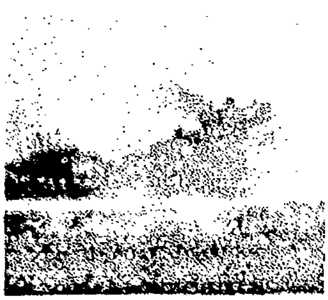
US Army Corps of Engineers



TECHNICAL REPORT EL-88-17

PREDICTION OF DUST PROPENSITY FOR MILITARY OPERATIONS IN DESERT AREAS

by

William K. Dornbusch, John N. Strange, Allen D. Rooke, Jr.

Science and Technology Corporation
101 Research Drive
Hampton, Virginia 23666-1340

November 1988

Final Report

Prepared for DEPARTMENT OF THE ARMY
US Army Corps of Engineers
Washington, DC 20314-1000

Under Contract No. DACA39-85-C-0006

Monitored by Environmental Laboratory
US Army Engineer Waterways Experiment Station
PO Box 631, Vicksburg, Mississippi 39181-0631

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

AD-A203 599

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S): Technical Report EL-88-17

6a. NAME OF PERFORMING ORGANIZATION: Science and Technology Corporation

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION: USAEWES Environmental Laboratory

6c. ADDRESS (City, State, and ZIP Code): 101 Research Drive, Hampton, VA 23666-1340

7b. ADDRESS (City, State, and ZIP Code): PO Box 631, Vicksburg, MS 39180-0631

8a. NAME OF FUNDING/SPONSORING ORGANIZATION: US Army Corps of Engineers

8b. OFFICE SYMBOL (If applicable)

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: Contract No. DACA39-85-C-0006

8c. ADDRESS (City, State, and ZIP Code): Washington, DC 20314-1000

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
			AT40 BO/069

11. TITLE (Include Security Classification): Prediction of Dust Propensity for Military Operations in Desert Areas

12. PERSONAL AUTHOR(S): Dornbusch, William K.; Strange, John N.; Rooke, Allen D., Jr.

13a. TYPE OF REPORT: Final report

13b. TIME COVERED: FROM ______ TO ______

14. DATE OF REPORT (Year, Month, Day): November 1988

15. PAGE COUNT: 111

16. SUPPLEMENTARY NOTATION: Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Armored vehicle; Desert; Dust emission; Dust propensity; Landform

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A study of desert terrain was undertaken to develop a methodology suitable for prediction of dust propensity. The study focused on Yuma Proving Ground (YPG), a part of the Sonoran Desert, as an aid in developing and illustrating the methodology. Geological landforms were identified and characterized by age and geomorphic processes, and residual fine materials (clays and silts) were predicted as percent by weight for the top 10-cm soil layer. Using a data base of previous vehicular dust trails at Fort Carson, Colo., and White Sands Missile Range, NM, a functional equation for dust emission by tracked vehicles was formulated, and an emission equation was developed by means of dimensional analysis. Using this equation and the dust-propensity predictions for YPG, tracked vehicle dust emissions were predicted.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL

22b. TELEPHONE (Include Area Code)

22c. OFFICE SYMBOL

DD Form 1473, JUN 86 Previous editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

PREFACE

This study is part of a continuing research effort intended to better describe battlefield dust, with the goal of predicting its effects on high-technology sighting, aiming, and tracking systems that will be employed in land warfare. It was sponsored by the Office, Chief of Engineers (OCE), US Army, and was monitored by the Environmental Assessment Group (EAG) of the Environmental Systems Division (ESD), Environmental Laboratory (EL), US Army Engineer Waterways Experiment Station (WES), Vicksburg, MS. The study was performed by Science and Technology Corporation (STC) under AirLand Battlefield Environment Support, Contract No. DACA39-85-C-0006, Work Unit AT40 BO/069. It spanned a period from June to December 1986. During this time, Mr. H. Wade West was Chief, EAG. Mr. Randall R. Williams, EAG, monitored the study and provided assistance and advice. Dr. Victor E. LaGarde was Chief, ESD, and Dr. John Harrison was Chief, EL.

The study was performed and this report was written by Messrs. William K. Dornbusch, John N. Strange, and Allen D. Rooke, Jr., all of the Vicksburg Office of STC. The report was edited by Ms. Lee T. Byrne of the WES Information Technology Laboratory, WES.

Computer support was provided by Dr. Edward Burlbaw and Mr. Daniel Healy of STC-Las Cruces, N. Mex.

COL Dwayne G. Lee, EN, was the Commander and Director of WES. Dr. Robert W. Whalin was Technical Director.

This report should be cited as follows:

Dornbusch, William K., Strange, John N., and Rooke, Allen D., Jr. 1988. "Prediction of Dust Propensity for Military Operations in Desert Areas," Technical Report EL-88-17, prepared by Science and Technology Corporation for US Army Engineer Waterways Experiment Station, Vicksburg, MS.

CONTENTS

Page

PREFACE.. 1

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT.......... 3

PART I: INTRODUCTION.. 4

Background.. 4
Purposes and Scope.. 4

PART II: GENERAL DISCUSSION OF WORLD DESERTS........................... 6

PART III: DEVELOPMENT OF DUST-PROPENSITY METHODOLOGY................... 10

Selection of Study Area... 10
Reference Material for Desert Studies............................... 10
Data Requirements for US Study Areas................................ 11
Characterization of Landforms....................................... 13
Landform Descriptions and Photo-Interpretation Keys................. 20
Terrain Attributes Relevant to Dust Emission and Development of Procedures for Their Determination............... 20
Landform Attributes Influencing Dust Accumulation................... 21
Specific Attributes Affecting the Propensity for Emission of Dust from Desert Soils............................ 27
Evaluation of Interaction of Terrain Attributes as They Affect Levels of Dust Emission.......................... 28
Development of Landform Map for Prediction of Dust Emission.. 30

PART IV: APPLICATION OF DUST-PROPENSITY METHODOLOGY TO WORLD DESERTS... 35

PART V: DUST PREDICTIONS... 40

Employment of the Dust-Propensity Methodology....................... 40
Development of an Emission-Factor Equation.......................... 40
Dust-Prediction Calculations.. 46

PART VI: SUMMARY AND CONCLUSIONS....................................... 52

PART VII: RECOMMENDATIONS.. 53

REFERENCES... 54

BIBLIOGRAPHY... 55

TABLES 1-15

APPENDIX A: DISCUSSION OF TYPES OF REFERENCE MATERIAL FOR DESERT STUDIES... A1

APPENDIX B: DETAILED DATA REQUIREMENTS FOR US STUDY AREAS.............. B1

APPENDIX C: DESCRIPTIONS OF DESERT LANDFORMS.......................... D1

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
feet	0.3048	metres
inches	2.54	centimetres
microns	0.001	millimetres
miles (US statute)	1.609347	kilometres
miles per hour	0.447	metres per second
pounds (force) per square foot	47.88026	newtons per square metre
pounds (force) per vehicular mile traveled	0.00277	newtons per metre
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square metres
square miles	2.589998	square kilometres
tons (force)	8.896444	kilonewtons
tons (short, 2,000 pounds)	907.1837	kilograms

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

PREDICTION OF DUST PROPENSITY FOR MILITARY OPERATIONS IN DESERT AREAS

PART I: INTRODUCTION

Background

1. The development of new, high-technology ground weapons, along with their sighting, aiming, and tracking systems, has added importance to the understanding and quantification of battlefield dust. This is an age-old problem, especially in desert terrain, where it has been long known to provide warning of battlefield maneuver while at the same time lending a degree of concealment to the force executing that maneuver. Battlefield dust degrades the performance of people and machines and may, at critical levels, prevent the proper functioning of electro-optical devices that require the passage of energy to sense or visually observe their targets.

2. The US Army Engineer Waterways Experiment Station (WES) has been engaged in a continuing study of the causes and effects of battlefield dust and other obscurants since 1978. As part of this study, Science and Technology Corporation (STC) was asked to review certain references accumulated by WES and to develop a geological methodology by which dust propensity could be predicted for a desert area in which military operations might be anticipated.

Purposes and Scope

3. In accordance with the statement of work provided by WES, the primary purpose of this study was to develop a dust-propensity predi ton methodology. To achieve this, an example area was chosen, and a methodology was developed and applied to this area. The area selected for this purpose was Yuma Proving Ground (YPG), Ariz., for the following reasons:

- a. Weather and terrain conditions at YPG are similar in many respects to desert areas of military interest in north Africa and the Middle East.
- b. YPG is readily available, and source material and terrain data, such as maps, aerial photography, imagery, etc., are generally

adequate and can be supplemented by first-hand observation as necessary.

c. YPG is available for testing of dust-producing activities, such as cross-country vehicular movement, exploding munitions, etc., thus permitting validation and refinement of dust-propensity methodology and predictions.

4. A second study purpose was to attempt to generalize the methodology to encompass, insofar as possible, reasonable quantification of pertinent parameters associated with deserts worldwide, with emphasis upon those of military interest.

5. When dust propensity is mentioned, the question that must immediately follow is: "Dust from what?" Obviously, the many activities that take place on a desert battlefield produce different quantities of dust. For this study, STC was initially asked, as a third study purpose, to consider five categories of activities in relation to the production of dust:

a. Vehicular traffic.

b. Explosions of conventional munitions.

c. Helicopter downwash.

d. Detonation of tactical nuclear weapons.

e. Wind (dust storms).

6. After the study had begun, it became obvious that constraints of time and funds dictated a narrowing of its scope with regard to consideration of the various activities listed above. It appeared that one of the greatest needs was for a means of predicting dust from tracked (armored combat) vehicles. With the concurrence of WES, the work was narrowed in scope to consider only tracked vehicular traffic, along with an attempt to formulate dust emission from those vehicles and to apply the formulas to the YPG.

PART II: GENERAL DISCUSSION OF WORLD DESERTS

7. The term "desert," as used in this report, describes areas with a mean annual precipitation of less than 10 in.*/year and in some years none at all. The term should be further qualified to apply to areas where evaporation exceeds precipitation. Thus, temperature/humidity must be equally important criteria to consider in the identification and delineation of desert areas. Deserts may be conveniently classified into four general types related to latitude and proximity to large masses of water such as oceans or inland seas: (a) polar or high latitude deserts characterized by year-round snow and ice conditions and sub-zero temperatures; (b) hot, middle latitude deserts occurring in continental interiors characterized by annual rainfall of less than 10 in. and mean temperatures of 80° F or higher during the hottest month; (c) trade-wind deserts such as the Sahara with negligible rainfall and great diurnal temperature ranges; and (d) coastal deserts with cold currents on the west coast of large land masses.

8. Since the purpose of this study is the development of a methodology for the prediction of dust propensity in desert landforms, the desert areas of primary interest are those of current or projected military focus. These desert areas occur in north Africa, the Middle East, and south-central Asia, an enormous tract of land occurring in the middle latitudes north of the equator. Middle latitude deserts also occur in the central and southwestern portions of the United States, east of the Sierra Nevada and west of the Rocky Mountains. These include the Great Basin, Sonoran, Mojave, and Chihuahuan deserts. All of these deserts fall into a vast area physiographically known as the Basin and Range Province of the Western United States. YPG is physiographically a part of the Sonoran Desert, which includes portions of northwestern Mexico, Arizona, and California. The YPG includes a wide variety of desert landforms that are generally considered representative of landforms occurring in middle latitude and trade wind deserts (Figure 1). There are, however, numerous landforms that occur in world deserts but do not occur within the limits of YPG, as well as significant variations in the physical attributes of the landforms that do occur. These additional landforms and

---

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

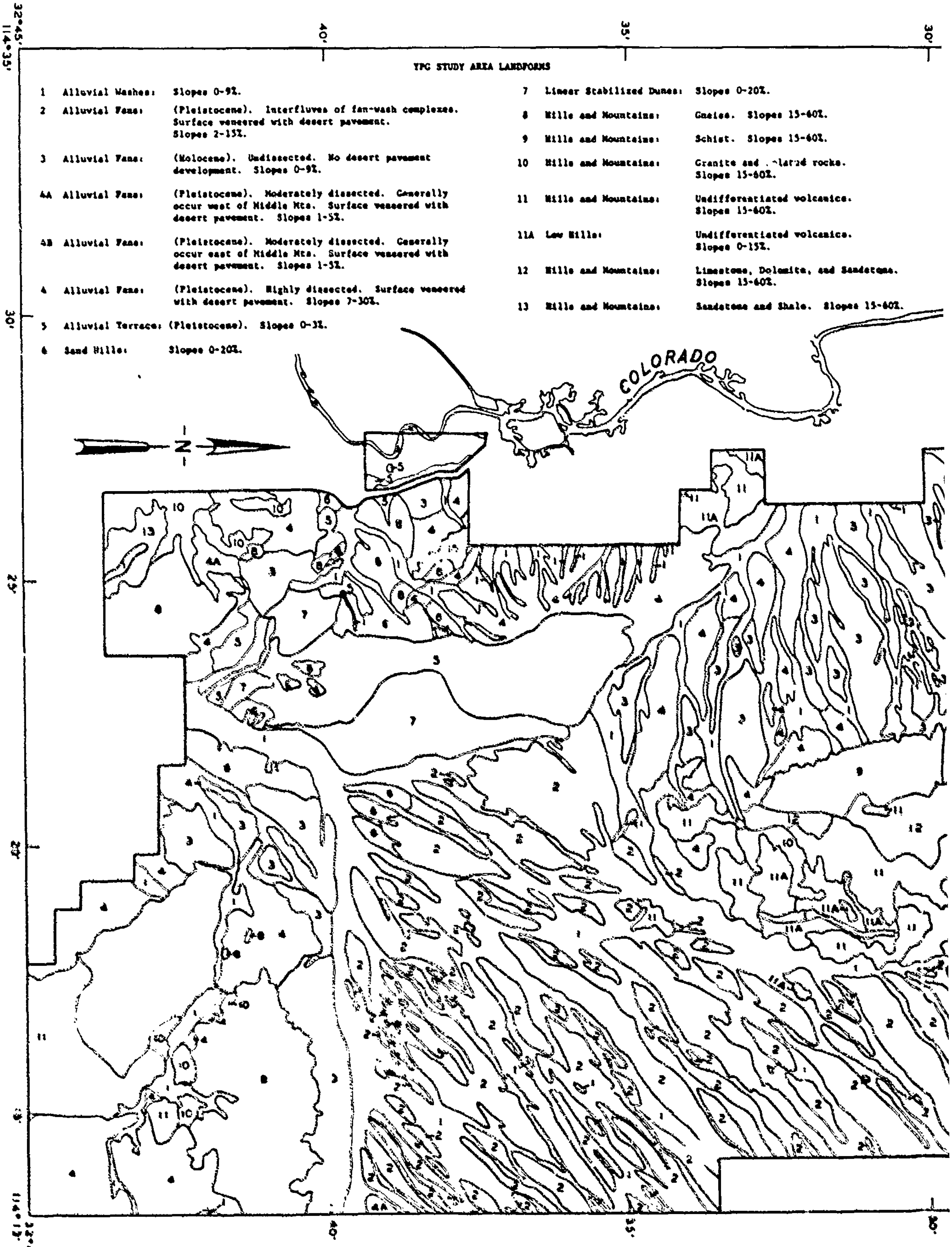
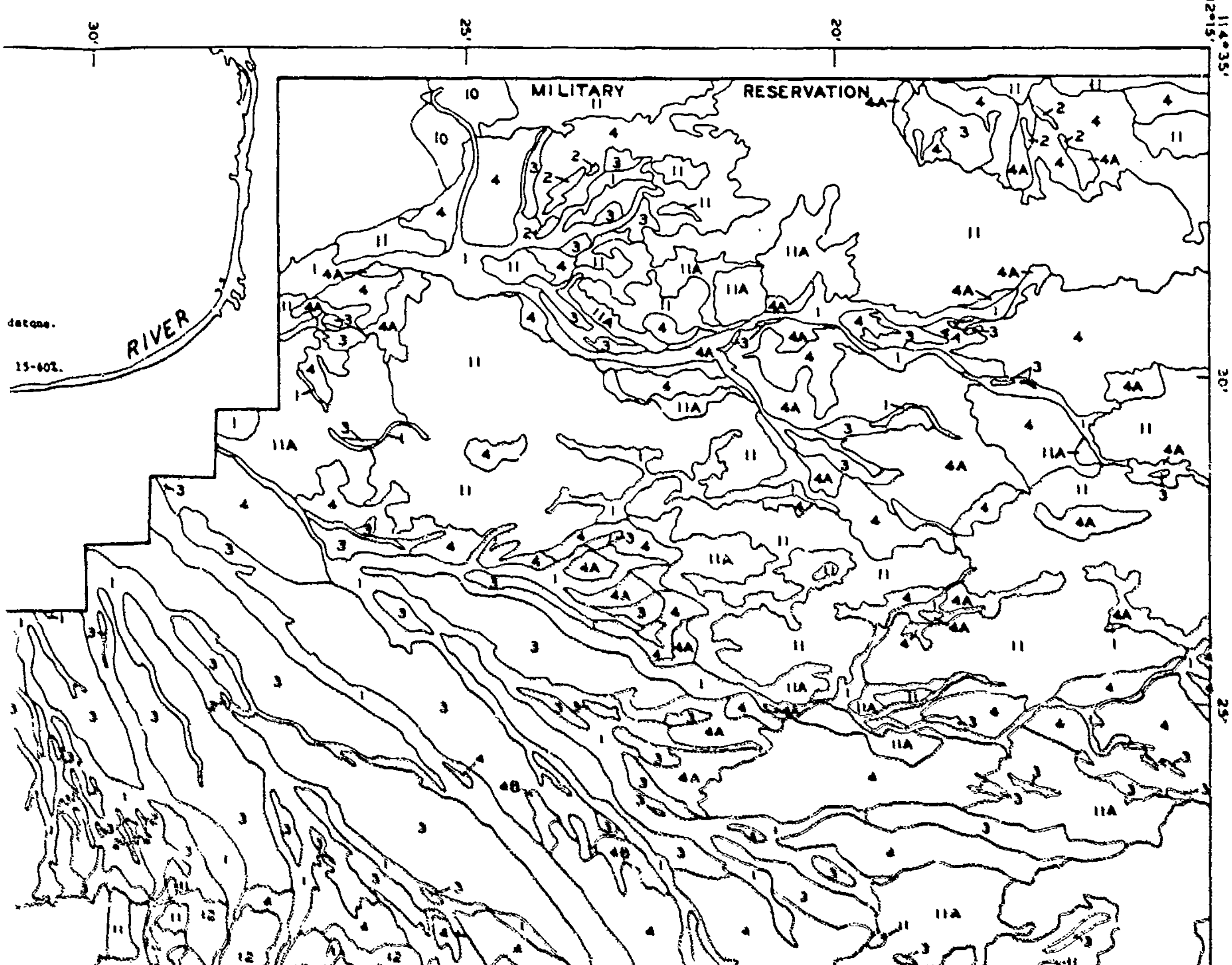


Figure 1. Landforms in study area of Yuma Proving Ground

1172


MILITARY RESERVATION
RIVER
datone.
15-602.
SCALE IN METERS
2000 0 2000 4000 6000 8000 10,000
30'
25'
20'
114°35'
32°15'
30'
25'
20'
15'

variations are found at locations within the gross desert area of Southwestern United States. Table 1 lists the most prominent and really significant landforms that occur in the Southwestern US deserts and estimates the percentage of occurrence of each. To assess the representativeness of each landform on a worldwide basis, the Sahara, Libyan, and Arabian deserts have been selected for comparative purposes and the percentage of occurrence of each US landform determined for each area. It should be stressed that these figures represent a gross generalization and are intended only to assess the representativeness of the Southwestern US deserts. The list of landforms reflects the physiographic nature of Southwestern United States, which is predominantly a basin and range province. Basin ranges, produced by faulting, occur in echelon arrangements separated by vast expanses of alluvial plains composed of debris eroded from the mountains. All of the listed landforms, except volcanics and sand dunes, are related to this repetitive physiographic sequence.

9. Table 1 also indicates the roughly calculated areal occupancy of each landform in square miles and the percentage that each represents of the total Southwestern US desert area. This listing should not be considered comprehensive of landform occurrence on a worldwide basis. Many landforms (for example, those occurring in plateau regions in middle latitude African and Asian deserts) have not been included. Since the geographic scope of this methodology is presently restricted to the YPG, this table is intended only to establish the general representativeness of the Yuma desert.

PART III: DEVELOPMENT OF DUST-PROPENSITY METHODOLOGY

Selection of Study Area

10. The dust-propensity methodology will be applied to middle latitude desert areas of the world of current or projected military focus. At the present, some of the most likely candidates are the deserts of north Africa, the Middle East, and south-central Asia. Since reference materials for these areas are either highly generalized or lacking and maps and photography are most often too small scaled for detailed landform analysis, these deserts represent poor choices as study areas for the development of dust-propensity methodology. In addition, these deserts are also remote and hostile, factors that render the field program phase of the methodology logistically costly and time-consuming, diplomatically complex, and militarily hazardous.

11. The practicable alternative for the development of this methodology is to select an accessible, convenient, and available area for which sufficient reference materials, maps, and photography exist in required detail. In addition, the area must be representative of the previously mentioned middle latitude deserts insofar as having high degrees of analogous landform components and surface conditions.

12. YPG in Arizona meets most of the above criteria. Since it is a US military reservation, there is no problem with access for the purpose of data collection and model validation. A mission of the YPG is to support various types of vehicle testing on desert courses. The YPG contains a diversity of desert landforms that have been determined to have analogous counterparts in the African and Asian deserts. Important landforms not found in YPG, such as playas and sand dunes, occur on other military reservations in the Southwestern United States and are available for field examination and testing if necessary.

Reference Material for Desert Studies

13. Desert areas are among the most poorly documented in the world, since they support sparse populations and are little used for agriculture. Sources of these documents may vary widely from one area to another and will not be included in this discussion. However, the various types of references

that are required for studies of deserts are outlined below and discussed in detail in Appendix A.

- a. Climatic reference material. These references include maps, reports, historical data on temperature and rainfall, and paleoclimatic information of the pleistocene epoch and tertiary period.
- b. Physiographic references. In addition to studies and reports, these may include small-scale maps and aerial imagery.
- c. Geologic references and maps. Geologic references may be subclassified under structural geology, stratigraphy, lithology, and origins and depositional history of Quaternary deposits. Geologic maps, usually small-scale, may be useful in conjunction with the references and topographic maps.
- d. Vegetation reference material. References on vegetation may come from several sources, such as texts on climatology or physical geography. They provide information that is useful in identifying landforms and surface soils and soil conditions.
- e. Hydrologic reference material. This is usually extracted from topographic maps and aerial imagery and is examined at both regional and local levels to identify major geological features and individual landforms. Drainage-pattern classifications are shown in Figure 2. Drainage patterns are useful in the identification of both depositional and erosional landforms on topographic maps and aerial imagery.
- f. Topographic reference material. Topographic maps, from small- to large-scale, are available for most land surfaces. In addition to their informational content, they serve as base maps for the portrayal of geologic and terrain data.
- g. Pedologic references. These consist of maps and reports, mostly on agriculture and engineering activities. Classifications vary widely and must be converted to US Classification System (USCS) textural terms.

Data Requirements for US Study Areas

14. Several types of data are considered necessary for detailed studies such as this, in which individual landforms are identified and their surface characteristics are described. Sources of these data, which in some instances did not completely cover the study area of this report, are outlined in the following and discussed in detail in Appendix B:

- a. Large-scale topographic maps and aerial imagery. The imagery should preferably be color and infrared.
- b. Reference material. References, discussed in general terms in Appendix A, should include detailed soil and geology reports.

