and its mechanical reactions to traffic loads is almost unknown[8,9].

The Committee on Snow Classification of the International Association of Scientific Hydrology has developed an International Snow Classification System[10] which includes more than 20 symbols for describing determined qualities of snow. One or more digits or letters are added to each symbol so that a snow classification would comprise between 50 and 100 symbols for a certain time and region. This system seems to be too complicated when it comes to the case under discussion, to be feasible for flight operations.

It can be concluded from test results[10] that it is practical to classify snow as dry, sticky, or moist and wet. The development of an air-dropped penetrometer for determining snow qualities seems to solve the problem very nearly. The results of several test programs have proved the feasibility of such a plan[11]. On the other side, the variety of snow conditions does not allow for a detailed classification of practical use as the results may already be quite different one hour later at a certain time and region.

The criterion by Casagrande gives a relation between the relative particle thickness and possible frost damage.

In a particular case, one will be restricted to determining the age of the snow layer, dimensions and shape of the snow particles, density, specific weight, free water content, and possible impurities. Shearing strength, tensile strength, temperatures of soil, snow and air, the so-called snow types: dry, moist and wet, its smooth or wavy surface, its kind of crust, it depth, particularly in the case of new snow, give sufficient information on the possible use for take-off and landing.

2.2.10 Ice

Scientific data on the bearing capacity of ice are incomplete. A test program of SIPRE examines several questions. The Snow, Ice and Permafrost Research Establishment has published a report[12] based on field tests and practical experiences which include a number of recommendations for establishment and maintenance of landing areas on ice.

In the case of ice fields one has generally to find out the kind of ice (sea water or fresh water), its age, depth of the water underneath, the distance to the banks and the percentage of salt. If necessary, water flow, pressure, ridges and cracks, and the tensile strength are of interest.

2.2.11 Water

The conditions on water surfaces can be classified without real difficulties. Length, width, wave height and slope, and wave distance are of essential interest, also secondary waves, corresponding to undulations of the soil. The specifications of obstacles are treated in the same way as usual landing areas are, but obstacles being under the water surface have to be taken into account.

2.3 Classification System for Unprepared Landing Areas

The Classification System for Unprepared Landing Areas[1] developed by use of the above mentioned parameters is divided into 4 categories where each category is described by a separate matrix. The 4 matrices given in Table 1 can be used together in order to describe an area. Each matrix describes part of the area by use of the above parameters.

2.3.1 Matrix I - The Landing Area

Each matrix is made up of two or three parameters, depending upon the matrix in question. Each parameter is divided into numerical class increments. Each such class increment is assigned a class designator for identification purposes.

In Table 2 the first two digits comprise a length class designator, the third digit a width slope class designator, and the fourth digit a length slope class designator. Taken together, the four digits comprise what may be called a matrix designator, in this case for Matrix I. In Figure 5 an example is given for the Matrix I designator. As to the length designator, there are no more comments required; they result from Table 2. The length slope is expressed in degrees and found according to Figure 6. The width slope is determined in the same way.

2.3.2 Matrix II - The Terrain Configuration

The Terrain Configuration refers to the ground undulation such as waves, bumps, mounds, ripples, etc. These inequalities of the land surface can be described by Matrix II parameter class designators.

In the classification system under consideration all ground inequalities consisting of soil are classified in Matrix II, and objects foreign to the soil that are imbedded in or loose on the surface in Matrix III (obstacles).

The Matrix II parameters incremental categories and class designators are shown in Tables 3 and 4. The parameters are: (i) the undulation height, (ii) the undulation slope and (iii) the undulation spacing. They refer to the measures indicated in Figure 7.

2.3.2.1 Undulation slope. The undulation slopes may be referred to as 'local slopes', as opposed to the 'area slopes' of Matrix I. They are measured with area slope, if one exists, as a base; if not, then with respect to the horizontal reference. In Figure 7 there is no area slope (Matrix I); therefore, the undulation slope is measured from the horizontal. When the area slope is not zero, the local or undulation slopes are measured as shown in Figure 8. Thus the undulation slopes in Matrix II are always additive to the slope from Matrix I.

2.3.2.2 Undulation height and spacing. Undulation spacing is expressed by the center-to-center distance between the highest points on the undulation as was shown in Figure 7.

The center-to-center distance categories and their class designators were shown in Table 4. It will be noted that each undulation height category has a separate range of increments for the center-to-center distance parameter. This is because of the wide range between the highest and lowest undulation height categories. The significant categories of undulation spacing are related in part to the height of the undulation.

In general, combining the shortest spacing with the highest undulation height means that the slopes would be in the 60^{o}-90^{o} category if the undulations were directly adjacent. In this case, it would be possible to estimate the slope of the undulations based upon their height and spacing. However, slope is still required as a parameter, since undulations may occur with considerably different slopes even though the height and spacing are similar. This is illustrated in Figure 9.

Undulation (A) has the same height and spacing as undulation (B), but it is clear that the slopes are quite different. This is the reason for extending the center-to-center distance categories to thousands of feet. These categories may be used to represent either long gradual sloping undulations or widely spaced undulations with steeper slopes.

2.3.2.3 The Matrix II designator. The series of class designators for Matrix II parameters result from the first, second and third digits of Table 3. Since the center-to-center distance (spacing) increments vary with the undulation height classes the procedure for determining the appropriate center-to-center distance class from the third digit is as follows:

Example of Matrix II Designator: 525

The first digit indicates an undulation height of two to five feet (Table 3). The second digit designates an undulation slope of four to six degrees. The undulation height class determines the appropriate center-to-center spacing group in Table 3. In this case, the undulation height class designator (5) means that the spacing group headed Undulation Spacing for Height Class (5) in Table 4 is used to determine undulation spacing. The spacing class designator (third digit 5) in that group indicates a spacing class of fifty to one hundred feet.

2.3.2.4 Complex undulations. In the case of small (secondary) undulations which may occur on large (primary) undulations, it may be necessary to use two Matrix II designations. The first would indicate the parameter values for the primary undulations and the second for the lower order undulations (see Figure 10).

2.3.2.5 Descriptive subscripts. Matrix II (Table 3) contains a number of letter subscripts that can be added to the Matrix II designator to describe the type of undulation. These subscripts follow the last (third digit) class designator in the Matrix II designator.

In some cases more than one subscript may be necessary. For example, in the case of undulation direction on a plowed field, three subscripts may be used; the subscript P indicates a plowed or cultivated field; subscripts L and/or W indicate the direction of the undulations.

Roads and highways (subscript R) may represent some of the best landing areas available in some areas. However, in many cases, the length may be inadequate and the width limitations may be severe.

Matrix II is also used to indicate ditches, holes, erosion gullies, etc., which may be defined as negative undulations. The same parameters are used to designate the dimensions of a ditch, for example, but the Matrix II designator is given a minus sign and enclosed in parentheses. In addition, the subscripts C, D, E, and H (see Table 3) indicate the type of depth undulation. Matrix II parameter dimensions for a negative undulation are shown in Figure 11.

In the case of negative undulations the Matrix II designator is given a minus sign, and the actual width dimension (in feet) can be included as part of the designator. An example of a Matrix II designator for a negative undulation is shown in Figure 12. The designation indicates erosion gullies 2 - 5 feet deep, 60 - 90 degrees slope depressions, spaced 6-10 feet apart, and a representative width of 3 feet.

2.3.3 Matrix III - The Surface Roughness (Obstacles)

The surface roughness of all types of obstacles ranging from small to large in size, and irrespective of natural or cultural origin. Rocks, boulders, bushes, trees, high weeds or grasses, fences, buildings, etc., are examples of obstacles that are of concern to the operation of aircraft from unprepared fields.

2.3.3.1 Height and spacing of obstacles. Matrix III consists of two quantitative parameters, the obstacle height and the edge-to-edge spacing (see Table 5). However, since rocks and bushes, for example, could have the same height and spacing, additional information is required to distinguish between the two. Therefore, descriptive subscripts have been provided to distinguish obstacle types.

2.3.3.2 Matrix III designator. The Matrix III designator will consist of only two digits (class designators); first digit: Obstacle Height Class Designator.

The letter subscript to indicate the obstacle type would be listed after the second digit. Similar to the case in Matrix II where a second designation can be made for different undulations, a second designation may be required in Matrix III to indicate the height and spacing of different obstacle types. Therefore, the Matrix III designator could appear as illustrated in Figure 13.

In the example, the Matrix III designator indicates: loose stones, 3-5 inches in height, and spaced 1-3 feet apart; and bushes 18-36 inches high, spaced 10-25 feet apart (see Table 5).

In order to indicate that an obstacle of a certain height and spacing is characterized by other than essentially vertical slopes (60-90 degrees), a numerical subscript may be used after the obstacle type subscript, to indicate a slope in degrees.

2.3.4 Matrix IV - Soil Description and Bearing Capacity

Matrix IV is used to describe the soil conditions that are of interest to aircraft designers and operators. One of the soil characteristics that is of primary concern to the design and operation of off-runway aircraft is the soil bearing capacity. That is, whether the soil has sufficient strength to support an aircraft with a minimum deformation[2]. To the aircraft designer the bearing capacity influences, among other items, his selection of tire size, wheel loading, and tire pressures. To the operator, the bearing capacity affects the selection of aircraft which may be used and how often they may utilize the area.

There are a number of test measures used for the determination of soil strength. Three of the better known tests to evaluate soil strength are described here.

2.3.4.1 California Bearing Ratio (CBR). The California Bearing Ratio[3,4] is a measure of the shearing resistance of a soil under carefully controlled conditions of density and moisture. The method has already been dealt with in Section 2.2.8.

2.3.4.2 Subgrade reaction modulus (The K value)[4]. The modulus of subgrade reaction or subgrade modulus is defined as the reaction of the subgrade per unit of area per unit of deformation. The units are pounds per square inch of area per inch of deformation.

2.3.4.3 Cone Penetrometers. The Airfield Cone Penetrometer[13] consists of a thirty-degree cone with a base diameter of one-half inch mounted on a graduated staff. The cone can be forced into the soil by hand. The load applied is measured by a proving ring and calibrated dial assembly. The penetration resistance in pounds per square inch is termed the cone index[3].

The soil strength scale that has been incorporated in Matrix IV for this classification system is the California Bearing Ratio[14]. Actually, any convenient scale may be substituted.

2.3.4.4 Unified Soil Classification System. The type of soil in the area may have considerable effect on extended aircraft operations. For example, the accumulation of moisture affects the strength of some soils more drastically than others. Therefore, knowledge of the soil type and the amounts and effects of rainfall on its strength is desirable for planning operations. For this reason, the Unified Soil Classification System[14,15] has been added to Matrix IV in order that the soil types may be included in the classification of unprepared landing areas.

A detailed discussion of the Unified Soil Classification System, its soil groups, and classifications tests,.is contained in References 4 and 16. Table 6 presents a summary describing the pertinent characteristics of the various soil groups with respect to roads and airfields. The range of field CBR values for each soil group is shown, indicating that the soil groups are arranged in their approximate order of desirability for airfield use[17].

2.3.4.5 Soil characteristics of operational interest. A number of soil characteristics that are of primary interest to the operation of aircraft from unprepared areas are not indicated in Table 6. One of the more important of these mentioned previously is the effect of moisture content on strength[5].

Two other soil characteristics that affect aircraft operations are the stickiness and slipperiness[20]. Generally, these characteristics are associated with fine-grained soils (silts and clays) of low bearing capacity. Table 7 presents a summary of the stickiness and slipperiness characteristics of the Unified Soil Classification System soil types. The table is from References 2 and 18, and is used to indicate the trafficability characteristics of soils with respect to military ground vehicles.

The stickiness and slipperiness effects are grouped into four descending levels of trafficability, as can be seen from the comments in Table 7.

2.3.4.6 Matrix IV designator. Matrix IV is illustrated in Table 8. Since there are fifteen categories of California Bearing Ratio and soil types, two digits are used for each category. The sequence of digits for designation pruposes in Matrix IV is first and second digits: California Bearing Ratio Class Designator, third and fourth digits: Unified Soil Classification Class Designator.

For example, the Matrix IV designator - 0508 - would designate a CBR between 8 and 9, and an inorganic silty soil, type (ML).

2.3.5 The Terrain Designator

The class designators for the Matrix parameters are written in a specified order to form the Matrix designator. They have been discussed in the sections describing Matrices I to IV. The four Matrix designators placed together comprise the *terrain designator*. The terrain designator is illustrated in Figure 14. By referring to Matrices I to IV, the terrain designator example in Figure 14 can be seen to indicate the following description of an assumed unprepared area:

Matrix I		(Matrix Designator: 1312)
Length:	600-700 feet	(from length class designator-1st and 2nd digits: 13XX)
Width slope:	2-4 degrees	(from width slope class designator-3rd digit: XX1X)
Length slope:	4-6 degrees	(from length slope class designator-4th digit: XXX2)
Matrix II		(Matrix Designator: 366)
Undulation height:	12-18 inches	(from height class designator-1st digit: 3XX)
Undulation slope:	6-10 degrees	(from slope class designator-2nd digit: X3X)
Undulation spacing:	10-25 feet	(from spacing class designator-3rd digit: XX6)
Matrix III		(Matrix Designator 15S)
Obstacle height:	3-5 inches	(from height class designator-1st digit: 1XX)
Obstacle spacing:	10-25 feet	(from spacing class designator-2nd digit: X5X)
Obstacle type:	Loose stones	(from identifying subscript-3rd digit: XXS)

Matrix IV		(Matrix Designator: 0508)
Soil strength:	CBR 8 to 9	(from soil strength class designator-1st and 2nd digits: 05XX)
Soil classification type (ML)		(from soil classification designator-3rd and 4th digits: XX08)

In classifying complex terrains where relatively nonhomogeneous conditions exist the terrain designator may become more complex. An example of a complex terrain designator for this purpose is illustrated in Figure 15. The terrain conditions indicated by this designator can be determined by referring to the appropriate class designators in Matrices I to IV and the Figures 10 and 13.

2.4 Utilization of the System of Classification

The classification system is considered by its authors to be a first phase of a comprehensive classification program. In a second phase certain regions could be tested, and the areas in question could be distinguished according to this system. In a third phase the influence of the nature of the soil (ground) on airplane design, and especially on landing gears, should be studied on a number of test areas.

The requirements to be met by the airplane and its landing gear must follow the terrain designator. In any case it includes the dimensions of the available landing area and existing undulations, and obstacles as well as the nature of the soil. The way to meet these 4 factors is decisive on how far a special airplane type can be used on unprepared areas. A great number of tests will be necessary in order to define these 4 factors in relation to suitable airplane types, and, also, to derive new developments. Table 8 shows the possible influence of the Matrix Parameters on the construction of airplanes. After frequent use of the system simplifications will be deduced dependent on equal or similar geographical regions the nature of which can make possible a combination of similar landing areas.

Most landing gears have been developed for use on prepared runways. Therefore most information is based on the evidence of certain landing gear characteristics. In general, take-off and landing are essentially more risky on unprepared areas.

A great number of tests will be necessary to give data to the airplane designers in order to develop types usable on various unprepared areas. These tests should especially refer to:

1. Rolling and sliding resistance of different wheel dimensions and arrangements, on different soils of various undulations;

2. Reaction of soil layers of different thickness and moisture content to loads, at different tire base areas, and arrangements of the wheels;

3. Influence of different surface conditions, like vegetation, snow and ice, at different temperatures and moisture contents;

4. Influence of various obstacles on the landing area and on rolling and sliding resistance of adequate landing gear types;

5. Advantages and disadvantages of different arrangements of the wheels and landing gear designs, concerning stability, manoeuvrability, braking and acceleration;

6. Influence of speed, landing gear type and wheel load, on stability and manoeuvrability on terrain of narrow undulation spacing, with small obstacles.

Already available test results should be completed in the same way in order to define the parameters included in the classification system; this concerns the requirements of safe flight operations on unprepared landing areas.

In this connexion, it seems to be important to examine the Design Criteria for Army Airfields[21]. Here specially prepared runways have been assumed, but as to dimensions, weight and performance, they are essentially based on similar types of aircraft as used on unprepared landing areas. In general, army airplanes have small weight, very low tire pressure and relatively short take-off and landing runs. Therefore shorter, narrower and less stabilized runways are sufficient for Army Airfields, than are necessary for Air Force fields and highspeed aircraft. In most cases higher undulations and slopes are admissible because of the moderate requirements to be met by the landing areas and concerning unobstructed approach zones.

Table 9 shows significant data for some Army airplanes.

The Flightstrip and Flightway nomenclature is given in Figures 16 and 17. Table 10 comprises the Design Criteria for Pioneer Army Airfields which are referred to minimum operational requirements[21].

The runway length is determined empirically for each airplane. It must not only include take-off and landing run, but also reasonable tolerances to all for the status of training of the pilots, for psychological factors, wind, snow, and other effects, as well as for unexpected mechanical defects. Therefore the runway length for take-off is determined by use of a safety factor dependent on ground elevation, climatic conditions and the slope of the area in question. The method to be used here is given in Table 11.

The simplest type of runway surfacing of Army airfields is a grass strip. In Table 12 minimum requirements concerning the bearing capacity of unsurfaced (sod) deliberate Army Airfields are defined. The area in question must have the required CBR-value for a given wheel load and tire pressure of the airplane.

Soil stabilization by means of special granulometry and compaction of the grown soil results in so-called Compacted Base Fields. The thickness of the wearing course follows from design charts, similar to those described in Section 3. Here a minimum thickness of 4 inches has been assumed.

Generally these two types of airfields can master a rather large traffic in dry weather, but in the wet season they soon become unserviceable.

They need improvement for continuous operation.

Portable surfaces are dealt with in some detail in Section 2.5.5. The usual flexible and rigid pavements need not be mentioned here as their use is generally not feasible in the case in question, because of a high rate of work and a long time required for construction.

2.5 Temporary Pavement of Unprepared Landing Areas

The nature of the soil mentioned in Matrix IV and its bearing capacity are most important to durability and availability of a landing area. Although the parameters dealt with in Matrices I - IV permit the use as unprepared landing areas, there will be probably no choice but to the use certain methods of artificial soil stabilization as take-off, landing and taxiing will ruin the surface, in most cases, after a short time, so that safe flight operations are no longer possible. Therefore, temporary soil stabilization of the landing area will be necessary in many cases.

During the last war quite a number of auxiliary methods were developed for rapid preparation of airfields. Essentially there are the following methods:

(a) Cement-soil stabilization

(b) Bituminous sand course

(c) Bituminous soil stabilization

(d) Soil stabilization by special granulometry

(e) Surfacing by metal sheets, grates and mats

(f) Surfacing by concrete grates.

2.5.1 Cement-Soil Stabilization

A report already exists[22] on a soil stabilization method by means of cement. The method and equipment are dealt with here. The equipment then used produced a 16 cm layer. Thicker layers could not be achieved because of the construction of millers, conveyers and mixers. At the time, thicker layers were not necessary as weight and wheel loads of the airplanes under consideration did not require thicker layers. From the beginning, airfields surfaced according to this method are of limited stability.

The latest equipment has been improved essentially and allows for considerably thicker surface layers. Although soil stabilization by means of cement is used today in most cases only for constructing subgrades, it can be used as a wearing course, i.e. for the stabilization of temporary airfields without special wear-resistant covering. Here the surface is not so smooth as required, e.g., for concrete pavements of public roads. The question of joints is less important when surfacing the soil by means of concrete. The mostly flexible bearing surfaces laid on stabilized subgrades are so thick, almost, that a perforation of joints and gaps is not to be feared. Contrary to this, position and type of joints are important if soil stabilization by means of concrete is identical either with only thin surface layers, used as protective covering against the atmospheric influence, or even with no special wear-resistant covering. So far as methods and equipment are concerned, there are no difficulties in cutting extra joints (gaps at the joint), and also spatial ones, into surfaces stabilized by means of concrete. The spacing of the joints is to be carried out very carefully, in accordance with the actual conditions, i.e. amount of shrinkage of the material and its tensile strength. Moreover it has to be considered that soil stabilization by means of concrete cannot easily compensate for the influence of shrinkage and temperature changes without causing cracks. This is due to the fact that compacted soils stick more or less tight to the subsoil. There are special aspects for the soil to be stabilized if frost is to be expected. In practice no anti-freeze surface layer can be built in when using soil stabilization methods where actually the grown soil - and no filled-up soil - is compacted. So allowance must be made for the danger of frost damage, as a matter of course, or one has to abandon soil stabilization in such cases.

Essentially one can distinguish 3 grades:

(a) Stabilization and compaction of the grown soil using only binding agents, in connexion with suitable machining;

(b) Method similar to (a), but, besides binding agents, special minerals are added in order to improve the granulometry of the soil;

(c) Preparation of surface layers by use of this method of soil stabilization; however, only materials brought near from elsewhere are used as aggregate instead of grown soil.

Consequently only the cases characterized under (a) and (b) belong to this special method of soil stabilization. The other one described under (c) is the so-called 'mixed-in-place' method where actually only a course of the conventional type is produced.

During the last war, all 3 grades of soil stabilization by means of cement were used successfully. The trains for runway construction, organized by the German Luftwaffe during the last years of the war, always used modern, flat dredging machines and two mixers, each. They were capable of producing a runway in 3-4 weeks. At this time an overall area of at least 75×10^6 m^2 was stabilized by means of cement.

2.5.2 *Bituminous Sand Course*

Between 1935 and 1939 bituminous sand course was the top ranking of all special methods. This method differed from the standard bituminous sand course in so far as its qualities were to meet special requirements of elasticity and compressive strength. Sand and filler were added to the mineral so that a minimum static strength of 6 kg/cm^2 of the prepared surface was achieved. The course was laid in 2 layers of 7-10 cm total thickness on a gravel bed of 10-20 cm thickness, without any concrete subgrade.

The lower layer had a thickness of 4-6 cm, with about 6% of bitumen, the softening point being at 40^oC. The upper layer had a thickness of 3-4 cm, with about 7% of bitumen of the same quality. The amount of filler was about 6%. This quality of bituminous sand is still very porous so that a special surface was necessary, i.e. a mastic covering of 6 kg/m^2 consisting of 55% sand, 20% filler, and 25% bitumen in order to obtain the dense surface required. The mastic was covered by a 6 kg/m^2 layer of bituminous or tarry sand.

Of course, it was possible to use tar as binding agent. However, a more accurate mixture was necessary adding 20% sand, and, at least, 6% filler in order to stabilize the tar covering sufficiently. This question was solved without difficulties by the admixture of special chemicals.

2.5.3 Bituminous Soil Stabilization

The method of soil stabilization by means of bitumen and tar[23] was used at the beginning of the war in order to stabilize complete runways on a number of airfields. Later on, its use had to be abandoned because of the scarcity of bitumen caused by the war.

The first task was finishing the formation, draining of the sandy or sticky grown soil, and cleansing it from plants. Then the soil was crushed by a special apparatus (Fig. 18); binding agents were admixed simultaneously. The mixture was compacted by rubber-tired rollers or caterpillars.

This kind of soil stabilization was carried out first by use of hot bitumen B 300 together with 5% anthracene oil. The consumption of binding agents was about 6% of the soil quantity, the thickness of the compacted course being 14 cm. It was most important to the final strength that the soil had already a certain bearing capacity before stabilizing it. If not so, soil with some cohesion was admixed in order to improve the soil qualities. Admixing of gravels to very fine-grained soils resulted in additional saving of bitumen. In doing so, it was important to improve the soil not only by one layer, but by about 20 cm in order to increase the durability. In other cases, bitumen of lower quality served as binder. Its viscosity was 90 s, measured in a 4 mm dia. nozzle, at 30^{o}C. Before use, it was carefully heated to 70-100^{o}C. The average performance of a mixer was about 6000 m^2 a day assuming a layer thickness of 7 cm.

The consumption of binding agents was about 12 kg/m^2; one more kg of binder was used for finishing. The binder was placed in 2-4 operations in order to achieve homogeneous layers and mixtures. One single process proved to be unsatisfactory.

The great advantage of this method was obvious as the greater part of the materials was already on the spot, so that only binder and aggregate had to be provided.

Most airfields stabilized by use of this method were situated near the North Sea and the Baltic so that binding agents were mostly brought near by tankers and then stored in large basins.

The total airfield area stabilized by use of this method was about 6×10^6 m^2. The runway surfaces stood the test well, the airplanes of that time having wheel loads of about 6 tons. Considering those relatively rigid landing gears, the elastic response of the surfaces proved a suitable means of accustoming pilots used to landing on grass runways to landing on rigid runways.

A rapid method, by Dr. Schirott[23], working with tar, was used in some cases and should be mentioned. According to this method the soil was mixed on the spot with relatively thin-bodied tar; sulfurychloride was added to the mixture. 8-12 kg/m^2 of binding agents were necessary for a compacted course of 8 cm thickness.

The tar-soil mixture was prepared by milling. Sulfurylchloride was squirted in by a sulfurylchloride final milling process. A first grade of compaction was accomplished by a multiwheel roller, the final compaction by means of a road roller. A standard surface preparation with about 1 kg/m^2 of tar-sand course compensated for porosity effects.

For further details on bituminous soil stabilization see References 23 and 24. Figure 18 shows a soil stabilization train.

2.5.4 Soil Stabilization by Special Granulometry

The method of soil stabilization by special granulometry which is useful for temporary preparation of airfields corresponds in principle to road making by means of soil. The principles of construction, maintenance and trafficability of streets made of soil have been dealt with in Reference 24, as well as the production of primitive equipment.

But a number of special points have to be considered when applying the principles of road making to operational terrains which are to be compacted. Thus, airfields have to meet special requirements as far as dust-free surfaces and safety against free-flying mineral particles are concerned. The first condition can be met by adding a certain percentage of hygroscopic agents, like calcium chloride, magnesium chloride, or sulphite liquor. A similar effect could be achieved by using grown soil as fine-grained material in the upper layers and sowing grass seed. Mostly the time required for the formation of sods capable of standing loads is not available. In general, the second requirement is met reliably only by special surface coverings, i.e. either by the use of methods of road making but with very fine-grained surface layers, or by preparation of bituminous surface coverings.