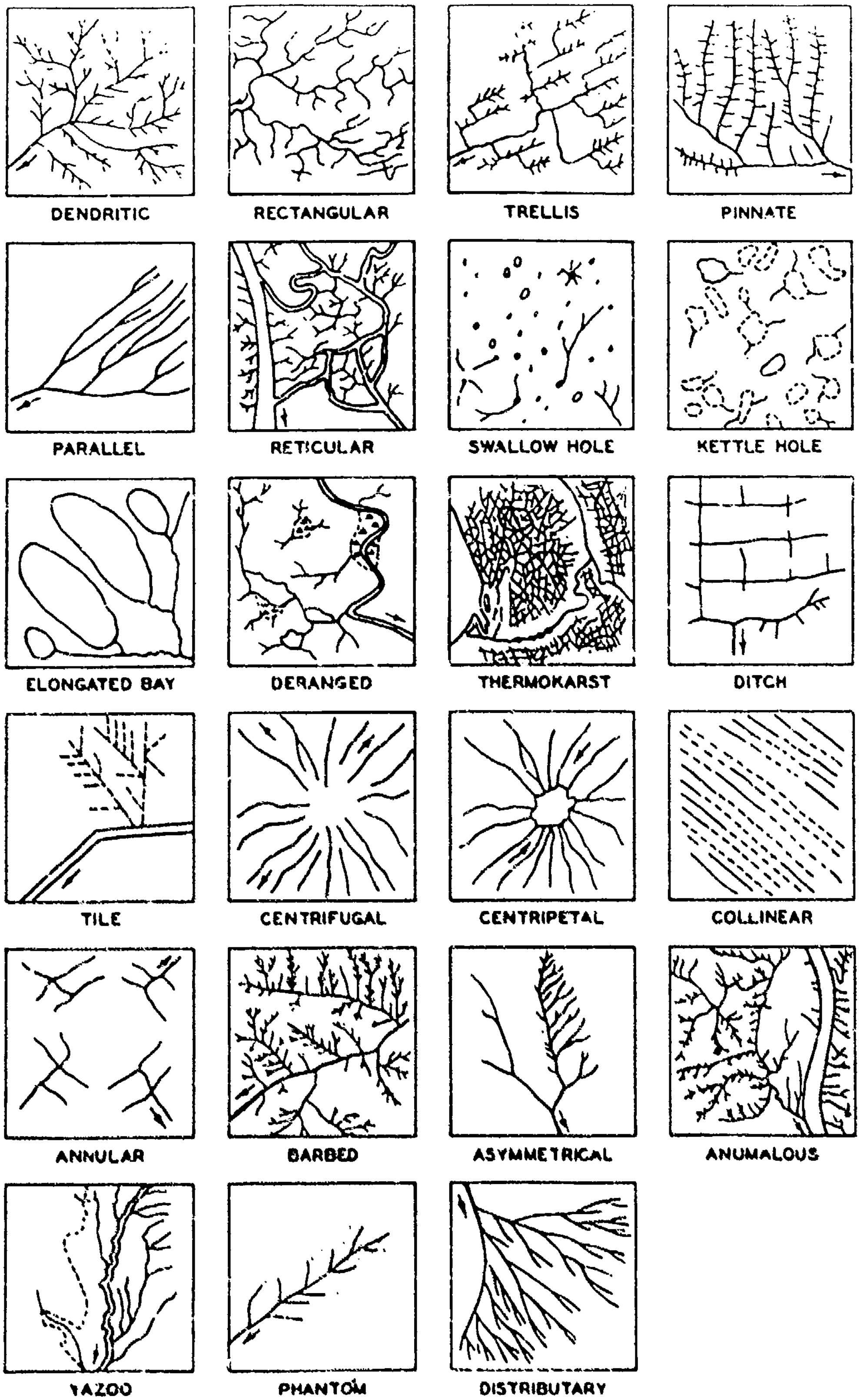


Figure 2. Drainage pattern types (Parvis 1950)

c. Personal contacts. Experts in the fields of geology and oils may be identified in a literature search.

d. Field program. Reconnaissance and data collection aid immeasurably in the establishment of ground truth for a study area.

Characterization of Landforms

15. Once the YPG was selected as the study area for the development of the preliminary methodology, an evaluation was made regarding reference material and data that were readily available. While the maps, photography, reports, and field data failed to meet the minimum requirements for conducting a detailed analysis of a study area, they were thought to be adequate for the scope of the current study that is to serve as a pilot for subsequent studies in the United States and in remote desert areas of the world.

16. A list of references is included in the Bibliography itemizing the maps, aerial photography, and soil, geological, and terrain reports that were used to characterize the landforms occurring at the YPG. No field program was possible during this preliminary phase of the study. As a result, many of the attributes associated with the component landforms were interpreted from the topographic maps and the aerial photography. Soil texture, the overriding landform attribute relating to dust emission, was estimated by associating individual landforms with soil survey reports covering portions of the YPG. A limited field program to collect ground truth data for validation purposes is a recommendation of this study.

17. The following procedures were used to analyze and evaluate the various processes and attributes related to the physical character of the various landforms.

a. Determination of geologic age. This determination is important both for consolidated materials (i.e., rock) and unconsolidated deposits. In the case of the former, age will provide some insight as to degree of weathering, as evidenced by maturity of drainage patterns and thickness of weathered deposits that flank outcrops. Age of unconsolidated deposits will in most cases be either Recent (Holocene) or Pleistocene. In deserts, Recent deposits developed mostly under arid climatic conditions; the soil profiles are immature and lack well-defined A, B, and C horizons. They generally occupy the lowest topographic positions. Pleistocene deposits were formed under more humid climatic conditions and are much older geologically, i.e., from 12,000 to 2-M years ago. Resultingly, profiles are much better developed with distinct A, B, and C horizons. The B or illuvial horizon is comparatively rich in clay-size particles, reflecting the more prominent role of chemical weathering during humid climatic cycles. These relict soils occur at higher elevations and topographic positions than the arid, Recent soils. Landforms, whose pedologic characteristics were formulated during distinct stages of geologic time, will be identified and described later in this methodology.

b. Geomorphic processes. Geomorphic processes refer to the physical or natural processes, residual, erosional, or depositional, which have produced the Recent and Pleistocene landforms and their associated soils. The five processes considered to be responsible for the landforms and soils occurring at the YPG are: (1) alluvial, (2) residual, (3) colluvial, (4) aeolian, and (5) lacustrine. These are discussed briefly to demonstrate their relevancy to the identification of landforms and soils. They will be treated in greater detail later in discussions pertaining to photo-interpretation keys for the identification of landforms and soils that have been produced by each of these processes.

(1) Alluvial process. The alluvial process involves the transport of weathered materials from their places of origin downslope by the action of running water. This water, resulting from desert rainstorms, moves downslope in established channels, across interfluves as sheetwash, and percolates downward through the sediments where porosity and permeability will permit. Since the intensity of desert rainfall will vary from one event to another, both the quantity and size of the particles that are transported will vary widely. At the YPG, the alluvial process is most active in the evolution of alluvial fan and apron deposits extending outward from the basin ranges that occur in parallel northwest-southeast sequences across the area. The texture and depth of these deposits vary widely from one locale to another, being primarily functions of geologic age and parent materials from which they were weathered. However, without exception and regardless of parent material, the coarsest particles are found near the apex of the fan and the finest at the toe. The alluvial process is responsible for floodplain deposits along major rivers and relict terrace deposits occurring adjacent to the floodplains but at higher elevations.

(2) Residual process. The residual process involves the weathering of the parent materials, usually rock, either mechanically or chemically, in situ. In desert environments, rocks disintegrate mechanically, and very little chemical weathering takes place. Since particles less frequently disintegrate to grain sizes smaller than silt, clay-size particles are seldom dominant in modern desert soils. However, since many of the alluvial fan and terrace deposits are Pleistocene in age and consequently were formed under a more humid climate, clay contents are

resultingly higher in these deposits. In deserts, since erosion generally removes weathered material at a faster rate than it can accumulate, residual deposits are comparatively thin, and the fraction that remains at the point of origin is composed predominantly of sandy gravels and cobbles with stones and boulders frequently associated. It should be briefly mentioned here, as it will be discussed in greater detail later in this methodology, that the mechanical weathering of rock in a desert environment is dependent largely upon the lithology of the rock and the joint patterns. Joint patterns are the net result of the lithology, formation thickness, and tectonic stresses that were acting upon the rock during the geologic time prior to its outcropping by faulting or other tectonic or weathering processes. The nature of residual deposits, in addition to the influences of lithology and jointing, is controlled by the degree of inclination of the slopes on which the weathering takes place and the degree of removal of fines by combined alluvial and aeolian action. Slope will influence the gravitational movement of particles downslope. Where residual deposits have surfaces composed of large angular fragments, entrapment of wind-transported fines from rich sources in close proximity occurs. In such situations, the fine fraction of the deposits may appear to be somewhat disproportionate.

(3) Colluvial process. The colluvial process involves the downslope movement of weathered particles from their point of origin, i.e., movement of the parent materials by gravitational forces. In deserts, deposits known as talus flank steep rock outcrops and, depending upon the angularity of the fragments, may equal or even exceed the angle of repose, i.e., 33 deg. These deposits are composed almost entirely of rock fragments, although wind-deposited fines may occur in the voids between fragments. It is quite possible for both colluvial and alluvial processes to be in action on the same landform. Material, usually unsorted and moving downslope by gravitational forces, may be modified by the action of rainwater and the finer fraction removed and transported, often great distances. The colluvial process plays only a minor role in the evolution of the landforms occurring at the YPG.

(4) Aeolian process. The action of wind winnows fine particles from surface deposits and transports them until the velocity is checked and the particles deposited against barriers, on surfaces with covers of large rock fragments, and against desert vegetation with the higher, denser populations receiving the greater volumes. Sand is seldom moved great distances by air currents but characteristically is moved along the ground in the direction of the prevailing wind. Thus, dunes are formed and continue to migrate until stabilized by vegetation. It is thought that relatively large volumes of silt and clay have been

removed from the floodplains of the Colorado and Gila rivers and have enriched the fine component of certain YPG landforms. The actual percentage of the fine component of surficial soils and deposits occurring at YPG that can be attributed to wind deposition cannot be determined. Deposits containing particles with mineralogies dissimilar to local parent materials from which the alluvium or colluvium is derived can probably be attributed to wind deposition.

(5) Lacustrine process. Lacustrine deposits within the general area are represented by fine-grained deposits that have filled Pleistocene lake beds and composed the associated terraces that represent once high lake levels. Many playas in the southwest desert areas have been formed by lacustrine processes during the Recent age. Others, however, represent remnants of once extensive Pleistocene lakes. The soils reflect the nature of the parent materials, which surround the basin, often mixed with salts that have been drawn from depth by capillary action. These surfaces are not protected from the wind, and thin veneers may be stripped off and transported to landforms with surfaces suitable for receiving the material.

c. Topographic expression of landforms. Topographic expression is essential not only to the identification of landforms but also to the determination of the variations of the terrain factors that compose the landform. Through the determination of often subtle distinctions regarding time, texture, and geometry within landforms, meaningful subdivisions of homogeneous associations of slope, parent materials, soils, vegetation, and drainage are possible.

(1) Slope. Slope can serve as a diagnostic parameter in the differentiation of landforms. Individual landforms are characterized by ranges of slope values as a function of time, processes, and parent materials. Erosion and deposition are continually at work modifying the physical character of landforms. Since erosion in desert areas proceeds at a much faster pace than soil formation, these residual materials are rapidly removed and transported downslope by alluvial and colluvial processes. Particle-size distribution and distance transported are functions of the intensity of individual climatic events, i.e., rainfall that may vary enormously from one event to the next. The net result is the transport and sorting of sediment downslope as a function of slope and particle size. With time, the depositional environments become filled to capacity, and slopes are accordingly lessened, thereby substantially decreasing the sorting efficiency of gravity.

(2) Relief. Relief is also a diagnostic parameter that is useful in the differentiation of landforms. Slope and relief combine to effectively separate landforms into two

general categories: mountains, hills, and plateaus, which represent the parent materials of desert soils and from which they are continually being removed by the processes of erosion; and plains and associated low-relief landforms, which are the net result of depositional processes acting upon unconsolidated materials eroded from high-relief areas composed of rock parent material. This distinction is considered an important one as high slope, high relief areas of rock with thin, stony residual soils are considered in this study to be areas of low dust propensity. In addition, except for occasional passes and man-made routes, they are largely no-go areas for vehicular mobility. The distinction between these basic types of landforms can be effectively made from large-scale topographic maps, i.e., 1:25,000 to 1:50,000, and to a lesser degree of accuracy from medium-scale maps, i.e., 1:250,000, etc. Further distinctions within these highs is possible from the combined analysis of the best available geologic maps and aerial imagery.

(3) Dissection. Dissection or drainage patterns considered on a gross scale are indicators of the nature of the materials or geologic age of the region. Local drainage patterns can be related to particular landforms and the materials that compose them. In addition, the depth of dissection is an indication of the depth of the sediments that compose the landform. Determination can be made as to whether drainage patterns are incipient, mature, or abandoned. Some appear subdued and only subtly discernible on aerial imagery, an indication of older and perhaps stable landforms of Pleistocene age.

d. Vegetation species, distribution, and density. These vegetation parameters may be diagnostic to the recognition of desert landforms and to the nature of the soils or surficial deposits that compose them. Certain species are related in their occurrence to intricate combinations of soil type, moisture content, slope, elevation, and even the degree of incidence of solar radiation. Many occur in diverse environments while others occur in unique assemblages characteristic of certain landforms. These associations become evident through extensive ground reconnaissance but more expeditiously by large-scale aerial imagery flown if possible during a period following heavy spring rainfall. Where relatively dense populations of desert shrubs occur in environments with suitable combinations of soil, slope, and ground moisture, entrapment of wind-transported fines is more likely to occur, provided a source lies in close proximity.

e. Drainage characteristics. Drainage has been previously discussed under topographic expression. Three important aspects of drainage are considered here to be worthy of repetition.

(1) Indicator of landform. Through combined map and imagery analysis, drainage pattern indicates landform and its

associated soils. Ground reconnaissance affords the only means of validation of soil predictions.

(2) Degree of development. Maturity of drainage patterns may be used as a general indicator of geologic age. Incipient or immature patterns suggest recent development while shallow, nonintegrated or abandoned channels are characteristic of relatively old landforms. The fine component of soils associated with landforms in different stages of development, as indicated by drainage patterns, may vary significantly.

(3) Depth of dissection. Depth of dissection and cross-sectional configuration of drainageways on a landform provide clues as to the textural nature of the soils. The cross sections of drainageways also provide clues as to the material they have eroded. V-shaped channels, for instance, generally indicate noncohesive, granular materials such as might be found on many alluvial fan surfaces. Channel cross sections are difficult to determine on imagery due both to the scale factor and the presence of relatively dense vegetative populations along the banks.

f. Soils. Soils are the dominant attribute of desert landforms that affect the emission of dust. Specifically, the upper 4 in. of the profile is thought to be the critical layer that interacts with the passing tracked vehicle. Similar to other landform attributes such as topography, vegetation, and hydrology, soils can be expressed in terms of several interdependent parameters, such as consistency, structure, texture, layering, moisture, etc., which affect the degree of emission from the surface. Since only the upper 4-in. layer is involved in this study, the parameters, structure, consistency, and moisture are not considered of primary importance. Layering is important since often a veneer or crust of a texture markedly different from the underlying horizon may be present, as, for instance, where a thin veneer of desert pavement overlies silt-sand mixtures. Texture is the dominant parameter that determines dust emission. The grain-size distribution of the upper 4 in. of the soil profile can be expressed in percentages of gravel, sand, and fines, i.e., silt and clay. It is the fine component that is disbursed into the atmosphere in the form of dust. Unless soil maps are available for the study area, soils are the most difficult attribute to determine from topographic maps and aerial photography. On aerial photographs, only tones provide any clue as to the identity of surface soils, and the photographic tone/soil texture relationship is a general one at best. Unless field data or detailed soil maps of the study area are available, soil can be determined only by its association with parent materials, topographic parameters, and vegetation.

(1) Parent materials-soils relationships. Parent materials can be determined from geology maps and/or aerial imagery.

The most desirable relationship occurs when the weathered products of hills and mountains or other landforms, which may represent parent materials, have been deposited downslope in close proximity to the source. Unfortunately, rocks are not always exposed at the surface in discrete units but rather in complexes, one type overlying another or occurring in contiguous outcrops. The mixing of the weathered products of these rock complexes by colluvial and alluvial processes results in depositional sequences of a composite nature. The greater distance the materials are from their points of origin, the more intricate the mixing. Where deposits can be attributed to a single parent material or rock type or where a certain rock is dominant, confident estimates of soil textures, distribution, and consistencies are possible. For example, soils occurring on alluvial fans that have been derived from granites or granite gneisses can be expected to be sandy in texture with few fines and fragments larger than cobbles. Soils derived from recent volcanics such as basalts can be expected to contain a higher percentage of coarser, angular fragments.

(2) Slope-topographic position-soils relationships. Slope and gravity effectively sort weathered materials as a function of their texture in a downslope direction. This sorting process is expedited by the heavy, albeit infrequent, desert rainstorms. Since these rainstorms vary significantly in their intensity from one event to the next, the runoff will vary in volume and velocity downslope. Thus, textures become mixed. Generally, textures near the apices of fans are coarser and more angular and the slopes steeper. Textures at the toes of the fans are comparatively fine, e.g., fine sands with varying percentages of silt and clay. The topographic position along the slope profile from the apex to the base is useful along with elevation in establishing the relative age of depositional landforms such as fans and terraces. Landforms of the same type, such as alluvial fans, may differ significantly in their textural characteristics.

(3) Vegetation-soil relationships. Generally vegetation species can be correlated with landforms. Since vegetation is related to physical terrain parameters, similar populations can be expected where slope, soil texture, soil moisture, porosity, and heat energy exert the same level of environmental influence. These parameters are interrelated, along with others such as topographic position, elevation, and topographic aspect, so it is impossible to weigh each parameter separately. Soil moisture is the overriding environmental parameter for plant growth and dissimilarities within the same landform unit can usually be attributed to moisture variation. Still, generalizations are possible, and crude correlations between landforms and plant populations are often useful

indicators of soil texture if certain of the other environmental parameters can be approximated. Since moisture levels are basic to the existence of all plant life, the densest concentrations can be expected in areas where levels are the highest. In deserts, these areas occur in and along the washes that carry the runoff of desert storms. This association greatly enhances the recognition of the drainage features both on the ground and from aerial imagery and enables analysis of the pattern and density of the integrated systems. These patterns and their textures are diagnostic of the nature of the parent materials that the drainage features have dissected. Without the benefit of large- to medium-scale photography or ground reconnaissance, vegetation analysis would not be a possible means of landform analysis and identification in world desert areas.

Landform Descriptions and Photo-Interpretation Keys

18. Desert landforms are physical features, either erosinal or depositional, which are repetitive in nature and predictable in terms of attributes regarding their geometric, hydrologic, pedologic or lithologic, and vegetative characteristics. By reason of this consistency in their characteristics, they are, to a degree, recognizable in the field, on maps, and on aerial imagery wherever they occur throughout the desert regions of the world. There are, however, internal variations in regard to their physical attributes that are controlled by local climatic and geologic conditions. For the purposes of this study, it was first necessary to establish criteria for the recognition of individual landforms and then, considering current and ancient climatic effects, dominant geomorphic processes, parent materials, and other lesser (but often significant) factors, to characterize these landforms in terms of geometric, hydrologic, vegetative, pedologic, and lithologic attributes relevant to dust development and accumulation. Descriptions of desert landforms occurring at or near YPG are detailed in Appendix C. YPG landforms are listed in Table 3.

Terrain Attributes Relevant to Dust Emission and Development of Procedures for Their Determination

19. Landforms have been determined as the basic element of terrain whose component attributes are consistent throughout its realm of occurrence

provided the climatic and geologic factors, which control its genesis and evolution, remain the same. Variations in climate and geologic materials result in often significant differences in such attributes as vegetation, surface composition, dissection, and hydraulic characteristics of the surface. However, at the YPG, climatic conditions are not variable since the entire area falls under the same climatic regime. Variations that do not occur in certain attributes of a particular landform are the result of variations in parent materials, physical processes, and situational factors such as topographic position, aspect, orientation, etc. If the factors that control the genesis and evolution of desert landforms are known, then it is possible to characterize the landforms in terms of their component attributes. When the details of the source materials are known, then characterization of the landforms is resultingly detailed and reliable. Among landform attributes are those relating to dust propensity. In the following paragraphs, those attributes that influence dust accumulation in terms of origin and quantity, as well as the attributes that influence dust emission resulting from natural or man-made activity, are discussed.

Landform Attributes Influencing Dust Accumulation

20. The allochthonous mode of dust accumulation considers both the contributions of fluvially transported sediments and those of aeolian origin. The actual determination of the percentage of fines occurring in a soil profile that can be attributed to residual, alluvial, or aeolian origin would require extensive field sampling and subsequent laboratory analysis and is beyond the scope of this report. However, to promote a better understanding of the accumulation of dust in desert landforms, these three modes of origin are described:

a. Residual dust. These particles, less than 74 μ, form in place from the weathering of the rock. In humid climates, chemical weathering is the predominant process for the production of fines from rock. In desert environments, due to the comparatively low moisture levels, chemical weathering is subordinate to mechanical weathering. The initial mechanical weathering occurs along joint planes, separating the rock into blocks or slabs ranging from several inches to several feet. Further disintegration occurs as a result of heating and cooling, freezing and thawing, and wetting and drying processes. Mechanical weathering alone would result in gravel and cobble soils with mixtures of sand and silt and a subordinate percentage of clay. Chemical weathering is an active process in deserts, although its weathered products represent a small fraction of the soil profile. Of far greater importance are soil profiles that were developed during the Pleistocene Epoch, when more humid climates prevailed. Relict Pleistocene landforms are frequent occurrences and are widely distributed throughout the YPG at present. However, except for some hill slopes, most residual Pleistocene landforms have been modified by recent erosional and depositional processes.

b. Alluvial dust. Alluvial dust or fine-grained sediment, i.e., less than 74 μ, is transported material of either residual or aeolian origin. The latter may consist of either mineral or salt particles, the former being predominant. The transported materials wash from upslope sources that may be residual, colluvial, alluvial, or eroded aeolian materials mantling existing landforms. With time, much of the fine-grained component of the alluvial soils will percolate downward in the soil profile, the B horizon having a higher silt-clay content than the A horizon. This relationship is comparatively more prevalent in Pleistocene landforms than in other Paleoclimates. Salts also permeate the profile and are derived primarily from the leaching of salt-rich igneous rocks in the adjacent uplands, with secondary enrichment from windblown materials that may have immediate or distant origins. At the YPG, carbonates are the prevalent type and with time may develop an indurated layer of calcium carbonate known as caliche. Where it occurs at or near the surface, it can contribute substantially to the total dust emission volume when stimulated by some activity such as vehicular passage. At YPG, landforms contain no more than 1-percent carbonates in the top 10 cm of the soil profile. Greater percentages do occur with increase in depth in some of the older landforms, e.g., Pleistocene alluvial fans.

c. Aeolian dust. Dust or fines of aeolian origin represent a significant percentage (often several percent) of the surface soils of desert landforms. The dust may have been deposited directly as a result of reduction in wind velocity or contact with a surface obstruction. The silt component of dust ranges in diameter from 2 to 74 μ while the clay consists of diameters less than 2 μ. It has been estimated that 80 percent of the dust found at YPG is of silt size (the other 20 percent being 10-percent fine sand and 10-percent clay) and that 80 percent of this amount is composed of quartz, with the remainder primarily calcite and feldspar. Approximately 1 percent of the total amount is composed of salt or carbonates. Generally, the medium- and coarse-grained silt is composed almost entirely of quartz, while the fine component is composed of calcite, feldspar, and salt.

21. The quantity of dust that will accumulate on a particular landform is related to certain general climatic, geologic, and time controls and to specific attributes of the various landforms themselves. These general and

specific controls and attributes are discussed briefly in the following paragraphs:

a. General controls.