Soil stabilization by special granulometry is a construction which is generally suitable as the subgrade of stabilized airfields of the usual type. Beyond that the construction of temporary airfields can be carried out in accordance with this method. The presence of the required materials, close at hand, is a prerequisite to this method. The required layer thickness can be calculated by use of the method of soil stabilization by special granulometry similarly to the calculation of flexible airfield surfaces of the conventional type. Wheel loads, specific tire pressures and the bedding parameters of the subsoil are the basis of calculation.

In Scandinavian countries, compaction of the soil by specially graded granulometry has been carried out for a long time. The so-called soil-streets in these countries are built by use of this method. It can be accomplished where there are clays and gravels in the subsoil. Clays act as binding agents. The main problem is how to prepare such a mixture of clay, gravel and sand that compaction yields a firm subgrade of a certain bearing capacity. During the war several Italian airfields were prepared in this way. Here gravels being in a depth of 0.6-1.2 m were plowed up to the surface and mixed with existing clay (see Fig. 19). The moisture content of the soil plays an important role. However, the durability of such a stabilization is not too great. So compacted fields require continuous repair.

2.5.5 *Surfacing by Metal Sheets, Grates and Mats*

In general the improvement of the surface conditions by means of metal surface elements is also a temporary effect. The metal surface elements increase the bearing capacity of the upper layers in all weather conditions. This method has found wide-spread use for rapid preparation of landing areas; it has well stood the test.

The point is - as in all other methods - to distribute concentrated wheel loads on areas larger than the tire contact surfaces in order to decrease the specific ground load. Metal sheets and grates are very soon distorted by traffic loads and only of limited use because of too great unevenness, if the dimensions of the plates and their moment of resistance against loads are not in reasonable correlation. In any case, the junctions of the plates or grates are most important elements which can be either completely flexible, or more or less rigid.

A combination of metal plates and grates, soil stabilization and compaction is usual. It is everywhere suitable where the bending strength and the weight of the grates should be kept in reasonable limits; furthermore the surfaces of compacted areas are to be protected against wear. Raising of dust and mineral particles is to be avoided to a certain degree.

The use of steel wire netting (Figs. 21 and 22) as a means of surface stabilization is an exception. This kind of stabilization was primarily used for the temporary preparation of airfields in deserts (North Africa). After planing the soil relatively close mats made of jute (Fig.20) or of such kind are spread out. Steel wire netting, the elements of which are interlaced with rounds, are put on the mats. One side of this steel wire netting is fixed to the soil by heavy grappling irons. Then tractors stretch the netting, and it is fixed under load to the soil by more grappling irons.

If the bearing capacity of the soil is not high enough these pre-loaded wire nettings will bear part of the wheel loads.

Because of prestress and deformation the loads are transformed to some extent into horizontally acting forces. These forces are compensated by grappling irons and by the frictional forces of the nettings on the surface. A rough technical calculation snows immediately that only relatively small wheel loads can be considered, due to the fact that the steel wire nettings normally used are rather weak, and the rigidity of grappling irons in the soil is problematic. Figures 23 and 24 show tested surfaces made of steel planks.

In general, none of these metal coverings comprises special devices for surface draining. If necessary, drain pipes must be provided under the surface, especially if the soil conditions are bad, e.g., soils of a certain cohesion which easily soak.

Often metal landing mats[21] are used on American Army airfields. They are portable, and rapidly and easily placed by untrained troops. All together, 4 different types are used. The old-style pierced steel planks (PSP) (Fig.25), and the pierced aluminium planks (PAP) have been replaced by the standard pierced steel planks M-6. No special devices are required for placing them. Damaged elements can be removed and repaired. The main disadvantages are:

The difficulties of concealment, the slipperiness in wet weather, frost and snowfall. On wet soil, the planks act like pumps, thus bringing particles of the soil on the surface. Finally they retard the draining of the surfaces to a certain degree.

For heavier wheel loads Type M-6 has been changed into somewhat heavier steel landing mats. The M-9 aluminium landing mat has been developed for shorter durability. The weight has been decreased considerably by use of aluminium.

In a special report[25] results are given about a series of braked taxiing and landing-impact tests made over metal landing mats and prefabricated membranes.

The thickness of the bearing layer on which the landing mats are laid depends upon the CBR-value of the soil and the decisive wheel loads. It is defined by use of similar design charts as is shown in Chapter 3. If a dry spell is to be expected one has to place a layer of mulch or burlap, if necessary, before placing the mats, in order to avoid raising of dust during flight operations. This precuation holds only for a certain time, especially during heavy traffic.

2.5.6 Surfacing by Concrete Grates

During the war one tried to get the same results in preparing temporary landing areas by use of pierced concrete or iron concrete grates instead of pierced steel planks.

Primarily economical reasons were decisive, especially as to the durability of concrete grates which are resistant to corrosion. Areas completely covered with concrete require special drainage devices. So one tried to use coverings which do not necessitate such devices. In addition, grass growing within the perforations of the concrete grates produces a certain concealment. Also here the problem of resistance against bending stresses in connexion with the load distribution on the surface is the decisive point. With regard to metal planks there is a difference as concrete grates are not deformed, but broken to pieces when applying extreme loads.

Another problem is the shearing strength of the joints between the elements as far as doweling of coverings made of concrete grates is concerned. Naturally this is decisive for the evenness of the covering. At this time, the last results of development were grates which were simply put together without any joints. Therefore they were used only on taxiways, dispersal areas, etc., where the airplanes taxy slowly. The plan view of the grates showed a hexagon with a number of circular perforations. So it was possible to put them together like honeycombs. The use of standard concrete or iron concrete was mainly an economical question. Iron concrete grates will always be preferred in case of higher wheel loads and safety factors. The general application or feasibility of these grates corresponds greatly to the use of steel grates. However, considerably longer durability is to be expected because of resistance to corrosion.

2.5.7 Surfacing by Wooden Elements

2.5.7.1 Timber mats. In some cases timber mats have been used for temporary stabilization of landing areas in Norway. The method is based essentially on production and placing of honeycombed quadratic grates made of planks (Figs. 26 and 27) set on edge. The same principles apply to wooden mats, in the same way as to steel, concrete or iron concrete grates. The relatively high bending resistance of timber mats is advantageous. Naturally the application of this method is restricted to regions with plenty of wood; it is a provisional set-up, especially as timber mats imbedded in the soil are only of limited durability, even if modern methods of impregnation are applied. For meeting the requirements timber mats are simply filled up with soil, or, if necessary, with mineral coverings of a certain thickness, by use of bitumen as binding agent so that sufficient safety is guaranteed against raising of dust and soil particles. Nearly the same results can be achieved by filling up the timber mats with top soil and sowing grass seed.

Another kind of timber mats made of planks is shown in Figure 28.

2.5.7.2 Wood paving. Wood pavings have been realized as another means of temporary stabilization, starting from the same conditions as to material, economy and durability. The paving consists always of round timber elements of 15-20 cm length, the diameter being between 10 and 20 cm. According to other methods the elements are placed on even soil. If necessary, subgrades of gravel or sand are prepared.

In order to achieve sufficient stability, it is necessary to brace the paving by means of planks set in between and outside, both in longitudinal and lateral direction. So the surface looks like a very wide-meshed set-up of timber mats filled up with round timber paving. In any case, timber seasons and shrinks. So one allows for rigid bracing and possible adjustment by providing double planks and putting wedges in between. The space between the round timber elements is not filled up, but for better surface finish, grown soil, and minerals mixed with bitumen (bituminous sand or chippings) are used as filler.

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3. UNDERCARRIAGES FOR OPERATION FROM UNPREPARED LANDING AREAS*

3.1 Introduction

3.1.1 Tactical Types of Aircraft

This paper concerns mainly the tactical types of aircraft used for operation from unprepared fields, whereas transport aircraft differ in so far as they may simultaneously have tactical and strategical functions.

As a result of the progressive development of modern remote-controlled weapons which in case of war will reach and destroy any target - particularly airports - though located well in the hinterland, this limitation will be no longer applicable. The technical solution of these problemes, i.e. the development of aircraft for strategical operations, independent of runway conditions, lies still in the distant future.

The present considerations should deal, therefore, with tactical types of aircraft only. These can be divided into four groups:

1. Ligt liaison, or all-purpose aircraft

2. Reconnaissance aircraft

3. Transport aircraft of all types

4. Fighter aircraft, especially strike fighters.

Their operational bases are situated either directly in the combat area or nearby. The army must be able to prepare the bases quickly and without considerable equipment. The dimensions of such airfields must be kept to a minimum, and their surface should be only roughly levelled and the largest obstacles removed.

3.1.2 Basic Requirements of such Aircraft with respect to Landing Gears

Aircraft operating from such airfields must meet two basic requirements:

1. Short take-off characteristics

2. Undercarriages designed for specially rough operations.

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The following sections are, therefore, intended for designers of such landing gears. The important factors result from the relations between unprepared fields and the construction of the landing gear.

3.2 Wheel Undercarriages

3.2.1 Specific Ground Load

Nearly all kinds of ground are changing their rigidity and, consequently, their bearing capacity due to weather variations. Heavy and long lasting showers are most dangerous for such temporary airfields. They very rapidly transform the soil-possibly an excellent runway under dry conditions - into a soft, muddy field and reduce its bearing capacity to a minimum. It is, therefore, of special importance to know thoroughly the bearing capacity of a landing area when determining whether or not a field is suitable for operations of a certain type of aircraft. Since this question is equally important for ground transport, a number of test methods have been developed evaluating comparative data as to the bearing capacity of various ground formations. More details are given in References 28 and 29*.

In most cases, no extensive ground measurements can be undertaken when choosing a landing field near the combat line. France, therefore, has attempted to establish a relation between the operational possibilities of a jeep - the weight and tyre inflation pressure of which are known - and the probable ones of an aircraft[1]. The Army could carry through this method at any time, but, of course, it cannot be considered as completely accurate and reliable. Landing areas could certainly be simply tested, but drawing up a relative evaluation chart would take a long time, as it could be based only upon statistical experiences.

Information about the nature of the surface and, above all, about the bearing capacity of a certain landing area alone are insufficient; in addition, the characteristics of the undercarriage in question have to be known to determine the operational limits of the aircraft.

A number of factors - dealt with later - are decisive for the landing gear loads acting on the ground. Once these factors are known, it can be decided as to what ground category the airplane under consideration can be operated from, without running into danger.

3.2.1.1 Tyre pressure recommendation. The decisive factor in the relation between landing field and undercarriage - wheels, skis or skids - is the specific ground load, with respect to the tyre inflation pressure.

The development of tyres in recent years shows distinctly the trend to raise steadily tyre inflation pressures. This is to reduce the weight of the tyre and the wheel on the one hand; on the other hand, to reduce the dimensions in order to compensate for the growing difficulties in stowage space for the retracted landing gear. Hereby the gross weights can partly be decreased. Reduced tyre diameters and higher specific runway loads resulted in stronger and more expensive concrete surfaces. Consequently, modern intercontinental aircraft, for instance, can only land on very few airports, which are of particularly high bearing capacity. Thus extensive work has been done to develop some new undercarriage arrangements aiming for decreased runway stresses.

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*See References - Section 3.7

This general trend to high tyre inflation pressures does, however, not contribute to solving the problems dealt with in this paper, but the experiences with new undercarriage assemblies are also to the benefit of the design of landing gears suitable for operation from unprepared landing areas.

It has been experienced that a sufficiently reduced tyre pressure - which is necessary for heavy aircraft like transports operating from landing areas of small bearing capacity - leads to wheel dimensions no longer used in practice. As a logical result, multi-wheel arrangements have been developed. Today, hardly any aircraft in the medium and heavy categories exists which is equipped with a single-wheel main landing gear, except some high speed aircraft, especially fighter types. Their wing sections, becoming increasingly thinner, involve an almost unsolvable problem for the stowage of the undercarriage when retracted.

Here single-wheel arrangements have to be maintained.

The tyre inflation pressure is - as mentioned earlier - one of the most important factors to be considered when operating from various kinds of landing areas. The chart below indicates the respective tyre pressures for different kinds of airfields:

Tyre Pressure Recommendations

Landing surface	*Max. tyre pressure*	
	lb/in^2	*kg/cm^2*
Aircraft carrier deck	above 200	14
Large military airfield, properly maintained	200	14
Large civil airfield, properly maintained	120	8.4
Small tarmac runway, good foundation	70 - 90	4.9 - 6.3
Small tarmac runway, poor foundation	50 - 70	3.5 - 4.9
Temporary metal runway	50 - 70	3.5 - 4.9
Hard grass, depending on soil	45 - 60	3.15 - 4.2
Wet, boggy grass	30 - 45	2.1 - 3.15
Hard desert sand	40 - 60	2.8 - 4.2
Soft, loose, desert sand	25 - 35	1.75 - 2.45

However, this chart serves only to give an approximate idea or to illustrate the tendency of the tyre pressure to decrease with smaller bearing capacities of the landing fields.

On the whole, it may be added that, considering the above types of landing areas - which are of interest to the present considerations - the corresponding lower tyre inflation pressures are suggested for single-wheel undercarriages, whilst the ones in the higher regions may be used for multi-wheel arrangements, in favourable cases, although this can only be considered a tendency.

3.2.1.2 California Bearing Ratio. In the twenties, the American Society of Civil Engineers started extensive experiments with the aim of determining the bearing capacity and the suitability of various types of ground surfaces for the construction of highways. From these tests, the so-called CBR-method (California Bearing Ratio) originated. This uses a standardized test procedure to examine the ground in question. It would exceed the purpose of this paper to describe this method in detail. Those particularly interested in it are referred to the condensed brochure[33].

The evaluated CBR-value represents the bearing capacity of the tested surface as a percentage of the bearing capacity of hardcore road-stones taken as 100%. Several years of testing roads yielded layout diagrams[33], thus making possible the estimation of the road layer thickness as well as the packing for any ground, together with the resulting stresses. The CBR-method is applicable to the so-called 'flexible pavement', in which a relatively thin wearing course transfers the load to the base. It is specially mentioned here as it comes close to the conditions of unprepared areas.

3.2.1.3 Influence of twin-wheel arrangements on CBR. During World War II the problem arose of building landing fields for heavy bombers in the most diverse places as quickly and with as little equipment as possible. In order not to lose any time with lengthy experiments, the results of the CBR method had been applied to the construction of taxiways by extrapolating to the substantially higher wheel loads of these bombers. But as the CBR method is based on single-wheel loads, the bomber B-29 was simultaneously submitted to tests, in order to determine the effect of twin-mounted or tandem-mounted wheel assemblies upon the bearing capacity of runways[32,33].

The principal results of these tests are shown in Figure 29. In this figure two extreme cases of runway construction are shown. Both pavements are assumed equally thick. The left hand illustration shows a relatively thin base of good bearing capacity, whereas the right hand illustration shows a very thick base with a poor bearing capacity. In both cases, the same B-29 main undercarriage with two parallel wheels and the same load has been used.

The left hand figure shows a thin base of high bearing capacity. The loads are symmetrically distributed on two separate parallel zones of the grown soil (subgrade).

By contrast, the right hand figure shows a material of lower bearing capacity which has been packed relatively thick, because of its low CBR value. The load cones, i.e. the stresses in the subgrade, overlap, so that critical stresses occur in the center part.

From this illustration it may be concluded that, besides the base bearing capacity, the center distance of both wheels and the width of the contact area of each wheel are also of importance to the subgrade load. The width of the contact area itself, at the same rolling load, is a function of the tyre size or its inflation pressure.

A similar effect of distance is found on tandem-mounted wheel assemblies.

The distribution of a given undercarriage load upon two wheels halves the subgrade load, consequently, only in the case of a base of high bearing capacity, or if both wheels are spaced relatively far apart, which can in practice not be realized on aircraft gears.

The reduction of the specific ground load by distribution of the weight on two or more wheels can, therefore, yield different values according to the importance of the above influence factors. In order to be able to compare different undercarriage arrangements as to their runway load or, with regard to a given landing gear, to state from which category of airfield safe operation is possible, the load distributed on several wheels is referred to an equivalent single-wheel load.

3.2.1.4 U.C.I. (Unit Construction Index). An evaluation method used in the U.S.A. consists of the calculation of a Unit Construction Index (UCI). Figure 30 shows the required diagrams and method of calculation. Development and fundamental data for these curves are given in References 32 and 35.

The table below classifies runways according to this method.

Category of runway	*Max. UCI*
Special Runways (permanent type concrete runways)	above 100
Full-Operational Runways (concrete or high-grade black top)	100
Minimum-Operation Runways	
Flexible Pavement	60
Landing Mat	40
Emergency Runways (landing mats)	25
Bare Soil (graded, CBR of 6 or better)	20
Bare Soil (unprepared)	less than 15

3.2.1.5 LCN and ICAO runways. The I.C.A.O. has adopted a Load Classification Number (LCN) for the undercarriage originating in similar test results[30]. Applying this number, the operation possibilities of the aircraft under construction can be taken from the table overleaf.

An enlarging on these methods is not called for because both methods assume an artificially planned landing ground, the reinforced subgrade of which is covered with a more or less strong wearing course[30,32,33]. Unprepared landing grounds, however, are not of concern here, except in some limited cases. Aircraft designers should nevertheless design the undercarriage of an aircraft, which will operate from unprepared fields, in accordance with one of the above methods, to ensure that it can match, at least, the most unfavourable ground categories stated in this table. An example of such a calculation is given in Figure 31.

I.C.A.O. - **Runways**

	ICAO Clas-sifi-cations	*W maximum single-wheel load (lbs)*	*Maximum tyre pressure associa-ted with this load lb/in.²*	*Equivalent load classification number*
Inter-Conti-nental Express	1	100,000	120	100
Inter-Conti-nental	2	75,000	100	72
Continental	3	60,000	100	60
Inter-City Express	4	45,000	100	48
Inter-City	5	30,000	85	30
Feeder Services	6	15,000	70	14
Light Services	7	5,000	35	--

It would be desirable to find also a similar evaluation method for the cases discussed for operation from unprepared fields. lds. It should be realized how difficult and lengthy experiments would be to achieve any usable results.

3.2.1.6 Danger of sinking in. The considerations up to now take for granted that the bearing capacity of the runway is - by a certain safety margin - greater than the corresponding load.

When operating from unprepared fields, it may easily happen that the load reaches just the possible limit, since it may considerably fluctuate due to the influence of weather. In this case an important factor has to be taken into account.

As long as the vehicle is moving on such a ground, there is little danger of sinking in. Every motorist, having once diverted from a hard-top road into a softened-up country lane, has had this experience. The wheels plough deep traces into the ground without blocking the car, since the soil has little time to move considerably. Only when stopping do the wheels sink in so far that finally the car is no longer able to start moving under its own power[1,6]. This has to be especially observed when choosing parking areas. Either the sub-soil itself must be of sufficient bearing capacity or the parking areas have to be reinforced by large plates or other means, distributing the loads upon a surface as large as possible.

3.2.2 Rolling Resistance

Particularly in take-off runs, but also when landing on unprepared grounds - above all, when the soil is muddy and the wheels of the landing gear sink in - the rolling resistance may become of decisive importance to the energy requirements. In any case the take-off run becomes considerably longer than on a levelled, prepared runway of good bearing capacity. The rolling resistance may increase so much that the acceleration required for take-off can no longer be reached. It depends upon many factors:

Condition of the ground and nature of its various soils, and the climatic conditions changing it;

Dimensions of the tyres and their inflation pressures;

Number of wheels and their arrangement;

Rolling speed;

Aerodynamic characteristics of the aircraft.

So it is almost impossible to get precise data about the rolling resistance from experiments. Even on a levelled concrete runway such tests become extremely complicated[1,6,10,17]. Nevertheless it will be endeavoured here to give an approximate survey regarding the amount and effect of the rolling drag on take-off conditions by recording various test-results mentioned in the available literature

3.2.2.1 Influence of the nature of the soil. The following details are taken from a German test-report issued during the war[6]. The soil is doubtless the most incalculable factor resulting sometimes in absolutely contrary values. Its characteristics are of decisive importance to the interaction of tyres and soil. It must, therefore, be realized that two basically different ground categories affect this interaction quite differently.

Excluding hard, rocky grounds, on which a minimum influence on the rolling resistance can be observed, and marshy soils - at any rate out of question for practical operation - we can distinguish:

(a) soils *without* cohesion, i.e. sand and gravel. They only carry load by means of internal friction as long as they are dry, but change conditions with increasing water content;

(b) soils *with* cohesion, i.e. clay, mud, and others. When dry they have a very strong bearing capacity, but lose it entirely with increasing water content.

A grass-covered surface can more or less balance out the reaction of both.

Tests carried out in England with a military heavy-duty truck[6] have resulted in the following rolling resistance figures:

	Sandy soil			*Muddy grass soil*		
Conditions of the soil	dry (soft)	moist	wet	dry (hard)	moist	wet
Tyre inflation pressure $lb/in.^2$	up to	57		58	20	11
Rolling resistance coefficient μ_0	0.25	0.154	0.145	0.047	0.145	0.19

This table indicates two interesting observations:

1. On sandy ground the rolling resistance coefficient decreases with increasing moisture content, whereas changing of tyre inflation pressures within practical limits remains without effect.

2. Increasing moisture content of soils with cohesion - in this case a muddy grass-plot - increases the rolling resistance coefficient to a high degree, even if simultaneously the tyre inflation pressure decreases considerably.

These results indicate that, according to the type of soil, absolutely contrary conclusions can be obtained. It is, however, important to note that on muddy soils the rolling resistance coefficients can be improved by reducing the tyre inflation pressure.

3.2.2.2 Influence of the rigidity of the tyres. Furthermore it is important that the rigidity of the tyres, especially of their side walls, influences the rolling resistance. A stiff tyre acts similar to a hard roll. Its contact area on the soil remains more or less rounded up and therefore sinks deeper into the soil.

By contrast, a less rigid tyre flattens up, adapts itself better to the ground, creates less deep rolling traces, and consequently reduces the rolling drag.

For undercarriages operating from unprepared landing fields it is desirable to provide a combination of lower inflation pressures and reduced tyre rigidity so as to decrease possibly rolling drag and to avoid extra power requirement for take-off.

3.2.2.3 Behaviour of multi-wheel arrangements. An interesting fact, although expected, came out of a further test with twin-mounted or tandem-mounted wheels. Tandem wheels give considerably lower rolling resistance, since the front tyre does the main work so that the aft wheel runs on an already smoothed-up and levelled track.

Parallel wheels both have to do this work, and, if they are mounted very close to each other, their soil deformations mutually encumber, thereby an increase of the rolling drag occurs.

3.2.2.4 Rolling resistance of initial motion and of continued motion. At a later stage it has to be considered that a difference exists between the rolling drag of initial motion, μ_1, and of continued motion, μ_2 whereby a rolling speed of about 20 - 30 knots is maintained during the tests.

For both values entirely different amounts can be assumed, whereby it cannot be stated clearly that one of the two is basically higher than the other. This depends a great deal upon the kind of soil and its moisture content.

On a relatively rigid soil the difference between the rolling drag in motion, μ_2, and of initial motion, μ_1, is insignificant. The wheel, having sunk to a certain depth at touch-down, is rolling on in a track of about the same depth[6]. It may even occur that the rolling wheel sinks in less than the stationary wheel. In this case μ_2 may become smaller than μ_1.

On a soft soil the conditions differ, in so far as the stationary wheel, having sunk into the soil to a certain degree, has found a sort of equilibrium in it. For initial motion, this equilibrium is disturbed, due to a part of the rear tyre contact surface being lifted off and, consequently, the total load acts on a smaller area. The tyre sinks deeper into the ground, and the rolling drag μ_2 increases. If the wheels sink in still deeper, movement is finally impossible.

On sandy grounds the moisture content plays an important role. Whilst moist sand is possibly an ideal runway at relatively low rolling drag, the work necessary to push away particles of dry, loose sand will greatly affect the rolling drag, depending upon the speed. From these observations it can be seen that - considering the many varied ground conditions - it is impossible to give precise data on μ_1 and μ_2. But, in order to give a certain idea of the rolling drag coefficients, some test results are cited as follows:

3.2.2.5 Test results. From an American report[12] on tests with the transport aircraft C 123, equipped with special low pressure tyres instead of normal ones, the following points arise:

1. Whilst there is little rolling drag on concrete runways or on solid ground in relation to the vertical load, it may increase to 0.5 of the vertical forces on unprepared fields. (Unfortunately no information is given as to μ_1 and μ_2).

2. On hard runways the rolling resistance is practically independent of the rolling speed. On unprepared grounds of low shear strength - assuming low pressure tyres fitted - it can be supposed to decrease with increasing rolling speed.

3. On soft soil of low shear strength low pressure tyres have a smaller rolling drag than those with higher pressures or even skis. As a further advantage low pressure tyres swallow up the unevenness of the runway.

These remarks cover in principle what has been said up to now. All that is lacking is the information that results may differ on sandy ground.

Also in France, recently, extensive tests have been made with different types of aircraft on various kinds of ground, by carrying out measurements of the rolling drag. The results are summarized as follows:

Tests with the prototype aircraft MD 450('Ouragan') with various tyre types and inflation pressures showed that the tyre inflation pressure has a minimum influence on the rolling drag when taxiing on concrete runways. On elastic ground, however, the rolling resistance increases, with increasing tyre inflation pressure, especially when beginning motion.

The softness of the ground changes the rolling resistance considerably, for a given tyre pressure. The following values have been obtained:

dry concrete	$\mu_1 = 0.02$	$\mu_2 = 0.03$
hard soil	$\mu_1 = 0.1$	$\mu_2 = 0.08$
soft soil	$\mu_1 = 0.13 - 0.22$	$\mu_2 = 0.09 - 0.1$

Here also μ_1 refers to the initial motion, whereas μ_2 has been found for a constant speed run in a straight line, at a speed of approximately 20 knots/hr.

According to this chart the rolling resistance on soft ground may attain 10 times the resistance on concrete, while the rolling resistance μ_2 can also become 3 or 4 times the value measured on concrete.

The given values of μ_2 refer to constant rolling speed.

Measurements of rolling drag during take-off with its variable speeds is indeed already extremely complicated on a good concrete runway. But it is hardly feasible on an open field with its irregularities and its varying soil conditions along the runway. For this reason the above French test report uses comparative runways on differentnt kinds of soil, or, in other parts the average acceleration during take-off.

As an example of the effects of rolling drag upon the length of take-off runs, a table is given below which has been compiled from the tests with the 'Ouragan' equipped with low-pressure tyres:

Runways, subject to same conditions:

dry cement	400 - 450 m	
dry soil	500 m	+ 10%
dry grass	450 - 500 m	+ 10%
moist grass	600 m	+ 33%
soaked grass	800 m	+ 78%
cement covered with snow	1000 m	+ 121%

These figures, which, of course, must not be generalized, indicate clearly how the take-off run increases on wet and slippery ground. When estimating operational possibilities on such ground, it has to be considered that the take-off run may be much longer than on concrete runways. This is very important for temporary space-confined combat line airfields. Tests with the 'Ouragan' have also shown that multi-wheel arrangements (in this case twin-wheels) are preferable to single ones. The following μ_1-values have been found during these tests:

Ground type	*Twin-wheels* 3.6 kg/cm²(51.2 psi)	*Single wheel* 3.5 kg/cm²(49.8 psi)
Concrete	μ_1 = 0.04	μ_1 = 0.02 - 0,03
Hard soil	μ_1 = 0.04	μ_1 = 0.1
Very soft soil	μ_1 = 0.13 - 0,14	μ_1 = 0.17

The difference is also apparent for rolling friction, but of lower intensity; unfortunately no figures have been indicated.

3.2.3 Braking Effect

The landing of aircraft on unprepared fields, which mostly will be narrow and the length of which will be limited, raises another problem. The braking devices of the aircraft must be particularly effective and reliable.

Aircraft with propeller engines lately have the possibility of braking by means of reversible thrust. After touch-down they often do not need wheel brakes. But for manoeuvring on the ground the wheel brakes must be as effective as on other aircraft; the same applies to aircraft with jet engines, even though they take advantage of the reversible jet.

It is a well-known fact that a blocked wheel, which slides on the ground instead of rolling, yields a very bad braking effect. So the braking effect of a wheel brake depends to a large extent upon the friction coefficient between wheels and runway.

3.2.3.1 Friction coefficient and nature of the soil. Even on concrete runways this coefficient varies considerably, according to whether the runway surface is dry or wet. Moreover, the rolling speed has a certain effect. Figure 32, published by E.C. Pike[30], demonstrates how this coefficient depends upon various conditions of the concrete surface.

Such measurements - being after all extraordinarily complicated on a levelled concrete runway - can practically not be carried out on unprepared territories. The friction between tyres and ground may yield uncontrollable values. On a somewhat moist, grass strip the adhesion of the wheels drops to a minimum. On the other hand an icy concrete runway is worse than a frozen grass-covered area, likewise a slightly softened-up soil without grass. This may originate from the fact that the tyres still grip on some rough ground elements.

Furthermore, the well-known steel mats are particularly critical; often they are placed to reinforce the surface of such temporary runways. Even under dry conditions, there exists danger of slipping. The pilot has to use the brakes very carefully. On wet steel mats the tyres lose their adhesion completely.

The French test report[1] already mentioned gives a table, obtained with a tyre of 27 × 6,5 - 12 and an inflation pressure of 100 p.s.i.

Cement	moist	$\cong$ 0.2
	snow-covered	< 0.15
	dry	$\cong$ 0.25 - 0.30
Bitumen	rough, wet	$\cong$ 0.04
	dry	$\cong$ 0.5

Any tread designs on the tyre surface have proved inadequate with such surface conditions. They are very quickly plugged up with soil or snow and then form a smooth surface.

3.2.3.2 Friction coefficient and tyre inflation pressure. The low pressure tyre has, however, proved entirely superior with regard to the braking power because of its better adhesion on wet soils where braking with high pressure tyres is impossible.

3.2.3.3 Automatic control of the braking moment. The condition of the runway surfaces has - as all tests have shown - a decisive influence on the friction coefficient, the values of which can vary over a wide range. Each landing field - to a high degree temporary ones - have spots of varied conditions. For example grass covered spots may alternate into sandy, dry, wet or frozen ones. When braking the pilot is unable to adjust the changing conditions of adhesion of the wheels and to obtain the most effective braking, i.e. the shortest landing run. It is, therefore, recommendable to fit the wheels with one of the regulators developed by different firms in recent years. They automatically control the brake pressure to avoid blockage or sliding of the wheels. The brakes should have a very progressive effect in order to possibly facilitate the control of the rolling direction and the distribution of brake energy. This is very important for manoeuvring the aircraft on the ground.

3.2.3.4 Steerable nose wheels. The nose wheels should be steerable since - as tests have demonstrated - self-regulating nose wheels tend to slide laterally and reduce the manoeuvrability of the aircraft considerably.

3.2.4 Undercarriage Resistance Requirements

The bearing capacity of temporary runways will, in any case, not be as regular and uniform as that of carefully built concrete runways.

3.2.4.1 Tests with the 'Noratlas'. Extensive tests[1] have been carried out - among others - in France with the prototype aircraft N 2501 Noratlas and have proved that even when taxiing on a relatively levelled grass strip considerably more rolling shocks are encountered per unit runway length than on concrete grounds. From force measurements it was found out by these tests that the forces acting on the undercarriages are not considerably higher - as far as the vertical and horizontal forces are concerned - than on concrete runways. This result may, however, differ entirely on a very bad and uneven ground. The lateral forces reach, however - according to the ground conditions - considerably higher values than those encountered under normal conditions. This observation is also obvious, assuming that an aircraft is for instance crossing diagonally over frozen rolling tracks or stones and other small obstacles.

3.2.4.2 Tests with 'ME-109'. Tests carried out in Germany during the war with the well-known fighter ME-109[3] yielded similar effects of early wear and tear. The wheels of the undercarriage of such an aircraft made in series had been replaced by skis. The test proved that the aircraft was apt to operate at most various snow conditions, but already after a few take-offs considerably enlarged bearing play could be observed. After some more than 80 take-off procedures, tests had to be abandoned since a skid attachment had broken.

3.2.4.3 Service life of undercarriages. At the same French test center experiences have been had concerning the undercarriage life period of another prototype aircraft operating from grass strips. It was apparent that the landing gear parts age earlier due to more frequent shocks. Parts, easily withstanding 500 landing procedures on a hard level ground, already after 50 landings were deteriorated to such an extent that further use was impossible. The moving parts of the shock absorbers are particularly concerned. Tyre deterioration increases, too, in an uncontrollable manner. Tyre fabric plys break or tyres suddenly burst much more frequently, which is probably due to over-rolling of stones. This latter observation also calls for the use of multi-wheel undercarriages for heavier aircraft in order to avoid a disaster in case a tyre should burst.

3.2.4.4 Increased stresses in landing gears. The stronger, aforementioned lateral forces produce an increased moment around the vertical axis of the wheel suspension of conventional undercarriage assemblies. All parts designed to transfer these torques - mostly the well known scissors - are subject to a greater wear and tear and, therefore should be designed especially strong.

The undercarriage transmits the rolling shocks to the fuselage. It is, therefore, necessary not only to design the undercarriage components and their joints specially robust, but also to build correspondingly the adjacent airframe components to which frequent shocks are transmitted.

At this point it should be noted that apart from special requirements for the landing gear, another factor originating from the above tests has to be considered for the design of an undercarriage. Aircraft taxiing on unprepared grounds whirl up dust, stones or mud. Assuming that several aircraft are taking-off successively one after the other, there will be an enormous cloud of dust. This may affect very critically propeller-powered aircraft, the undercarriages of which are generally exposed to the propeller slip-stream and then undergo a treatment similar to sand blasting. Undercarriage designers should bear this in mind and attempt if possible to protect the gear from this effect. Above all, very delicate apparatus, which often is located at the undercarriage or its wheel well, should be shielded or be placed where it is sufficiently protected. It should be noted here, that not only the undercarriages suffer from this dust. Also the sensitive air ducts of the jets or, for instance, the effect on the windows of the cockpit have to be considered, especially for new designs. In a formation take-off the pilot may possibly lose all visibility.

The increased load upon the undercarriage operating from unprepared grounds is particularly effective on the nose gears. Frequent failures during tests were due to very strong lateral forces (lateral to the wheel plane) when rolling on soft ground; for instance, steered nose wheels were particularly concerned. This is frequently due to circling when the nose wheels sink more or less deep into the ground. This fact has to be observed for the dimensioning of nose gears.

3.2.4.5 Advantages of swivel lever assemblies. It seems appropriate to point out another factor which may influence the nose gear design. Arrangements with relatively small cant of the wheel or wheels (i.e. the space between the tyre contact point on the ground and the reference point of the gear's swivel-axis referred to the ground) tend to turn across the actual rolling direction when taxiing on soft ground or on snow, which inevitably leads to failures. The reason for this is that the point of attack of the ground loads, which is placed behind the swivel-axis when rolling on a level rigid runway, slips forward due to the snow and earth piling up in front of the wheel. If the theoretical cant is small, this point of attack may slip in front of the gear's swivel-axis thereby producing a moment which tends to turn the wheel.

For aircraft operated from unprepared fields, the cant of the nose wheels should not be chosen too small. Undercarriages with swivel-levers meet this requirement very favourably and are especially suitable to overrun bumps and obstacles. As an example, the Noratlas nose gear is shown in Figure 33.

Thanks to their excellent adaptability to ground unevenness these swivel-lever layouts are successfully used also for main undercarriages. We recall the prototype aircraft AR 232 which had been developed in Germany as a combat transport aircraft during the war. Its undercarriage arrangement differed from the conventional type in order to operate from very bad fields and to over-roll 10 feet wide ditches and other considerable obstacles without difficulties. Figure 34 shows a normal tricycle undercarriage, the nose wheels as well as the main gear wheels being fixed on swivel levers, designed for landing and take-off from a level field. In addition, eleven smaller twin-wheels, each one spring-mounted and also fixed on swivel-levers, were fitted to both sides of the fuselage bottom.

The normal undercarriages could be lowered to various positions. For landing on level fields they were lowered so far as to roll only on them alone in order to avoid useless rolling drag. On very bad grounds, however, the normal undercarriages were only lowered to such a degree, that simultaneously with the large wheels the small wheels also contacted the ground so that the load was distributed upon a considerably enlarged contact area.

Tests with this arrangement had been so successful that manufacturing of larger series had been planned. It is noteworthy that the auxiliary small wheels could be dismantled if the aircraft was scheduled to operate only from level fields. In this case its pay load could be increased by approximately 1200 lbs (i.e. approx. 10% of the normal pay load).

But also quite modern aircraft profit by the advantages of swivel-lever undercarriages, as e.g. the large Douglas transport aircraft C 133. Two twin-wheels are mounted on swivel levers on each side of the fuselage. The levers are independently spring-suspended. This landing gear matches nearly each type of ground excellently (description under Section 3.2.5).

3.2.5 Examples of Manufactured Wheel Undercarriages

At the end of these sections, some pictures are shown of tactical aircraft and their undercarriages, which have proved their suitability for operation from unprepared fields by thorough tests.

3.2.5.1 Do 27. Figure 35 illustrates the new German liaison or multi-purpose aircraft Do 27, its landing gear being fitted with especially large tyres of extremely low tyre pressure (28.5 p.s.i.). Due to this the aircraft is able to operate even from loose sand. In addition skis can be mounted, as shown in the above figure, in order to allow for landing on deep snow.

3.2.5.2 Twin Pioneer. As a further example of a light all-purpose aircraft, the 'Twin Pioneer' is shown in Figure 36 developed by the Scottish Aviation Company and particularly suitable for impracticable fields.

With regard to this function special attention should be paid to the sturdy undercarriage with twin wheels, which actually would not be required for the weight of this aircraft.

3.2.5.3 G 91. From the variety of tactical support fighters the G 91, chosen by NATO, is shown in Figure 37. This aircraft claims to operate also from semi-prepared or grass-covered runways in spite of its excellent flight performances. This can obviously be achieved by the undercarriage design equipped with swivel-levers, the advantages of which were already discussed. The relatively large tyres have an inflation pressure of on 50 p.s.i. (3.5 kg/cm^2), which is unusually low for a modern fighter aircraft. One can realize that even such high-speed aircraft can operate from poorly prepared fields if the undercarriage is designed appropriately.

3.2.5.4 C 133. Figures 38 and 39 represent a very interesting undercarriage: it is the main gear of the largest American transport aircraft Douglas C 133 with a gross weight of 226000 lbs. This undercarriage consists of two tandem-mounted twin-wheels, each one stowed in special wells on both sides of the fuselage. The axis of each twin-wheel is attached to the lower end of a lever which is spring-suspended by means of a shock absorber. Contrary to the so-called bogie-undercarriages, the tandem-mounted twin-wheels, which are coupled together (Ref. 3), and where the shocks are mutually transferred from one twin-wheel to the other, each twin-wheel of the C 133 is independently sprung. Practically there are four independent undercarriages. This layout, with all four levers pointing to the rear, has the advantage of a particularly good cross-country mobility. Such an undercarriage assembly is, however, only realizable if the required stowage space is available, and if allowance is made for increased drag due to the wells.

3.2.6 Tandem-undercarriages

With the steadily increasing gross weights of almost all aircraft categories in recent years, it became necessary to change over from single and twin-wheel arrangements and to proceed to a new gear design with more wheels which generally was called 'tandem landing gear'. The reasons were, on one hand, the increasing wheel dimensions, which became bulky, heavy, and, on the other hand, exceeded the allowable load of a single wheel, even on the best concrete runway.

The same considerations apply - as discussed earlier - still more to those types of aircraft operating from unprepared landing fields. Besides an improvement of the specific ground load, the tandem-mounted multi-wheel undercarriages, consisting of two or more wheels trailing in line, offer further considerable advantages.

3.2.6.1 Advantages of tandem-undercarriages. It turns out that four wheels of equal bearing capacity and tyre pressure have proved considerably lighter than two wheels only. For a medium military transport aircraft of approximately 100,000 lbs, the weight of four wheels, e.g., had been evaluated at 795 lbs, whereas two wheels weighed 910 lbs, for the same performance. This is quite a noticeable difference in weight.

As a further advantage, the relatively small moment of inertia of a small wheel results in reduced spin-up-forces at the touch-down, and thus decreases the stresses upon the whole aircraft.

Distributing the load upon several wheels grants, furthermore, an increased safety in case of tyre failure, which is of special importance for the types of aircraft dealt with in this paper, as, when operating from unprepared fields, a greater tyre wear and tear must be taken into account.

3.2.6.2 Disadvantages and problems of tandem-undercarriages. The tandem arrangement raises problems which are not encountered in conventional undercarriages and involves certain disadvantages or difficulties as follows:

(a) Circling is more difficult, and the turning circle is limited

(b) Increased tyre abrasion

(c) Strong stresses on the undercarriage when manoeuvring

(d) More complex and heavier undercarriage construction

(e) Tendency to pitching and its prevention.

Disadvantages (a) to (d) are very closely allied to each other and refer to the circumstance that on tandem-gears lateral forces are applied to each wheel when turning, which are not only due to centrifugal forces. Each wheel is forced into a track which does not correspond with its center plane. These relations are drawn up in the attached sketch Figure 40.

Mainly four factors determine the magnitude of the lateral forces:

1. The cornering angle

2. The vertical wheel load

3. The tyre rigidity

4. The friction coefficient between tyre and soil.

The lateral forces can be defined by means of empirically defined diagrams. The attached diagram (Fig. 41) applies to aircraft tyres used nowadays. At a small cornering angle the wheel is only laterally distorted; with increasing cornering angle an additional lateral sliding occurs. The beginning of the side-force-coefficient-curve is thus mainly determined by the tyre flexibility, the remainder of the curve and its maximum by the tyre adhesion to the soil. The maximum value is given by the corresponding adhesion friction coefficient (the diagram in Figure 41 states the sliding coefficients of friction).

It would exceed the purpose of this paper to enter into the design methods exposed in the paper of Hancock and Person[23]. In any case, the side forces develop a moment M_0, counter-acting to the turning of the aircraft, which has to be compensated for by the steering mechanism of the nose wheel.

The cornering angle and therewith the side forces or moments increase proportionally to the decrease of the turning circle radius. These moments cause extremely high stresses to the undercarriage system, so that all structural components transferring this torsion should be solidly built. It may be that the undercarriage rigidity limits the rolling radius. The actual radius should not fall below this value. This, of course, restricts the manoeuvring qualities of the aircraft.

The required undercarriage rigidity can only be attained by means of a certain structural effort, cancelling partly the above advantage in weight of several small wheels.

The sliding movement of the wheels when cornering causes, of course, increased wear and tear.

The difficulties pointed out under (e) mainly appear at the so-called bogie-undercarriages. These are tandem gears where the front and aft-wheels of a unit are either attached to a common beam, swiveling around a centre pin fixed on the under-carriage structure (Fig. 42), or on two levers, the one pointing to the front, the other one to the rear, and which also have a common centre pin and are coupled with each other by means of rods (Fig. 43). This flexibility around a lateral axis is required so that for the various landing positions all wheels will carry load as soon as possible and the ground loads are distributed equally. Due to over-rolling bumps or irregular effect of the different brakes, pitching oscillations of the undercarriage may occur with this arrangement, which will be transferred to the fuselage and there cause dangerous stresses.

To avoid this, such bogie-undercarriages are equipped with hydraulic shock-absorbers appropriately located. Thus pitching oscillations can be suppressed[22].

As a further step to prevent this rotation, the braking moments of each wheel are not taken directly from its axis - as is normal for conventional undercarriages - but transferred to a fixed point of the landing gear by means of levers and rods. The result is, as shown in Reference 19, that the braking moment - provided that the rods are correctly arranged - produces no or only a small torque around the centre pin of the nose gear so that irregular braking effects do not cause pitching.

These brief remarks show that tandem-undercarriages create further problems, involving, of course, more complex and heavier constructions.

3.3 Skis and Skids

A wheel undercarriage doubtless gives the aircraft the best flexibility for ground manoeuvring. But in spite of all the aforegiven hints its use is unfortunately yet limited.

3.3.1 Skis

As is generally known, operation from snow-covered fields is made possible by the installation of skis. In most cases, undercarriages are designed to fit either wheels or skis as required, or sometimes even both. Figure 35 shows for example such an undercarriage assembly on a Do 27.

At this point it may be recalled that undercarriage designers should allow for increased loads with regard to the stresses, particularly caused by lateral forces.

Since, principally, no unsolvable problems arise from the application of skis as long as the snow conditions allow operation of aircraft at all, as tests even with the large American transport aircraft C-130 'Hercules' have proved, it is not worthwhile to go further into this matter.

Some indications are given in Reference 30 as to the most favourable design of skis.

3.3.2 Skids

Softened-up, muddy territories of poor bearing capacity require, however, special means. Here wheel undercarriages fail since, even at low tyre pressures, the specific ground load is still too high, and an adequate braking effect generally cannot be attained. Such a field allows ground loads of not more than 12 - 15 p.s.i., which approximately corresponds to a human foot.

With reference to the known skids of gliders, similar arrangements were developed for powered airplanes. This was, however, only possible due to the invention of jet engines as in these special cases their distance from the ground was of no importance, so that the skids could be fitted directly to the bottom side of the fuselage.

3.3.2.1 Description of the skids of the Me 163 and the AR 234. During World War II the aircraft Me 163 and AR 234 were built in Germany and equipped with such skids instead of the hitherto used conventional undercarriages (Fig.44). However, the decisive factor for this novel assembly was rather to reduce the gross weight of these two aircraft by abolition of the undercarriage than to operate from unprepared landing fields. Light gross weight was of essential importance in the early times of jet engine development, their performances being still poor at that time. The skid arrangement of the Me 163 for instance required only 2.4% of the take-off weight. Such a low value has never been obtained with any wheel-type undercarriage.

Both aircraft were mounted on a wheeled trolley for take-off which released the aircraft when the take-off speed was reached and remained on the ground. Landing was effected on the skid, equipped with shock absorbers and lowered by means of hydraulic cylinders.

Unfortunately no indications are available as to the operational qualities of these aircraft on a particularly bad ground. It is, however, known that quite a number of this type of aircraft were used for combat operation.

3.3.2.2 Description of the 'Baroudeur'. After World War II similar aircraft types had been designed or suggested at various places. So, among others, the well-known French prototype aircraft SE 5000 'Baroudeur', a fighter aircraft with supersonic speed, originated. Construction and test results are briefly reported in Figures 45 and 46.

This aircraft has two parallel short main skids, attached under the fuselage near the center of gravity, and furthermore a third small skid at the tail. The skids are made of light metal, lowered and retracted hydraulically. They are fitted on the airframe with rubber buffers. An easily removable sheet steel face serves as the actual gliding surface. The skids are fitted with brake spurs which the pilot can operate all together or separately, whereby the spurs will penetrate into the earth. In this way a certain manoeuvring capability can be achieved. The brake effect differs, however, very much depending on the ground conditions.

This aircraft was, contrary to the above German types, specially designed for operation from unprepared fields. For the take-off procedure it is also mounted on a trolley equipped with low pressure tyres which in turn was powered by an additional jet engine to assist during take-off. When the aircraft becomes airborne the trolley is released from the aircraft and is stopped in a minimum distance by means of ingenious automatic braking devices.

In special cases, the aircraft can carry the trolley in flight, so that the trolleys had not to be shipped separately when the unit moved to another place of action. In this case the aircraft lands on the wheels of the trolley.

However, under normal circumstances the aircraft lands on the skid and it does not even sink into very bad soil. Tests have proved the following landing runs evaluated from 26 feet height[24]:

wet, slippery ground	(0.2 friction coefficient)	3280 ft
dry, stony ground	(0.3 friction coefficient)	2625 ft
with lowered brake spurs	(0.6 friction coefficient)	1350 ft

On wet grass and moist soil the aircraft is able to manoeuvre on its skid on its own power and can even take-off under favourable conditions. The high friction values on sand or dry soil, however, make it impossible.

In most cases, the trolley is, therefore, required. Consequently, the same problems arise for the unit trolley-aircraft, equal to those which have been dealt with in the preceding sections concerning wheeled undercarriages. There is, however, an essential difference in so far as the trolley may be equipped with large tyres of an extremely low inflation pressure (28.45 p.s.i.) which would not have been possible for a retractable undercarriage attached to the aircraft in view of weight and stowage space. Tests have shown, for instance, that the trolley on which the aircraft is mounted does not sink even into loose sandy beaches as long as it is moving, but when the trolley stops the front wheels disappear in the sand and the aircraft cannot be moved except with outside help.

Experience obtained with the above mentioned two German aircraft showed that the somewhat complicated handling of the combination trolley + aircraft involves certain difficulties in operation. The take-off of several aircraft under restricted space conditions is a difficult matter because of the trolleys remaining on the ground. The landing procedure is also difficult and dangerous, as the aircraft is immovable on dry sand. For this reason in France everything has been tried out to facilitate and speed up the required wind-up as fast as possible after landing of the aircraft. For this, a jeep is used which is equipped with a winch in order to put the aircraft on its trolley.

To complete this discussion, the following must be pointed out. The aircraft stability around its fuselage axis is at a minimum when moving on skids placed closely together at the center of the fuselage. The ailerons, therefore, have to be very effective, or, as some authors suggested, support skids have to be provided near the wing tips.

3.4 Wheels and Skids Combined

The preceding paragraph pointed out that the skid arrangement may involve certain difficulties when manoeuvring on the ground.

3.4.1 Tests with 'Ouragan'

An interesting and, as it appears, very effective solution to eliminate this disadvantage has been examined in France on a specially designed undercarriage of the prototype aircraft 'Ouragan'. An auxiliary skid was fitted between both main gear wheels (Fig.47). On hard soils the aircraft rolls quite normally on the wheels, the skid does not touch the ground. Only on soft grounds, when the wheels sink in, does the skid begin to carry load, thereby enlarging the contact area and avoiding further sinking in. The provisional conversion of a normal undercarriage was, however, a fault in so far as on very soft and muddy ground, soil particles stuck between skids and wheels and blocked the wheels[1,5].

It is quite conceivable that the designer can avoid this disadvantage, if he provides enough space between the two elements.

3.5 Caterpillar Track Gears

All hitherto described types of aircraft still require a certain preparation of the runway for their practical operations, i.e. the runway must be roughly levelled, holes and ditches must be filled up and obstacles removed.

Two tactical types of aircraft, however, cannot be satisfied with this restriction. These are the so-called Light Liaison or All-Purpose Aircraft and Combat Zone Transport Aircraft, which are required to operate in the combat area, possibly even from really unprepared grounds.

Germany finally lost the great encircling battle at Stalingrad as in the long run it was impossible to adequately keep up the air supply of the encircled troops. The few airfields available were continuously exposed to raids and destructions, and, in spite of all efforts, they could not be maintained in a condition allowing the transport aircraft with their normal wheel undercarriages of that time, to land and take off without enormous losses. Similar experiences were obtained during the war in Korea and on other occasions[27].

Therefore, development work has been undertaken at different places to design adequate undercarriages, suitable for cross-country runs, which are able even to take bigger obstacles and larger trenches and to manoeuvre on destroyed airfields.

All these designs finally refer to the caterpillar tracks which are successfully used on ground-bound vehicles, such as armoured cars or agricultural tractors.

Here, not all layouts can be recorded which have been projected and tested more or less successfully in recent years. But some later constructions will be mentioned which, as far as it is known, turned out to be usable[22,5,30,2].

3.5.1 Tube-type Caterpillar Track Gears

First of all, we are to note the tube track gear developed by the Italian engineer, Count Bonmartini, which up to now has been fitted to and tested on several small aircraft.

3.5.1.1 Description of the landing gear of the Do 27. Figure 48 illustrates a Do 27 fitted with such a caterpillar tube track gear.

As is distinctly recognizable, this construction provides a thick rubber belt travelling around two wheels which are fixed on a common beam. This support, in turn, is connected with a shock strut by means of a pivot. A hydraulic cylinder damps the pitching movements of the wheel system, similar to tandem undercarriages. Figure 49 shows the aircraft manoeuvring on very rough terrain.