(1) Climate. Both modern climates and paleoclimates must be considered when determining dust accumulation. Paleoclimates older than Pleistocene are not considered significant. However, knowledge of Recent and Pleistocene climatic regimes is necessary to assess the nature and quantity of dust deposition in a particular desert area. The modern climatic history is necessary to determine wind directions and velocities throughout the year, the amount and distribution of precipitation in respect to its effects upon weathering and erosion, and temperature and precipitation regimes and their effects upon the evolution of vegetation and soils.

(2) Geology. Geologic structure and lithology, together with climate, control the development of landforms and the surface soils that are characteristically associated with them. Faulted and folded rock masses resulting from tectonic activity produce hills and mountains, while rock formations not contorted by internal pressures may remain in horizontally stratigraphic depositional sequences, or they may have been reduced by erosion to the peneplain stage of the geomorphic cycle. The Basin and Range Province, in which the YPG is geographically situated, has been intensively faulted, resulting in a more or less parallel sequence of hills and mountains thrust upward to elevations of thousands of feet. The weathered debris from these uplands has, over extended periods of geologic time, provided the parent materials for the depositional landforms that, together with the uplands, comprise the terrain at the YPG. The lithology of the rocks composing the hills and mountains controls the physical character of the weathered debris.

(3) Time. Time is an important consideration both in regard to climate and to geology. The importance of climate and geology has been previously discussed. The two conspire to produce landforms that develop over extended periods of geologic time. With the exception of the hills and mountains occurring at the YPG, which are Tertiary or older in age, the remaining landforms are Recent or Pleistocene in age. The age distinction is a necessary one in landform identification, since surface material, soil profile, and depth of dissection may differ markedly as a function of age.

b. Specific attributes. These landform attributes directly affect the amount of dust or fines occurring in the soil profile. They are not unique to a particular landform but collectively interact to produce environments that have predictable levels of efficiency for the accumulation of dust. Landforms, analogous in terms of previously discussed general genetic factors or controls and these specific attributes, may be expected to have comparable levels of dust in their soil profiles.

(1) Texture. Desert soils can be divided into three categories according to grain size: fines, i.e., silt and clay, sand; and gravel and rock fragments of greater diameter, such as cobbles and stones. The higher the percentage of the gravel-plus component, the greater the capacity of a soil to trap dust particles. If two landforms have approximately the same percentage of surface gravels, the older of the two, e.g., Pleistocene versus Recent, can be expected to have the higher associated percentage of fines. Texture is more accurately determined in the field through the use of selected sampling procedures. Sample sites should be related to landforms and subdivisions of landforms. Classification should be determined through use of standard USCS sieves, the No. 4 separating the gravel component from the sand and fines and the No. 200 separating the sand from the fine component. Sample sites should be correlated with tones displayed on aerial imagery. Texture can be determined exclusively from aerial imagery without field validation if relatively high levels of generalization are acceptable. Generally, light tones are indicative of coarser textures and dark tones, fine textures. However, the almost total absence of moisture in the surface soils results in lighter tones overall. The surface of a playa is composed of fine silts, clay, and salts and, unless moist, appears white or light gray on aerial imagery. Determination of the parent materials of desert landforms is useful in determining texture, since the weathering characteristics of specific rock types are predictable. In remote desert areas with only medium- to small-scale maps available and possibly small-scale imagery, texture determination is possible only through the identification of landforms and associated parent materials.

(2) Surface roughness. Surface roughness is a measure of the microtexture of a surface or the amplitude and frequency of small relief features that characterize a surface. This texture may result from the dense occurrence of rock debris such as boulders, stones, and cobbles, shrub-coppice dunes, or may be ingrained in the surface of the landform itself. An example of the latter would be an intricately dissected upper portion of an alluvial fan. Whatever the origin of the microrelief features, the net effect is entrapment of dust particles. The efficiency of the surface as a trap increases as the amplitude and density of the obstacles increase. Determination of roughness can best be determined in the field using the root-mean-square (RMS) method. This procedure requires taking elevation measurements along a traverse of

approximately 300 ft at 1-ft intervals. The differential between successive elevations is calculated. These incremental differences (X_i) are then used in the following formula to determine the RMS of the traverse:

$$\text{RMS} = \frac{\sqrt{\sum_{i=1}^{n} X_i^2}}{n}$$

Values range from 0.1, on an almost perfectly smooth surface, to 5.0 or higher on a surface with a high incidence of boulders and stones. It is doubtful if roughness could be adequately determined from even large-scale aerial photography. Intricate dissection should be identifiable, but measurement of the depth would require time-consuming and costly photogrammetric methods. Roughness can be predicted by knowledge of landforms in a particular area, the nature and proximity of parent materials, slope, topographic position, age of the landform, and the nature of the soils that compose the landform. The method mentioned last would be most applicable in remote desert areas with only small- to medium-scale maps and photography available.

(3) Porosity and permeability. These parameters are measures of the percentage of pore space between soil particles and the degree to which these pore spaces are interconnected. They control the efficiency with which surface water, laden with fines, will percolate downward through the soil profile and deposit portions of its fine load. Ultimately, the pores become clogged, and the surface waters that normally penetrate the profile remain at the surface as runoff, carrying with them the suspended fines. Accurate determinations of porosity and permeability can be made only from field samples. Acceptable estimates can be made by associating soils with particular landforms. The age of the landform is an important consideration, since older landforms such as Pleistocene alluvial fans may have become impermeable. Since there is a high level of correlation between porosity and permeability and the grain-size distribution of soil profiles characteristic of desert landforms, the procedures described above for texture would apply provided field sampling is not feasible.

(4) Gradient. Landforms with high levels of surface roughness, high porosities, and low gradient are most suitable for the accumulation of transported dust. Much of the dust infiltrates the porous silts and eventually forms a B horizon rich in fines, i.e., silt and clay. Steeper gradients have greater volumes of surface runoff and thus less infiltration. Smooth surfaces with low porosities and permeabilities have low potential for the entrapment

of wind and water-transported fines. Landforms with steep or abrupt slopes oriented transverse to wind transporting fines from copious upwind sources, such as playas, intercept proportionally larger quantities than landforms with orientations parallel to the wind. If the receiving surface is smooth and unvegetated and has low porosity, the deposited materials will not accumulate over a period of time. Gradient or slope can be determined from large-scale topographic maps or photogrammetrically from aerial imagery. However, measurements can be most accurately taken in the field. If neither of the above methods is possible, as might be the case in a remote, inaccessible desert area, slopes can be approximated by identification of their relative position along the longitudinal axis of the landform. For example, the upper slopes of alluvial fans may exceed 15 to 20 percent while the toe slopes are characteristically 1 to 2 percent. Gradients in central portions of the fan could be estimated as 7 to 10 percent.

(5) Aspect of orientation. Landforms occurring on the sides of hills or mountains, or those sheltered from prevailing moisture and sediment-laden winds, reveal significant dissimilarities in the thicknesses of the resulting soils, their moisture regimes, and the types and abundance of vegetation they support. Also landforms sheltered by steep east-west trending ridges in the middle and northern latitudes receive minimal solar insolation and thus have higher moisture regimes and more prolific vegetation populations. The direction of the prevailing winds can be determined from climatic records of the particular desert area. The aspect or orientation of the landforms can be readily determined from large-scale topographic maps or aerial imagery.

(6) Vegetative cover. The denser and higher the vegetative populations on the surface of a landform, the greater the efficiency of the landform for the entrapment of transported dust. Vegetation serves a purpose similar to surface roughness, and the two features conspire to increase the dust entrapment potential of a surface. Roughness is most severe on steep, upper slopes with a low moisture regime and thin soil cover, a combination of attributes that characteristically supports relatively thin populations of vegetation. The distribution and density of vegetation can most effectively be evaluated from large-scale aerial imagery. Specie determination and determination of plant height and diameter require onsite observation. Classic associations of vegetation species and landforms are known for the YPG; however, these associations are not known for remote world desert areas. Since vegetation populations are not readily discernible on small-scale aerial imagery, characterization of landforms in remote desert regions would rely primarily on written accounts.

Considering the variability of the attributes that interact to control the accumulation of fines in the soil profile of different landforms, accurate prediction of texture is possible only under the dominant influence of a single attribute or a clearly definable combination of attributes.

Specific Attributes Affecting the Propensity for Emission of Dust from Desert Soils

22. The following are attributes, both natural and man-made, that directly influence the propensity for dust from the surface of desert landforms.

a. The quantity of fines occurring in the top foot (4 in. for this study) of the soil profile. This measurement includes the surface crust, if present, and the immediate underlying layer. For tracked vehicles, single pass, the top 4-in. layer is considered the most relevant. If the remaining fraction of the soil is predominantly gravel and cobble-size fragments, a different emission rate might be expected than if the remaining fraction were made up entirely of fine sand.

b. The degree of cohesion or induration of the surface soils. Cohesive soils would have lower emission rates than noncohesive soils under ordinary circumstances. The driving power of a tracked vehicle should minimize the difference substantially. If the cohesion is moisture-related, the particles driven into the air will have a stronger tendency to remain aggregated. In some cases, indurated layers of calcium carbonate or gypsum composed of cemented fine particles may lie at or near the surface and will produce lower emission rates than noncohesive soils.

c. The nature and effectiveness of the surface layer. The surface layer, in this context, includes such phenomena as partial or complete layers of gravel pavement, hard-to-firm crusts on playas and loess plains, and dense populations of cobble and stone-size rock debris. However, the degree to which this surface layer of rock debris of various densities affects the emission rates of underlying fines when stimulated has not been conclusively determined at this time.

d. Vegetation. Landforms with dense populations of grasses and low shrubs would to some degree suppress the emission of dust from the surface layer. This deterrent effect would result from the combined action of the exposed portions of the plants and root systems.

Evaluation of Interaction of Terrain Attributes as They Affect Levels of Dust Emission

23. For the purposes of this study, the overriding attribute of desert landforms that affects dust emission is soil texture, specifically, the percentage of the upper layer of the soil profile that is composed of fines, i.e., silts and clays. For the tracked vehicles that are considered in this study, the upper 4 in. has been determined to be the critical layer. The quantity of fines in this upper layer, which is available for emission under the influence of a driving agent, is called the silt load. The dispersal of fines into the atmosphere when this layer has been disturbed would result from a pure relationship between the percentage of fines in the layer and the driving force if it were not for other attributes of the landform that singularly or collectively inhibit the level of emission. These attributes and a qualitative assessment of their effect upon dust emission from different landforms are discussed as follows:

a. Soil consistency. For optimum emission, when sufficiently stimulated, noncohesive soils have the highest potential provided that other landform attributes have no or minimal influence. Soils with more cohesive consistencies resulting from temporarily higher moisture regimes may range from friable to hard. Soils with hard consistencies are less prone to disperse into the atmosphere as individual particles than soils with loose consistencies if comparable driving forces are applied.

b. Soil layering. Since the upper 4 in. has been determined to be the critical layer for producing the dust cloud resulting from tracked vehicular traffic, this layer most often displays few dissimilarities in either texture or consistency. However, the surface itself is often veneered with a thin layer of desert pavement or a loose veneer of rock debris of assorted sizes. These surface veneers, to a significant but as yet undetermined degree, suppress optimum emission of the fine component into the atmosphere.

c. Soil mixtures. For a given percentage of fines in the top 4 in. of the soil profile, there may be a highly variable mixture of the remaining particles in regard to grain size. For example, if the silt plus clay fraction is 25 percent, the remaining 75 percent may be pure sand or sand-gravel mixtures. The proportion of fines, sand, and gravel in the profile affects the emissivity of dust into the atmosphere. In addition, larger-than-gravel sizes may also be included in this interval and further confuse the rate of emission. Accurate assessment of the effect of particle mixing will require field testing under carefully controlled conditions.

d. Slope. Slope indirectly affects dust emission so no pure mathematical relationships are possible. There are linear relationships between slope and particle size, soil moisture content, and the incidence of rock debris over the surface of the soil. To a lesser extent, vegetation is influenced by slope since high slopes with rock outcrops and dense populations of stones and boulders and thin soil are sparsely vegetated.

e. Vegetation. While vegetation is a critical landform attribute on certain desert landforms where soil and moisture conditions combine to create a favorable environment for dense populations, the landforms occurring at the YPG are, for the most part, too sparsely populated for plant life to have a significant effect upon dust emission. Loess plains occurring on the margins of deserts support stands of grass of such density as to have measurable effects upon dust emission. Vegetation accumulates wind-transported fines and often deposits shrub coppice-dunes and such, which may reach heights of a metre or more.

24. There is little doubt that combinations of different values of the five desert landform attributes (paragraph 23) would create a wide range of dust emissivity levels. For example, soils composed of 100-percent fines that are loose, dry, and unvegetated and are without an overlying veneer of gravels or rock debris would create the optimum scenario for dust propensity. However, such a situation occurs very rarely in nature, so the interaction of the various attributes always conspires to produce a scenario that results in less than optimum dust emission. Since the individual contribution of each attribute as it affects dust propensity has not been determined, it is necessary to base predictions on the single, overriding landform attribute, soil texture. The remaining attributes are not disregarded, but are considered subordinate factors.

25. Unfortunately, soil texture, specifically the percentage by weight of the surface soil layer, is the most difficult attribute to determine. Only by onsite sampling can exact percentages be determined, and these percentages can vary significantly within a single landform as a function of slope, topographic position, and most important, parent materials. Since it is not feasible to sample each discrete landform unit, the grain-size distribution of the critical layer is determined by analogy. The analogy of landforms is established by analysis of the tonal, textural, and geometric qualities they exhibit on aerial imagery and determination of slope, topographic position, geomorphic process, and parent materials from large-scale topographic and

geologic maps. Even landforms that indicate high degrees of analogy from the analysis of detailed source materials may contain significant variations in the percentage of fines in the surface layer of the soil. However, the greater the detail of the source materials and the more soil samples that have been analyzed for a particular landform unit, the narrower the range for the predicted fines. Predictions within a 5-percent range should be considered exceptionally good.

26. In remote desert areas, the characteristics of landform attributes must be inferred or interpreted from the generalized source material. Predictions of soil texture, which determine silt load, become increasingly less accurate as the quality of these materials diminishes. Thus, lower levels of accuracy in predicting the fine content of surface soils must be expected in remote areas. For example, estimates of the fine content in the surface soils of a particular landform in a restricted, well-documented study area might range from 10 to 20 percent. In a remote, poorly documented desert area, estimates based on generalized references of questionable accuracy might cover a much broader range, say from 5 to 35 percent.

Development of Landform Map for Prediction of Dust Emission

27. The landform is the basic element of the desert landscape, the component into which all physiographic units are divisible. A desert plain, for example, can be divided into alluvial fans and aprons, alluvial flats, terraces, washes, and playas if the drainage within the plain is interior. The landform is defined in terms of geomorphic process or processes responsible for its evolution, geologic time, parent material, and various physical attributes (previously discussed) such as soil, slope, topographic position, drainage, and vegetation. Each landform can be described in terms of these attributes, which are controlled by process, parent material, geologic time, and climate. All landforms are repetitive and predictable features. They are recognizable on topographic maps and aerial imagery. However, internal variations in the physical attributes of landforms result from variation in the controls that influence their evolution. Landforms, such as alluvial fans, can be said to be analogous when they are the same geologic age, formed by the same geomorphic process, and composed of materials eroded from similar parent materials.

28. A military vehicle crossing desert terrain must negotiate a succession of contiguous landforms that have been determined to be trafficable. The vehicle routes will most often occur on lower slopes of landforms whose surfaces are relatively undissected, have a low incidence of surface obstacles, such as boulders, and are sparsely vegetated. Each of the landforms crossed by the vehicle will be composed of soils that are varying mixtures of gravel, sand, silt, and clay. The loose fine material on the surface, or that which can be readily loosened by a tracked vehicle, is designated as the silt load. The silt load, together with other terrain and vehicular parameters, determines the quantity of dust that is lofted by a single-vehicle passage. Predictions of dust emission along a vehicle's route are dependent upon characterization of the individual landforms that are crossed in terms of silt-load values.

29. Time and funding did not permit evaluation of the entire YPG in terms of the dust emission potential of all the included landforms. Following the examination of the geographic limits of the YPG and a preliminary assessment of the availability of maps, photography, and reference material, the approximate western third of the reservation was selected for detailed study. The area, designated on DMATC 1:50,000 map as the Cibola Range, is actually a range map consisting of portions of four 1:50,000 topographic maps. These quadrangles are Picacho (3150 III) NW, Red Hill (3150 II) NE, Red Bluff Mountain (3149 I) SE, and Laguna (3149 IV) SW. Photographic coverage within this area consisted of 1:58,000 color infrared and 1:24,000 black and white. The photography covered only a subordinate portion of the study area. The area was covered by a small-scale geology map of the State of Arizona.

30. Available references, which were used during the study, consisted of US Department of Agriculture (USDA) soil survey reports covering portions of the study area and several terrain studies of the YPG and the desert area of the Southwestern United States. Numerous other references describing conditions and processes relating to desert landforms on a worldwide basis were reviewed. Those that made a significant contribution to the conduct of this study are included in the bibliography (Appendix A).

31. The initial landform delineations resulted from the simultaneous examination of topographic maps and aerial photography. Further definition within major landform types was made on the basis of geologic age, parent materials, topographic position, slope, and drainage patterns. All landform

delineations were made on a transparent overlay of the 1:50,000 Cibola Range map. Landforms identified were alluvial fans, washes, alluvial flats, terraces, sandy plains and low dunes, sandy hills, and hills and mountains. The alluvial fans were subdivided on the basis of geologic age, i.e., Recent or Pleistocene, topographic position and slope, and degree of dissection. Hills and mountains were further subdivided on the basis of rock type or combination of rock types. Examination of the entire YPG indicated that all major desert landforms and landform variants are included in the study area, with the exception of playas and loess plains.

32. Characterization of landforms in terms of the relevant attributes (paragraph 18 and Appendix C) was possible using the photo-interpretation keys described and the soils and terrain reports covering the study area. Descriptions of the soil profiles occurring within individual landforms were based on data included in the soil survey reports. Since these reports did not cover the terrain included in the vehicle route selected to demonstrate the dust-prediction technique developed later in this report, soil characterization of landforms within this corridor was effected by analogy. For example, alluvial fans and washes occurring along the vehicle corridor were determined to be analogous with fans and washes occurring within the area mapped by the soil survey report. The analyses of soils in the mapped area were confidently applied to analogous landforms throughout the study area by reference to the landform map. Since the laboratory analysis of each soil type or series included in the various reports is based on soil samples taken at a number of sites where the host landforms occur, the percentage of fines in the upper 4 in. of the profile is presented as a range rather than as an absolute value. For example, the percentage of fines in the upper 4 in. of the soil profile of a moderately dissected alluvial fan, based on samples taken at 20 separate and widespread occurrences of that landform, may range from 10 to 20 percent. However, since the percentage of fines for each occurrence of the landform is related to such attributes as slope, age, topographic position, and parent materials, this range can be narrowed by considering different combinations of these variables. For instance, the percentage of fines on a fan of Recent age, occurring on a low topographic position, with a nearly level slope and with soils eroded from the same parent materials as the other occurrences, would have a percentage of fines close to 20 percent. If the fans were of

Pleistocene age, occupying an upper topographic position, with a moderate slope, the percentage would be closer to 10 percent.

33. The route selected for the tracked vehicles in this study did not include all of the landforms and variations thereof. Those included within the route are thought to be representative of lower slope landforms negotiable by tracked vehicles. The upper slopes of alluvial fans and hills and low mountains are improbable routes for cross-country vehicular operations, due to the presence of closely spaced obstacles, steep slopes, and intense dissection.

34. The landform characterizations presented in this report are considered tentative. Only limited field data were available to validate predictions and interpretations. It is very desirable that at least a limited field program be conducted at the YPG to validate the methodology prior to future applications in remote desert areas of the world. Figure 3 is a generalized flowchart outlining the methodology developed in this report. The chart identifies different levels of generalization for landform attribute characterization. The chart further identifies the materials and techniques required for the characterizations.

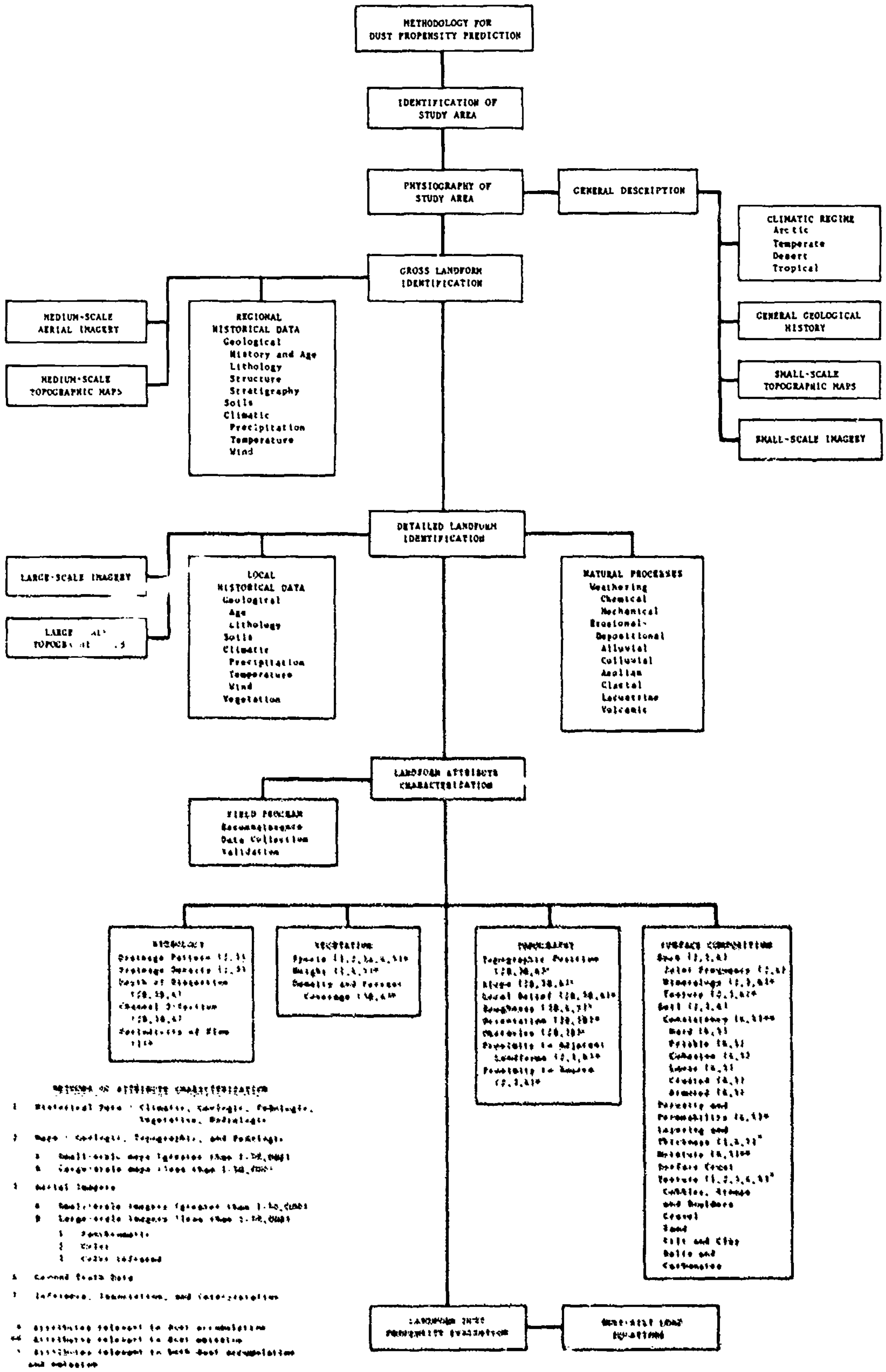


Figure 3. Methodology flowchart for dust-propensity prediction

PART IV: APPLICATION OF DUST-PROPENSITY METHODOLOGY TO WORLD DESERTS

35. As previously stated, dust propensity of world desert landforms may be of vital concern to the military planner. The possibility of a military confrontation in desert regions of Africa or Asia focuses attention on the cross-country mobility capabilities of certain combat and logistical vehicles, both tracked and wheeled. The North African Campaign of World War II established that dust resulting from vehicle traffic had significant effects upon the success or failure of a mission. While dust was recognized as a battlefield problem, no effective solution to its numerous adverse effects has evolved.