3.5.1.2 Description of the landing gear of a 'Piper'. In another case, a 'Piper-Cub' was fitted with Bonmartini-gears[5]. However, four wheels were mounted in tandem arrangement over which the rubber belt ran (Fig.50). The two front- and rear-wheels of this arrangement can move somewhat, independently from each other, so that the undercarriage can very well adapt itself to ground irregularities and can cross larger ditches and holes.

Since the rubber belt contributes little to the gear's spring suspension, the travel of the shock absorbers must be chosen much larger than for a tyre-wheeled landing gear, for the purpose of providing the required energy absorption capacity at the landing impact.

3.5.2 Caterpillar Track Gears

For large aircraft, as for instance transports, another solution had been chosen in America. Undercarriages suitable for cross-country work had been developed, here resembling the caterpillars of heavy tanks.

3.5.2.1 Description of the prototype undercarriages of the B 36 and the C 119. Figure 51 represents such a test undercarriage fitted to the B 36 bomber. As is shown, two large wheels are mounted in the front and rear parts where the brakes are installed. A number of outrigger wheels are placed between these wheels, each one with separate shock absorber and movable independently from the others. Endless rubber belts which are reinforced with steel cables travel around this system of wheels and rolls. The illustration shows two such assemblies arranged at the right and at the left hand side of the large shock absorber absorbing the landing impacts[25].

The nose undercarriage is designed in the same way, but all parts are kept somewhat smaller, as its loads are considerably lower.

Similar undercarriages have also been tested on other large aircraft, like the B 50 and C 119 (Fig.52).

Using such caterpillar track gears, the ground contact area increases considerably and thereby the specific ground load decreases. The wheel undercarriage of the B 36, for instance, causes a ground load of 157 p.s.i. compared with only 57 p.s.i. for the caterpillar track gear. The number of operational airfields is thus highly increased, which is most important for combat operations. Similar effects have been achieved with caterpillar track gears for other aircraft[25].

It can be seen easily that such undercarriages are combined with certain disadvantages and involve difficulties. They are, in any case, heavier than wheel undercarriages. A comparison of the undercarriage weights of the B 36 shows the following values:

conventional landing gear	16000 lbs
track gear	21600 lbs

This means an increase from 5.35% to 7.2% of the gross weight. On the C 119 the increase in weight represents 1.78%[25,30].

The complicated construction results in more expensive manufacturing and maintenance.

Its larger dimension makes the stowage of the retracted gear more difficult.

The larger rolling drag requires higher engine performances for take-off at the sake of reduced pay loads.

Tests have shown certain difficulties. With a cross-wind landing the belts tend to come off due to high side forces. Thus the belts are subjected to great wear and tear.

When braking fast they tend to slip on the rolls; the result presents irregular brake effect and also increased abrasion.

But these types of undercarriages are still in progress of development and it is assumed that constructions will be worked out which will be able to overcome these difficulties. However, it can hardly be expected that such undercarriages will be mounted on all aircraft used for tractical operations. The disadvantages stated make it advisable to equip only a certain number of aircraft with these caterpillar track gears and to keep them at the disposal for very difficult operations from rough and destroyed airfields.

3.6 Résumé

The undercarriages of aircraft operating from unprepared fields are subject to particularly strong loads. Therefore, certain factors have to be considered for their design, which result from the mutual influences between landing gear and ground. Partly they differ considerably from those of prepared level runways.

It should be specially noticed that unprepared grounds have generally a poor and very variable bearing capacity. This fact favours the design of possibly large contact surfaces between undercarriage and ground, i.e. to choose low tyre inflation pressures and to distribute the load upon several wheels.

Increased rolling drag and lower adhesion coefficients (when braking) influence very much the required take-off or landing runs.

Frequent and stronger shocks ask for solid undercarriage constructions. Above all, the moving parts and their pivots must be carefully designed and sturdily constructed.

For operations from particularly unfavourable grounds skid undercarriages have proved successful. But in spite of all efforts, up to now, they could not succeed because of the complicated handling of the aircraft.

Other special landing gears with tube tracks and caterpillars are disadvantageous in weight and cause certain difficulties. It seems that no solution has yet been found which is fully satisfactory.

It may, therefore, be concluded, that multi-wheel assemblies can meet with a great deal of operational conditions.

In any case the conventional undercarriage arrangements will not be practicable for operations from unprepared fields. For the new design of such aircraft, special means have to be provided for the undercarriage.

3.7 References

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4. OPERATING AIRCRAFT FROM TEMPORARY AIRFIELDS

The main problem in operating aircraft from temporary airfields is the question whether a certain type of aircraft is suitable for operation from a certain airfield. Use and serviceableness of aircraft operating from combat-line airfields essentially depend upon the accuracy and reliability of the data available on airfield and aircraft.

Since temporary airfields can be classified by a number of parameters (see Section 2.3), it seems logical to develop also an analogous classification system for aircraft to be operated from such fields. So, after a simple comparison of the parameters of airfield and aircraft it can be decided which aircraft is suitable for operation from certain fields. In the available literature no proposals could be found as to the development of a classification system for aircraft. Therefore, in the following an attempt is made to find a solution of this problem.

The characteristic data of the aircraft, as far as operations from temporary airfields are concerned, are compiled in Table 13 and compared with the airfield parameters. Column 1 comprises the characteristic data of the aircraft which depend on the values given in column 2. In column 3, the corresponding parameters of the airfield are presented which are described by the matrices (see Section 2.3) of column 4.

The required lateral clearance of the airfield follows from the span of the aircraft plus an additional cleared area to allow for possible errors of the pilots. The dimensions of this cleared area depend mainly on the low-speed qualities of the aircraft in question. This means that the aircraft must have sufficient aileron and rudder effectiveness without exceeding the tolerable stick-forces and -travels. Aircraft of good low-speed qualities should not require more than 1.5 times the wing span. The required field width can be defined numerically by means of a parameter corresponding to the second parameter of Matrix III.

Take-off and landing distances depend on several parameters which are not all included in the airfield parameters. The thrust or the brake horsepower of jet engines, turboprops or reciprocating engines highly depend on the air temperature. Wind conditions, and rolling resistance - which is a function of the weather conditions (humidity, temperature) and of the soil conditions - are further parameters which cannot be determined in advance, their classification being nearly impossible. A reasonable limitation of the system could be the definition of rolling distances for mean values of these varying parameters by simply determining the required length. For operation the useful load has then to be adapted to the actual circumstances. So the maximum utilization of airfields and aircraft would mainly be a question of fast communication.

The over-run distances are again a function of the low-speed qualities - for landing mainly an efficient glide angle control - and of the scatter of take-off and landing performances of aircraft of the same type. Aircraft with high thrust-to-weight ratio and short take-off and landing ground runs will need overrun distances of the same order of magnitude as the optimum rolling distances because of possible errors of the pilots. It is likely that the introduction of automatic landing systems will represent important progress in the use of the smallest temporary airfields, especially by allowing shorter overrun distances.

The characteristic take-off and landing ground runs of a special aircraft can be defined by a parameter according to the first parameter of Matrix I. Before doing so, the length slope must be taken into account. This can be done easily by use of already prepared tables.

The required ground clearance of the aircraft can be defined by a parameter corresponding to the first parameter of Matrix III.

A specification of the landing gears which is comparable with the corresponding airfield parameters is of special importance. According to the first parameter of Matrix IV, it is possible to characterize the relations between the actual wheel loads and wheel dimensions and tire pressure by definition of a mean minimum CBR-value. Variations of the CBR-value due to weather changes can probably be compensated for only by varying the useful load to some extent. Tests on these questions have not been carried out or published up to now. The cross-country mobility - a function of the wheel base, of the shock strut characteristics and of the maximum rolling speed could be defined by numerical values similar to those of Matrix II.

The wheel track is a limit for the maximum allowable width slope of the airfield. The maximum allowable width slope for aircraft of relatively large track width may be limited by the maximum possible angle of bank for stationary flight. The characteristic data for the allowable width slope of a certain aircraft can be represented according to the third parameter of Matrix I.

In Table 14 the parameters of airfields and aircraft which are described by the different parameters of the four matrices are again compiled. According to the proposed classification system (see Tables 2, 3, 4, 5) a certain aircraft can operate from a certain airfield, if - for Matrices I - III - the parameters of the aircraft are equal to or greater than those of the airfield, and - for Matrix IV - equal to or smaller than those of the airfield. A change of position of the first parameter of Matrix IV should be practical (increasing values for decreasing CBR-values). This would considerably facilitate the use of the system, since an aircraft could operate from a certain field provided that all aircraft parameters be equal to or greater than those of the field. Before comparing the matrices, the numerical values of the aircraft parameters have to be corrected in correspondence with weather and soil conditions, which can be done easily by use of prepared tables.

The proposals made in this section as to a combined classification of airfields and aircraft are not more than a first effort towards a joint classification of airfields and aircraft. After more thorough studies it will probably turn out that completion and improvement of the proposed classification system are necessary.

TABLE 1

Matrices

Matrix I - The Landing Area

1. Actual Length
2. Width Slope
3. Length Slope

Matrix II - The Terrain Configuration

1. Undulation Height
2. Undulation Slope
3. Undulation Spacing

Matrix III - The Surface Roughness

1. Obstacle Height
2. Obstacle Spacing
3. Obstacle Type

Matrix IV - Soil Description and Bearing Capacity

1. Soil Bearing Capacity (California Bearing Ratio)
2. Soil Classification (Unified Soil Classification System)

TABLE 2

Matrix I - The Landing Area

Area Length (1st and 2nd Digits-Matrix I)	
Class designator	*Actual length available (feet)*
00	> 10000
01	8000 - 10000
02	6500 - 8000
03	5000 - 6500
04	4000 - 5000
05	3000 - 4000
06	2500 - 3000
07	2000 - 2500
08	1500 - 2000
09	1000 - 1500
10	900 - 1000
11	800 - 900
12	700 - 800
13	600 - 700
14	500 - 600
15	400 - 500 +)
16	300 - 400 +)
17	200 - 300 +)
18	100 - 200 +)
19	50 - 100 +)

Width Slope (3rd Digit-Matrix I)	
Class designator	*Width slope (degrees)*
0	0 - 2
1	2 - 4
2	4 - 6
3	6 - 9
4	9 - 12
5	12 - 15
6	15 - 20
7	20 - 30
8	30 - 45
9	> 45

Length Slope (4th Digit - Matrix I)	
Class designator	*Length slope (degrees)*
0	0 - 2
1	2 - 4
2	4 - 6
3	6 - 9
4	9 - 12
5	12 - 15
6	15 - 20
7	20 - 30
8	30 - 45
9	> 45

Note - The Parameter Categories are read:

From and including the shorter length and up to but *not* including the longer length or greater slope.

+) These dimensions may be considered as area diameters unless a width limitation is indicated.

TABLE 3

Matrix II - The Surface Configuration

Undulation Height (1st Digit-Matrix II)		*Undulation Slope (2nd Digit-Matrix II)*		*Undulation Spacing (3rd Digit-Matrix II)*
Class designator	*Height (inches or feet as indicated)*	*Class designator*	*Slope (degrees)*	*Center-to-center distance**
0	< 3"	0	0 - 2	*See Table 4 for center-to-center distance values and class designator.
1	3" - 6"	1	2 - 4	
2	6" - 12"	2	4 - 6	
3	12" - 18"	3	6 - 10	
4	18" - 24"	4	10 - 15	
5	2' - 5'	5	15 - 20	See Section 2.3.2.3 for the procedure to determine the class designator and the center-to-center distance category.
6	5' - 10'	6	20 - 30	
7	10' - 25'	7	30 - 45	
8	25' - 50'	8	45 - 60	
9	50' - 100'	9	60 - 90	

Note - The parameter categories are read: From and including the lesser, and up to, but *not* including the greater, height or slope.

Descriptive Subscript Legend

C - Small stream or creek

D - Ditch or embankment (cultural rather than natural formations)

E - Erosion gullies (natural rather than cultural formations)

H - Holes (irrespective of how formed)

M - Mounds

P - Plowed, tilled or cultivated furrows

R - Roads

S - Sand dunes or sand ripples

W - Undulations parallel to width

L - Undulations parallel to length

TABLE 4

Matrix II (Cont'd)

Center-to-Center Spacing and Class Designators for Undulation Height Categories

Undulation Spacing for Height Class (0)	
(less than 3 inches height)	
Class designator	*Center-to-center distance (feet)*
0	> 10
1	8 - 10
2	6 - 8
3	5 - 6
4	4 - 5
5	3 - 4
6	2 - 3
7	1 - 2
8	0.5 - 1
9	< 0.5

Undulation Spacing for Height Class (1)	
(3 - 6 inches height)	
Class designator	*Center-to-center distance (feet)*
0	> 250
1	100 - 250
2	50 - 100
3	25 - 50
4	10 - 25
5	5 - 10
6	3 - 5
7	2 - 3
8	1 - 2
9	< 1

Undulation Spacing for Height Class (2)	
(6 - 12 inches height)	
Class designator	*Center-to-center distance (feet)*
0	> 500
1	250 - 500
2	100 - 250
3	50 - 100
4	25 - 50
5	10 - 25
6	5 - 10
7	2 - 5
8	1 - 2
9	< 1

Undulation Spacing for Height Class (3)	
(12 - 18 inches height)	
Class designator	*Center-to-center distance (feet)*
0	> 750
1	500 - 750
2	250 - 500
3	100 - 250
4	50 - 100
5	25 - 50
6	10 - 25
7	5 - 10
8	2 - 5
9	< 2

TABLE 4

Matrix II (Cont'd)

Undulation Spacing for Height Class (4)	
(18 - 24 inches height)	
Class designator	*Center-to-center distance (feet)*
0	> 1000
1	750 - 1000
2	500 - 750
3	250 - 500
4	100 - 250
5	50 - 100
6	25 - 50
7	10 - 25
8	3 - 10
9	< 3

Undulation Spacing for Height Class (5)	
(2 - 5 feet height)	
Class designator	*Center-to-center distance (feet)*
0	> 2500
1	1000 - 2500
2	500 - 1000
3	250 - 500
4	100 - 250
5	50 - 100
6	25 - 50
7	10 - 25
8	6 - 10
9	< 6

Undulation Spacing for Height Class (6)	
(5 - 10 feet height)	
Class designator	*Center-to-center distance (feet)*
0	> 2500
1	1500 - 2500
2	1000 - 1500
3	500 - 1000
4	250 - 500
5	100 - 250
6	50 - 100
7	25 - 50
8	12 - 25
9	< 12

Undulation Spacing for Height Class (7)	
(10 - 25 feet height)	
Class designator	*Center-to-center distance (feet)*
0	> 2500
1	2000 - 2500
2	1500 - 2000
3	1000 - 1500
4	750 - 1000
5	500 - 750
6	250 - 500
7	100 - 250
8	50 - 100
9	< 50

TABLE 4

Matrix II (Cont'd)

Undulation Spacing for Height Class (8)	
(25 - 50 feet height)	
Class Designator	*Center-to-center distance (feet)*
0	> 2500
1	2000 - 2500
2	1500 - 2000
3	1250 - 1500
4	1000 - 1250
5	750 - 1000
6	500 - 750
7	250 - 500
8	100 - 250
9	< 100

Undulation Spacing for Height Class (9)	
(50 - 100 feet height)	
Class Designator	*Center-to-center distance (feet)*
0	> 2500
1	2000 - 2500
2	1750 - 2000
3	1500 - 1750
4	1250 - 1500
5	1000 - 1250
6	750 - 1000
7	500 - 750
8	200 - 500
9	< 200

TABLE 5

Matrix III - The Surface Roughness (Obstacles)

Obstacle Height (1st Digit-Matrix III)	
Class Designator	*Height (inches or feet as indicated)*
0	< 3"
1	3" - 5"
2	5" - 7"
3	7" - 9"
4	9" - 12"
5	12" - 18"
6	18" - 36"
7	3' - 6'
8	6' - 10'
9	> 10'

Obstacle Spacing (2nd Digit-Matrix III)	
Class Designator	*Edge to edge distance (inches or feet as indicated)*
0	> 1000'
1	500' - 1000'
2	100' - 500'
3	50' - 100'
4	25' - 50'
5	10' - 25'
6	3' - 10'
7	1' - 3'
8	6" - 12"
9	< 6" (very dense)

Note - The parameter categories are read: From and including the first number, to but *not* including the second number (Heights and spacings).

Descriptive Subscript Legend

B - Bushes

C - Cultivated Crops

G - Grasses

D - Tree Stumps

T - Trees

F - Fence

H - Hedges

M - Transient man-made obstructions (Haystacks etc.)

P - Permanent man-made obstructions (Buildings, Power lines etc.)

R - Rocks (imbedded as opposed to loose)

s - Stones (loose surface rocks)

TABLE 6

Soil Characteristics Pertinent to Roads and Airfields

Major divisions (1)	(2)	Letter (3)	Symbol: Hatching (4)	Symbol: Color (5)	Name (6)	Value as foundation when not subject to frost action (7)	Value as base directly under bituminous pavement (8)	Potential frost action (9)	Compressibility and expansion (10)	Drainage characteristics (11)	Compaction equipment (12)	Unit dry weight lb per cu.ft (13)	Field CBR (14)	Subgrade modulus k lb per cu.in. (15)
COARSE GRAINED SOILS	GRAVEL AND GRAVELLY SOILS	GW		Red	Well-graded gravels or gravel-sand mixtures, little or no fines	Excellent	Good	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment, steel-wheeled roller	125-140	60-80	300 or more
		GP		Red	Poorly graded gravels or gravel-sand mixtures, little or no fines	Good to excellent	Poor to fair	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment, steel-wheeled roller	110-130	25-60	300 or more
		GM d		Yellow	Silty gravels, gravel-sand-silt mixtures	Good to excellent	Fair to good	Slight to medium	Very slight	Fair to poor	Rubber-tired equipment, sheepsfoot roller; close control of moisture	130-145	40-80	300 or more
		GM u		Yellow		Good	Poor	Slight to medium	Slight	Poor to practically impervious	Rubber-tired equipment, sheepsfoot roller	120-140	20-40	200 to 300
		GC		Yellow	Clayey gravels, gravel-sand-clay mixtures	Good	Poor	Slight to medium	Slight	Poor to practically impervious	Rubber-tired equipment, sheepsfoot roller	120-140	20-40	200 to 300
	SAND AND SANDY SOILS	SW		Red	Well-graded sands or gravelly sands, little or no fines	Good	Poor	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment	110-130	20-40	200 to 300
		SP		Red	Poorly graded sands or gravelly sands, little or no fines	Fair to good	Poor to not suitable	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment	100-120	10-25	200 to 300
		SM d		Yellow	Silty sands, sand-silt mixtures	Good	Poor	Slight to high	Very slight	Fair to poor	Rubber-tired equipment, sheepsfoot roller; close control of moisture	120-135	20-40	200 to 300
		SM u		Yellow		Fair to good	Not suitable	Slight to high	Slight to medium	Poor to practically impervious	Rubber-tired equipment, sheepsfoot roller	105-130	10-20	200 to 300
		SC		Yellow	Clayey sands, sand-clay mixtures	Fair to good	Not suitable	Slight to high	Slight to medium	Poor to practically impervious	Rubber-tired equipment, sheepsfoot roller	105-130	10-20	200 to 300
FINE GRAINED SOILS	SILTS AND CLAYS LL < 50	ML		Green	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity	Fair to poor	Not suitable	Medium to very high	Slight to medium	Fair to poor	Rubber-tired equipment, sheepsfoot roller; close control of moisture	100-125	5-15	100 to 200
		CL		Green	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	Fair to poor	Not suitable	Medium to high	Medium	Practically impervious	Rubber-tired equipment, sheepsfoot roller	100-125	5-15	100 to 200
		OL		Green	Organic silts and organic silt-clays of low plasticity	Poor	Not suitable	Medium to high	Medium to high	Poor	Rubber-tired equipment, sheepsfoot roller	90-105	4-8	100 to 200
	SILTS AND CLAYS LL > 50	MH		Blue	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	Poor	Not suitable	Medium to very high	High	Fair to poor	Sheepsfoot roller	80-100	4-8	100 to 200
		CH		Blue	Inorganic clays of high plasticity, fat clays	Poor to very poor	Not suitable	Medium	High	Practically impervious	Sheepsfoot roller	90-110	3-5	50 to 100
		OH		Blue	Organic clays of medium to high plasticity, organic silts	Poor to very poor	Not suitable	Medium	High	Practically impervious	Sheepsfoot roller	80-105	3-5	50 to 100
HIGHLY ORGANIC SOILS		Pt		Orange	Peat and other highly organic soils	Not suitable	Not suitable	Slight	Very high	Fair to poor	Compaction not practical	-	-	-

Notes:

1. Column 3, Division of GM, and SM groups into subdivisions of d and u are for roads and airfields only; subdivision is on basis of Atterberg limits; suffix d (e.g., GMd) will be used when the liquid limit is 28 or less and the plasticity index is 6 or less; the suffix u will be used when the liquid limit is greater than 28.
2. Column 7, values are for subgrades and base courses except for base course directly under bituminous pavement.
3. In column 8, the term 'excellent' has been reserved for base materials consisting of high quality processed crushed stone.
4. In column 9, these soils are susceptible to frost as indicated under conditions favorable to frost action described in the text.
5. In column 12, the equipment listed will usually produce the required densities with a reasonable number of passes when moisture conditions and thickness of lift are properly controlled. In some instances, several types of equipment are listed, because variable soil characteristics within a given soil group may require different equipment. In some instances, a combination of two types may be necessary.
   (a) *Processed base materials and other angular materials.* Steel-wheeled rollers are recommended for hard angular materials with limited fines or screenings. Rubber-tired equipment is recommended for softer materials subject to degradation.
   (b) *Finishing.* Rubber-tired equipment is recommended for rolling during final shaping operations for most soils and processed materials.
   (c) *Equipment size.* The following sizes of equipment are necessary to assure the high densities required for airfield construction: Crawler-type tractor -- total weight in excess of 30,000 lb; Rubber-tired equipment -- wheel load in excess of 15,000 lb, wheels loads as high as 40,000 lb may be necessary to obtain the required densities for some materials (based on contact pressure of approximately 65 to 150 psi); Sheepsfoot roller -- unit pressure (on 6- to 12 sq.in. foot) to be in excess of 250 psi and unit pressures as high as 650 psi may be necessary to obtain the required densities for some materials. The area of the feet should be at least 5 per cent of the total peripheral area of the drum, using the diameter measured to the faces of the feet.
6. Column 13, unit dry weights are for compacted soil at optimum moisture content for modified AASHO compactive effort.

TABLE 7

Trafficability Characteristics of Soils in Wet Season

Soils	*Unified soil classification system*	*Slipperiness effects*	*Stickiness effects*	*Comments*
Coarse-grained, cohesionless sand and gravels	GW, GP, SW, SP	Slight to none	None	Will support continuous traffic of military vehicles with tracks or with high-flotation tires. Moist sands are good, dry sands only fair. Wheeled vehicles with standard tires may be immobilized in dry sands.
Inorganic clays of high plasticity, fat clays	CH	Severe to slight	Severe to slight	Usually will support more than fifty passes of military vehicles. Going will be difficult at times.
Clayey gravels, gravel-sand-clay mixtures	GC	Severe to slight	Moderate to slight	Often will not support forty to fifty passes of military vehicles, but usually will support limited traffic. Going will be difficult in most cases
Clayey sands, sand-clay-mixtures	SC			
Gravelly clays, sandy clays, inorganic clays of low to medium plasticity, lean clays, silty clays	CL			
Silty gravels, gravel-sand-silt mixtures	GM	Moderate to slight	Slight	Usually will not support forty to fifty passes of military vehicles. Often will not permit even a single pass. Going will be difficult in most cases.
Silty sands, sand-silt mixtures	SM			
Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity	ML and CL-ML			
Inorganic silts, fine sandy or silty soils, elastic silts	MH			
Organic silts and organic silty clays of low plasticity	OL			Data from Refs. 2 and 18
Organic clays of medium to high plasticity, organic silts	OH			

TABLE 8

Design Influence

Parameter	*Influences*
A. *MATRIX I - The Landing Area*	
1. Length	(a) Take-off and Landing Speeds
	(b) Braking Requirements
	(c) Aircraft Weight
	(d) Power Requirements
	(e) Useful Load
2. Length and Width Slope	(a) Take-off and Landing Ground Roll
	(b) Braking Requirements
	(c) Overturning-Landing Gear Geometry
B. *MATRIX II - The Terrain Configuration*	
1. Undulation Height	(a) Ground Clearances
2. Undulation Slope	(b) Shock Strut Characteristics
3. Undulation Spacing	(c) Tire Sizes
	(d) Gear Strength
	(e) Overturning-Landing Gear Geometry
	(f) Taxi Thrust
	(g) Braking Requirements
C. *MATRIX III - The Surface Roughness (Obstacles)*	
1. Obstacle Height	(a) Ground Clearances
2. Obstacle Spacing	(b) Overturning-Landing Gear Geometry
	(c) Landing Gear Type (wheel, skid, combination etc.)
	(d) Tire Sizes
	(e) Tire Life (Pressures)
	(f) Shock Strut Characteristics
	(g) Gear Strength
D. *MATRIX IV - Soil Description and Strength*	
1. Soil Type	(a) Landing Gear Type (wheel, skid, etc.)
2. Soil Strength (CBR)	(b) Rolling and Braking Coefficient
	(c) Steering Requirements
	(d) Sizes, loadings, pressures, spacing, number of tires, skids, skis etc.