36. A practical method for determination of dust propensity for the various terrains within desert regions would represent a significant capability for the military planner. Unfortunately, these determinations may not be feasible in the field during a campaign. Often routes across enemy terrain are not selected until shortly before operations are executed. The best solution to this problem probably requires having dust-emission predictions available in advance. Since the operational environment may be both expansive and hostile, regional evaluation of dust propensity can only be done using remote methods. It is on this premise that the current study has been initiated.

37. Desert regions of the world fortunately have many physical similarities (Table 1). These properties are the result of geomorphic processes acting upon geologic materials under restrictive climatic regimes. In deserts with low rainfall and high temperatures and high rates of evaporation, such as the deserts of the Southwestern United States, northern Africa, the Arabian peninsula, and south-central Asia, strong physiographic similarities have evolved. The YPG has been determined to be representative of the desert region of the Southwestern United States and to have landforms with a relatively high degree of analogy to those occurring in the African and Asian deserts. As a result, it seemed logical that the YPG be selected as the desert study area for the development of the dust-propensity methodology.

38. The scope of this study has been geographically restricted to the western one-third of the YPG (Figure 1). Within this area, landforms have been delineated using available 1:50,000 topographic maps and medium-scale (1:58,000) aerial photography. The landforms have been characterized in terms

of all of the relevant attributes that have been determined to affect dust emission. Dust-emission predictions have been developed for each of the landforms based on consideration of these attributes with particular emphasis on texture or the percentage of fines in the surface soil layer. It is hoped that these emission values will be validated through experimentation at some future date. Refinements are anticipated following laboratory analysis of soil samples that would be collected during a future field program.

39. Dust-emission predictions for each landform are based primarily on surficial silt load. The prediction is modified by vegetative cover and by the presence of a surface gravel or heterogeneous rock debris cover, either or both of which will suppress the emission level.

40. In the absence of explicit silt-load measurements, this parameter is estimated from the percentage of fines. Thus, the more specific the percentage of fines that can be calculated for a particular landform, the more precise the emission predictions become. Unfortunately, as has been previously stressed, variability within an individual landform unit can be on the order of several percent and for the total occurrence of the same landform throughout the study area might result in variation of the fine component on the order of 10 percent or more. Variation in the fine content of two landforms of the same type but geographically removed from each other can most probably be explained by difference in the parent materials, slope, or topographic position. It is doubtful if the attributes that control the texture of a soil profile at a specified location can ever be conclusively evaluated insofar as the contribution of each. An unusually heavy rainstorm can deposit a veneer of coarser material over previously existing soils in a very short period of time and significantly offset the normal sorting effects of slope and gravity. Since it is impossible to weigh all the attributes that control soil texture in an ever-changing environment, precise predictions of dust emission are also obviously impossible. Only intense sampling of soils and coordinate landform parameters would provide the detailed data necessary to refine dust emission predictions. Until that time, available data will dictate the level of generalization that is required.

41. If predictions of the YPG are to a degree generalized, then it follows that predictions based on landform analogy in remote desert areas of the world will suffer an even greater degree of generalization. This circumstance results from characterization of coordinate landform attributes from often

highly generalized source materials, e.g., medium- to small-scale topographic, soil, and geologic maps and aerial imagery. For example, individual landforms can be delineated at the YPG from 1:50,000 topographic maps and 1:58,000 aerial photography. These landforms can be characterized from numerous reports that describe the pertinent attributes in required quantitative terms. In desert regions in African and Asia, the delineation of individual landforms is not normally possible, due to the reduced scale of the available maps and imagery. A large depositional plain flanking a mountain front in a remote desert area might contain alluvial fans and aprons, washes, alluvial flats, terraces, pediments, and even small hills not identifiable on topographic maps with 50- to 100-m contour intervals. If imagery is available, some refinements will be possible in distinguishing landform boundaries and perhaps general characterization of component attributes and parent materials. The recognition and characterization of landforms and landform attributes will be effected with the procedures developed for the YPG. Field validation for landform characterizations in foreign desert areas will probably not be possible, nor will validation of dust-emission predictions.

42. An additional consideration that will have a substantial impact on the applicability of this methodology to world deserts is that world deserts include the broad spectrum of landform types related to diverse geologic and climatic interactions, while the YPG is limited to those which have resulted from a relatively restricted geologic scenario in a relatively homogeneous climatic regime. Some of these complex desert terrains will be difficult to characterize in terms of classic landform types, particularly with the generalized methodology resulting from the relative paucity of detailed data and the availability of only small-scale maps and imagery. For example, extensive areas of desert plains occur in world deserts that are underlain by complex sequences of sedimentary and metamorphic rocks. These plains may be either depositional or erosional surfaces, and the overlying residual soils may be altered significantly by alluvial and aeolian processes. Identification and delineation of individual landforms would not be possible, and estimates of soil texture would be based largely on soil types weathered from the predominate rock types, drainage patterns, and regional slopes. While it is not anticipated that analyses of all desert landscapes would prove this difficult, it should be stressed that the examination of terrain from a compressed perspective as required by small-scale maps and imagery eliminates identification

of many landforms that are discernible on large-scale maps and imagery. The net result is a generalization of landforms into a regional complex characterized by a relatively broad range to dust-propensity values.

43. In selecting routes for military operations involving large numbers of tracked and wheeled vehicles, the cross-country mobility characteristics of the terrain over which they will travel must be taken into consideration. The degree of difficulty that the vehicles experience is determined by both single attributes of the terrain or combinations of attributes. The more significant of these attributes are slope, dissection, surface obstacles, vegetation (especially that along washes and associated with shrub-coppice dunes), and barriers such as escarpments and terraces. Soil per se is not as critical as these other attributes unless in combination with such attributes as slope, soil moisture, and obstacles.

44. Where possible, tactical routes will follow terrain with relatively low slopes (0 to 5 percent), undissected to slightly dissected, free of dense patterns of surface obstacles of sufficient size to require maneuvering by passing vehicles, and with a low incidence of nonnegotiable barriers. The generation of dust along these routes will be the subject of emission predictions. The above criteria eliminate the majority of desert terrains, including such landforms as hills and mountains, upper portions of alluvial fans, escarpments, badlands, moist and slat-encrusted playas, extensive dune fields (except perhaps for vehicles specially equipped to negotiate soft sand), broken lava flows, boulder fields, dissected plains and plateaus, and numerous others. As a result, even in remote desert areas, negotiable terrains can generally be identified through the examination of available maps and imagery. Negotiable terrains must be interconnected so as to provide continuity of passage through the region from origin to destination. This requirement further eliminates large areas of otherwise negotiable terrains that are surrounded by no-go landforms.

45. Thus, it will not be necessary to map and characterize the total area of a foreign desert selected for dust-propensity studies. Identification of feasible routes will in most instances eliminate the majority of the desert area from detailed study and enable a focusing of attention on the landforms that lie along these routes. Areas that are contiguous to possible routes that are considered negotiable or of questionable negotiability may be included for characterization and dust-emission prediction.

46. The focus of the study can then be directed to the landforms that occur within the limits of the potential "go" areas or routes. Where individual landforms and parent materials can be identified, analogies can be made with YPG landforms. Where they cannot, their presence within these zones must be inferred from association and from indirect indicators.

PART V: DUST PREDICTIONS

Employment of the Dust-Propensity Methodology

47. The dust-propensity methodology developed in Part III should have several applications in the planning of military operations in desert areas. Here, however, it has a single application: determination (or prediction) of near-surface soil composition--especially fine material--for use in dust predictions. In this portion of the study, the YPG landform characterization is put to use, along with available ground truth, to identify soil composition to a depth of 10 cm (4 in.), or the approximate depth to which the soil may be expected to contribute to dust caused by the passage of a tracked vehicle (Table 3).

48. A study objective is to predict dust-lofting by two distinctly different tracked vehicles operating over desert terrain at five speed levels. From the landform map of Figure 1, a hypothetical 10-mile vehicle course was selected (Figure 4). This course, which is traversed from south to north in the dust prediction developed herein, begins in the Truck Hill Course area of YPG, west of the Mobility Test Area, and ends at the intersection of Water Tank and West Cibola access roads. It was chosen for several reasons:

- a. It is tactically realistic as a course that may be traversed by a tracked combat vehicle.
- b. Some ground-truth soils data are available in this general area.
- c. It traverses two rather distinct areas of vegetative cover.
- d. It is available for possible future validation trials.

49. In the next portion of the study, existing data are examined, and a dust emission-factor equation is developed for application to selected tracked vehicles operating on the course specified in Figure 4.

Development of an Emission-Factor Equation

Data base complication

50. The data base compiled for developing an emission-factor equation for tracked vehicles is presented in Table 4. The White Sands Missile Range (WSMR) test data were taken from PEI Associates, Inc. (1986); the Fort

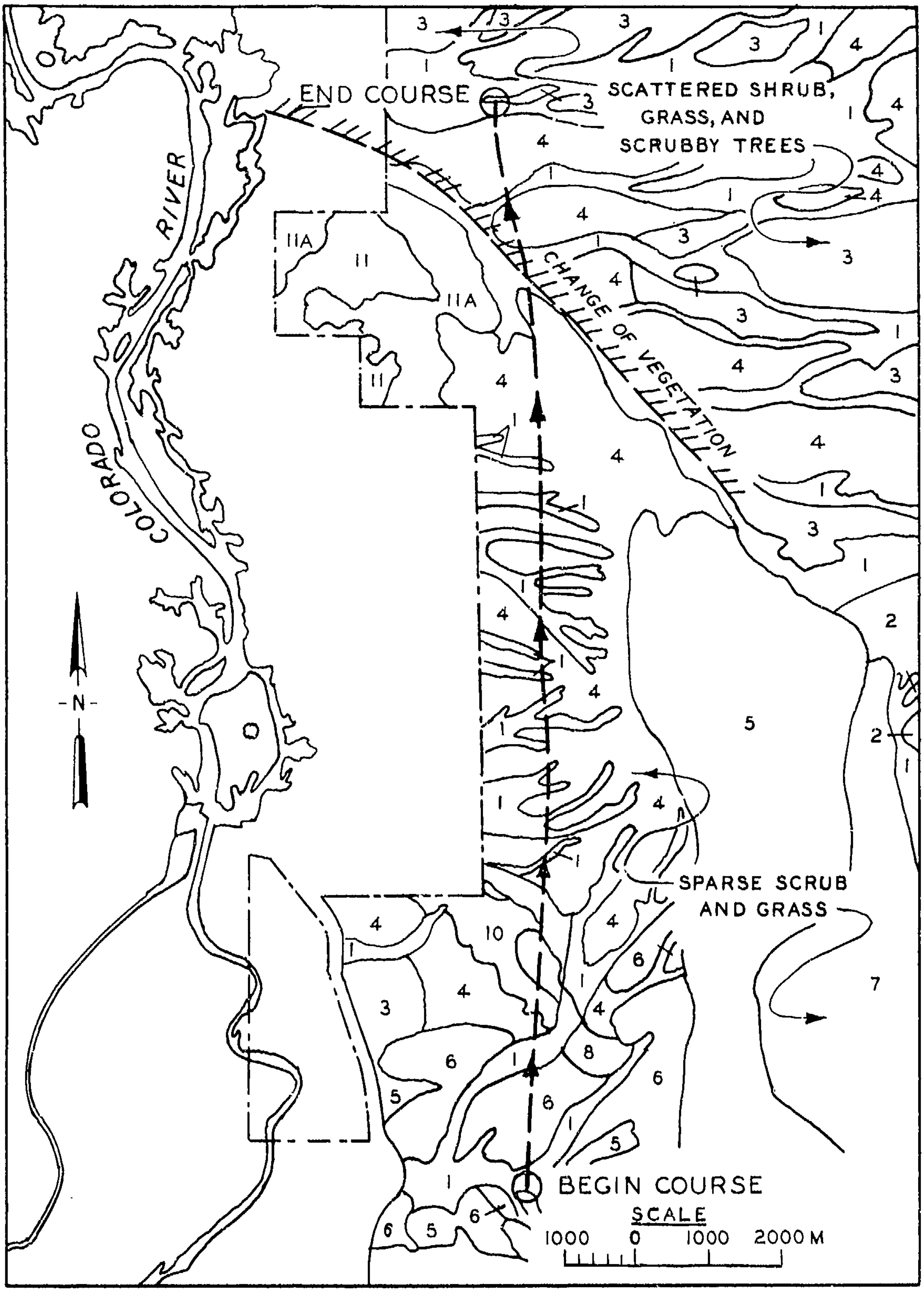


Figure 4. Hypothetical vehicle course near western boundary, YPG, for dust predictions

Carson Dust Obscuration Test data were derived from Hoock (1985) and Long, Williams, and Davis (1985), where measured dust emissions in pounds per vehicular mile traveled (VMT) were read directly from graphs of dust emission E versus vehicle speed S. (See Table 4 for test data source information.) Graphic "read-off" was necessary because tabulated data for the Fort Carson tests were not available. Measures of other parameters were derived from text material within PEI Associates, Inc. (1986); Hoock (1985); and Long, Williams, and Davis (1985) and from estimates based on personal knowledge of the area. For example, the silt load at Fort Carson was determined on the basis that silt load in the upper 10-cm layer is directly proportional to the percentage of fines in the same layer. For WSMR, where comparative data are available, it was learned that the average percentage of fines (by weight) in the 10-cm layer amounted to 8.67 percent and the average silt load in the layer was 0.11 lb/ft^2 (28 observations). These data suggest that

$$SL = 1.27 (PF) \tag{1}$$

where SL is the silt load in lb/ft^2 and PF is the percentage of fines expressed as a decimal. To provide a silt-load statistic for Fort Carson, the average percentage of fines was determined from 51 gradation curves plotted in Long, Williams, and Davis (1985). The individual percentages of fines were taken from the gradation curves by reading off the plots the percentage of the sample that had particles smaller than 74 μ; the average of the values so determined was 65 percent. Using Equation 1, the following is obtained:

$$SL = 1.27 (0.65)$$
$$SL = 0.83 \ lb/ft^2$$

This value for the silt load at Fort Carson was used in the development of the data base presented in Table 4.

Data scatter

51. The data base includes test data for three different tracked vehicles from tests conducted at Fort Carson and WSMR. At these sites, the vehicular tests were along straight-line courses, thereby generating individual vehicular dust clouds essentially the same as would result from vehicles moving in a column appropriately spaced. While other dust trials involving

military vehicles at other sites have been conducted, test procedures were such as to make the test results invalid for this study, e.g., the courses that were run were sinusoidal, elliptical, or circular. In other tests, dust clouds were generated by dragging a matrix of obstacles behind various vehicles. In view of these conditions, such test results were not deemed appropriate to this study.

52. The scatter within the data base becomes apparent when various plots are made. For example, when emission load E (lb/VMT) is plotted against vehicular speed S (mph) for a given type vehicle, a scatterband approaching an order of magnitude results. The scatter is probably due to two principal sources: (a) variations in the soils along the test course and (b) instrumentation measuring techniques, the latter being probably the chief source of scatter. Various dust-measuring techniques have routinely been shown to give values that are close to an order of magnitude apart; certainly, a difference of a factor of 6 or 7 is not at all uncommon. The width of the scatterband associated with the data in Table 4 is very close to an order of magnitude--generally about a factor of 8 or 9, depending on the particular abscissa value chosen.

53. Obviously, any emission-factor equation developed from the data base will average out the scatter inherent within the data base; therefore, such an equation must include a plus or minus caveat to reflect the uncertainty in the actual calculated value. Certainly, additional tests, with intensive efforts at quality control in the soil sampling and dust-measuring techniques, are sorely needed, including careful measuring of the percentage of fines and the silt loads along the test course.

Approaches taken and recommendations

54. Two independent approaches were used in developing emission-factor equations that adequately describe the data base: namely, dimensional analysis and multiple linear regression (MLR) analysis. Unfortunately, the MLR analysis did not provide believable results. The dimensional analysis approach is discussed in the following paragraphs:

55. A general functional equation that related E to pertinent independent variables that conspire to form a general solution can be formulated so as to describe the phenomena of dust emission associated with linear movement of tracked vehicles within a given topographical scenario. Such an equation may well take the form:

$$E = f\ (PS,\ SL,\ MC,\ W,\ TAC,\ S,\ SFA,\ H,\ g) \qquad (2)$$

where

E = dust emission, lb/VMT

PS = percentage of silt (or percentage of fines) in the upper 10-cm layer of soil, dimensionless

SL = silt load (loose fines immediately available for lofting) on the surface, lb/ft^2

MC = soil moisture content, percent by weight, dimensionless

W = vehicular weight, short tons

TAC = total tread area in contact with the ground, ft^2

S = vehicular speed, mph

SFA = silhouette frontal area of vehicle, ft^2

H = vehicular clearance, ft

g = gravitational constant, 32.2 ft/sec^2

56. With W , TAC , and g chosen as normalizing or repeating variables, the functional equation yields a dimensional analysis functional equation having seven dimensionless terms:

$$\frac{E\sqrt{TAC}}{W} = f\left[\frac{(SL)(TAC)}{W},\ PS,\ MC,\ \frac{S}{\sqrt{g}^{4}\sqrt{TAC}},\ \frac{SFA}{TAC},\ \frac{H}{\sqrt{TAC}}\right] \qquad (3)$$

The available data base is grossly inadequate to perform an analysis to this degree of sophistication. If however, one assumes:

a. That deserts are dry and moisture content variation is thus not a significant variable (moisture content of the upper 10-cm layer considered to be less than 5 percent, 90 percent of the time).

b. That vehicle shape (SFA) is roughly the same for the tracked vehicles of interest.

c. That the silt load is an appropriate measure of dust propensity in the 10-cm layer, then

$$\frac{E\sqrt{TAC}}{W} = f\left[\frac{(SL)(TAC)}{W},\ \frac{S}{\sqrt{g}^{4}\sqrt{TAC}}\right] \qquad (4)$$

A plot of

$$\frac{E\sqrt{TAC}}{W} \text{ versus } \frac{(SL)(TAC)}{W}$$

revealed no specific or definable dependence on the speed numeric; therefore, the two numerics

$$\frac{(SL)(TAC)}{W} \text{ and } \frac{S}{\sqrt{g}\sqrt[4]{TAC}}$$

were combined by multiplying the two and simplifying. This yields

$$\frac{(SL)(TAC)^{3/4}S}{\sqrt{g}\ W}$$

When E TAC/W is plotted against this numeric on logarithmic (log-log) paper, a correlation of the form is obtained by the method of least squares (using all 78-line items from Table 4):

$$\frac{E\sqrt{TAC}}{W} = 25.2\left[\frac{(SL)(TAC)^{3/4}S}{\sqrt{g}\ W}\right]^{0.73} \quad (5)$$

When simplified, Equation 5 reduces to:

$$E = 7.1\ W^{0.27}\ (SL)^{0.73}\ (TAC)^{0.05}\ S^{0.73} \quad (6)$$

In metric units, Equation 6 becomes

$$E = 2.03 \times 10^{-4}\ W^{0.27}\ (SL)^{0.73}\ (TAC)^{0.05}\ S^{0.73} \quad (7)$$

where E is in newtons per metre, W is in newtons, SL is in newtons per square metre, TAC is in square metres, and S is in metres per second.

57. In order to reflect the factor-of-9 scatterband width, the numerical coefficient 7.1 in Equation 6 should have a range from approximately 2.4 to 21; thus with near certainty, one would expect the true value of a predicted E to be described by the equation:

$$E = k\ W^{0.27}\ (SL)^{0.73}\ (TAC)^{0.05}\ S^{0.73} \quad (8)$$

where $k = 7.1$ in describing a single average-value prediction and where the scatterband in which the true value will fall with a confidence level of about 0.95 is defined by $2.4 \leq k \leq 21$.

58. Referring to Table 4, column 14 shows the calculated emission loads using Equation 6. Column 15 presents a ratio of calculated versus measured emissions. The mean of this column ($n = 78$) is 1.18, indicating that, on the average, Equation 6 overpredicts emissions by roughly 18 percent, although, as pointed out earlier, the high and low values can be underpredicted or overpredicted by as much as a factor of 3.

59. The standard deviation for the 78 observations is 0.68, and the median is 1.01. The mean of a new data set (column 15 statistic) would be expected to fall within the range of 1.1 to 1.3 with a probability of 0.7. Similarly, with a probability of 0.95, a new data set mean would fall between 1.0 and 1.4. Thus Equation 6 will provide a prediction for a random single observation that falls within a calculated value plus or minus a factor of 3 with 95-percent confidence. The variability of soils and the discrepancies in measuring techniques preclude a more accurate prediction methodology at this time. Actually, Equation 6 overpredicts on the low end, where measured values of E are around 20, and underpredicts when measured values are in excess of about 200.

Dust-Prediction Calculations

60. Equation 8 ($k = 7.1$) is the basis for the vehicular dust predictions for the YPG. Ten prediction tables were generated (Tables 5-14), one for each of the two selected test vehicles at five speeds. Immediately preceding these tables is a key explaining column headings and the manner in which the tables should be read. To improve readability, vertical and horizontal arrows are used to show repetitive entries. The prediction tables employ English units and notations that have been commonly used in this field of study. However, conversion of E to metric units can be accomplished with Equation 7; the conversion of other parameters can be accomplished by using the conversion table at the front of this report.

61. The M113 armored personnel carrier and the M60 main battle tank were the vehicles selected for dust predictions; the calculations are for speeds from 5 through 25 mph, in 5-mph intervals. In reality, a vehicle traversing the course of Figure 4 would probably do so at the entire range of speeds as it negotiates the undulating and sometimes rough terrain.

62. The prediction tables show two emission-factor E columns; the first of these is a solution of Equation 8, with $k = 7.1$, while the far right-hand column TSP includes one or more multiplier adjustments to the first E column. These adjustment factors are discussed below:

- a. The TSP adjustment factor is intended to convert Equation 8 ($k = 7.1$) solution to total suspendable particulate $\leq 30\ \mu$, generally considered the upper size limit for the persistent dust cloud. Based upon 18 soil samples taken near the course areas, (Long and Williams 1959) the mean ratio TSP/total fines = 0.484, with small-sample standard deviation = 0.244.
- b. Near-surface particles $\geq$ gravel size (retained on No. 4 sieve, or 4.76 mm in USCS will probably suppress dust, but to what degree is not known. An estimated, linear adjustment is given in Table 15.
- c. Vegetative ground cover also suppresses dust, again by an unknown amount. Table 15 also contains an estimated linear adjustment for vegetation.

Thus, the persistent dust emitted in terms of pounds per vehicular mile traveled is expected to fall between the two E columns in the prediction tables.

63. Figures 5 through 8 plot dust emissions for the M113 and M60, each traversing the course of Figure 4 at 15 and 25 mph. Values are from Tables 7 and 9 for the M113 and Tables 12 and 14 for the M60. The plots show the repetitive nature of the dust-cloud calculations as the vehicles alternately cross the narrow washes of landform 1A and the alluvial fans, aprons, and fan terraces of landform 4.

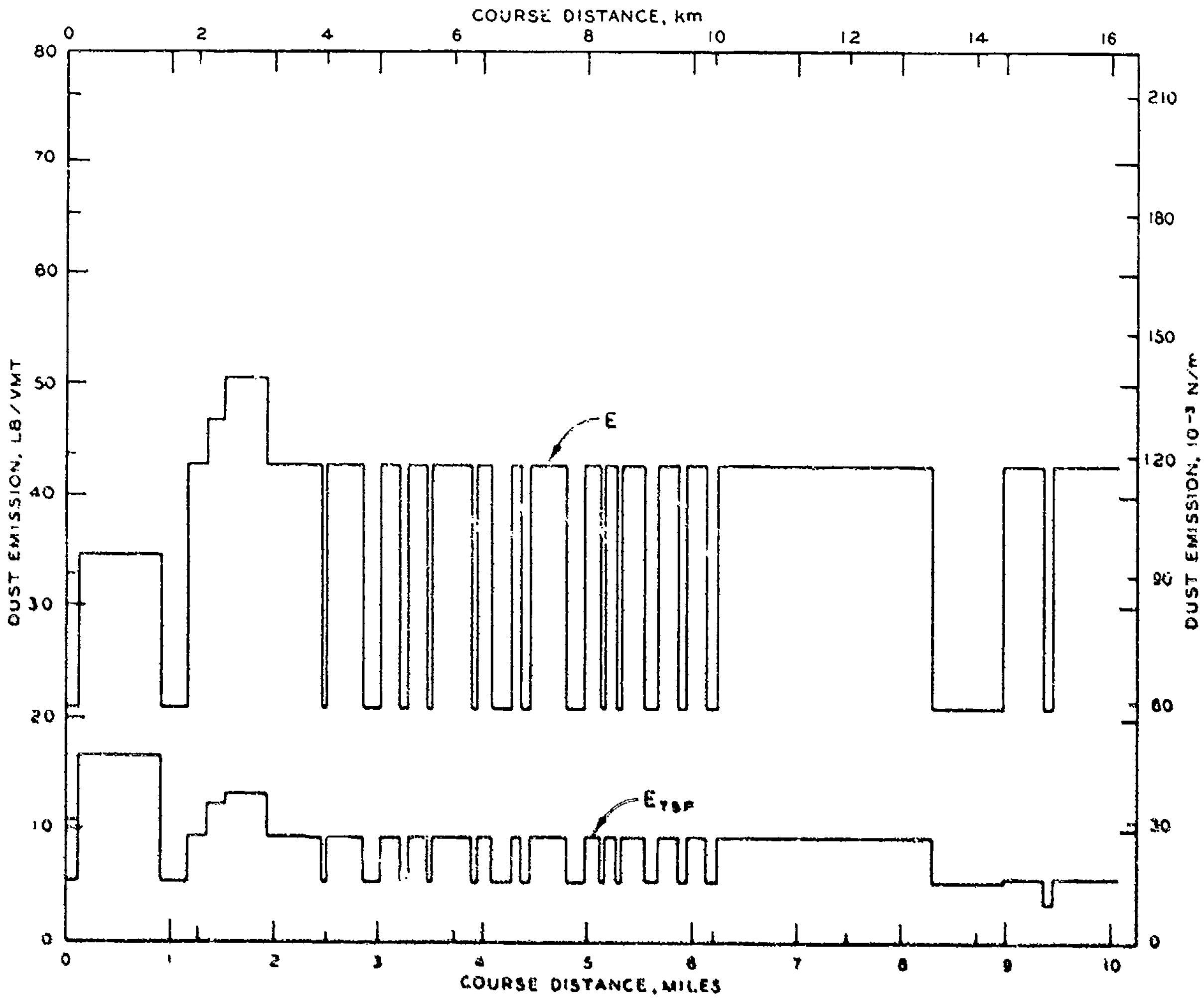


Figure 5. Predicted dust emission for M113 traversing the curve indicated in Figure 4 at 15 mph

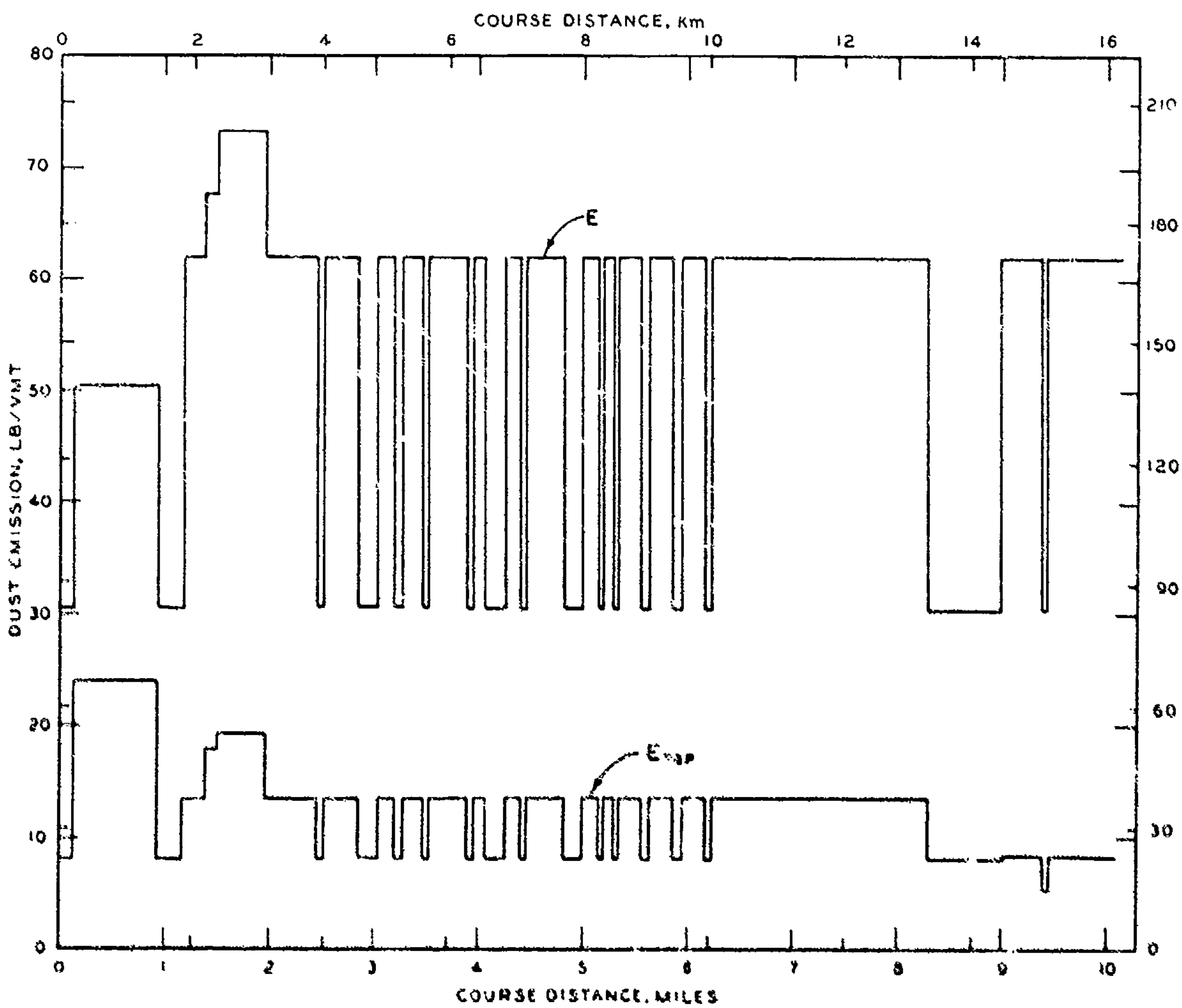


Figure 6. Predicted dust emissions for M113 traversing the course indicated in Figure 4 at 25 mph

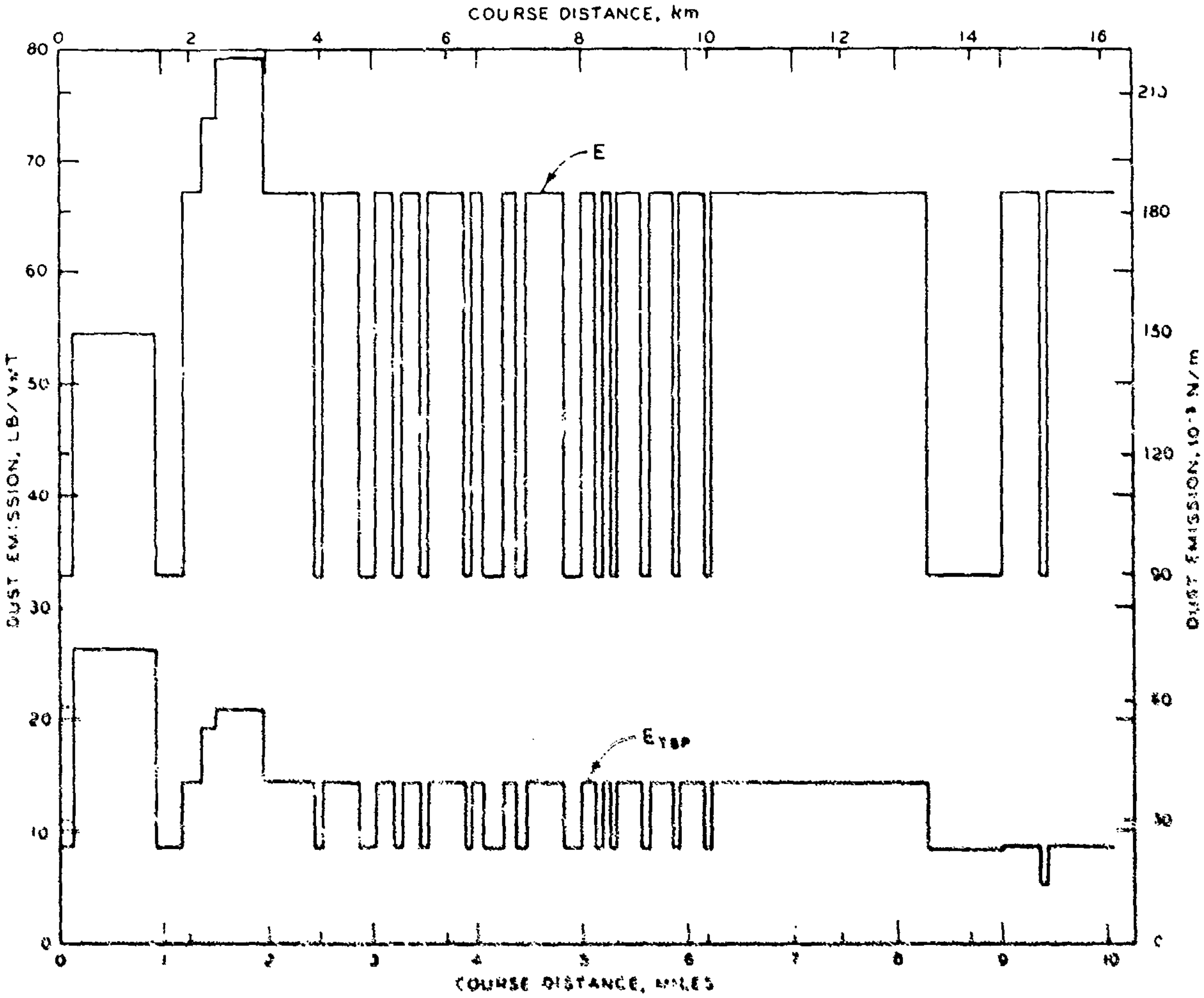


Figure 7. Predicted dust emissions for M60 traversing the course indicated in Figure 4 at 15 mph

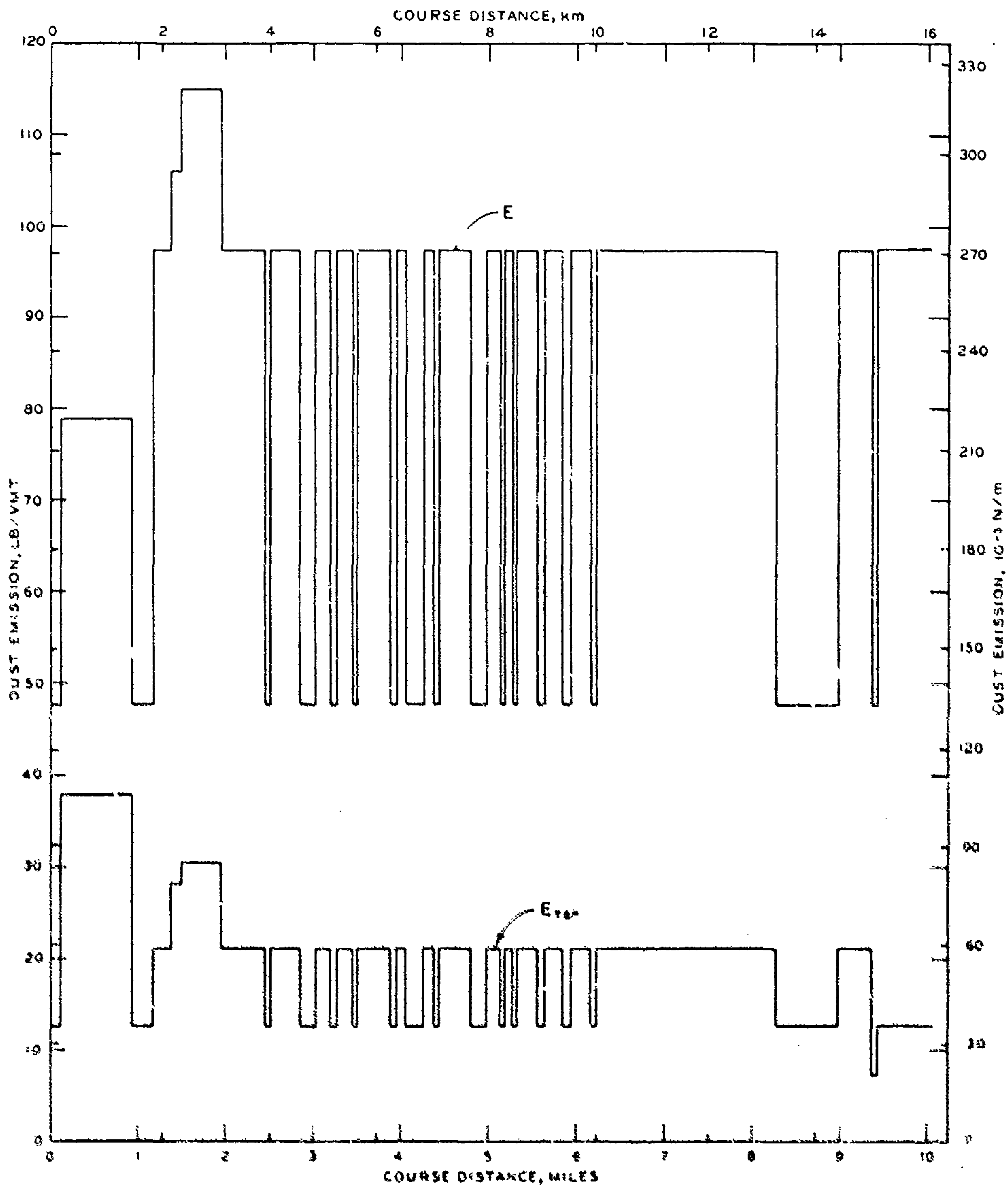


Figure 8. Predicted dust emissions for M60 traversing the course indicated in Figure 4 at 25 mph

PART VI: SUMMARY AND CONCLUSIONS

64. A general geological methodology is developed in this study to characterize landforms so as to predict their propensity to produce dust under single-vehicle passage. In the broadest sense, it is applicable to deserts worldwide, but further research is required to enable usable predictions in areas for which mapping and/or imagery are at a scale that precludes detailed study and for which little or no ground truth may be available. This methodology has been applied to the YPG, a desert area for which a considerable amount of geological information is available, with apparently satisfactory results.

65. Using a near-surface soil-composition prediction and based upon previous vehicular dust trials, a minimal data base for tracked vehicles operating in desert or near-desert terrain has been developed and subjected to dimensional analysis and multiple linear regression, resulting in the equation

$$E = k\, W^{0.27}\ (SL)^{0.73}\ (TAC)^{0.05}\ S^{0.73} \qquad \text{(8 bis)}$$

where

E = emission factor in lb/VMT

W = vehicular weight, short tons

SL = silt load, lb/ft^2

TAC = total tread area in contact with the ground, ft^2

S = vehicular speed, mph

and where k equals 7.1 on the average, but ranges from 2.4 to 21 in order to describe the inherent data scatter.

66. From the above equation and for a hypothetical single-vehicle course at the YPG, dust predictions are developed for two widely used tracked vehicles, the M113 armored personnel carrier and the M60 main battle tank, operating at five speeds. Estimated adjustment factors are applied to give an upper-lower average value for dust-emission rates.

PART VII: RECOMMENDATIONS

67. The geological methodology portion of this effort should be studied further in order to broaden the predictive capability and thus approach a worldwide predictive capability for desert areas of military interest.

68. The vehicular-dust data base (Table 4) should be expanded by gleaning from existing test data appropriate parameters currently unreported and by additional field trials, enabling a refinement of the prediction equation so as to provide a higher degree of accuracy and confidence in dust predictions. Specifically, field trials at the YPG, accompanied by additional ground-truth data collection, are highly recommended in order to validate current procedures or to provide a quantitative basis for revision thereof.

69. Vehicular-dust predictions should accompany the broadened geological methodology, with field validation where feasible.

70. A single-vehicle dust plume study should be conducted to establish the physical dimensions of the plume, its dynamics, and dust concentration levels.

71. Finally, the more realistic problem of multiple-vehicle dust-plume coalescence should be addressed.

REFERENCES

Hoock, Donald W. 1985 (Oct). Computational Models for Battlefield Dust Clouds, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, N. Mex.

Long, Katherine, and Williams, Randall R. 1959 (Mar). Petrographic and Particle-Size Analysis of Terrain Samples Taken from Vehicle Test Courses at Yuma Test Station, Arizona, and Aberdeen Proving Ground, Maryland, Southwest Research Institute, San Antonio, Tex.

Long, Katherine, Williams, Randall R., and Davis, Roger E. 1985 (Dec). "Results of Dust Obscuration Tests (DOT) Using Explosives," Technical Report EL-85-12, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Parvis, Merle. 1950 (Nov). "Drainage Pattern Significance in Airphoto Identification of Soils and Bedrocks," Soil Exploration and Mapping, Highway Research Board Bulletin No. 28, Washington, DC, pp 36-62.

PEI Associates, Inc. 1986 (Jun). Collection of Dust-Emission Data at the White Sands Missile Range, New Mexico: Volume I, Golden, Colo.

BIBLIOGRAPHY

Airphoto Interpretation Laboratory. 1954. Environmental Desert Terrain Study at the Yuma Test Station: Interim Report, Joint Highway Research Project, Engineering Experiment Station, Purdue University, under contract to US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Carroll, D. 1970. Rock Weathering, Plenum Press, New York.

Clements, Thomas, et al. 1957. A Study of Desert Surface Conditions, prepared by University of Southern California for Environmental Protection Research Division, Quartermaster Research and Development Center, Natick, Mass.

Dornbusch, William K., Jr. 1982. "Natural Processes Influencing Terrain Attributes; Report No. 1, Prediction of Residual Soil Texture in Humid Temperature Climates of the Federal Republic of Germany and Selected Analogous Portions of the United States: Pilot Study," Technical Report GL-82-2, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Dornbusch, William K., Jr., and Kolb, Charles R. 1966. "Analogs of Yuma Terrain in the Middle East Desert," Technical Report No. 3-630, Report 4, Vols 1 and 2, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Gerson, Ran. 1985. Terrain Evaluation of US Army Yuma Proving Ground as a Model for Mid-Eastern Deserts, Jerusalem, Israel.

Gerson, Ran, et al. 1985a. A Procedure for Evaluation of Dust Potential in Desert Terrains Based on a Study in the Deserts of Israel and the Sinai, Physical Geography, Institute of Earth Sciences, The Hebrew University of Jerusalem, Jerusalem, Israel.

__________. 1985b. Dust Availability in Desert Terrains, a Study in the Deserts of Israel and the Sinai, Physical Geography, Institute of Earth Sciences, The Hebrew University of Jerusalem, Jerusalem, Israel.

Meyer, M. P., and Knight, S. J. 1961. Trafficability of Soils: Soil Classification, Technical Memorandum No. D-240, Sixteenth Supplement, US Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Millett, John A., and Barnett, H. Frank. 1970. "Surface Materials and Terrain Features of Yuma Proving Ground (Laguna, Arizona-California Quadrangle)," Technical Report No. 71-14-ES, US Army Natick Laboratories, Natick, Mass.

__________. 1971. "Surface Materials and Terrain Features of Yuma Proving Ground (Red Hill, Red Bluff Mt., and Roll Quadrangles)," Technical Report No. 71-56-ES, US Army Natick Laboratories, Natick, Mass.

US Army Engineer Waterways Experiment Station. 1960. "The Unified Soil Classification System, Appendix A: Characteristics of Soil Groups Pertaining to Embankments and Foundations, and Appendix B: Characteristics of Soil Groups Pertaining to Roads and Airfields," Technical Memorandum No. 3-357, Vicksburg, Miss.

__________. 1963. "Forecasting Trafficability of Soils: Airphoto Approach," Technical Memorandum No 3-331, Report 6, Vols 1 and 2, Vicksburg, Miss.

US Department of Agriculture. 1980. Soil Survey of Yuma-Wellton Area, Parts of Yuma County, Ariz., and Imperial County, Calif.

US Department of Agriculture. 1984 (Sep). Soil Survey of US Army, Yuma Proving Ground, Yuma County, Ariz.

Table 1

Distribution of Landforms Within Selected

World Desert Areas

Landform	Southwestern US		YPG		Sahara	Libyan	Arabian
	Area*	%	Area*	% (est)	%	%	%
Playas	834	1.1	--	--	1	1	1
Desert flats	15,834	20.5	210	10	10	18	16
Bedrock fields and pediments	507	0.7	210	10	10	6	1
Alluvial terraces and floodplains	900	1.2	--	--	1	3	1
Alluvial fans and aprons	24,210	31.4	734	35	1	1	4
Dunes	450	0.6	--	--	28	22	26
Washes	2,345	3.6	105	15	1	1	1
Badlands	2,031	2.6	--	--	2	8	1
Volcanic cones and fields	120	0.2	--	--	3	1	2
Desert hills and mountains	29,556	38.1	838	30	43	39	47
Totals	76,787	100.0	2,097	100	100	100	100

* In square miles.

Table 2

Geologic Time Table, Postmesozoic Divisions of Geologic Time

ERAS	PERIODS	EPOCHS OR SERIES
CENOZOIC	Quaternary	Holocene - 12,000 to Present* (Recent) Pleistocene - 12,000 to 2,000,000
	Tertiary	Pliocene - 2,000,000 to 10,000,000 Miocene - 10,000,000 to 25,000,000 Oligocene - 25,000,000 to 35,000,000 Eocene - 35,000,000 to 55,000,000 Paleocene - 55,000,000 to 65,000,000
MESOZOIC	Undifferentiated	

* Numbers in each division indicate approximate number of years from present.