TABLE 9

Specifications of Army Airplanes

Aircraft type *Army designation*	*Observation*	*Utility*		*Command*
	L-19 *(Bird Dog)*	*L-20* *(Beaver)*	*U-1* *(Otter)*	*L-23* *(Twin Bonanza)*
Gross weight, lbs.	2,400	4,820	7,600	6,000
Max. wheel load, lbs.	1,150	2,350	2,850	2,700
Tire pressure, psi	22	25	28	35
Length	25'0"	30'4"	41'10"	31'6"
Wingspan	36'0"	48'0"	58'0"	45'5"
Height	9'2"	10'5"	12'7"	11'4"
Tread	7'5"	10'2"	11'2"	12'10"
Minimum take-off ground run*, ft	420	480	550	1,000
Take-off distance to clear 50 foot obstacle**, ft	730	830	980	1,580

* Hard surface, sea level, 59°F, and no wind

**From a dead stop

TABLE 10

Design Criteria for Pioneer Army Airfields

Runway

1. Length (to next larger 100 ft): Corrected take-off ground run multiplied by (safety factor)	1.10
2. Width (minimum)	50' sod or unpaved or 25' shoulder to shoulder gravel or better road; open field
3. Shoulder width (minimum)	0'
4. Lateral clearance or flight strip width	150'
5. Runway surfacing	In-place sod or compacted base course
6. Longitudinal grade (maximum)	10%
7. Maximum rate of change in grade per 100 ft on vertical curves	1%
8. Minimum sight distance across vertical curves (height of eye 5') to a point 5' above runway surface	1/2 runway length
9. Minimum distance PI to PI on vertical curves	200'
10. Transverse slope (minimum)	Natural surface
11. Transverse slope (maximum)	5%
12. Cleared areas, maximum slope	Unlimited

Approach Zone

13. Length (from end of flight-strip)	500'
14. Glide angle ratios from end of flightstrip:	
Airfield for day use only	20 : 1
Airfield for day and night use	30 : 1

TABLE 11

Method of Determining Corrected Take-off Ground Run

Take-off ground runs plus	*Altitude correction plus*	*Temperature correction plus*	*Slope correction times*	*Safety factor*
Take-off ground run for individual aircraft is shown in Table 9. For soft surfaces increase figure shown by 7%	Altitude correction is + 15% of the take-off ground run for each 1000' increase in altitude above 2000'. Add this figure to the take-off ground run	For each 10°F. increase in temperature above 59°F., add a temperature correction of + 4% (take-off ground run plus altitude correction)*	For each 1% of effective gradient over 2% add a slope correction of + 20% (take-off ground run, plus altitude correction, plus temperature correction).	Multiply the figure obtained for take-off ground run, after correcting for altitude, temperature, and slope, by the safety factor for the class airfield in question as shown in Table 10.

*The temperature to be considered is the mean temperature for the warmest period during which it is expected that operations will be conducted from the airfield.

TABLE 12

Minimum CBR Requirements for Unsurfaced (Sod) Deliberate Army Airfields

Wheel load (lbs)	*Minimum CBR*	
	50 psi tire pressure	*100 psi tire pressure*
1,000	4	8
2,000	5	10
4,000	7	13
6,000	9	15
8,000	10	17
10,000	11	19
15,000	13	21
22,000	15	24
30,000	17	28

TABLE 13

Comparison of Parameters

1	2	3	4*
Aircraft parameters	*Dependent on*	*Corresponding airfield parameters*	*Listed in*
Required Field Width	Wing Span lateral clearance	Unobstructed area	Matrix III
Take-off and Landing Performance Take-off ground run Landing ground run	Atmospheric Pressure, Temperature Wind Direction and Speed Area Slope Rolling Resistance Gross Weight Engine Performance Clearances due to tolerances	Airfield length Length slope (CBR-value?)	Matrix I Matrix I (Matrix IV)
Required Ground Clearance	Distance Ground-Wing or Ground Clearance of Propellers	Obstacle height	Matrix III
Landing Gear Characteristics	Wheel Load Tire Pressure Tire Diameter Tire Thickness Wheel Base Shock Strut characteristics Max. Rolling Speed Track Width	Soil bearing capacity (CBR-value) Runway conditions Width slope	Matrix IV Matrix II Matrix I

*See Section 2

TABLE 14

Described Parameters of Airfield and Aircraft

Matrix	*Parameter*	*Airfield parameters*	*Aircraft parameters*
I	1	Field length	Take-off and landing ground run
	2	Width slope	Maximum allowable width slope
	3	Length slope	(Taken into account under I.1)
II	1	Undulation height	Landing gear characteristics
	2	Undulation slope	
	3	Center-to-center distance	
III	1	Obstacle height	Required ground clearance
	2	Obstacle spacing (field width)	Required field width
	3	Nature of obstacles	
IV	1	Soil bearing capacity	Required bearing capacity
	2	Soil type	(μ-value?)

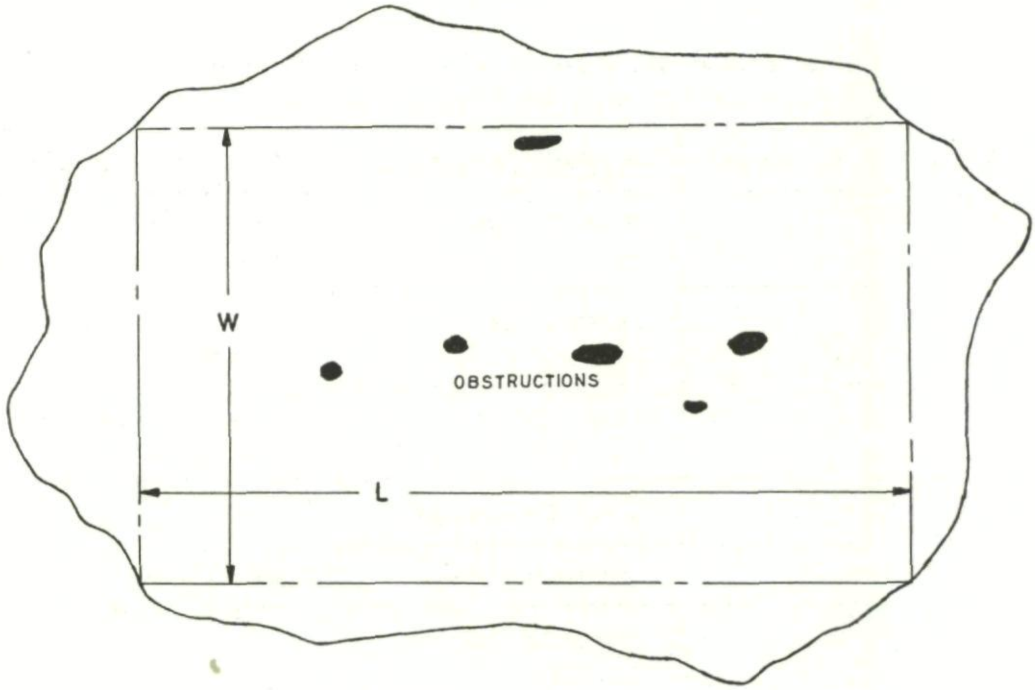


Fig. 1 Obstructed area

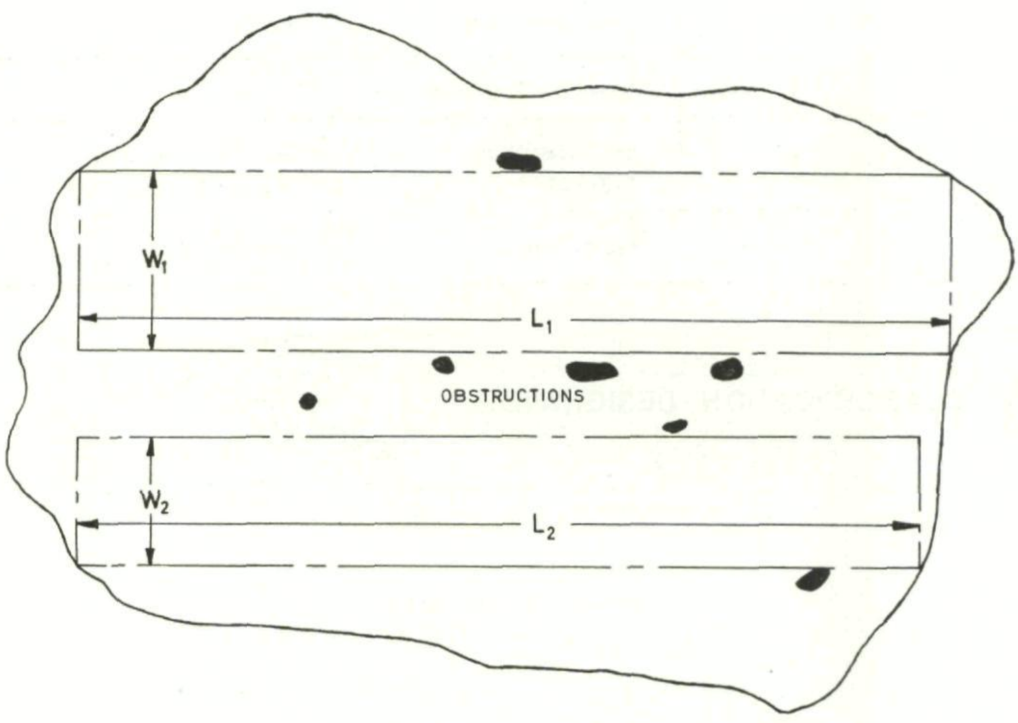


Fig. 2 Divided area

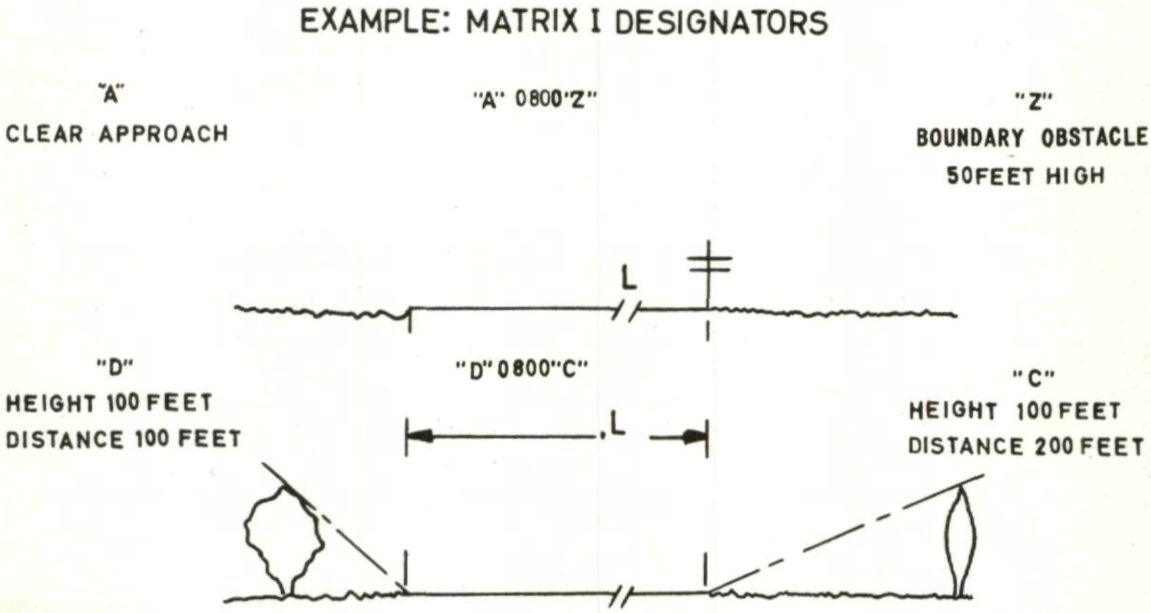


Fig. 3 Designation of approach and climb-out obstacles

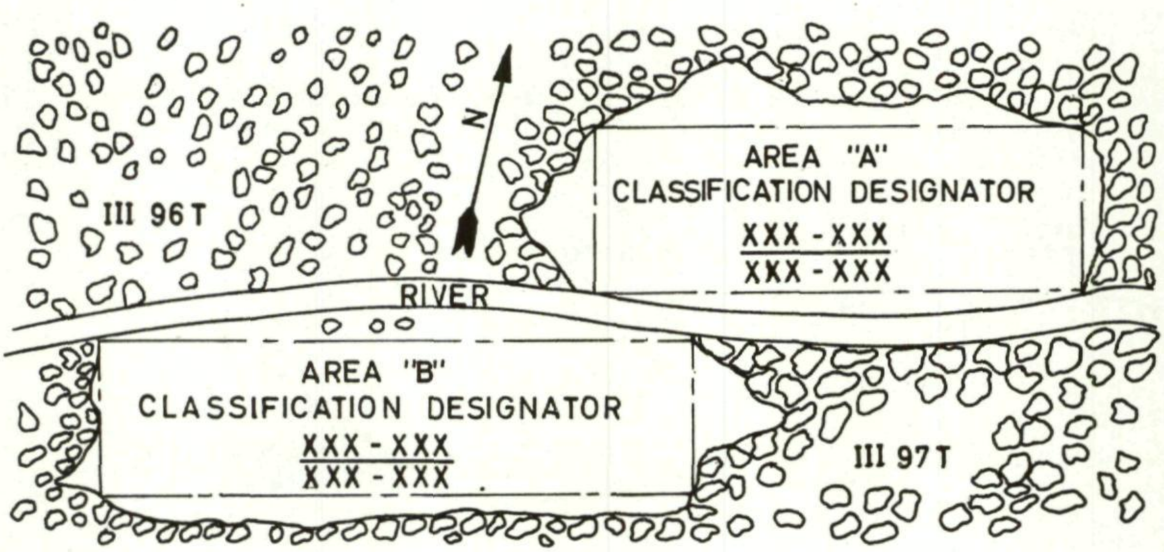


Fig. 4 Denied area

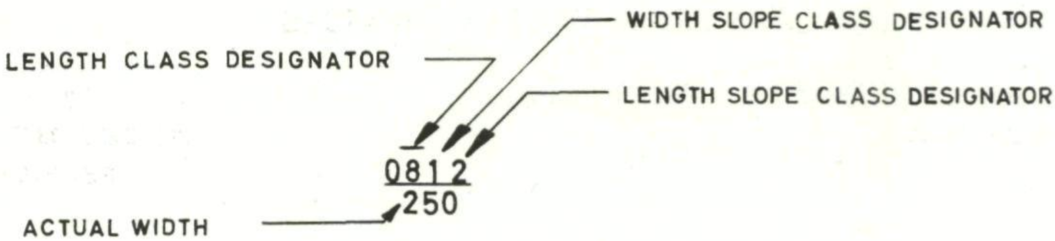


Fig. 5 Example: Matrix I designator - width-limited case

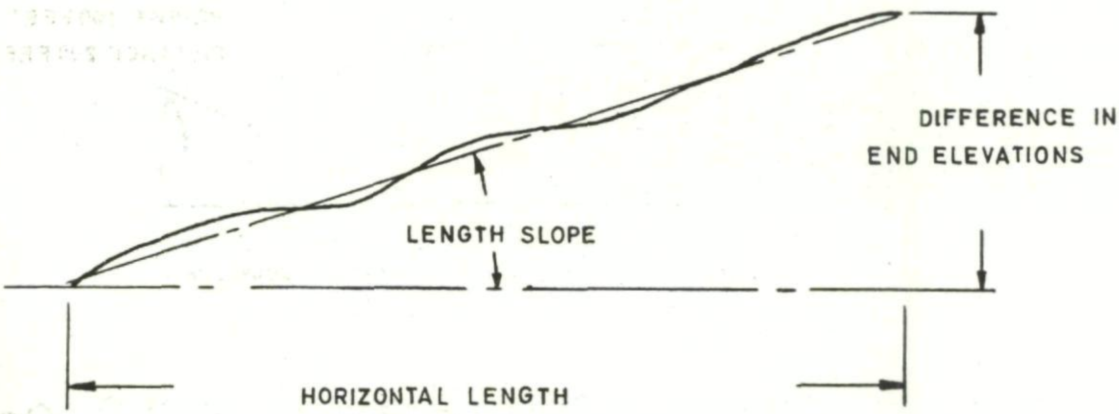


Fig. 6 Area profile view - Matrix I length slope

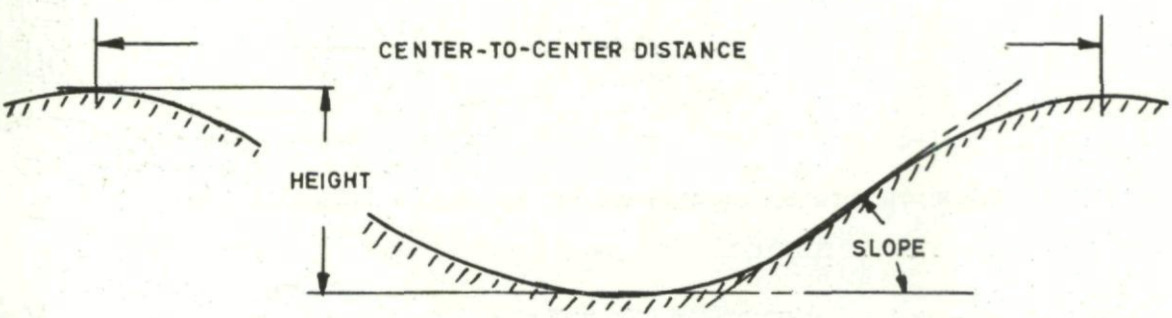


Fig. 7 Undulation parameters

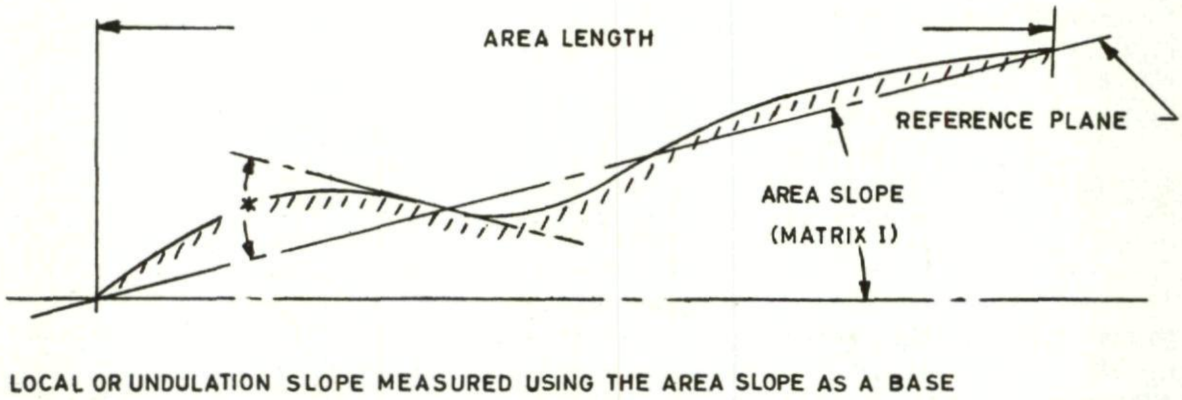


Fig.8 Undulation slope measurement

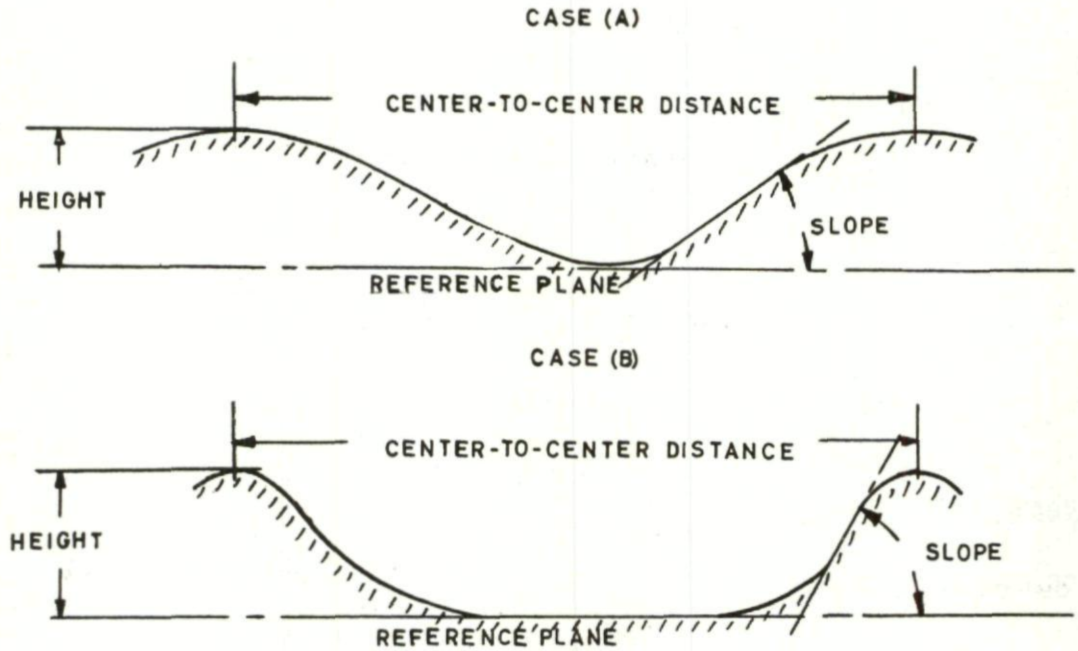


Fig.9 Undulation spacing and height equal - slopes unequal

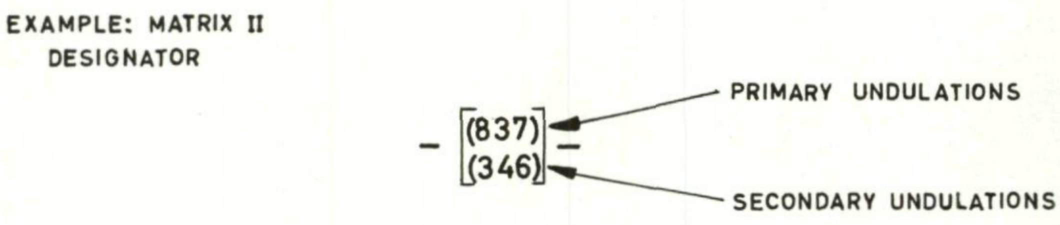


Fig.10 Complex undulation designator

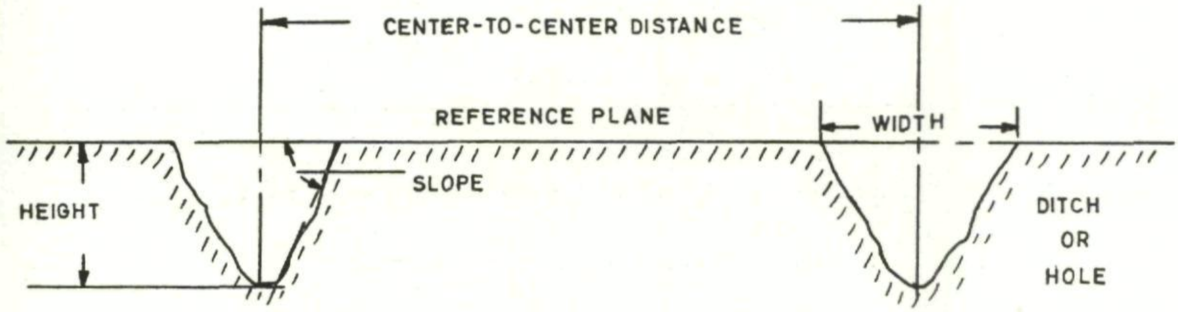


Fig.11 Negative undulations

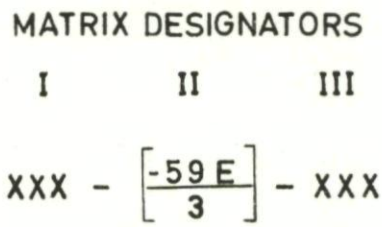


Fig.12 Matrix II designator - negative undulations

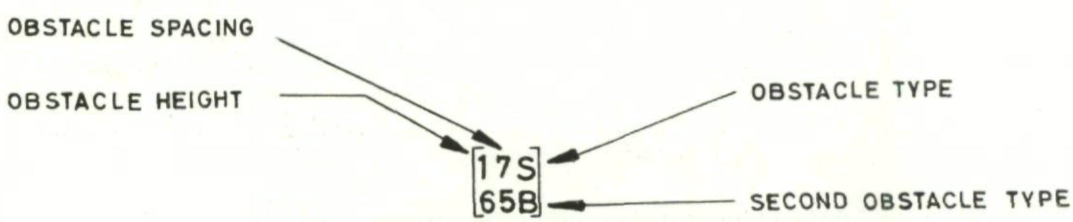


Fig.13 Matrix III multiple designator

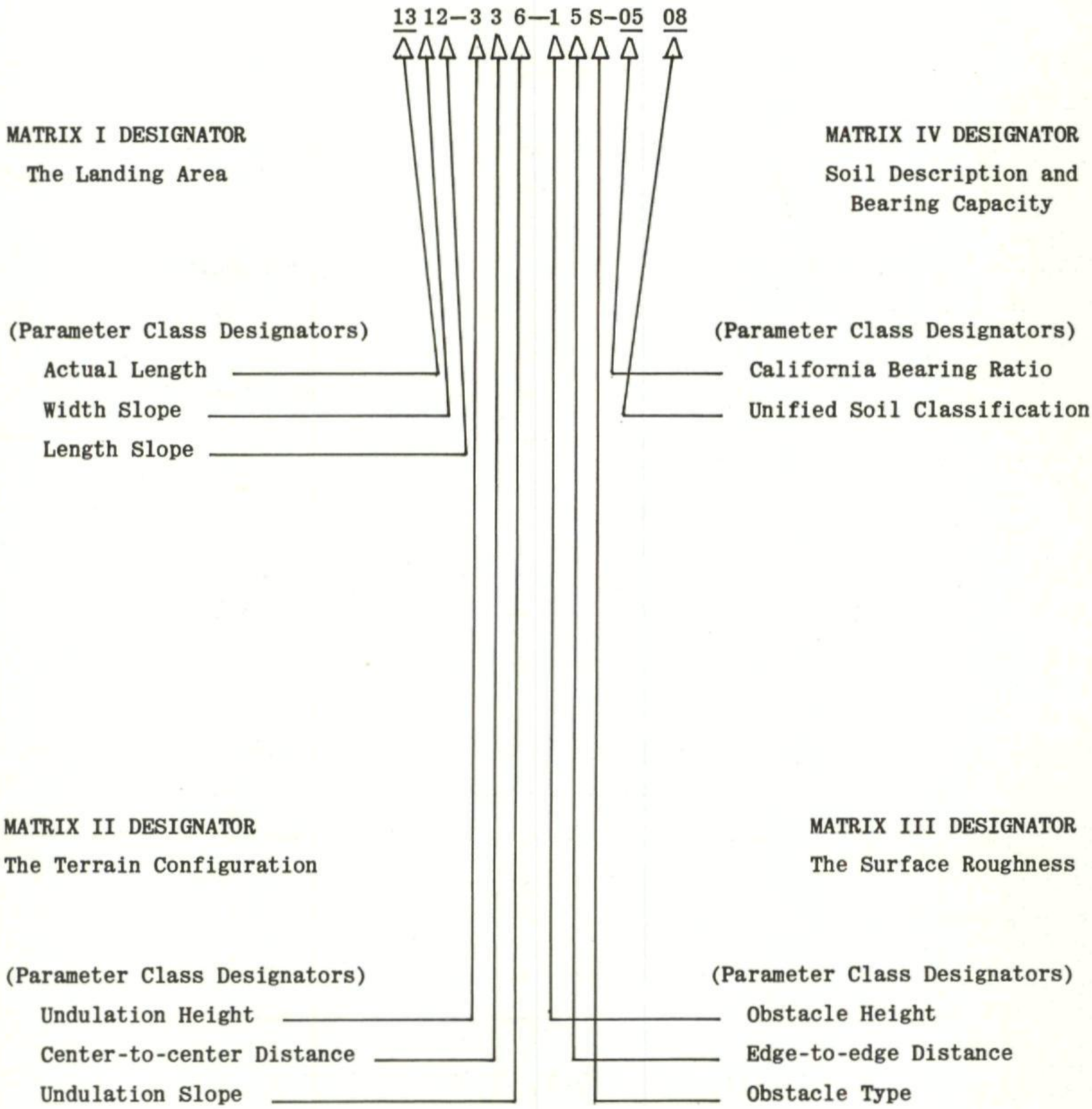


Fig. 14 The terrain designator

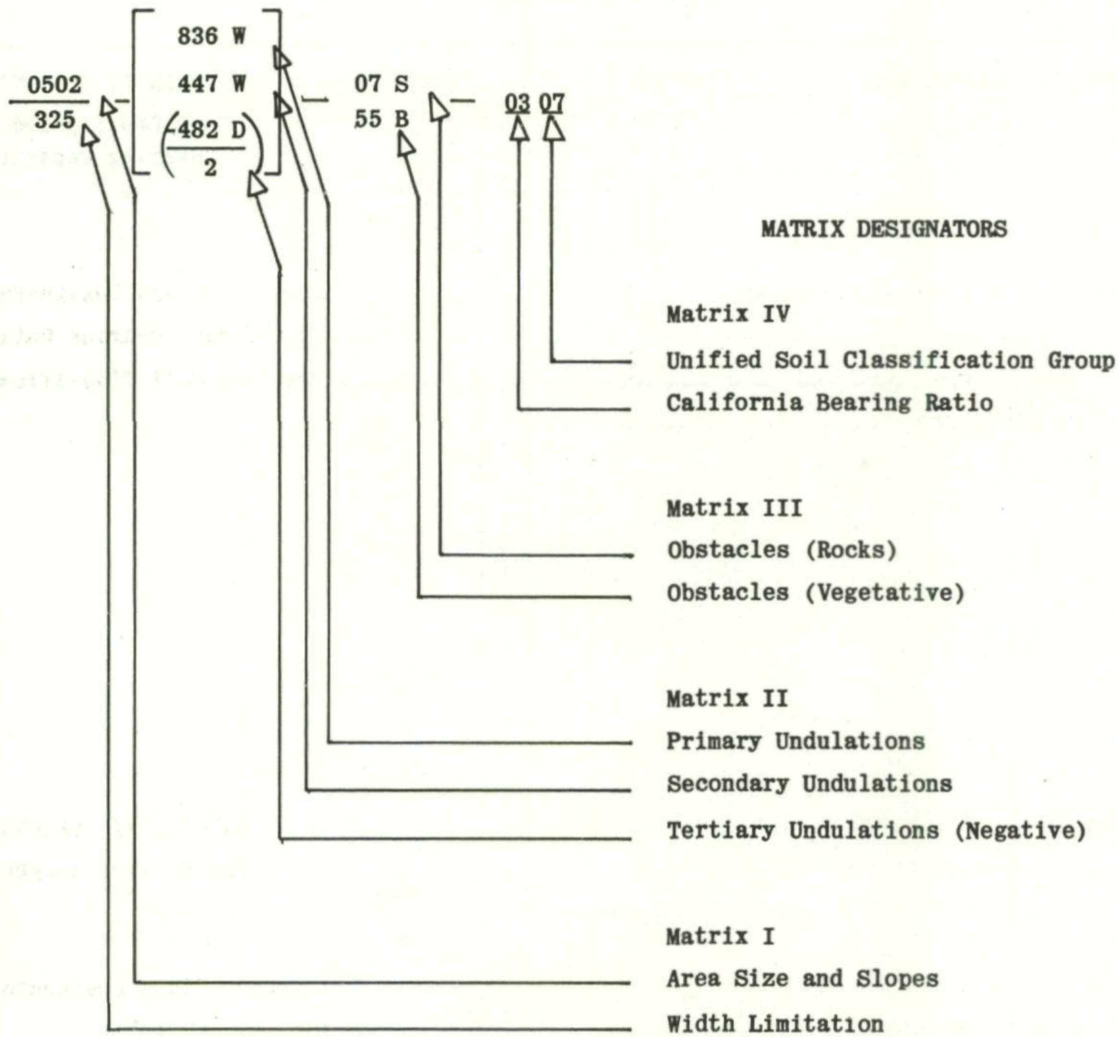


Fig.15 A complex terrain designator

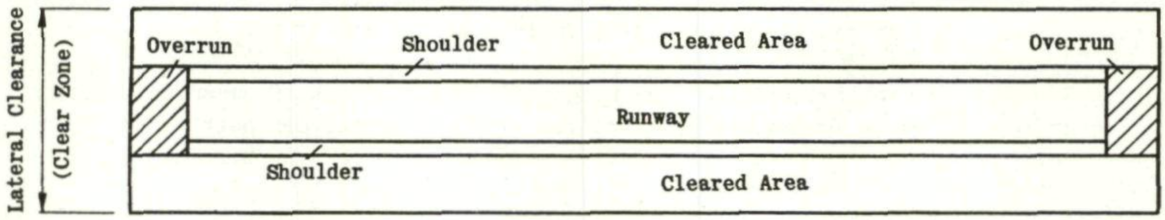


Fig.16 Flightstrip nomenclature

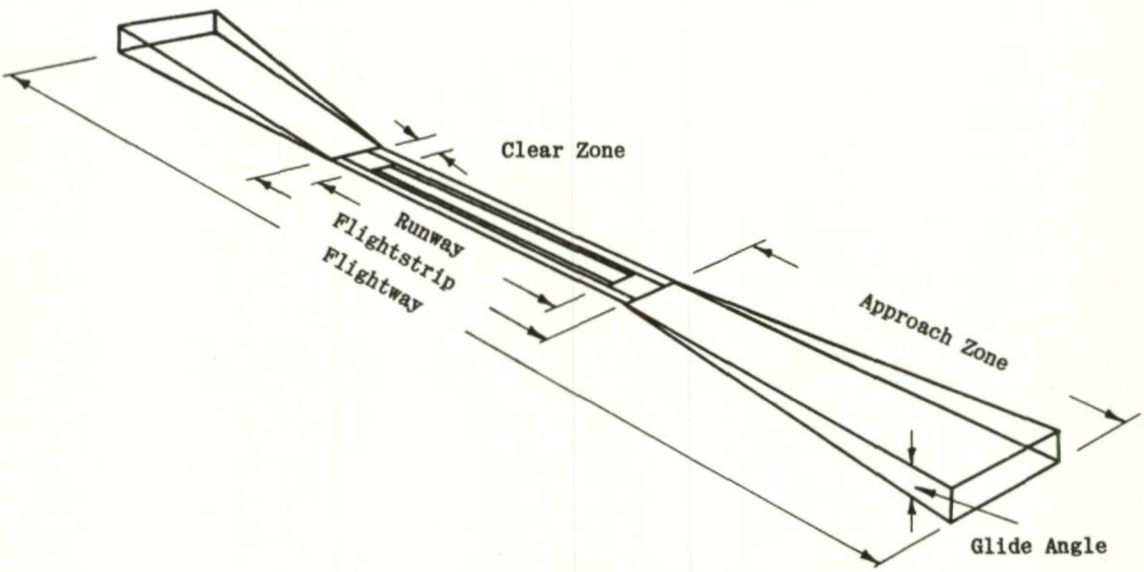


Fig.17 Flightway nomenclature

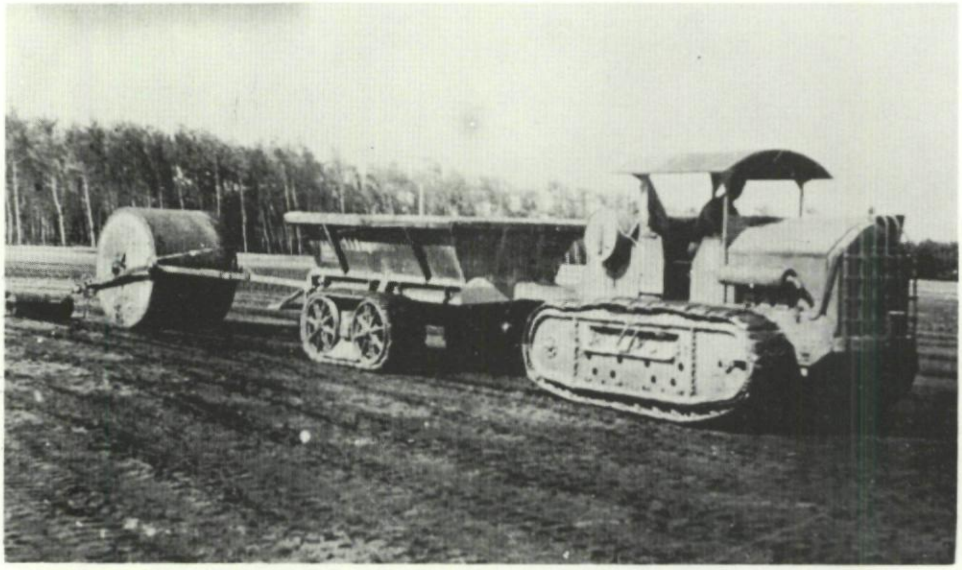


Fig.18 Train for cement-soil stabilization

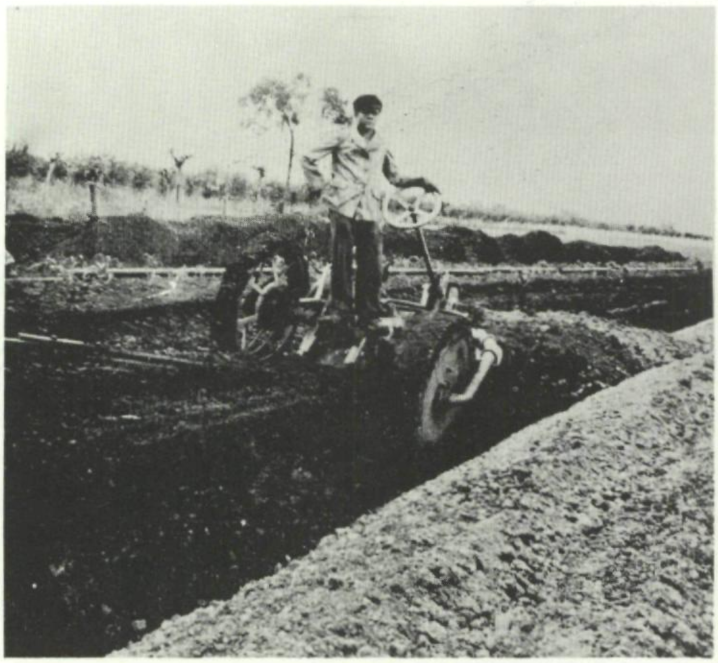


Fig.19 Plowing-up of gravels

Fig. 20 Laying of jute mats

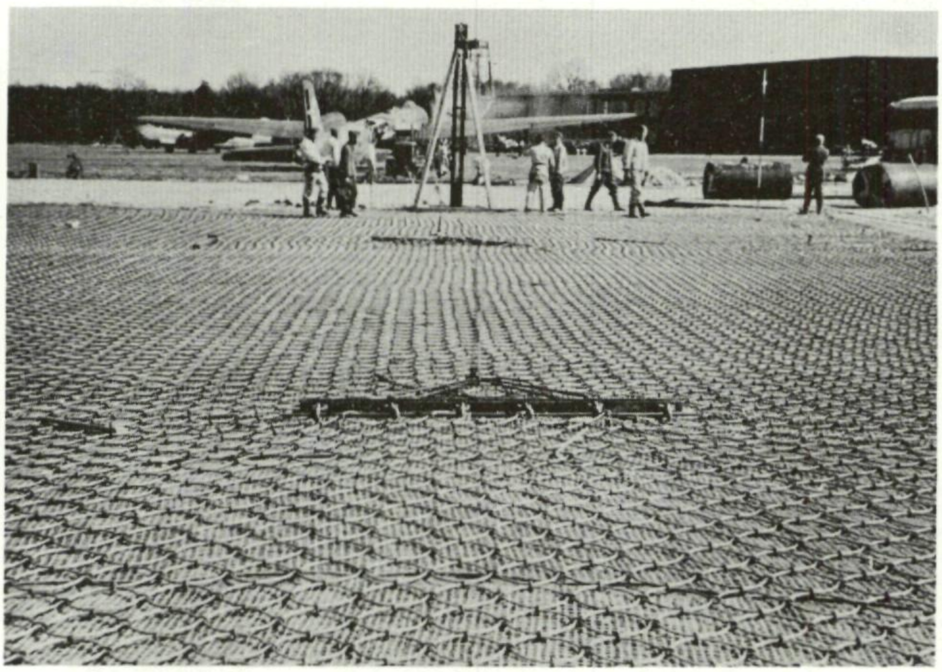


Fig. 21 Mats made of steel wire netting

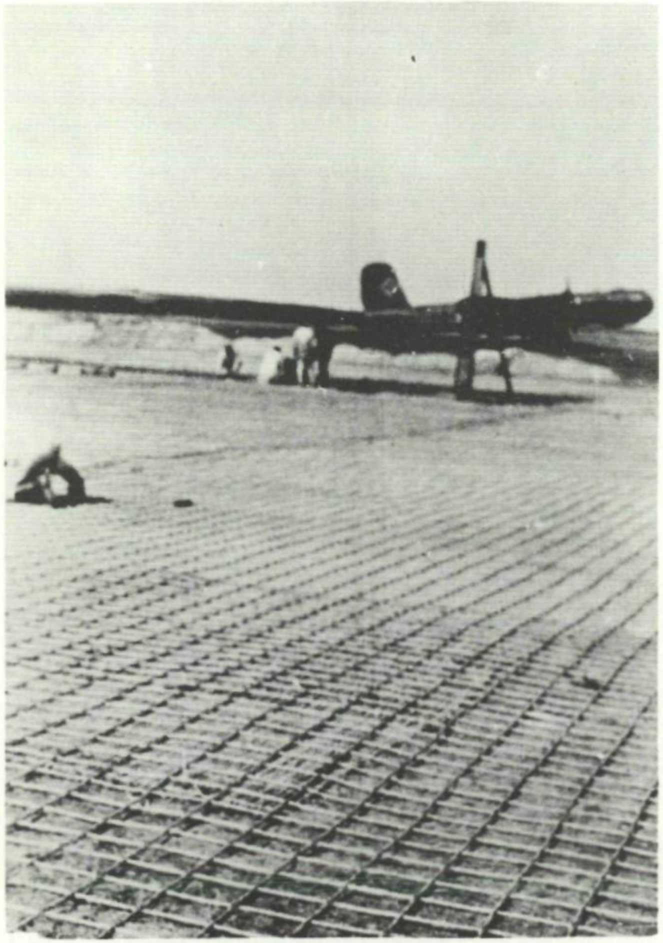


Fig. 22 Steel mats, normally used in iron concrete

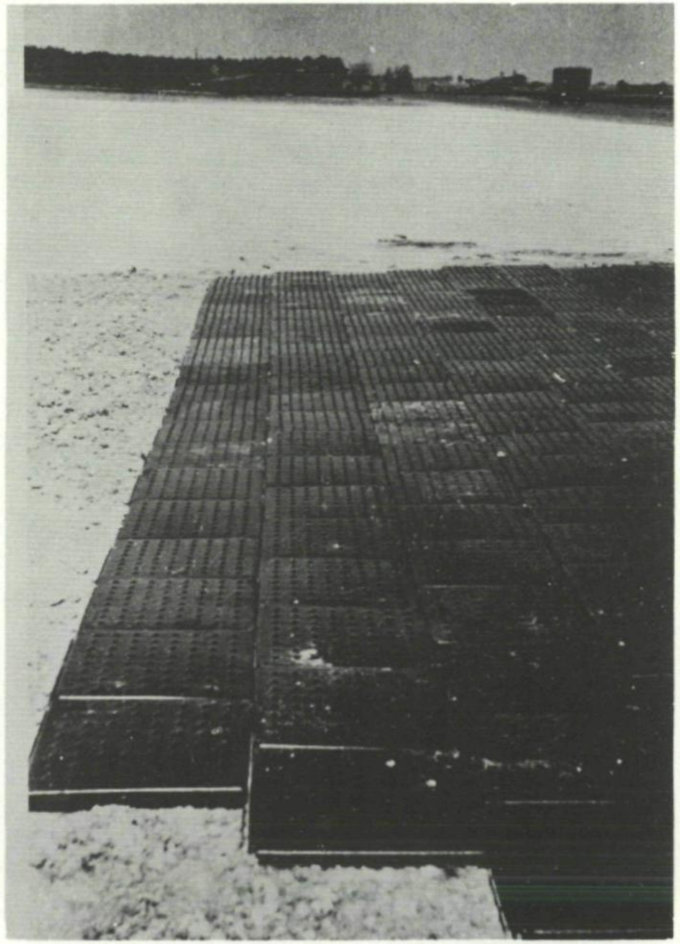


Fig. 23 Surfacing by metal sheets

Fig. 24 Surfacing by metal sheets

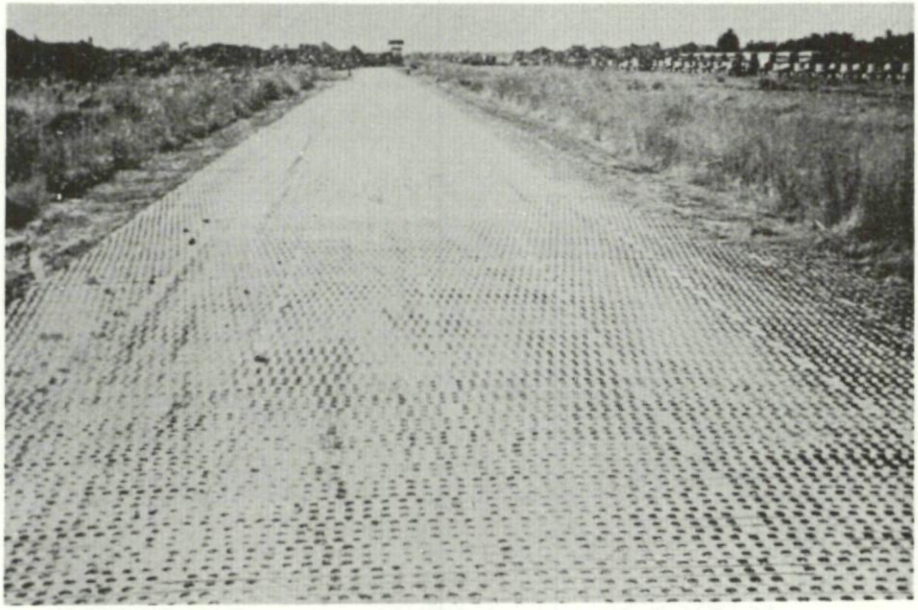


Fig. 25 PSP-covering

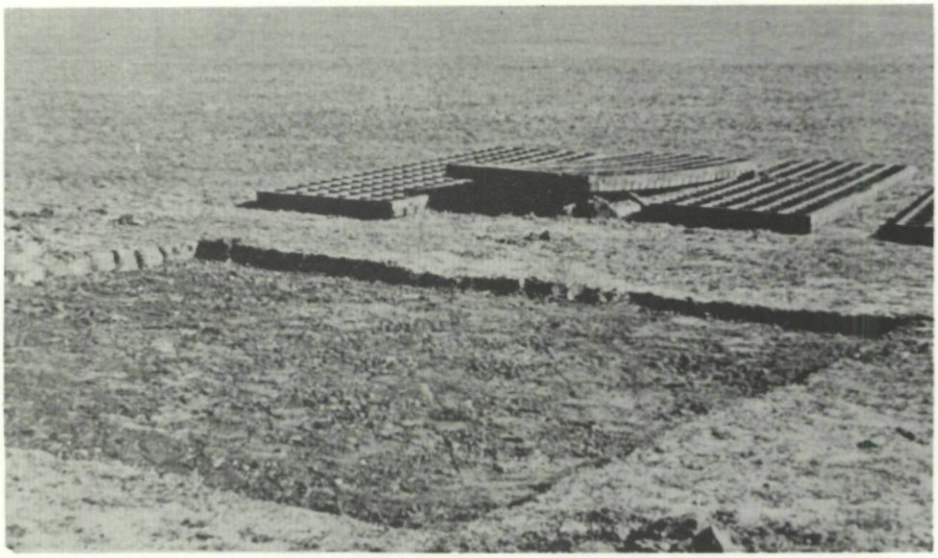


Fig. 26 Timber mats

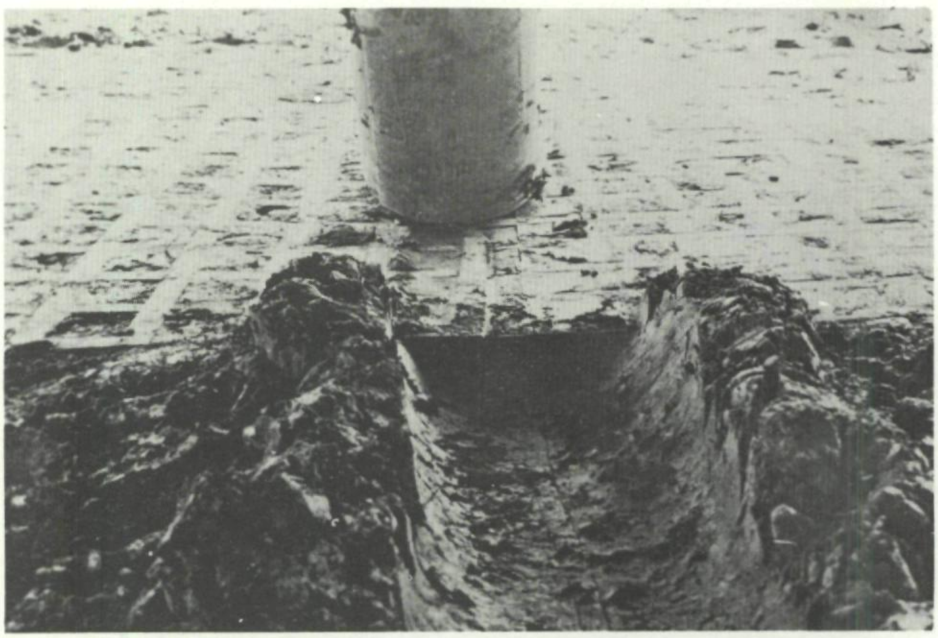


Fig. 27 Imbedded timber mats

Fig. 28 Timber mat runway

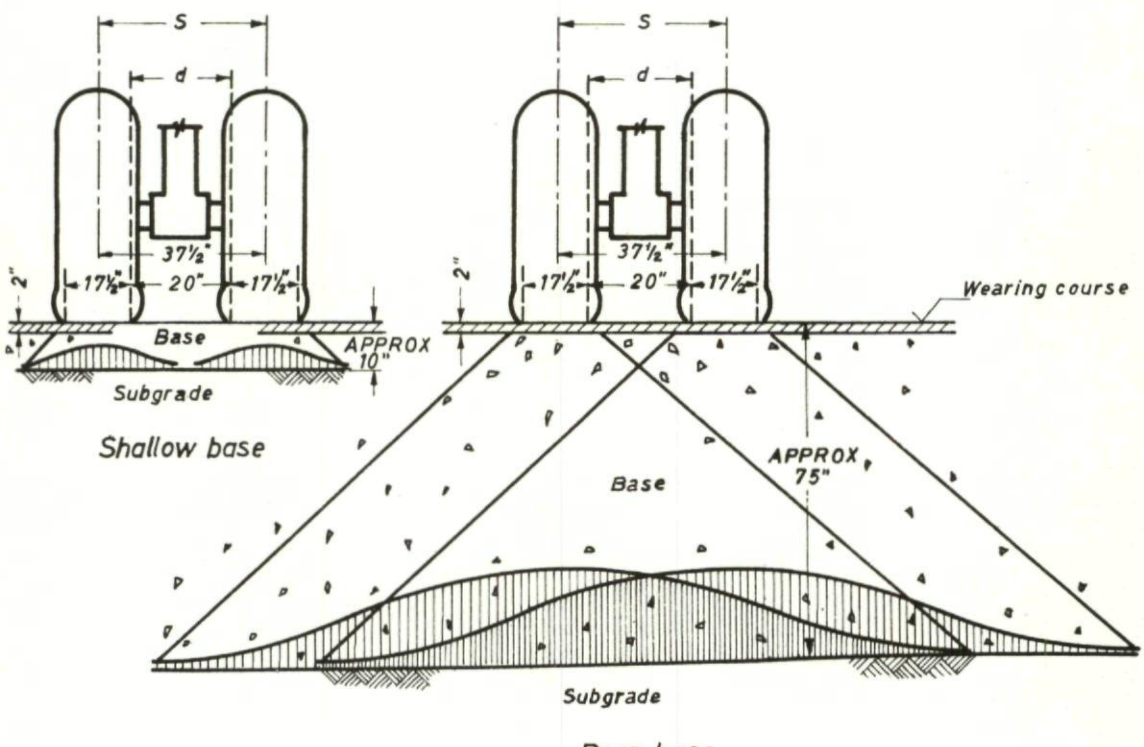
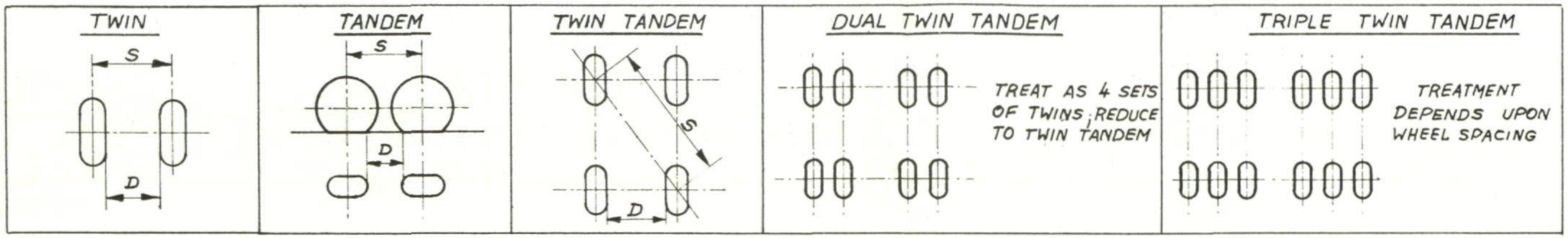


Fig. 29 Schematic diagram of B-29 twin wheel assembly



BASIC PROCEDURE

ILLUSTRATIVE ASSUMPTIONS: EQUIVALENT SINGLE WHEEL LOAD (ESWL) - 30 KIPS
TIRE INFLATION PRESSURE - 200 PSI

1. ENTER THE LOAD SCALE WITH THE EQUIVALENT SINGLE WHEEL LOAD, PT (1).
2. PROCEED HORIZONTALLY TO THE TIRE INFLATION CURVE, OF THOSE USED IN DETERMINING THE UCI, WHICH CORRESPONDS TO THE AIRCRAFT TIRE INFLATION PRESSURE, PT (2).
3. PROCEED VERTICALLY FROM PT (2) TO THE UCI SCALE, PT (3).