Table 3

YPG Landforms and Surface Soils

Landform		Slope	Soil	Surface Soils, 0 to 10-cm depth				
No.	Description	Slope %	Soil Series	Fines %	Sand %	Gravel %	≥ Gravel %	Remarks
1A	Recent alluvial wash, west of Middle Mountains	0–5	Carrizo	0–15	50–55	35–45	0–10	—
1B(1)	Recent alluvial wash, east of Middle Mountains	0–3	Carrizo	20–30	45–70	15–30	0–5	—
1B(2)	Recent alluvial wash, east of Middle Mountains	0–3	Cuerda	35–50	45–65	0–5	—	—
2	Alluvial apron, Lower Pleistocene, interfluve	0–7	Cristobal	15–20	35–40	40–50	0–20	Surface veneered with particles ≥ gravel size (desert pavement)
3A	Gravelly, undissected fans, aprons, and terraces (Recent)	0–10	Carrizo	15–25	20–30	45–65	0–5	—
3B	Gravelly, undissected fans, aprons, and terraces (Recent)	0–10	Momoli	10–30	30–55	35–60	0–5	—
4	Gravelly, dissected fans, aprons, and fan terraces	15–30	Gunsight	10–30	25–45	45–65	0–10	90 percent of surface veneered with desert pavement
4A	Moderately dissected, gravelly fans, aprons, and terraces west of Middle Mountains	1–5	Ajo	10–30	30–50	40–60	5–10	95 percent of surface veneered with desert pavement
4B	Moderately dissected, gravelly fans, aprons and terraces east of Middle Mountains	0–5	Growler	15–50	22–55	10–62	—	95 percent of surface veneered with desert pavement
5	Sandy terrace	0–3	Superstition	15–25	75–85	—	—	—
6	Sandy hills and dunes	0–20	Rositas	5–25	75–95	—	—	—
7	Linear, stabilized dunes	0–10	Rositas	5–25	75–95	—	—	—
8	Gneiss hills	15–60		20–30	45–65	15–25	10–45	—
9	Schist hills	15–60	—	30–40	25–55	15–35	15–35	—

(Continued)

Table 3 (Concluded)

Landform		Slope	Soil	Surface Soils, 0 to 10-cm depth				
No.	Description	%	Series	Fines %	Sand %	Gravel %	≥ Gravel %	Remarks
10	Hills, granite and related rock	15-60	--	10-35	25-85	5-40	10-45	--
11	Hills, volcanic, undifferentiated	15-60	--	15-80	0-80	5-35	5-50	--
11A	Low hills, volcanic, undifferentiated	2-15	--	15-25	25-45	40-50	20-40	--
12	Hills, limestone, dolomite, sandstone	15-60	--	35-80	45-90	10-75	5-40	--
13	Hills, sandstone and shale	15-60	--	35-70	40-95	5-25	5-35	--

Table 4

Data Base for Determining Emission-Factor Equations

1 Line Item	2 Trial Designation*	3 Silt** %	4 Silt Load† lb/ft^2	5 Silt Load† N/M^2	6 TAC†† ft^2	7 TAC†† m^2	8 Vehicle Weight‡ tons	9 Vehicle Weight‡ 10^4 N	10 Vehicle Speed‡‡ mph	11 Vehicle Speed‡‡ m/sec	12 Measured Emission § lb/VMT	13 Measured Emission § 10^{-3} N/M	14 Calculated Emission Equation 6 lb/VMT	15 Ratio: Column 14 / Column 12
1	C-01-01	65	0.83	39.7	21.8	2.03	11.7	10.4	6.95	3.11	17	48	58	3.41
2	C-02-01	↓	↓	↓	↓	↓	↓	↓	6.95	3.11	26	70	58	2.23
3	C-03-01	↓	↓	↓	↓	↓	↓	↓	10.25	4.58	42	116	77	1.83
4	C-04-01	↓	↓	↓	↓	↓	↓	↓	10.25	4.58	57	158	77	1.35
5	C-05-01	↓	↓	↓	↓	↓	↓	↓	12.00	5.37	44	123	86	1.95
6	C-06-01	↓	↓	↓	↓	↓	↓	↓	12.00	5.37	100	276	86	0.86
7	C-07-01	↓	↓	↓	↓	↓	↓	↓	12.35	5.52	79	218	88	1.11
8	C-08-01	↓	↓	↓	↓	↓	↓	↓	12.35	5.52	93	257	88	0.95
9	C-09-01	↓	↓	↓	↓	↓	↓	↓	13.00	5.81	41	113	91	2.22
10	C-10-01	↓	↓	↓	↓	↓	↓	↓	13.00	5.81	51	141	91	1.78

(Continued)

* The letter "C" designates Fort Carson, Colo.; "W" designates White Sands Missile Range, N. Mex. The first two-digit number refers to the trial number within each test series. The last two-digit number identifies the vehicle type: 01 is the APC M113; 02 is the M-60 tank; 03 is the APC M114.

** Percentage of silt for the Fort Carson data determined by averaging the percentage of fines from 51 gradation curves contained in Long, Williams, and Davis (1985) and thereafter assumed constant for all trials. The White Sands (W series) percentage of silt values represent actual measured quantities as reported in PEI Associates, Inc. (1986).

† Fines load represents the quantity of surface fines (lb/ft^2) immediately available for lofting.

†† TAC represents the total track area in contact with the ground. Areas were obtained from various Army Field Manuals, e.g., FM 5-35.

‡ From FM 5-35: "Engineers Reference and Logistical Data," Headquarters, Department of the Army, April 1971.

‡‡ Fort Carson data obtained from "Review and Interpretation of Technical Knowledge on Terrain Dust Potential for Military Vehicles and Explosives," PEI Associates, Inc., April 1985, and from "DOT Test Analysis - Derived Dust Production Rates for Tracked Vehicles," US Army Atmospheric Sciences Laboratory, White Sands Missile Range, N. Mex., November 1983. White Sands data obtained from "Collection of Dust-Emission Data at White Sands Missile Range, N. Mex., Vol I," PEI Associates, Inc., June 1986.

§ Values rounded to the nearest whole number. Measured emissions are from references cited in footnote ‡‡ above.

Table 4 (Continued)

1 Line Item	2 Trial Designation*	3 Silt** %	4 Silt Load† lb/ft^2	5 Silt Load† N/M^2	6 TAC†† ft^2	7 TAC†† m^2	8 Vehicle Weight‡ tons	9 Vehicle Weight‡ 10^4 N	10 Vehicle Speed‡‡ mph	11 Vehicle Speed‡‡ m/sec	12 Measured Emission § lb/VMT	13 Measured Emission § 10^{-3} N/M	14 Calculated Emission Equation 6 lb/VMT	15 Ratio: Column 14 / Column 12
11	C-11-01	65	0.83	39.7	21.8	2.03	11.7	10.4	13.45	6.01	82	227	94	1.15
12	C-12-01								13.45	6.01	160	442	94	0.59
13	C-13-01								14.00	6.26	38	106	96	2.53
14	C-14-01								14.00	6.26	115	318	96	0.83
15	C-15-01								14.85	6.64	50	140	101	2.02
16	C-16-01								14.85	6.64	70	194	101	1.44
17	C-17-01								15.20	6.80	100	276	102	1.02
18	C-18-01								15.20	6.80	110	304	102	0.93
19	C-19-01								15.85	7.09	97	268	106	1.09
20	C-20-01								15.85	7.09	109	301	106	0.97
21	C-21-01								18.25	8.16	103	283	117	1.14
22	C-22-01								18.25	8.16	123	339	117	0.95
23	C-23-01								18.50	8.27	112	308	118	1.05
24	C-24-01								18.50	8.27	165	456	118	0.72
25	C-25-01								19.65	8.79	72	199	124	1.72
26	C-26-01								19.65	8.79	94	260	124	1.32
27	C-27-01								19.90	8.90	84	231	125	1.49
28	C-28-01								19.90	8.90	202	560	125	0.62
29	C-29-01								22.00	9.84	90	249	134	1.49
30	C-30-01								22.00	9.84	205	567	134	0.65
31	C-31-01								23.00	10.28	102	283	138	1.35
32	C-32-01								23.00	10.28	205	567	138	0.67
33	C-33-01								23.90	10.69	132	366	142	1.08
34	C-34-01								23.90	10.69	160	442	142	0.89
35	C-35-02								5.20	2.32	30	82	74	2.47
36	C-36-02								9.80	4.38	50	138	117	2.34
37	C-37-02								12.00	5.37	90	249	135	1.50
38	C-38-02								12.15	5.43	120	332	137	1.14
39	C-39-02								13.40	5.99	61	169	147	2.41
40	C-40-02				64.8	6.02	51	45.4	13.90	6.21	80	220	151	1.89

(Continued)

Table 4 (Continued)

1 Line Item	2 Trial Designation*	3 Silt** %	4 Silt Load† lb/ft²	5 Silt Load† N/M²	6 TAC†† ft²	7 TAC†† m²	8 Vehicle Weight‡ tons	9 Vehicle Weight‡ 10^4 N	10 Vehicle Speed‡‡ mph	11 Vehicle Speed‡‡ m/sec	12 Measured Emission § lb/VMT	13 Measured Emission § 10^{-3} N/M	14 Calculated Emission Equation 6 lb/VMT	15 Ratio: Column 14 / Column 12
41	C-41-02	65	0.83	39.7	64.8	6.02	51	45.4	14.70	6.57	145	401	157	1.08
42	C-42-02								16.80	7.51	300	830	173	0.58
43	C-43-02								17.20	7.69	122	339	176	1.44
44	C-44-02								17.80	7.96	195	539	181	0.93
45	C-45-02								18.10	8.11	80	220	183	2.29
46	C-46-02								18.80	8.41	270	747	188	0.70
47	C-47-02								19.10	8.52	300	830	190	0.63
48	C-48-02								21.30	9.52	355	982	206	0.58
49	C-49-02								21.60	9.64	690	1908	208	0.30
50	C-50-02								24.30	10.9	835	2309	227	0.27
51	W-01-03	10.2	0.31	14.8	25.3	2.35	7.55	6.72	15.00	6.7	101	280	44	0.44
52	W-02-03	10.0	0.31	14.8					16.00	7.2	169	467	46	0.27
53	W-04-03	11.5	0.19	9.1					12.00	5.4	86	238	26	0.30
54	W-06-03	8.1	0.06	2.9					13.00	5.8	5	14	12	2.40
55	W-16-03	9.3	0.04	1.9					30.00	13.4	16	45	16	1.00
56	W-17-03	8.3	0.05	2.4					30.00	13.4	19	51	19	1.00
57	W-18-03	9.9	0.05	2.4					30.00	13.4	25	70	19	0.76
58	W-19-03	9.5	0.05	2.4					20.00	9.0	21	57	14	0.67
59	W-20-03	10.3	0.07	3.4					20.00	9.0	20	55	18	0.90
60	W-21-03	10.4	0.06	2.9					20.00	9.0	20	55	16	0.80
61	W-22-03	6.8	0.11	5.3					26.00	11.6	12	32	31	2.58
62	W-23-03	5.0	0.07	3.3					26.00	11.6	19	52	22	1.16
63	W-24-03	3.9	0.03	1.4					26.00	11.6	18	51	12	0.67
64	W-25-03	7.6	0.11	5.3					29.00	13.0	14	38	34	2.43
65	W-26-03	9.0	0.14	6.7					29.00	13.0	65	178	40	0.62
66	W-27-03	7.2	0.16	7.7					29.00	13.0	41	113	44	1.07
67	W-28-03	3.3	0.04	1.9					30.00	13.4	10	27	16	1.60
68	W-29-03	10.9	0.12	5.8							74	205	37	0.50
69	W-30-03	7.0	0.06	2.9							65	178	22	0.34
70	W-31-03	6.4	0.05	2.4							34	94	19	0.56

(Continued)

Table 4 (Concluded)

1 Line Item	2 Trial Designation*	3 Silt** %	4 Silt Load† lb/ft^2	5 Silt Load† N/M^2	6 TAC†† ft^2	7 TAC†† m^2	8 Vehicle Weight‡ tons	9 Vehicle Weight‡ 10^4 N	10 Vehicle Speed‡‡ mph	11 Vehicle Speed‡‡ m/sec	12 Measured Emission § lb/VMT	13 Measured Emission § 10^{-3} N/M	14 Calculated Emission Equation 6 lb/VMT	15 Ratio: Column 14 / Column 12
71	W-32-03	11.5	0.16	7.7	25.3	2.35	7.55	6.72	30.00	13.4	51	141	45	0.88
72	W-33-03	8.2	0.10	4.8							56	155	32	0.57
73	W-34-03	8.7	0.12	5.8							28	77	37	1.32
74	W-35-03	11.8	0.17	8.1							87	241	47	0.54
75	W-36-03	7.8	0.10	4.8							80	221	32	0.40
76	W-37-03	9.4	0.07	3.4							24	66	25	1.04
77	W-38-03	12.6	0.11	5.3							43	119	34	0.79
78	W-39-03	9.5	0.07	3.4							41	113	25	0.61

KEY TO DUST-PREDICTION TABLES 5-14

Notation: Reading columns from left to right.

W = vehicular weight, short tons (2,000 lb)

TAC = total tread area in contact with ground

S = vehicular speed

SL = silt load

E = dust emission in pounds per vehicular mile traveled (lb/VMT)

TSP = total suspendable particulate (grain size ≤ 30 μ)

Structure. Vertical arrows identify entries that carry through more than one line entry. Thus, W, TAC, S in each table are the same for all line entries.

Horizontal arrows indicate repetitive information within a line entry. Thus, landform 1A encountered at course distance 0.92-1.18 miles (third line entry) has the same mean percentage of fines and silt load as shown for 1A in the first line entry, and also the same TSP and gravel (and particles ≥ gravel) adjustment factors. In this case, it also has the same vegetative cover adjustment factor, but this factor changes near the end of the course.

Calculation. Mean percents of fines are derived from Table 3. Adjustment factors for particles ≥ gravel in size are from Tables 3 and 15. Vegetative cover adjustment factors are also taken from Table 15.

$$SL = 1.27 \text{ (mean fines expressed as decimal fraction)}$$

$$E = 7.1\, W^{0.27}\, (SL)^{0.73}\, (TAC)^{0.05}\, S^{0.73}$$

$$E_{TSP} = E \times \text{(TSP adjustment factor)} \times \text{(gravel adjustment factor)} \times \text{(vegetative cover adjustment factor)}$$

Note that E and E_{TSP} are included for each line entry, even though repetitive.

Table 5

Dust-Emission Prediction Calculations, M113, 5 mph

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
11.7	21.8	5	0. – 0.12	1A	7.5	0.0952	9.37	0.48	0.55	1.00	2.47
			0.12– 0.92	6	15.0	0.190	15.5		1.00		7.44
			0.92– 1.18	1A			9.37				2.47
			1.18– 1.38	4	20.0	0.254	19.2		0.45		4.15
			1.38– 1.50	10	22.5	0.286	20.9		0.55		5.51
			1.50– 1.96	8	25.0	0.318	22.6		0.55		5.97
			1.96– 2.46	4			19.2				4.15
			2.46– 2.52	1A			9.37				2.47
			2.52– 2.86	4			19.2				4.15
			2.86– 3.02	1A			9.37				2.47
			3.02– 3.20	4			19.2				4.15
			3.20– 3.28	1A			9.37				2.47
			3.28– 3.46	4			19.2				4.15
			3.46– 3.51	1A			9.37				2.47
			3.51– 3.89	4			19.2				4.15
			3.89– 3.97	1A			9.37				2.47
			3.97– 4.07	4			19.2				4.15
			4.07– 4.27	1A			9.37				2.47
			4.27– 4.39	4			19.2				4.15
			4.39– 4.45	1A			9.37				2.47
			4.45– 4.81	4			19.2				4.15
			4.81– 4.99	1A			9.37				2.47
			4.99– 5.15	4			19.2				4.15
			5.15– 5.19	1A			9.37				2.47
			5.19– 5.29	4			19.2				4.15
			5.29– 5.33	1A			9.37				2.47
			5.33– 5.57	4			19.2				4.15
			5.57– 5.65	1A			9.37				2.47

NOTE: Read columnar entries from lines for appropriate landforms (1A or 4) above.

(Continued)

Table 5 (Concluded)

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
11.7	21.8	5	5.65– 5.85	4			19.2	0.48		1.00	4.15
			5.85– 5.95	1A			9.37				2.47
			5.95– 6.17	4			19.2				4.15
			6.17– 6.23	1A			9.37				2.47
			6.23– 8.29	4			19.2				4.15
			8.29– 8.99	1A			9.37				2.47
			8.99– 9.37	4			19.2			0.60	2.50
			9.37– 9.43	1A			9.37				1.48
			9.43– 10.07	4			19.2				2.50

Table 6

Dust-Emission Prediction Calculations, M113, 10 mph

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
11.7	21.8	10	0 – 0.12	1A	7.5	0.0952	15.5	0.48	0.55	1.00	4.10
			0.12– 0.92	6	15.0	0.190	25.7		1.00		12.3
			0.92– 1.18	1A			15.5				4.10
			1.18– 1.38	4	20.0	0.254	31.8		0.45		6.86
			1.38– 1.50	10	22.5	0.286	34.6		0.55		9.15
			1.50– 1.96	8	25.0	0.318	37.4		0.55		9.88
			1.96– 2.46	4			31.8				6.86
			2.46– 2.52	1A			15.5				4.10
			2.52– 2.86	4			31.8				6.86
			2.86– 3.02	1A			15.5				4.10
			3.02– 3.20	4			31.8				6.86
			3.20– 3.28	1A			15.5				4.10
			3.28– 3.46	4			31.8				6.86
			3.46– 3.51	1A			15.5				4.10
			3.51– 3.89	4			31.8				6.86
			3.89– 3.97	1A			15.5				4.10
			3.97– 4.07	4			31.8				6.86
			4.07– 4.27	1A			15.5				4.10
			4.27– 4.39	4			31.8				6.86
			4.39– 4.45	1A			15.5				4.10
			4.45– 4.81	4			31.8				6.86
			4.81– 4.99	1A			15.5				4.10
			4.99– 5.15	4			31.8				6.86
			5.15– 5.19	1A			15.5				4.10
			5.19– 5.29	4			31.8				6.86
			5.29– 5.33	1A			15.5				4.10
			5.33– 5.57	4			31.8				6.86
			5.57– 5.65	1A			15.5				4.10

NOTE: Read columnar entries from lines for appropriate landforms (1A or 4) above.

(Continued)

Table 6 (Concluded)

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
11.7	21.8	10	5.65– 5.85	4			31.8	0.48		1.00	6.86
			5.85– 5.95	1A			15.5				4.10
			5.95– 6.17	4			31.8				6.86
			6.17– 6.23	1A			15.5				4.10
			6.23– 8.29	4			31.8				6.86
			8.29– 8.99	1A			15.5				4.10
			8.99– 9.37	4			31.8			0.60	4.12
			9.37– 9.43	1A			15.5				2.46
			9.43–10.07	4			31.8				4.12

Table 7

Dust-Emission Prediction Calculations, M113, 15 mph

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
11.7	21.8	15	0 – 0.12	1A	7.5	0.0952	20.9	0.48	0.55	1.00	5.51
			0.12– 0.92	6	15.0	0.190	34.6		1.00		16.6
			0.92– 1.18	1A			20.9				5.51
			1.18– 1.38	4	20.0	0.254	42.7		0.45		9.23
			1.38– 1.50	10	22.5	0.286	46.6		0.55		12.3
			1.50– 1.96	8	25.0	0.318	50.3		0.55		13.29
			1.96– 2.46	4			42.7				9.23
			2.46– 2.52	1A			20.9				5.51
			2.52– 2.86	4			42.7				9.23
			2.86– 3.02	1A			20.9				5.51
			3.02– 3.20	4			42.7				9.23
			3.20– 3.28	1A			20.9				5.51
			3.28– 3.46	4			42.7				9.23
			3.46– 3.51	1A			20.9				5.51
			3.51– 3.89	4			42.7				9.23
			3.89– 3.97	1A			20.9				5.51
			3.97– 4.07	4			42.7				9.23
			4.07– 4.27	1A			20.9				5.51
			4.27– 4.39	4			42.7				9.23
			4.39– 4.45	1A			20.9				5.51
			4.45– 4.81	4			42.7				9.23
			4.81– 4.99	1A			20.9				5.51
			4.99– 5.15	4			42.7				9.23
			5.15– 5.19	1A			20.9				5.51
			5.19– 5.29	4			42.7				9.23
			5.29– 5.33	1A			20.9				5.51
			5.33– 5.57	4			42.7				9.23
			5.57– 5.65	1A			20.9				5.51

NOTE: Read columnar entries from lines for appropriate landforms (1A or 4) above.

(Continued)

Table 7 (Concluded)

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
11.7	21.8	15	5.65– 5.85	4			42.7	0.48		1.00	9.23
			5.85– 5.95	1A			20.9				5.51
			5.95– 6.17	4			42.7				9.23
			6.17– 6.23	1A			20.9				5.51
			6.23– 8.29	4			42.7				9.23
			8.29– 8.99	1A			20.9				5.51
			8.99– 9.37	4			42.7			0.60	5.54
			9.37– 9.43	1A			20.9				3.31
			9.43–10.07	4			42.7				5.54

Table 8

Dust-Emission Prediction Calculations, M113, 20 mph

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
11.7	21.8	20	0 - 0.12	1A	7.5	0.0952	25.7	0.48	0.55	1.00	6.78
			0.12- 0.92	6	15.0	0.190	42.6		1.00		20.5
			0.92- 1.18	1A			25.7				6.78
			1.18- 1.38	4	20.0	0.254	52.7		0.45		11.4
			1.38- 1.50	10	22.5	0.286	57.5		0.55		15.2
			1.50- 1.96	8	25.0	0.318	62.1		0.55		16.4
			1.96- 2.46	4			52.7				11.4
			2.46- 2.52	1A			25.7				6.78
			2.52- 2.86	4			52.7				11.4
			2.86- 3.02	1A			25.7				6.78
			3.02- 3.20	4			52.7				11.4
			3.20- 3.28	1A			25.7				6.78
			3.28- 3.46	4			52.7				11.4
			3.46- 3.51	1A			25.7				6.78
			3.51- 3.89	4			52.7				11.4
			3.89- 3.97	1A			25.7				6.78
			3.97- 4.07	4			52.7				11.4
			4.07- 4.27	1A			25.7				6.78
			4.27- 4.39	4			52.7				11.4
			4.39- 4.45	1A			25.7				6.78
			4.45- 4.81	4			52.7				11.4
			4.81- 4.99	1A			25.7				6.78
			4.99- 5.15	4			52.7				11.4
			5.15- 5.19	1A			25.7				6.78
			5.19- 5.29	4			52.7				11.4
			5.29- 5.33	1A			25.7				6.78
			5.33- 5.57	4			52.7				11.4
			5.57- 5.65	1A			25.7				6.78

NOTE: Read columnar entries from lines for appropriate landforms (1A or 4) above.

(Continued)

Table 8 (Concluded)

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
11.7	21.8	20	5.65– 5.85	4			52.7	0.48		1.00	11.4
			5.85– 5.95	1A			25.7				6.78
			5.95– 6.17	4			52.7				11.4
			6.17– 6.23	1A			25.7				6.78
			6.23– 8.29	4			52.7				11.4
			8.29– 8.99	1A			25.7				6.78
			8.99– 9.37	4			52.7			0.60	6.84
			9.37– 9.43	1A			25.7				4.07
			9.43–10.07	4			52.7				6.84

Table 9

Dust-Emission Prediction Calculations, M113, 25 mph

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
11.7	21.8	25	0 - 0.12	1A	7.5	0.0952	30.3	0.48	0.55	1.00	8.00
			0.12- 0.92	6	15.0	0.190	50.2		1.00		24.1
			0.92- 1.18	1A			30.3				8.00
			1.18- 1.38	4	20.0	0.254	62.0		0.45		13.4
			1.38- 1.50	10	22.5	0.286	67.6		0.55		17.9
			1.50- 1.96	8	25.0	0.318	73.1		0.55		19.3
			1.96- 2.46	4			62.0				13.4
			2.46- 2.52	1A			30.3				8.00
			2.52- 2.86	4			62.0				13.4
			2.86- 3.02	1A			30.3				8.00
			3.02- 3.20	4			62.0				13.4
			3.20- 3.28	1A			30.3				8.00
			3.28- 3.46	4			62.0				13.4
			3.46- 3.51	1A			30.3				8.00
			3.51- 3.89	4			62.0				13.4
			3.89- 3.97	1A			30.3				8.00
			3.97- 4.07	4			62.0				13.4
			4.07- 4.27	1A			30.3				8.00
			4.27- 4.39	4			62.0				13.4
			4.39- 4.45	1A			30.3				8.00
			4.45- 4.81	4			62.0				13.4
			4.81- 4.99	1A			30.3				8.00
			4.99- 5.15	4			62.0				13.4
			5.15- 5.19	1A			30.3				8.00
			5.19- 5.29	4			62.0				13.4
			5.29- 5.33	1A			30.3				8.00
			5.33- 5.57	4			62.0				13.4
			5.57- 5.65	1A			30.3				8.00

NOTE: Read columnar entries from lines for appropriate landforms (1A or 4) above.