PROCEDURE TO DETERMINE THE EQUIVALENT SINGLE WHEEL LOAD

ILLUSTRATIVE ASSUMPTIONS: TWIN GEAR; 20 KIP GEAR LOAD
150 PSI TIRE PRESSURE; D = 12"; S = 20"

A. ENTER THE LOAD SCALE WITH THE LOAD PER WHEEL, PT (A), AND THE GEAR DIMENSION SCALE WITH THE DIMENSION D/2, PT (B). PLOT THE POINT OF INTERSECTION, (C).
B. ENTER THE LOAD SCALE WITH THE GEAR LOAD, PT (D), AND THE GEAR DIMENSION SCALE WITH THE DIMENSION 2S, PT (E). PLOT THE POINT OF INTERSECTION, (F).
C. CONNECT POINTS (C) AND (F) WITH A STRAIGHT LINE.
D. FIND THE INTERSECTION OF THE LINE (C) - (F) AND THE TIRE INFLATION PRESSURE CURVE, OF THOSE USED IN DETERMINING THE ESWL, WHICH CORRESPONDS TO THE AIRCRAFT TIRE INFLATION PRESSURE, PT (G). SHOULD THE LINE (C) - (F) NOT INTERSECT THE PROPER TIRE INFLATION CURVES, EXTEND THE LINE FROM POINT (C) HORIZONTALLY TO THE LEFT AND FROM POINT (F) HORIZONTALLY TO THE RIGHT UNTIL IT DOES INTERSECT THE PROPER TIRE INFLATION PRESSURE CURVES.
E. FROM (G) PROCEED HORIZONTALLY TO THE LOAD SCALE AND READ THE ESWL, PT (H).
F. PROCEED FROM (H) TO (I) AND (J), AS ABOVE, TO DETERMINE THE UCI.

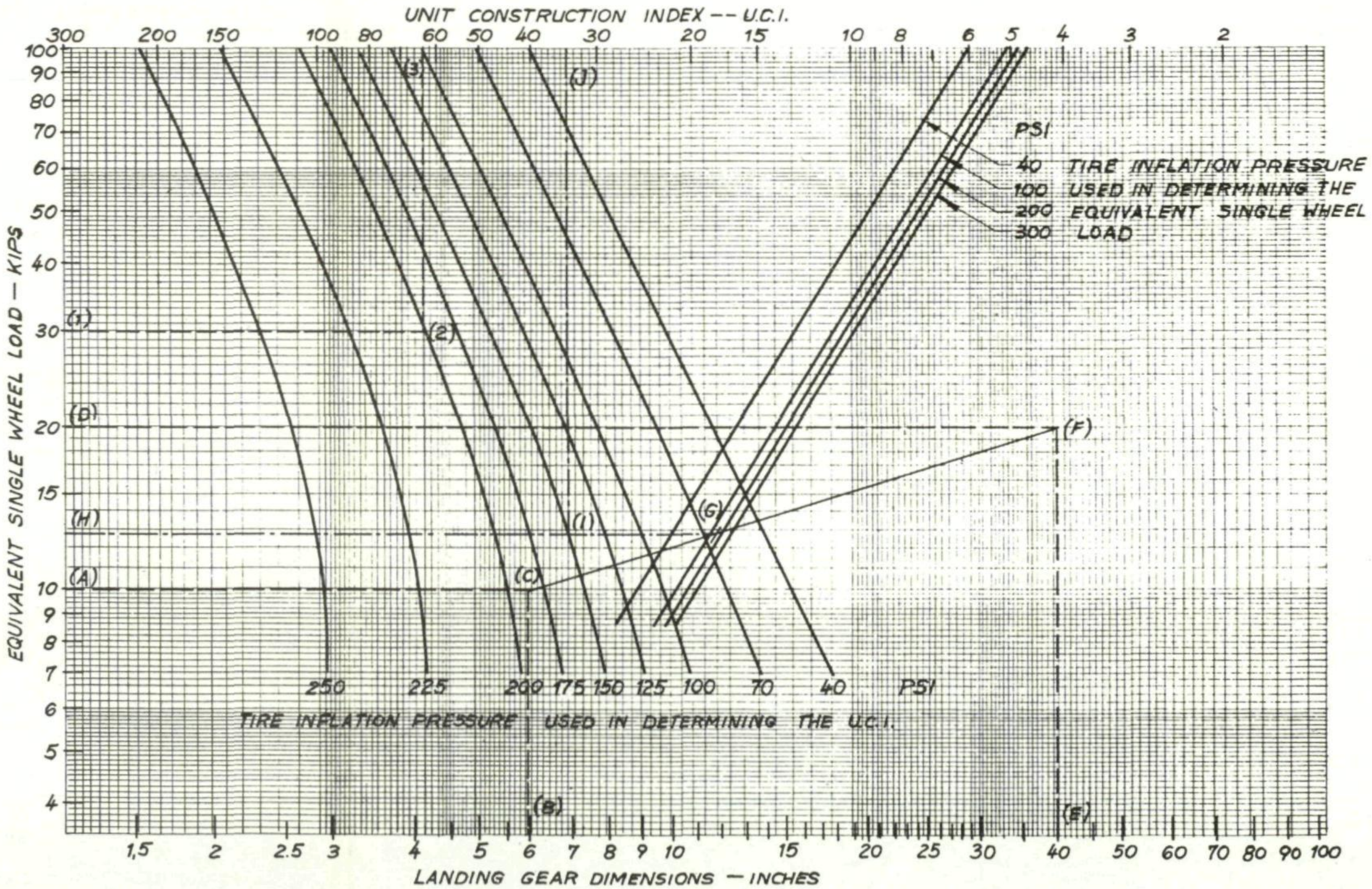


Fig.30 Unit construction index - U.C.I.

NOTE : E = EQUIVALENT SINGLE WHEEL LOAD (lb)
S = MAXIMUM STATIC LOAD ON ONE MAIN UNDERCARRIAGE UNIT AT MAXIMUM DESIGN TAKE-OFF WEIGHT (lb)
P = TIRE PRESSURE (p.s.i.)

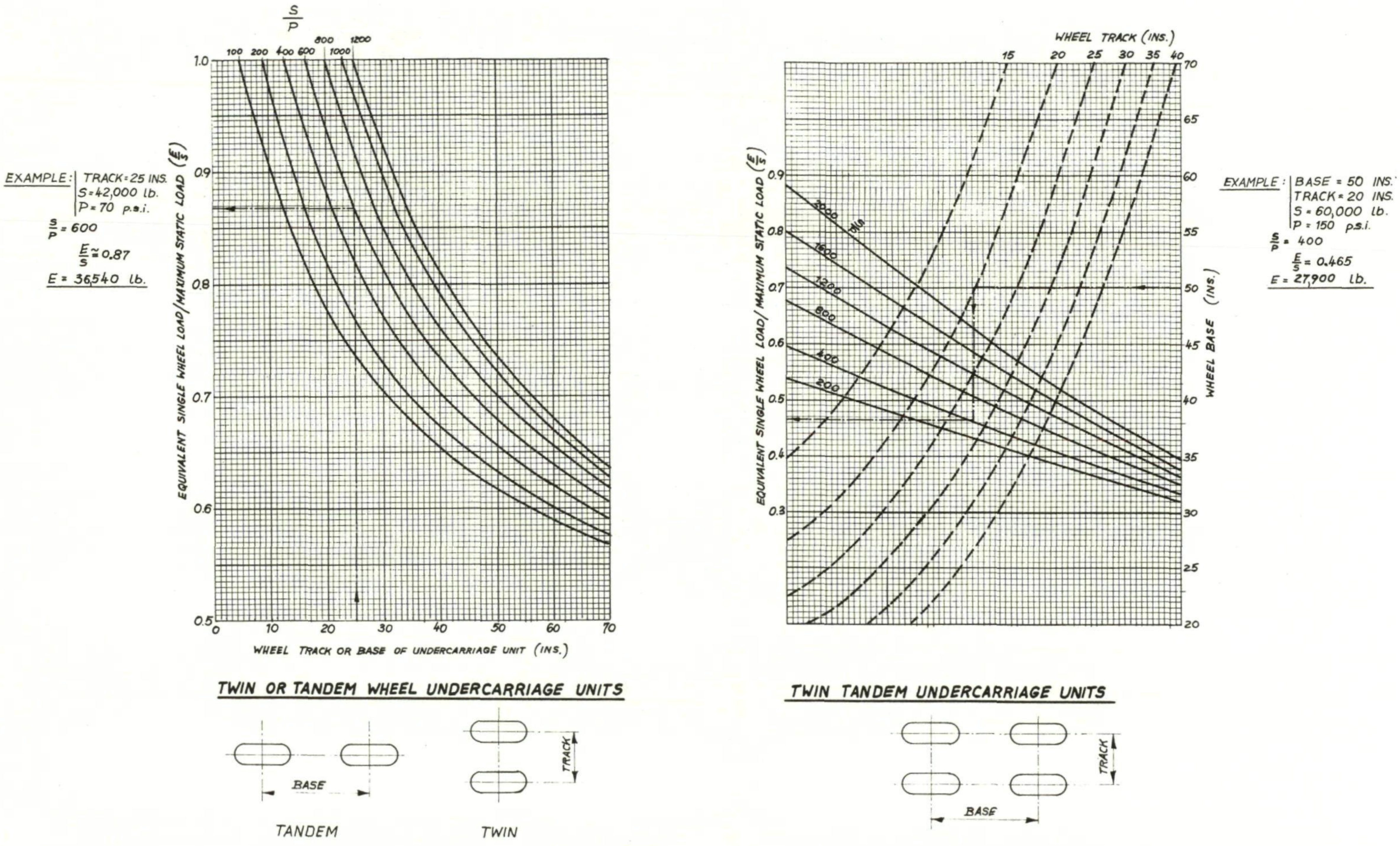
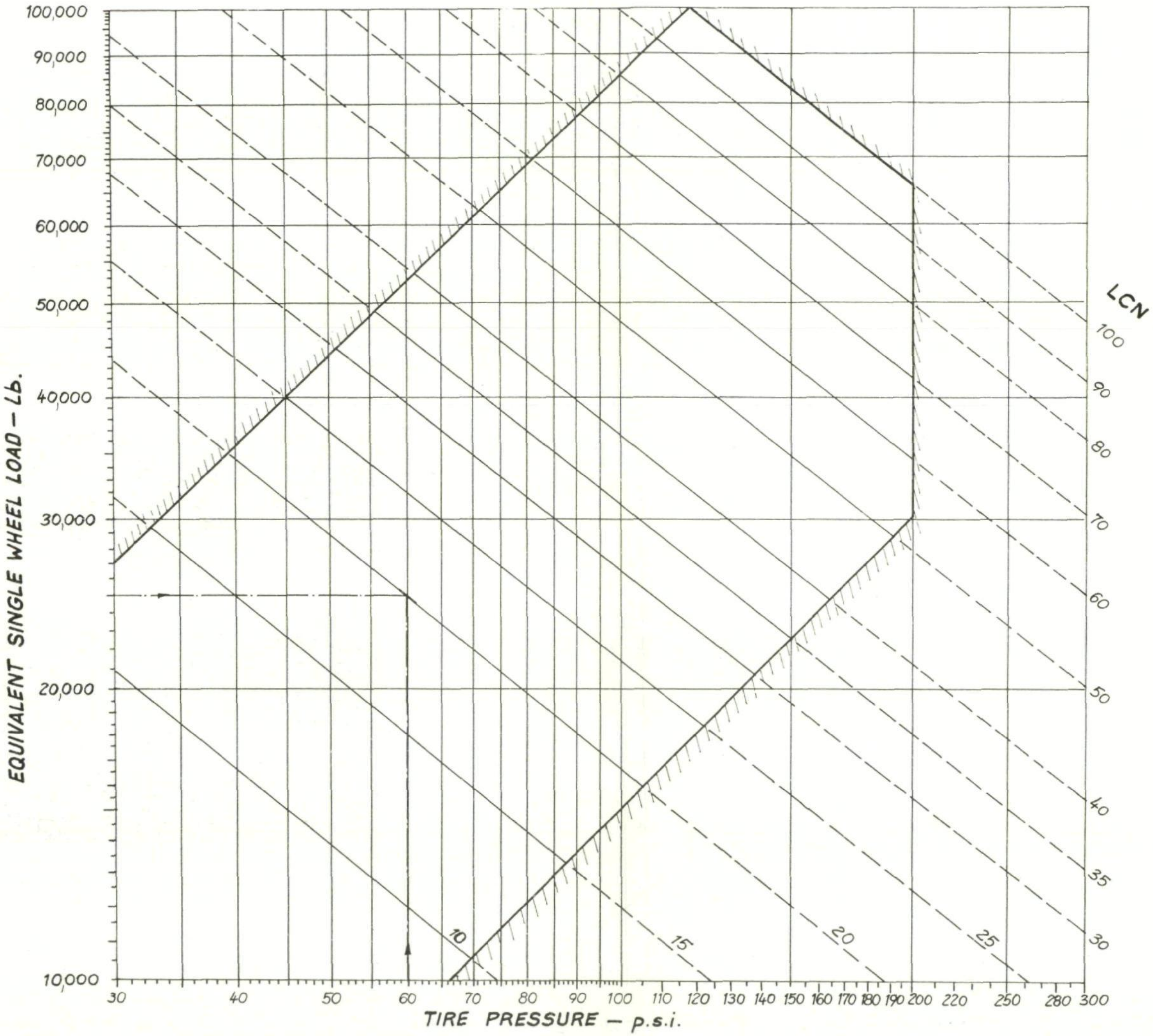


Fig.31 Load classification number - LCN



EXAMPLE:
EQUIVALENT SINGLE WHEEL LOAD
E = 25,000 Lb.
TIRE PRESSURE P = 60 p.s.i.
LCN = 20

Fig. 31(a) Load classification number - LCN

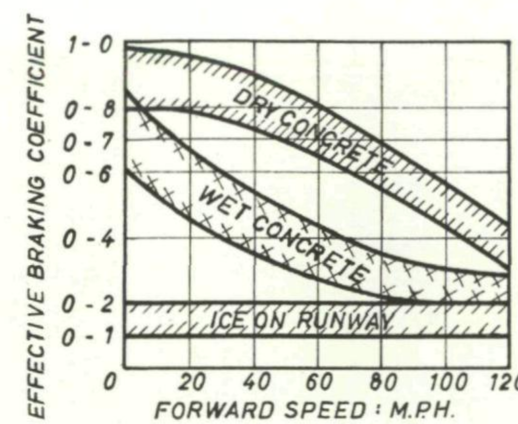


Fig.32 Effective braking coefficient

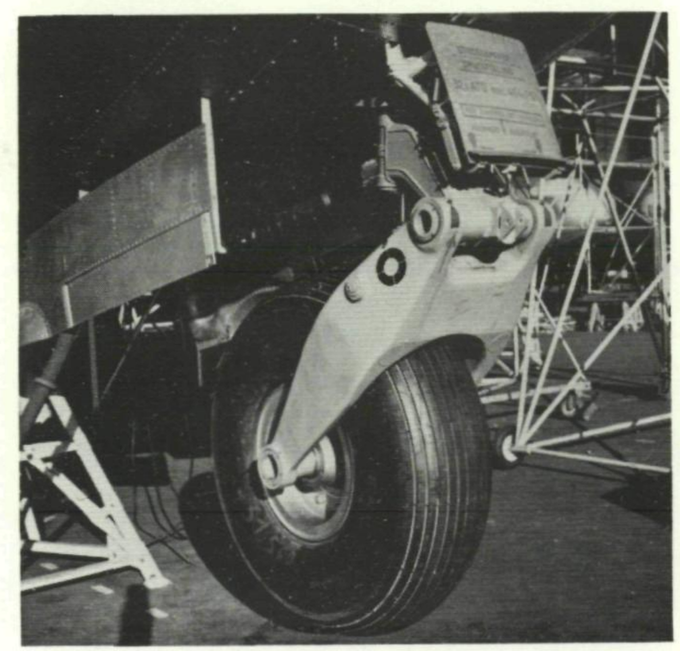


Fig.33 Nose-undercarriage of 'Noratlas'