(Continued)

Table 9 (Concluded)

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
11.7	21.8	25	5.65– 5.85	4			62.0	0.48		1.00	13.4
			5.85– 5.95	1A			30.3				8.00
			5.95– 6.17	4			62.0				13.4
			6.17– 6.23	1A			30.3				8.00
			6.23– 8.29	4			62.0				13.4
			8.29– 8.99	1A			30.3				8.00
			8.99– 9.37	4			62.0			0.60	8.16
			9.37– 9.43	1A			30.3				4.80
			9.43–10.07	4			62.0				8.16

Table 10

Dust-Emission Prediction Calculations, M60, 5 mph

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
51.0	64.8	5	0 - 0.12	1A	7.5	0.0952	14.7	0.48	0.55	1.00	3.88
			0.12- 0.92	6	15.0	0.190	24.4		1.00		11.70
			0.92- 1.18	1A			14.7				3.64
			1.18- 1.38	4	20.0	0.254	30.1		0.45		6.50
			1.38- 1.50	10	22.5	0.286	32.8		0.55		8.67
			1.50- 1.96	8	25.0	0.318	35.5		0.55		9.37
			1.96- 2.46	4			30.1				6.50
			2.46- 2.52	1A			14.7				3.64
			2.52- 2.86	4			30.1				6.50
			2.86- 3.02	1A			14.7				3.64
			3.02- 3.20	4			30.1				6.50
			3.20- 3.28	1A			14.7				3.64
			3.28- 3.46	4			30.1				6.50
			3.46- 3.51	1A			14.7				3.64
			3.51- 3.89	4			30.1				6.50
			3.89- 3.97	1A			14.7				3.64
			3.97- 4.07	4			30.1				6.50
			4.07- 4.27	1A			14.7				3.88
			4.27- 4.39	4			30.1				6.50
			4.39- 4.45	1A			14.7				3.88
			4.45- 4.81	4			30.1				6.50
			4.81- 4.99	1A			14.7				3.88
			4.99- 5.15	4			30.1				6.50
			5.15- 5.19	1A			14.7				3.88
			5.19- 5.29	4			30.1				6.50
			5.29- 5.33	1A			14.7				3.88
			5.33- 5.57	4			30.1				6.50
			5.57- 5.65	1A			14.7				3.88

NOTE: Read columnar entries from lines for appropriate landforms (1A or 4) above.

(Continued)

Table 10 (Concluded)

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
51.0	64.8	5	5.65- 5.85	4			30.1	0.48		1.00	6.50
			5.85- 5.95	1A			14.7				3.88
			5.95- 6.17	4			30.1				6.50
			6.17- 6.23	1A			14.7				3.88
			6.23- 8.29	4			30.1				6.50
			8.29- 8.99	1A			14.7				3.88
			8.99- 9.37	4			30.1			0.60	3.91
			9.37- 9.43	1A			14.7				2.18
			9.43-10.07	4			30.1				3.91

Table 11

Dust-Emission Prediction Calculations, M60, 10 mph

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
51.0	64.8	10	0 - 0.12	1A	7.5	0.0952	24.4	0.48	0.55	1.00	6.45
			0.12- 0.92	6	15.0	0.190	40.5		1.00		19.4
			0.92- 1.18	1A			24.4				6.45
			1.18- 1.38	4	20.0	0.254	50.0		0.45		10.8
			1.38- 1.50	10	22.5	0.286	54.4		0.55		14.4
			1.50- 1.96	8	25.0	0.318	58.8		0.55		15.5
			1.96- 2.46	4			50.0				10.8
			2.46- 2.52	1A			24.4				6.45
			2.52- 2.86	4			50.0				10.8
			2.86- 3.02	1A			24.4				6.45
			3.02- 3.20	4			50.0				10.8
			3.20- 3.28	1A			24.4				6.45
			3.28- 3.46	4			50.0				10.8
			3.46- 3.51	1A			24.4				6.45
			3.51- 3.89	4			50.0				10.8
			3.89- 3.97	1A			24.4				6.45
			3.97- 4.07	4			50.0				10.8
			4.07- 4.27	1A			24.4				6.45
			4.27- 4.39	4			50.0				10.8
			4.39- 4.45	1A			24.4				6.45
			4.45- 4.81	4			50.0				10.8
			4.81- 4.99	1A			24.4				6.45
			4.99- 5.15	4			50.0				10.8
			5.15- 5.19	1A			24.4				6.45
			5.19- 5.29	4			50.0				10.8
			5.29- 5.33	1A			24.4				6.45
			5.33- 5.57	4			50.0				10.8
			5.57- 5.65	1A			24.4				6.45

NOTE:
Read columnar entries from lines for appropriate landforms (1A or 4) above.

(Continued)

Table 11 (Concluded)

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
51.0	64.8	10	5.65- 5.85	4			50.0	0.48		1.00	10.8
			5.85- 5.95	1A			24.4				6.45
			5.95- 6.17	4			50.0				10.8
			6.17- 6.23	1A			24.4				6.45
			6.23- 8.29	4			50.0				10.8
			8.29- 8.99	1A			24.4				6.45
			8.99- 9.37	4			50.0			0.60	6.48
			9.37- 9.43	1A			24.4				3.87
			9.43-10.07	4			50.0				6.48

Table 12

Dust-Emission Prediction Calculations, M60, 15 mph

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	[illegible] lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
51.0	64.8	15	0 – 0.12	1A	7.5	0.0952	32.8	0.48	0.55	1.00	8.66
			0.12– 0.92	6	15.0	0.190	54.3		1.00		26.1
			0.92– 1.18	1A			32.8				8.66
			1.18– 1.38	4	20.0	0.254	67.1		0.45		14.5
			1.38– 1.50	10	22.5	0.286	73.2		0.55		19.3
			1.50– 1.96	8	25.0	0.31	79.1		0.55		20.9
			1.96– 2.46	4			67.1				14.5
			2.46– 2.52	1A			32.8				8.66
			2.52– 2.86	4			67.1				14.5
			2.86– 3.02	1A			32.8				8.66
			3.02– 3.20	4			67.1				14.5
			3.20– 3.28	1A			32.8				8.66
			3.28– 3.46	4			67.1				14.5
			3.46– 3.5'	1A			32.8				8.66
			3.51– 3.89	4			67.1				14.5
			3.89– 3.97	1A			32.8				8.66
			3.97– 4.07	4			67.1				14.5
			4.07– 4.27	1A			32.8				8.66
			4.27– 4.39	4			67.1				14.5
			4.39– 4.45	1A			32.8				8.66
			4.45– 4.81	4			67.1				14.5
			4.81– 4.99	1A			32.8				8.66
			4.99– 5.15	4			67.1				14.5
			5.15– 5.19	1A			32.8				8.66
			5.19– 5.29	4			67.1				14.5
			5.29– 5.33	1A			32.8				8.66
			5.33– 5.57	4			67.1				14.5
			5.57– 5.65	1A			32.8				8.66

NOTE:
Read columnar entries from lines for appropriate landforms (1A or 4) above.

(Continued)

Table 12 (Concluded)

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
51.0	64.8	15	5.65– 5.85	4			67.1	0.48		1.00	14.5
			5.85– 5.95	IA			32.8				8.66
			5.95– 6.17	4			67.1				14.5
			6.17– 6.23	IA			32.8				8.66
			6.23– 8.29	4			67.1				14.5
			8.29– 8.99	IA			32.8				8.66
			8.99– 9.37	4			67.1			0.60	8.70
			9.37– 9.43	IA			32.8				5.20
			9.43–10.07	4			67.1				8.70

Table 13

Dust-Emission Prediction Calculations, M60, 20 mph

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
51.0	64.8	20	0 - 0.12	1A	7.5	0.0952	40.5	0.48	0.55	1.00	10.7
			0.12- 0.92	6	15.0	0.190	67.0		1.00		32.2
			0.92- 1.18	1A			40.5				10.7
			1.18- 1.38	4	20.0	0.254	82.8		0.45		17.9
			1.38- 1.50	10	22.5	0.286	90.3		0.55		23.8
			1.50- 1.96	8	25.0	0.318	97.6		0.55		25.8
			1.96- 2.46	4			82.8				17.9
			2.46- 2.52	1A			40.5				10.7
			2.52- 2.86	4			82.8				17.9
			2.86- 3.02	1A			40.5				10.7
			3.02- 3.20	4			82.8				17.9
			3.20- 3.28	1A			40.5				10.7
			3.28- 3.46	4			82.8				17.9
			3.46- 3.51	1A			40.5				10.7
			3.51- 3.89	4			82.8				17.9
			3.89- 3.97	1A			40.5				10.7
			3.97- 4.07	4			82.8				17.9
			4.07- 4.27	1A			40.5				10.7
			4.27- 4.39	4			82.8				17.9
			4.39- 4.45	1A			40.5				10.7
			4.45- 4.81	4			82.8				17.9
			4.81- 4.99	1A			40.5				10.7
			4.99- 5.15	4			82.8				17.9
			5.15- 5.19	1A			40.5				10.7
			5.19- 5.29	4			82.8				17.9
			5.29- 5.33	1A			40.5				10.7
			5.33- 5.57	4			82.8				17.9
			5.57- 5.65	1A			40.5				10.7

NOTE: Read columnar entries from lines for appropriate landforms (1A or 4) above.

(Continued)

Table 13 (Concluded)

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
51.0	64.8	20	5.65– 5.85	4			82.8	0.48		1.00	17.9
			5.85– 5.95	1A			40.5				10.7
			5.95– 6.17	4			82.8				17.9
			6.17– 6.23	1A			40.5				10.7
			6.23– 8.29	4			82.8				17.9
			8.29– 8.99	1A			40.5				10.7
			8.99– 9.37	4			82.8			0.60	10.7
			9.37– 9.43	1A			40.5				6.42
			9.43–10.07	4			82.8				10.7

Table 14

Dust-Emission Prediction Calculations, M60, 25 mph

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
51.0	64.8	25	0 - 0.12	1A	7.5	0.0952	47.7	0.48	0.55	1.00	12.6
			0.12- 0.92	6	15.0	0.190	79.0		1.00		37.9
			0.92- 1.18	1A			47.7				12.6
			1.18- 1.38	4	20.0	0.254	97.5		0.45		21.1
			1.38- 1.50	10	22.5	0.286	106		0.55		28.1
			1.50- 1.96	8	25.0	0.318	115		0.55		30.3
			1.96- 2.46	4			97.5				21.1
			2.46- 2.52	1A			47.7				12.6
			2.52- 2.86	4			97.5				21.1
			2.86- 3.02	1A			47.7				12.6
			3.02- 3.20	4			97.5				21.1
			3.20- 3.28	1A			47.7				12.6
			3.28- 3.46	4			97.5				21.1
			3.46- 3.51	1A			47.7				12.6
			3.51- 3.89	4			97.5				21.1
			3.89- 3.97	1A			47.7				12.6
			3.97- 4.07	4			97.5				21.1
			4.07- 4.27	1A			47.7				12.6
			4.27- 4.39	4			97.5				21.1
			4.39- 4.45	1A			47.7				12.6
			4.45- 4.81	4			97.5				21.1
			4.81- 4.99	1A			47.7				12.6
			4.99- 5.15	4			97.5				21.1
			5.15- 5.19	1A			47.7				12.6
			5.19- 5.29	4			97.5				21.1
			5.29- 5.33	1A			47.7				12.6
			5.33- 5.57	4			97.5				21.1
			5.57- 5.65	1A			47.7				12.6

NOTE:
Read columnar entries from lines for appropriate landforms (1A or 4) above.

(Continued)

Table 14 (Concluded)

W tons	TAC ft^2	S mph	Course Distance miles	Landform	Mean Fines %	SL lb/ft^2	E lb/VMT	TSP Adjustment Factor	Gravel Adjustment Factor	Vegetative Cover Adjustment Factor	E_{TSP} lb/VMT
51.0	64.8	25	5.65– 5.85	4			97.5	0.48		1.00	21.1
			5.85– 5.95	1A			47.7				12.6
			5.95– 6.17	4			97.5				21.1
			6.17– 6.23	1A			47.7				12.6
			6.23– 8.29	4			97.5				21.1
			8.29– 8.99	1A			47.7				12.6
			8.99– 9.37	4			97.5			0.60	12.6
			9.37– 9.43	1A			47.7				7.56
			9.43–10.07	4			97.5				12.6

Table 15

Adjustment Factors for Vehicular Dust

Factor for Particles ≥ Gravel in Size		Factors for Vegetative Cover	
Percent ≥ Gravel	Adjustment Factor (Multiplier)	Vegetative Cover %	Adjustment Factor (Multiplier)
<1	1.00	--	--
1-10	0.95	<11	1.00
11-20	0.85	11-20	0.90
21-30	0.75	21-30	0.80
31-40	0.65	31-40	0.70
41-50	0.55	41-50	0.60
51-60	0.45	51-60	0.50
61-70	0.35	61-70	0.40
71-80	0.25	71-80	0.30
81-90	0.15	81-90	0.20
91-100	0.05	91-100	0.10

APPENDIX A: DISCUSSION OF TYPES OF REFERENCE MATERIAL FOR DESERT STUDIES

General Data Types

1. Desert areas are among the poorest documented in the world since they support sparse populations and are little used for agriculture due to unfavorable climates. Sources of these documents will not be included in this discussion since they may vary widely from one area to another. However, various types of general reference material that are required for all areas are discussed in the following paragraphs.

Climatic Reference Material

Maps

2. Most climatic maps are small-scale, and boundaries between climatic types based on rainfall and temperature records are indefinite and ever changing. If the selection of the limits of the study area is based on strategic criteria, then the actual boundary between the desert and adjacent steppe or arid and semiarid climates is not the most important consideration. However, from the standpoint of dust propensity, these boundaries are significant.

Reports

3. A general report or text may cover the entire region or study area and provide generalized climatic data for initial characterization. Detailed reports will likely be available for local areas within the region and may contain historical temperature and rainfall records.

Historical temperature and rainfall data

4. Weather stations occur widely throughout the world and are maintained by an agency of the government in which they are geographically located. Daily temperature and rainfall measurements are taken, and daily records may be available for 20 years or more. Thus, physiographic regions and even individual landforms may be characterized in terms of temperature and rainfall averages and extremes.

Paleoclimatic information

5. The three preceding sources of climatic data are concerned with modern climatic descriptions and records. Paleoclimatic data, which must be correlated with geologic time (Table 2), will most likely be found in geological and physiographic references. Paleoclimatic data older than Quaternary and Tertiary are not considered to be of vital interest in the analysis of currently existing landforms and soils. From the standpoint of associating dust with landforms of different ages, it is generally found that the older landforms contain the larger quantities.

- a. Pleistocene. The Pleistocene is represented by older sequences of depositional and volcanic landforms. The climate was significantly humid during this epoch, and the deposition of dust from northern latitudes was much more prolific than during the Holocene.
- b. Tertiary. The Tertiary, too, was represented by humid climatic conditions. Remnants of Tertiary depositional landforms occur as relict alluvial fans. Also, considerable volcanic activity was evident during this period.

Physiographic Reference Material

6. The regional physiographic picture of the study area is a necessary first step. General references are usually available, and these, together with small-scale topographic maps and small-scale aerial imagery, permit an initial physiographic assessment of the entire region, including the study area. The same geologic processes responsible for the evolution of the entire region produced the system of component landforms that occur in the study area. Through the understanding of various geologic processes responsible for the evolution of these landforms and their associated soils, predictions within remote and often inaccessible regions are made possible.

7. The final step is the identification, description, and delineation of major landforms and their associated soils. This is accomplished by the collective examination of the general physiographic data, medium- and small-scale topographic maps, and small-scale aerial imagery. Hills and mountains may be separated from plains and plateaus. Depositional landforms may in many cases be separated from erosional or residual landforms.

Geologic Reference Material

Types of geologic information

8. Geologic reference material includes general reports and references covering the entire desert region and specific references that cover only limited portions. Localized reports are found where studies of specific geologic interest were conducted. The following types of geologic information are useful for the characterization of the landforms occurring within the study area and provide general insight as to the nature of the soils that have developed from the parent materials composing the landforms.

- a. Structural. Structural geology reports provide a regional picture of how tectonic forces have created modern landscapes. In the Southwestern United States, for example, faulting has created the basin and range landscape that is evident today. In addition, enormous quantities of molten rock have outpoured and have been deposited over preexisting rocks.
- b. Stratigraphic. The geologic age of the various rock units that occur within the area establishes the sequence in which they occur. The distribution of each rock unit throughout the study area must be determined since this distribution is significant to the genesis of the component landforms occurring within the region in general and the study area specifically.
- c. Lithologic. The chemical and mechanical weathering of different rock types not only controls the traditional shape or form of a landform but is the mechanism by which the associated soils are formed. The chemical composition and the grain size of various rocks are the most important considerations in the determination of the residium or debris that will form from the weathering process. It should be noted that while chemical weathering or decomposition is the most important type of weathering in humid climates, mechanical weathering or disintegration of rock is the overwhelmingly dominant process in the desert. Erosion in deserts is more active than weathering, and the weathered products or debris are usually removed as fast as they appear. Chemical weathering is important in relict soils of Pleistocene and Tertiary age, formed when climates were much more humid than at present.
- d. Origin and depositional history of Quaternary deposits. The vast majority of the landforms in deserts relevant to the emission of dust are composed of unconsolidated Quaternary deposits. While these deposits are similar in age, they may be significantly dissimilar with respect to the natural processes by which they were formed as well as the parent materials from which they originated. It is therefore important to know the depositional history of these deposits and their distribution throughout the study area.

Geologic maps

9. If a regional geologic map that covers the entire study area is available, it will, by necessity, be small-scale, e.g., 1:1,000,000. Resultingly, formations will be grouped according to geologic age so that distinctions between individual formations will be lost. Thus, the valuable correlation between surficial deposits and their parent materials is not directly determinable from small-scale geology maps. It will be unlikely that coverage of large-scale geology maps will be available for the entire study area; such maps usually accompany highly specialized investigations. It is possible from existing large-scale maps, together with accompanying topographic maps and aerial imagery, to develop relationships that may be extrapolated into areas where detailed coverage is lacking. Many of these relationships will be discussed later in this report. There are three types of information available from geologic maps, whether small- or large-scale, that are considered useful to this study:

a. Surface distribution of component rock types. As previously stated, small-scale geologic maps usually combine rock units or formations according to age, and detailed differentiation is not possible.

b. Lithologic descriptions of rock units. These descriptions are included in the accompanying legends. It is considered imperative that the mineralogical composition of each rock type be known since it represents the parent materials from which surface deposits are formed.

c. Distribution of Quaternary deposits. The dust-potential characteristics of Quaternary deposits are directly related to the parent materials from which they originated. Geologic maps depict the general distribution of these deposits, even though there is seldom distinction made regarding texture or the natural process by which they were formed. These maps usually correlate well with topographic maps since the deposits are most prevalent in areas of low slope occurring on floodplain terraces and on alluvial fans and aprons at the bases of mountains. There are exceptions to this general rule, however, such as soil-free pediments at the base of some mountains and extensive plains containing residual soils overlying horizontally bedded sedimentary rocks.

Vegetation Reference Material

10. Vegetation maps covering specific areas of interest are a rarity. Generalized vegetation maps often accompany climatic maps or may be included

in texts of climatology or physical geography. Useful vegetative data accompany soil survey reports; however, such reports are unlikely to be available for study areas that occur within the limits of military reservations and even less likely to be available for world desert environments. However, from the examination of the available maps, references, and aerial imagery, the following vegetative data must be extracted, interpreted, or deduced.

Determination and description of vegetation species

11. Species are often related to relatively restrictive climatic regimes, occur at certain elevations, and are associated with preferred soil types. Vegetation species can usually be identified from general references, although distributions must be determined from large-scale vegetation maps and/or aerial photography.

Distribution and relationship to component landforms in the study area

12. Most individual landforms occurring in a desert environment are characterized by unique associations of plants. Certain species may occur only on a particular landform as a result of unique associations of physical attributes, such as slope, moisture content and depth to the water table, and texture and chemistry of the soil. These species, if recognizable on aerial photography, are diagnostic of those certain landforms and facilitate their identification.

Agricultural practices

a. Harvesting and planting schedules. In desert areas suitable for crops, harvesting and planting schedules will vary with crop type. Since each type may be related to soil type, soil moisture, slope, and other factors, crop types may serve as general indicators of texture. In addition, the height and density of the plants are factors to consider in determining the dust-emission potential of various agricultural soils.

b. Irrigation requirements and schedules. In agricultural areas, the irrigation requirements of crops are general indications of the texture, porosity, and permeability of the soil. Crop types with different moisture requirements have irrigation schedules adjusted for their needs. Soil moisture can be either determined in the field or estimated from airborne imagery, such as color infrared photography.

c. Field crop patterns. Often field patterns are useful indicators of crop types or irrigation practices. Circular patterns in the Southwest, for example, indicate irrigation associated with certain crop types. The presence of these patterns indicates particular soil types and soil moisture conditions.

Hydrologic Reference Material

13. Hydrologic information required for this study is extracted from topographic maps and aerial imagery. Generally, the larger the map scale and the smaller the contour interval, the greater the detail in which drainage lines are shown. Most drainage lines are discernible on large- or medium-scale imagery. Color infrared photography, sensitive to surface moisture conditions, is the optimum.

Regional drainage patterns

14. Regional drainage patterns are useful in describing the general physiographic character of a region. Major drainage patterns reflect either past or present cycles of erosion. Regional drainage patterns are affected by major geologic controls such as past tectonic events, slope, size of drainage basin, and the nature of the rock or unconsolidated materials in which the channels are scoured. In plateau regions, it is not uncommon for drainageways to follow major joint patterns or to be deflected by plateau escarpments. Patterns are often diagnostic of bedrock types on which they are developed. For instance, sandstone plateaus usually have dendritic gross drainage patterns or rectangular patterns if jointing exerts strong controls. In basaltic plains, most drainage is internal, and organized drainage is generally lacking. Hills composed principally of limestone and shale most often have trellis drainage (Figure 2).

Local drainage patterns

15. Local or low-order drainage patterns are restrictive in that they occur entirely or almost entirely within the limits of a particular landform. In this context, they are diagnostic of that landform and thus represent a useful interpretative key that can be applied to both large-scale topographic maps or aerial imagery. Alluvial fans characteristically have dendritic drainage patterns radiating from their apices, where they debouch from the hills or mountains. Many playas appear to be featureless while others have poorly developed centripetal patterns. Surface drainage in sand dune areas is

absent. Low-order drainage in granitic mountains is often rectangular, following joint planes.

Topographic Reference Material

16. Topographic maps are universally available at a scale of 1:250,000 or smaller with a variety of contour intervals. Scales of 1:50,000 and 1:25,000 are generally available for developed countries of the world and for limited portions of undeveloped countries, such as desert areas, surrounding large urban areas or areas of projected agricultural development. The following topographic data can be obtained from these maps:

Slope

17. Slope can be obtained by measuring contour density. Vertical rise per measured horizontal interval will give a measure of slope. Breaks in slope are used as a convenient means of delineating landform boundaries.

Form

18. Contours on topographic maps may be considered as form lines for major landform types such as hills, mountains, floodplains, etc. Thus, they provide a general overview of the study area.

Topographic position

19. If the limits of a landform can be determined from topographic map analysis, topographic position measured along the longitudinal axis of the landform can be approximated. Topographic position can often be related to soil texture, soil moisture, and surface roughness.

Pedologic Reference Material

20. Pedologic materials are available as maps and reports, both often included in the same reference. They vary widely in detail and quality. In addition, they are oriented toward various fields of interest, such as agriculture and engineering, so that terms, units, and descriptions are often not correlative.