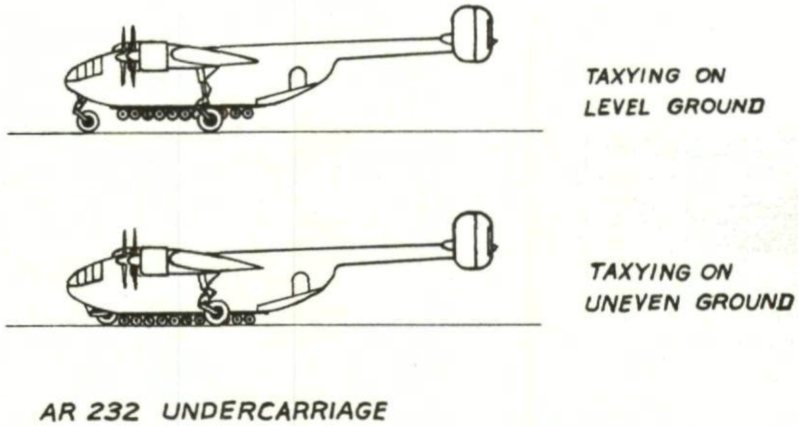


Fig.34 Multi-wheel undercarriage of AR 232

Fig.35 Undercarriage of DO-27 with wheels and snow skis

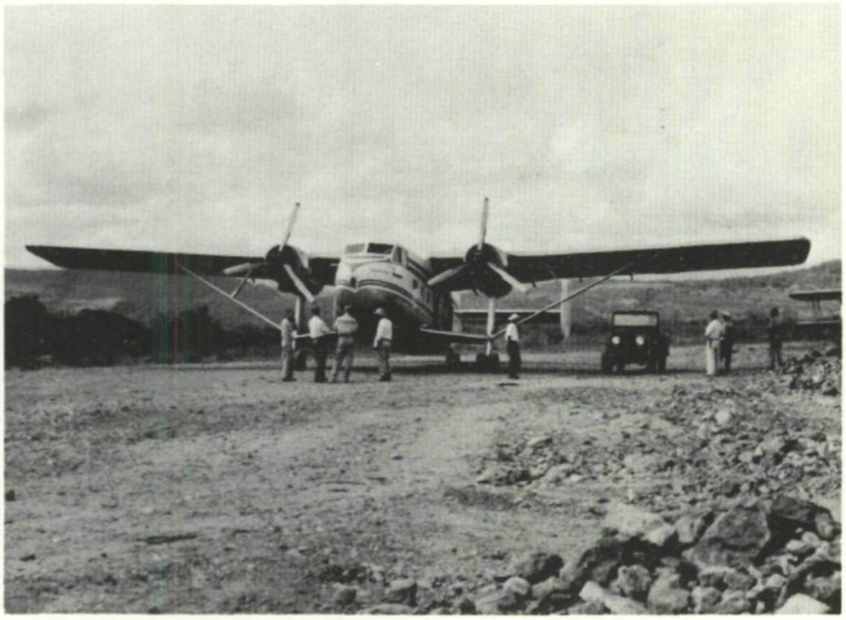


Fig.36 Scottish aviation 'Twin-Pioneer' on semi-prepared runway

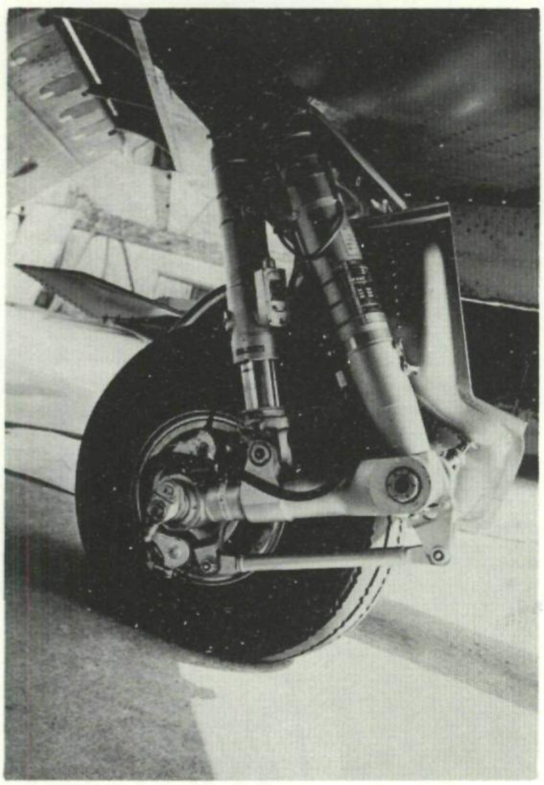


Fig.37 Nose undercarriage of G-91

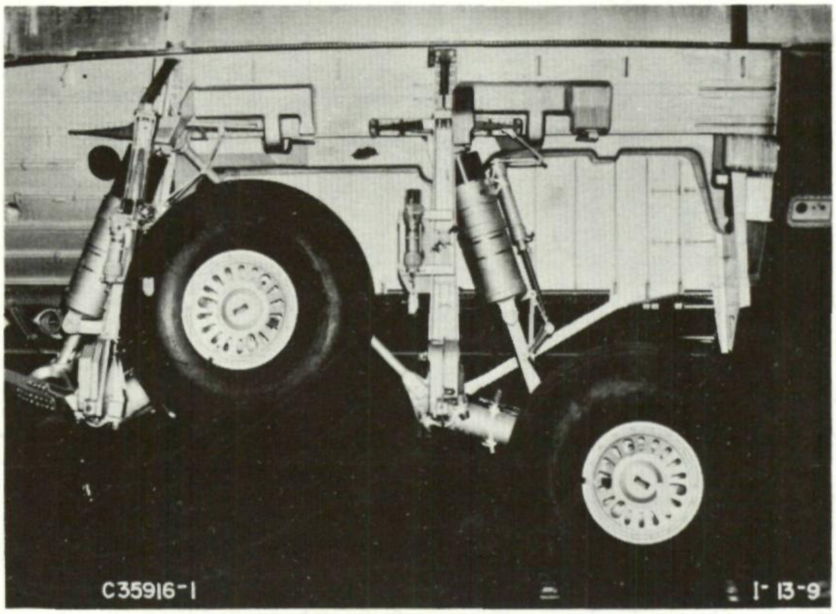


Fig. 38 Main landing gear of C-133

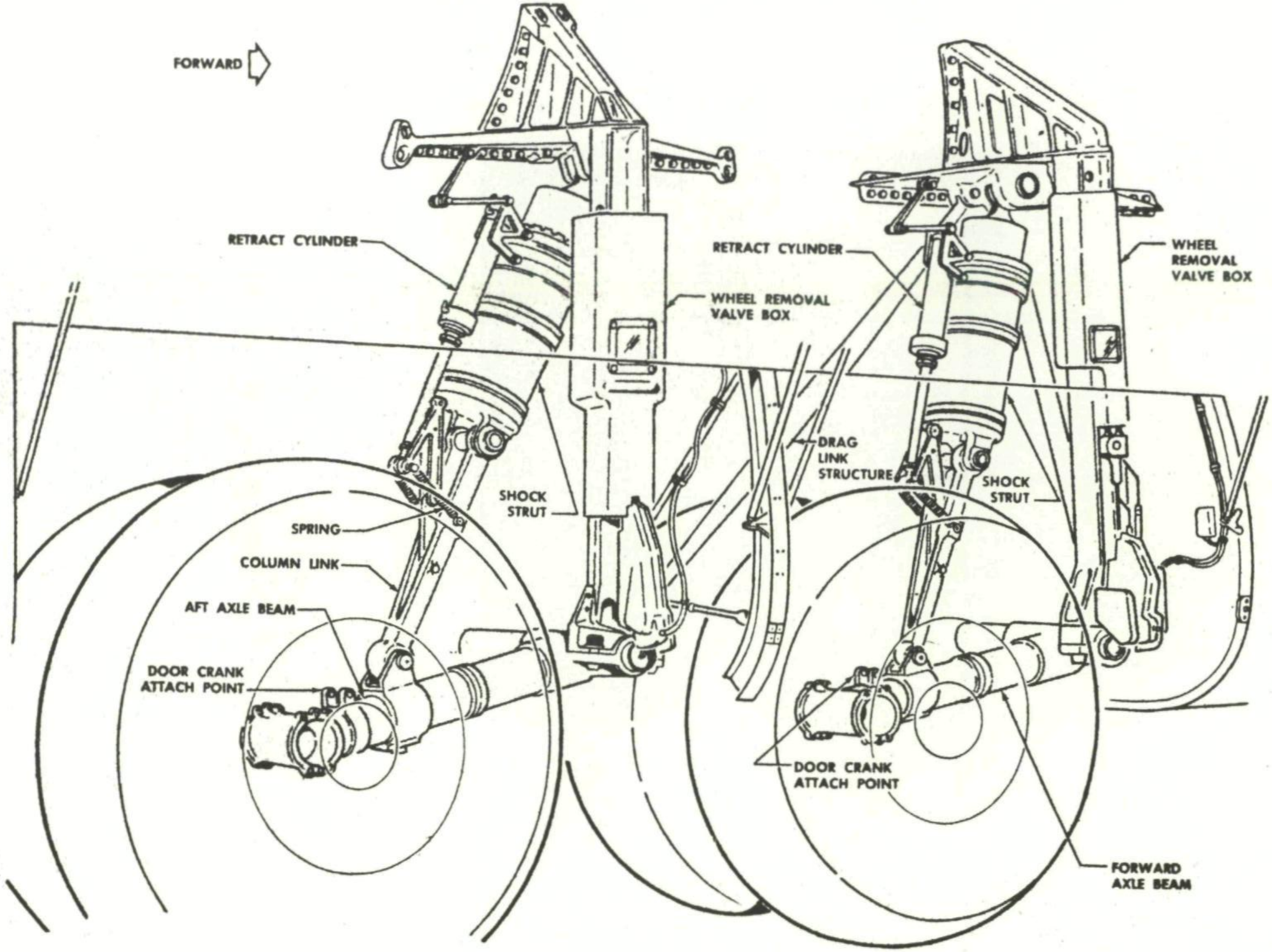


Fig.39 Main landing gear of C-133

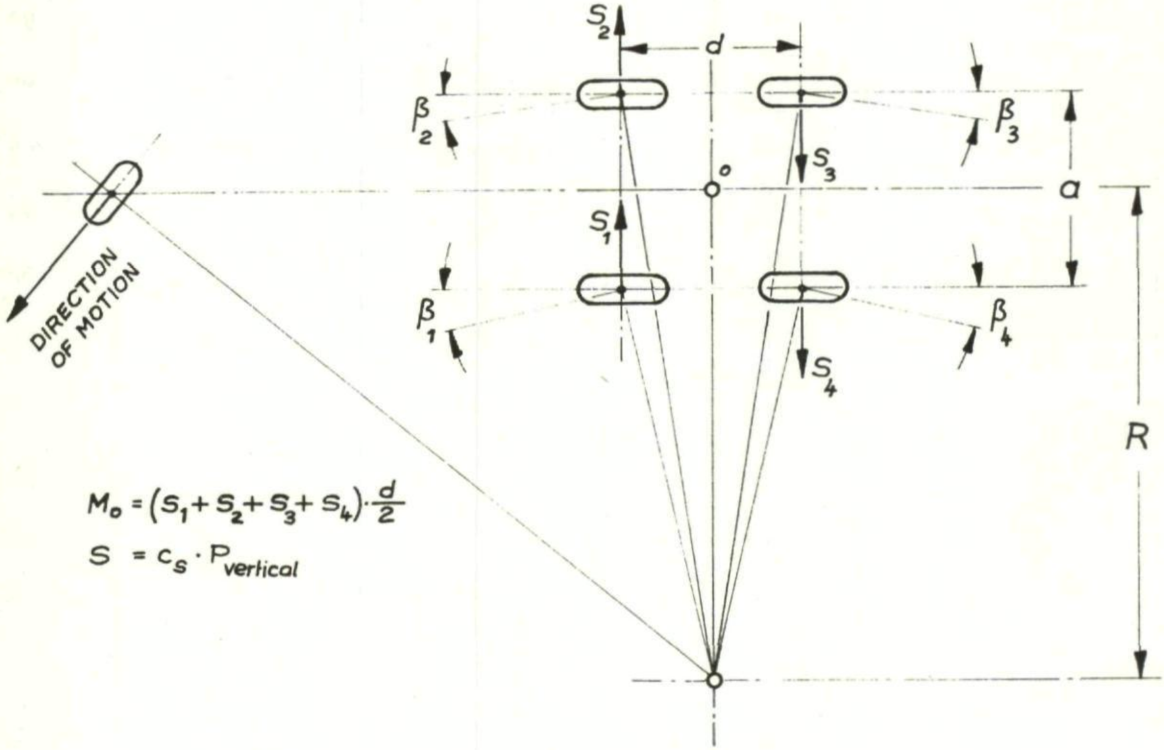


Fig. 40 Side-loads on tandem wheels in a turn

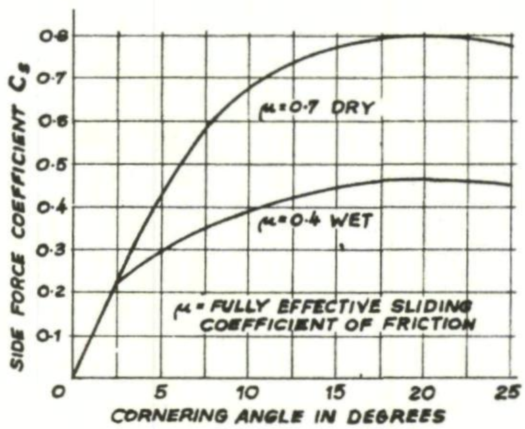


Fig. 41 Side-force coefficient C_s

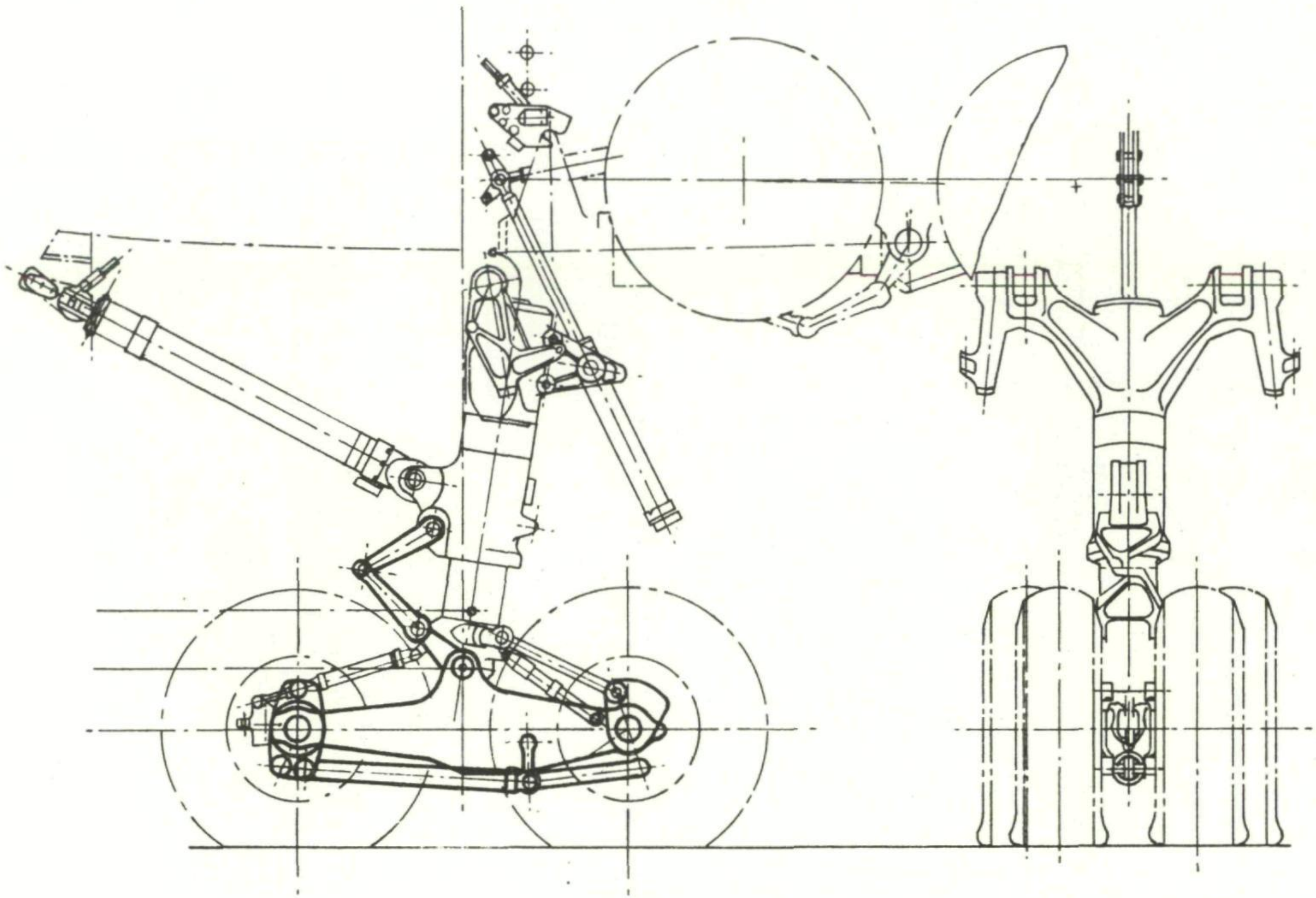


Fig. 42 The Bristol 'Britannia' main landing gear

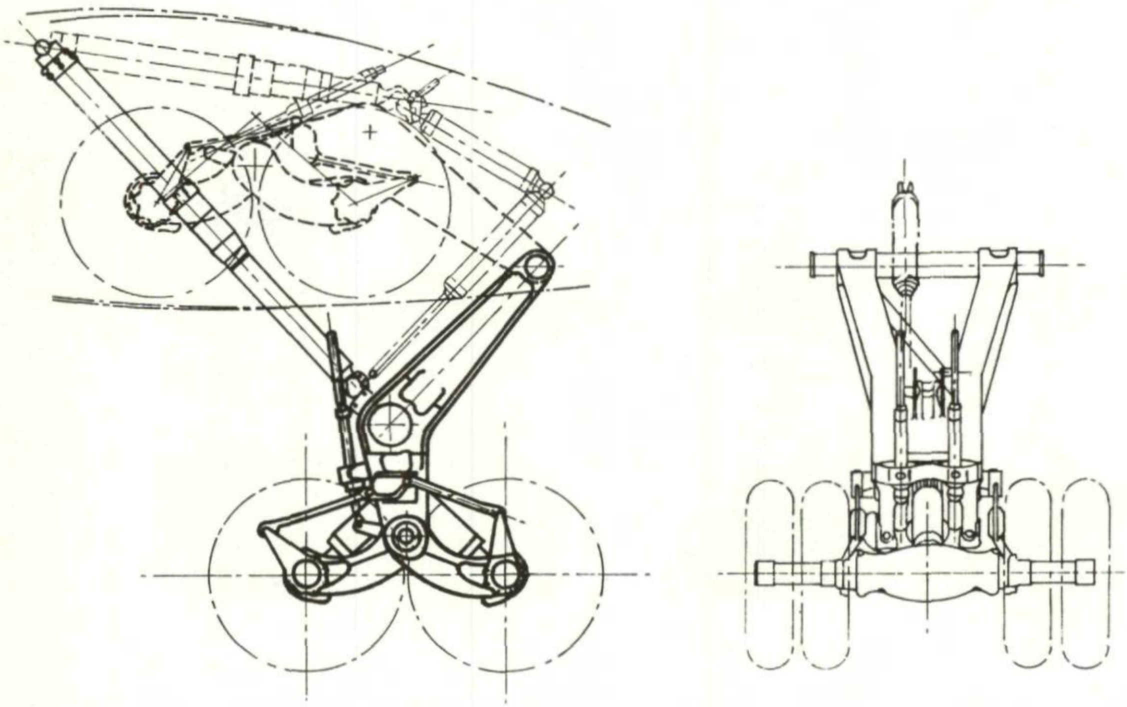


Fig.43 The 'Brabazon II' main landing gear

Fig.44 The Arado 234 with skid landing gear on its trolley

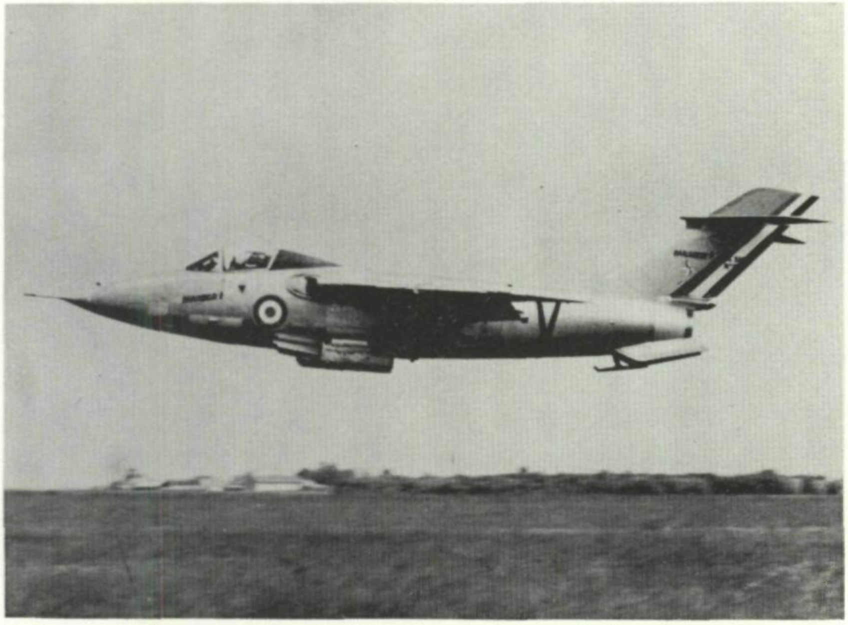


Fig. 45 The S.E. 5000 'Baroudeur' with landing skids, side view

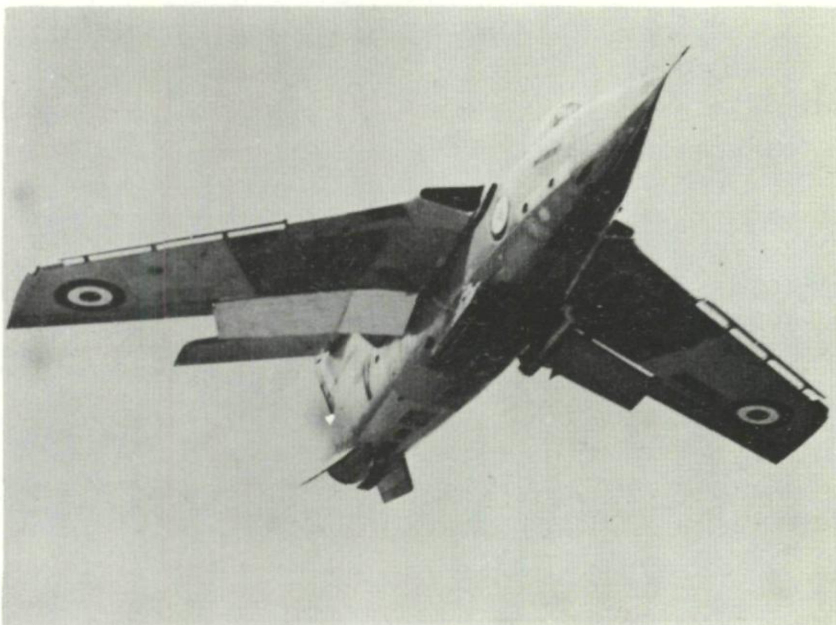


Fig. 46 The S.E. 5000 'Baroudeur' with landing skids, front view

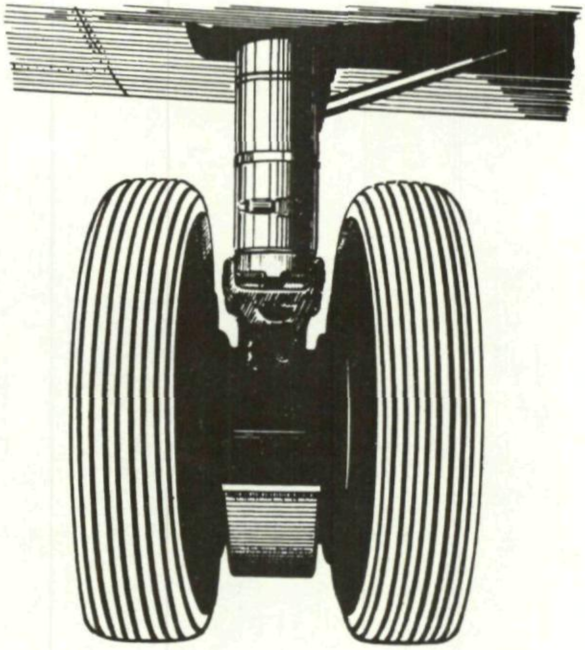


Fig. 47 A twin-wheel undercarriage with skids ('Ouragan')

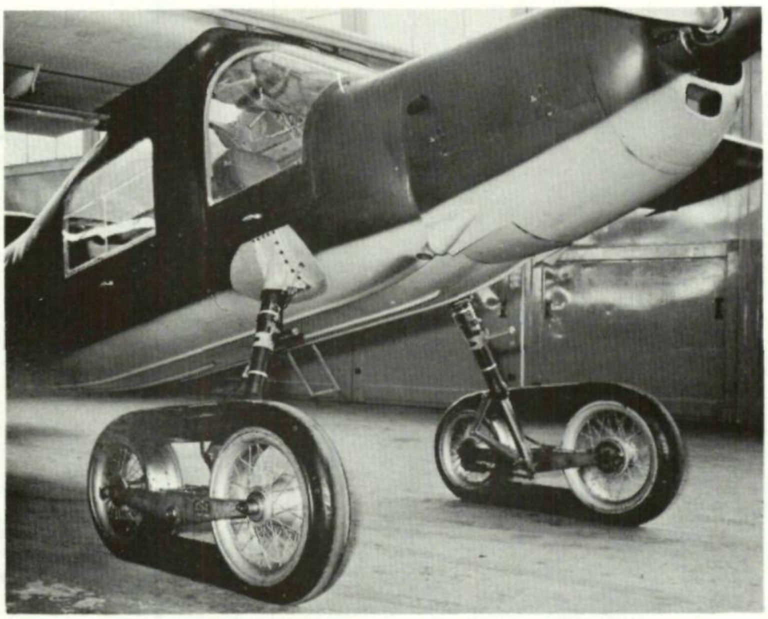


Fig. 48 The Bonmartini track gear on the DO-27

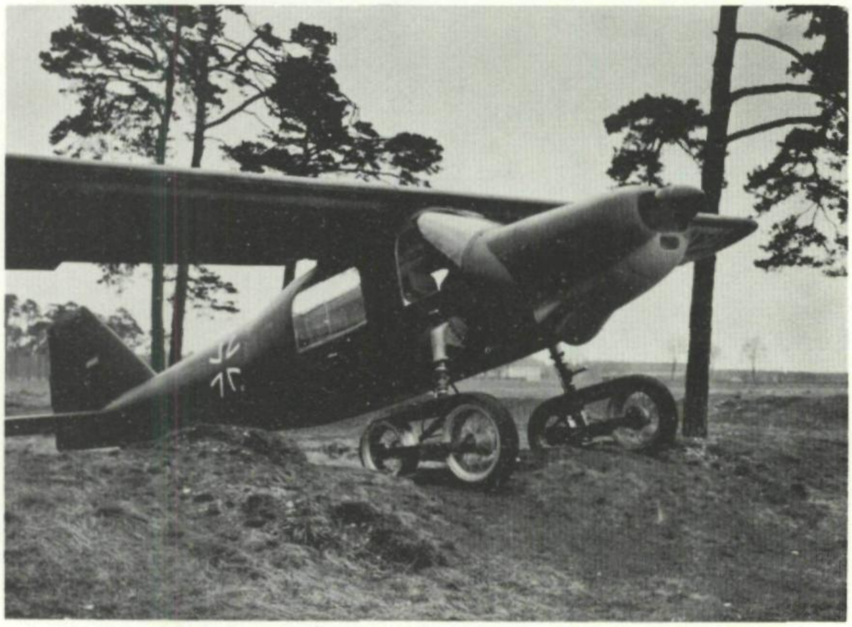


Fig. 49   The DO-27 with track gear on natural terrain

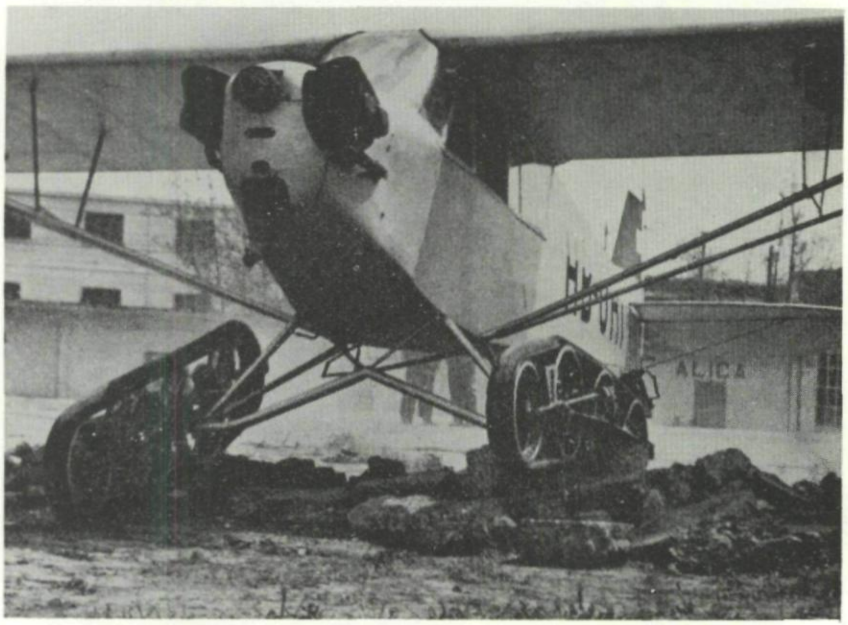


Fig. 50   Another aircraft with Bonmartini track gear takes big obstacles

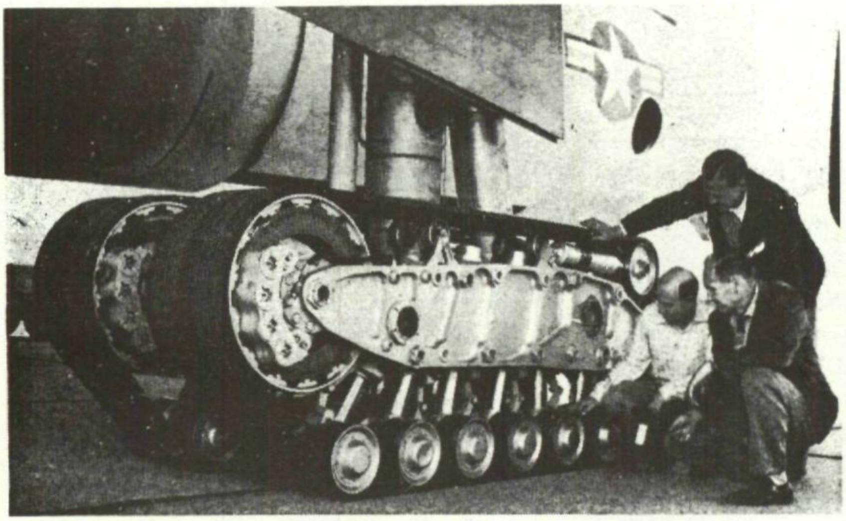


Fig. 51 The track main gear of the Convair B-36

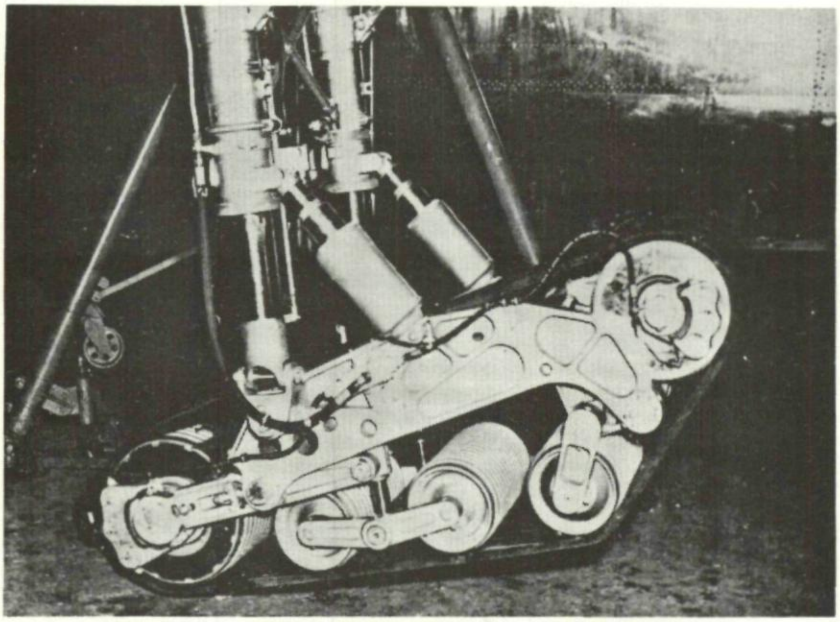


Fig. 52 The track main gear of the Fairchild 'Packet'

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