Maps

21. Maps in developed countries are most often oriented toward the agricultural potential of the soils. The maps are usually large scaled and cover the nonforested portions of the country. Unfortunately, the

agricultural units cannot be accurately translated into textural terms. Analysis of pedologic material, along with geologic and topographic maps of the same area, usually enables reliable estimates of the engineering characteristics of the soils to be made. Small-scale maps of the world at a scale of 1:2,500,000 that describe soils in agricultural terms have been prepared for the Food and Agricultural Organization. Also, undeveloped countries are covered by small-scale soil maps; however, the units are described in nontextural terms, and the degree of detail is inadequate for landform characterization.

Reports

22. Textural materials, which usually accompany the soil maps, amplify the unit designations appearing in map legends. Those for specific countries are often in a foreign language and require skilled translation.

APPENDIX B: DETAILED DATA REQUIREMENTS FOR US STUDY AREAS

1. The following data types are considered minimal for detailed characterization of relevant landform attributes in a restricted study area. The data requirements would apply to study areas on military reservations in the Southwestern United States. While the scope of this preliminary study is the Yuma Proving Ground (YPG), it is understood that other areas may be included later to ensure that a complete range of desert landforms and associated soils have been evaluated.

a. Large-scale topographic maps (1:50,000). These maps have less than 10-m contour interval.

b. Large-scale aerial imagery. Photographs will be used for landform delineation, drainage pattern analysis, surface soil identification, vegetation species and distribution, and the presence of surface rock textures coarser than gravel. The following types of photography are considered:

(1) Color. Color photography reveals soils in their natural tones and optimizes distinction between surface textures. It is also useful in the identification of parent materials.

(2) Color infrared. This type is sensitive to moisture conditions and thus is ideally suited for identifying drainage features. Also due to the higher moisture conditions that prevail in the washes, vegetation is almost continuous along the banks, further enhancing its recognition. Distinction of landforms is often enhanced on color infrared photography when separated by drainage lines.

(3) Black and white. This type of photography represents the last choice; however, it is the most readily available coverage, especially if soil surveys of the study areas have been conducted. All features are revealed in gray tones. Generally, coarser soils appear in lighter tones; however, high moisture contents create darker tones and minimize differentiation of soil textures. Living vegetation appears in darker tones than the soil background and on large-scale photography is readily recognizable. Drainage lines are enhanced by the plant populations that occur along their banks.

c. Reference material. Reference material for dust-propensity predictions on landforms in selected US study areas differs from that previously described only in detail and in the scope of geographic reference, i.e., limited to the study area. The types of reference material required for this phase of the study are identified and discussed as follows:

(1) Soil and geology reports. The availability of reports that deal specifically with the study area is generally limited.

At the YPG, a soil survey report covers a portion of the reservation while the remaining portion of Yuma County has been included in a separate report. The latter is significant since often geomorphic and pedologic units can be extended into reservation areas not covered and the textural definitions of these units, i.e., soil series, applied to reservation landforms. Portions of the reservation that have not been mapped and for which quantitative textural data are lacking must be characterized by analogy. Landforms and soil series that are delineated on the 1:24,000 photo maps can be closely correlated. Once these correlations are established, based in part on consideration of a number of geologic and topographic factors that control or contribute to soil development, recognition of analogous landforms or variance that can be achieved by this method is possible. Determination of the degree of analogy or variance that can be achieved by this method is a requirement of the field program. Restrictive geology reports may also make important contributions to the characterization of desert landforms. Such reports may cover an entire county or be restricted to a particular mountain range. The plates that accompany such reports usually delineate the occurrence of the various geologic formations, and the text provides detailed lithologic descriptions. These descriptions are useful in the prediction of the textural character of the surface soils that compose the depositional landforms flanking the rock outcrops. Each rock unit has certain unique distinguishing features that are recognizable on aerial photography of the area. Once these interpretation keys have been developed, they can be confidently applied to stratigraphic units occurring out of the area of specific study included in the report.

(2) Soil data. Soil data within the study area may be available in the form of profiles, borings, well logs, etc., often with accompanying laboratory analysis. These data, if they can be accurately located, are useful in the pedologic characterization of the landforms in which they occur. Such data may be available from the Post Engineer or from engineering contractors who have been involved in various construction activities within the study area. Soil data determined to be applicable to study objectives can substantially reduce field effort for data collection and subsequent laboratory analysis of samples.

d. Personal contacts. Contacting individuals with acknowledged expertise regarding the geology/soils in the area of study is often a wise investment of time. These individuals are often identified during the literature survey and by contacting State and government agencies who have produced reports and maps of the area. Such individuals can often provide explanations for problems that result from a limited understanding of the geologic events that have controlled the evolution of the landforms and associated soils in the study area.

e. Field program. A field program involving reconnaissance and data collection within the study area is considered essential to project objectives. The field program provides a means of validating the landform-soils relationships on which the dust-propensity predictions are based.

2. The current study did not have all of the above data types available for use during the investigative phase of the study. Materials and data that were available are considered less than optimal to meet the requirements of the study. For example, only partial coverage of medium-scale color infrared photography was available; soil surveys covered only a fraction of the mapped area; and no laboratory analysis of soils occurring in association with landforms along the traverses selected for the tracked vehicles was available.

APPENDIX C: DESCRIPTIONS OF DESERT LANDFORMS

The following landforms and their attendant descriptions and photo-interpretation keys occur at or near the Yuma Proving Ground (YPG) and as such represent only a subordinate number of those occurring on a worldwide basis. Their representativeness has been established in Table 1 (see main text). It should be emphasized that the extension of this methodology to remote deserts of the world will require identification and characterization of additional landforms as well as variations of those occurring at the YPG, where different climatic and geologic histories must be considered.

a. Alluvial fans and aprons. Alluvial fans are cone-shaped deposits occurring at the base of mountains, hills, or escarpments. They develop where streams emanating from the uplands experience a sufficient reduction in gradient to deposit their loads. The fans, steepest near the uplands, slope gently outward with a continually decreasing gradient and are characterized by braided stream channels that score their surfaces. Where a succession of fans overlap or coalesce along the base of the upland, alluvial aprons are formed.

(1) Geometry. The landform is composed of two basic components: the relatively flat to undulating interfluve area and the bounding, braided drainage channels. The interfluves are the predominant component. Slopes generally vary from about 1 to 50 percent or more near the base of the mountains. The incidence of steep-sided drainageways averages from about 2 to 10 per mile depending upon the topographic position along the longitudinal profile where a perpendicular 1-mile traverse is measured. Relief defined as the vertical differential between the interfluve crest and the immediately adjacent flow lines will vary from a few to as much as 100 ft, depending upon the proximity to the apex. The interfluves are convex, being more pronounced near the apex of the fan. The surface of the older fans is veneered with a coarsely fitted mosaic of gravels stained with desert varnish, underlain by an unconsolidated layer of silt or silt, sand, and gravel mixtures.

(2) Drainage. The gross drainage pattern is radial-dendritic in plan from the apex of the fan (Figure 2 in main text). Individual channels are of the braided variety. The braided pattern results from the deposition of coarse-grained materials, predominantly sands and gravels, in the channels of aggrading drainageways. The channels are eventually filled, forcing the ephemeral streams to develop a new channel. The end result is a system of braided channels separated by channel bars or interfluves. The banks of the channels are lined with relatively dense linear

populations of shrubs and stunted trees, a relationship that greatly enhances their recognition on aerial photography.

(3) Parent materials. The parent materials of these vast alluvial deposits vary greatly, even along a single mountain front. However, some general observations that assist in the characterization of fans and aprons are possible:

(a) The coarser and more angular the material that has weathered from the parent rock, the steeper the slope. The slope may approach the angle of repose near the apex of the fan.

(b) As a general rule, the coarsest materials composing the fans will be found nearest the apex and the finest at the toe where slopes are nearly level. Since the material is transported following desert rainstorms and the intensity of these storms will vary significantly from one event to the next, particle sizes become resultingly mixed.

(c) Source areas containing coarse-grained igneous rocks, such as granite and granite-gneiss, produce sandy soils and fragments seldom larger than cobbles. Fine-grained igneous rocks characteristically weather into angular fragments with a predominance of gravel and cobble sizes. The associated soils are sand-silt mixtures. Fine-grained, resistant sedimentary rocks, such as limestone, produce an abundance of angular fragments of gravel, cobble, and stone size that are the major component of the soils on the middle and upper slopes. Soils on the toe of fans whose sediments are derived principally from limestone source materials are silty in texture.

(4) Soils. Alluvial fans and aprons are composed of coarse alluvium. They are composed of varying mixtures of gravel, sand, and silt. Minor amounts of clay may be present in the lower topographic positions. The coarser mixtures occur on the higher topographic positions of the fans and the finest mixtures near the toe. Generally, the B horizon is finer in texture, having been enriched by the downward percolation of rainwater carrying fines in solution. Fans and aprons of Pleistocene are usually mosaicked with a thin, nearly continuous layer of blackened gravels called desert pavement, which has a crusty texture. This pavement does not occur or is poorly developed on the lower Recent fans and aprons. Near the mountain front, the fans are highly dissected, and the crested interfluves have virtually been stripped of the desert pavement.

(5) Vegetation. Certain species of vegetation are characteristic of alluvial fans and aprons. These populations are stratified from the apex of the fan, where coarser soil, less moisture, and higher elevations occur, to the toe with

finer soils, higher moisture conditions, and lower elevations. Also different populations occur on the interfluves than are found along the intermittent washes. For example, creosote bush-bur sage populations are dominant on the lower portions of alluvial aprons. Palo verde, ironwood, and mesquite are woody types that line the banks of washes on lower slopes. Saguaro and ocotillo are found on upper alluvial fan slopes.

b. Alluvial flats. Alluvial or desert flats have low relief and slope and, except for playas, occupy the lowest portions of desert basins. In basins of interior drainage, they are the transitional landform from the higher alluvial aprons to the playa surfaces, which represent the lowest elevations and the flattest slopes. They are widespread and occur frequently and in many situations other than the above sequence. Their characteristics are relatively constant, and they are easily recognizable on maps and photography.

(1) Geometry. Slopes are generally less than 2 percent and local relief from several inches to several feet. Numerous shallow washes cross their surface and represent the subordinate component of the landform. The flats are generally light toned on aerial photography with the washes appearing in lighter tones than the interfluves. The surface monotony is occasionally broken by low, isolated hills or volcanic cones, lava flows, and low sand dunes.

(2) Drainage. Drainage patterns are shallow and vary from braided on the upper limits of the landform to centripetal toward the center of the basin in topographic settings where external drainage is absent. Cross-selections of channels are shallow and saucer shaped. Bank slopes are gentle to moderate.

(3) Parent materials. Parent materials are the same as for alluvial fans and aprons occurring upslope. Mixing of the soils that compose the flats is more complete since they are further from the source than the aprons. However, the compositions still reflect the finest component of the material weathered from rock outcrops, which is the source of the alluvially transported debris composing the landform.

(4) Soils. The soils that compose the flats are predominantly fine sands and silts with subordinate clay contents. Many flats are exceedingly gravelly both on the interfluves and in the washes. Others are completely devoid of gravels, a reflection of the nature of the parent materials. Rock fragments larger than gravel are uncommon.

(5) Vegetation. Low shrubs are the most frequent vegetation types consisting most commonly of creosote, burrobush, mormon tea, and several species of sage. The banks of some of the larger washes may support thin strands of low, scrubby trees such as palo verde, mesquite, and ironwood.

The shrubs on the interfluves may be spaced from several to 10 or more feet apart and are generally less than 6 feet in height. Ground cover may range from 5 to 25 percent.

c. Pediments. Pediments are gently inclined plains or surfaces, which may occur at bases of hills and mountains, sloping away from the uplands toward the center of the basin. They are erosional surfaces but locally may be thinly veneered with coarse alluvium. Numerous rock outcrops occur, and isolated bedrock hills or inselbergs are common. Photographic tones generally reflect the nature of eroded rock type. Light tones occur on portions veneered with alluvium.

(1) Geometry. Slopes are gentle, generally less than 5 percent, but may be 10 to 15 percent at the contact with the adjacent uplands. Local relief may range from 2 to 20 ft. Contacts with adjacent alluvial fans may be difficult to determine geometrically. The longitudinal profile is concave upward.

(2) Drainage. Drainageways are shallow; deep drainage is generally lacking. Bedrock exposures along the shallow drainageways are common. Poorly developed but subdued dendritic drainage patterns may sometimes be recognized.

(3) Parent materials. The pediment, as the name implies, is a lower slope of the exposed mountain mass and thus has the same composition. Pediments are most frequently associated with igneous rocks, especially coarse-intrusive types.

(4) Soils. Soils are present only as a discontinuous and thin veneer overlying bedrock. Soils that do occur are predominantly coarse grained with an abundance of gravels and cobbles.

(5) Vegetation. Vegetation is largely restricted to the patches of thin soil cover and is similar in nature to the alluvial aprons with which it often merges in a downslope direction.

d. Alluvial terraces. These landforms normally occur between the floodplain and the alluvial apron on the east and the valley wall on the west. The large area designated as a terrace and containing the YPG Headquarters and the Laguna Airfield is a Pleistocene terrace of the Colorado River. Also identified as terraces are small, lateral portions of washes that lie at elevations slightly higher than the active wash and thus are not normally inundated except during flooding associated with heavy and infrequent rainfall.

(1) Geometry. Slopes of alluvial terraces in a direction perpendicular to the contours are normally between 1 and 3 percent. In a direction parallel to the contours, slopes rarely exceed 1 percent. The escarpments, which characteristically define the upper and lower contacts with adjacent landforms, may exceed 10 percent and, where constrained by the valley wall, exceed 30 percent. The

surface of the terrace is relatively smooth and relief low; the relief that is present results from drainageways crossing in a downslope direction and from the transitional scarps to adjacent landforms. Elevation lies above the active floodplain.

(2) Drainage. Drainage patterns are usually poorly developed or lacking. Terraces situated downslope from alluvial aprons are crossed by the lower reaches of these ephemeral drainageways. These channels may be braided and components of gross dendritic patterns beginning at the apex of the fans. Drainage within the large Pleistocene terrace of the Colorado River is without well-organized patterns since, due to its flat slopes and sand composition, much of the received flow is internal.

(3) Parent materials. The old terrace of the Colorado River is composed largely of sediments carried and deposited by the river during periods of overbank flow. The original composition has been altered at the surface by deposition of recent alluvium from the adjacent uplands of varied composition and the deposition of aeolian material, dominantly fine sand. The small isolated terraces flanking the washes are similar in composition to the washes and adjacent interfluves.

(4) Soils. Soils that compose terraces are relict floodplain soils that are above the level of modern inundation. As a result, they consist of similar depositional environments found in the active floodplain. Most frequently, they are fine-grained soils but are often sandy, depending upon the textural nature of the source materials. At YPG, the old Colorado terrace is veneered with sand and silt of both alluvial and aeolian origin. The narrow terraces along the washes are older depositional environments and contain varying percentages of gravels, sand, and silt often stratified, since the sequences are related to climatic events of varying intensity.

(5) Vegetation. The surface of the terrace is sparsely populated with low shrubs, cacti, and thin grasses. Along the banks of the shallow washes, low, scrubby trees and taller shrubs occur. In the open plain, creosote and sage bushes are the most frequent types with occasional colonies of low grasses. Along the banks of washes, tamarisk, mesquite, and palo verde are woody types closely associated with the shrubs. The terraces associated with the wash and interfluve complexes are similar in their vegetative populations to the fans and aprons. Descriptions of the vegetation types can be found under the discussions of those landforms.

e. Washes. Desert landforms are dissected by patterns of drainageways that are useful in identifying specific landforms and establishing the geographic limits of the landforms or contacts between them. The drainageways may be incipient, mature, or relict. The determination of this stage of maturity, which is a function of geologic time and other physical and climatic factors, is often a key to the characterization of the landforms in which the drainage patterns are superimposed. Geometrically, washes are highly variable, due to the high level of runoff following desert rainstorms, which generally are much more severe than in humid climates. Typically, washes are narrow, deep, and steep sided along their upper reaches near the mountain front, and their beds are choked with coarse rock debris. At their lower extremes, where they debouch onto alluvial flats and playas, they are wide and shallow, with banks ranging from gentle to steep. The beds are predominantly sandy locally with high silt and/or pebble contents.

(1) Geometry. Washes are composed of sinuous or anastomosing systems of channels in their middle or lower reaches. In their upper reaches, they are narrow and deeply entrenched in the fan surface, and lateral migration is not possible. With each thunderstorm, large volumes of eroded debris are washed from the uplands. Channels become full and blocked, and new ones develop. The result is a braided appearance that is quite conspicuous on aerial photographs.

(2) Drainage. Washes that occur on alluvial fans and aprons are dendritic, radiating in a fan configuration from the apex of the fan. The channels are anastomosing and form braided patterns, which may change from one period following heavy rainfall to another. The washes are readily distinguished from the fan or apron that they dissect by their lighter photographic tones within the channels and the darker tones of the comparatively dense colonies of vegetation that line the banks.

(3) Parent materials. The parent materials in which the washes are entrenched are those that compose the host fans, aprons, or other landforms. The washes are the result of both erosional and depositional alluvial processes; however, the net result is predominantly an erosional feature. The banks are cut in the host landform, while the bottom is composed of materials deposited during flooding following rainfall events.

(4) Soils. The soils that compose the washes are related to the parent materials of the sediment that is transported during the flood periods and to the topographic position and slope of the landform on which a particular reach of a wash occurs. They are commonly gravel, sand-silt mixtures, becoming coarser in an upslope direction. Cobbles, stones, and even boulders frequently choke the beds of the washes, especially in the upper reaches. Since the lithology of the source material or rock is highly variable, the ratio of the different particle sizes is also variable. However, some generalizations are possible. For example, fine-grained igneous rocks produce angular fragments of rock or gravel, cobble, and stone size and fine-grained to fine,

sandy soil; coarse-grained igneous rocks produce subangular to subrounded rock fragments of gravel and cobble size and sand-silt mixtures; coarse-grained sedimentary rocks produce subrounded to angular fragments and sand-silt mixtures; and fine-grained sedimentary rocks such as shale produce platy rock fragments of cobble size and fine-grained soils, i.e., silt and clay.

(5) Vegetation. Plant populations are relatively dense along the banks of washes in comparison with those of the interfluve areas. Vegetation within the washes is infrequent except on the bars that are slightly topographically higher than the adjacent swales. At YPG, low scrubby trees such as palo verde, mesquite, ironwood, and tamarisk occur along with low shrubs such as creosote and sage. Woody vegetation types are less frequent on middle and upper slopes. Here low shrubs and occasional stands of thin grasses are the characteristic populations.

f. Playas. Playas are lacustrinelike ephemeral lake beds that occur in closed basins of interior drainage in desert climates. Playas occupy the lowest portion of the basin and thus capture most of the drainage that reaches the lower slopes. The great majority of the time playas are dry and generally contain water for only a few days at a time every year or so. They may remain moist for short periods following the evaporation of the water. No playas occur within the limits of the YPG. However, they are an important and widespread desert landform and have perhaps the highest dust propensity of all desert landforms. Loessal plains also have high dust propensities, but due to their characteristically dense plant populations, they have lower emission potential. The playa in closest proximity to the YPG occurs south of the Gila River in Cristobal Valley between the Mohawk and Eagle Tank Mountains. This playa has been used periodically by the Luke Air Force Base as a gunnery range. Its current status is unknown. Playas have been classified into five basic types, each with characteristic surface conditions: dry playas, moist playas, lime pan playas, crystal body playas, and compound playas. Approximately one-half of the playas occurring in the Southwestern US desert are of the dry playa type. The playa occurring in Cristobal Valley south of YPG is thought to be the dry type; thus the following discussion will be restricted accordingly:

(1) Geom. .ry. Playas are the flattest landform that occurs in deserts. Slopes are less than 1 percent, and relief from one extreme to the other seldom exceeds a few feet. Local relief is less than 1 foot except for the occurrence of surface relief features such as dunes and shallow washes and infrequent crevasses. The transition to surrounding desert landforms such as alluvial or desert flats is almost imperceptible. Microgeometry is present on the playas in the form of desiccated polygons that develop during the drying process following periods of inundation. The edges

may warp upward, especially those with surface mixtures of fines and salts.

(2) Drainage. Drainage patterns are largely absent on the surface of playas. Occasional shallow, relict drainage features are found that are inactive continuations of those extending from higher, adjacent landforms, e.g., alluvial flats. Drainage patterns in the marginal landforms are largely centripetal, although development is rudimentary. On some playas, incoming drainage is channeled through an alluvial flat into one end of the playa.

(3) Parent materials. The surface of the playa is made up of the finest fractions that have eroded from the surrounding uplands. Where these uplands are fine grained, the playa soils are silts and clays; where they are coarse grained, higher proportions of fine sands and silts are evident. Where the rocks are igneous and metamorphic types containing high concentrations of salt-producing minerals, the salts are mixed with the fines.

(4) Soils. The soils of playas are always fine grained. Some fine sands are mixed with the silts and clays as are dissolved salts. In addition, salts are drawn to the surface of the playa by capillary action, thus increasing the silt-salt ratio over a period of time. The fine-grained, usually dry, and unvegetated surface of the playa appears in white tones on aerial imagery due to its high reflectivity.

(5) Vegetation. The surface of most playas is devoid of vegetation. Low shrubs may occur along relict drainageways and on stabilized dunes that occasionally interrupt the monotony of the playa surface; these appear in dark tones on black and white photographs. Shrubs on the dunes usually die as the dunes grow in height and the shrub roots are unable to reach the water table.

g. Loess plains. These plains are depositional surfaces occurring either in deserts or in the transitional zone between arid and semiarid climates. As in the case of playas, loess plains do not occur within the limits of the YPG. Tyson Wash, occurring at the coordinates 114°15'W, 33°30'N, has soils that closely approximate those of a loessal plain.

(1) Geometry. Loess plains can vary from relatively flat to undulating or rolling. The loess plains are actually aeolian deposits of silt size that have blanketed other landforms. The deposits may also occur on hills, especially on the north-facing slopes. Thus, they tend to conform to existing slopes but have a leveling effect, the deposited silt smoothing out surface irregularities.

(2) Drainage. In semiarid regions or in cases where drainage patterns were developed during more humid climatic conditions, loess plains characteristically develop regional patterns. Local patterns are typically pinnate. If the

plains were formed during the Recent Epoch and in an arid climate, drainage patterns may be poorly developed or even lacking. Much of the drainage may be internal if permeability is high. If the deposits are relatively thin overlying and conforming to existing landforms on which they have been deposited, the plains assume the same patterns as the host landform. Gullies usually have V-shaped channels.

(3) Parent materials. Parent materials of loess deposits are difficult to ascertain. Often the material has traveled great distances before being deposited upon host landforms. Much was removed from vast glacial deposits during the Pleistocene by strong prevailing winds. The glacial deposits themselves, such as till, are eroded material whose source may have been thousands of miles from the site of deposition. The deposits with the greatest thickness are those in closest proximity to the source.

(4) Soil. Approximately 90 percent of a loess soil sample will pass the No. 200 sieve and would thus be classified as fines. However, silt is the predominant grain size, and the US Classification System (USCS) classification is most often ML, with CL being the most frequent subordinate type. Clay is usually present, the amount varying as a function of slope and topographic position. The remaining fraction is very fine-grained sand. Old deposits occurring in a desert may have been enriched by recent deposition from upslope sources, in which case the surface veneer may vary somewhat from the underlying soils. The deposits may also undergo erosion by running water during periods following the infrequent rainfall and by the wind.

(5) Vegetation. In semiarid climates, loess plains are characteristically grasslands. The downward percolation of water in these deposits is so rapid that in thick deposits shrubs and trees are characteristically lacking. In the deserts, the associated vegetation is comparatively sparse, consisting of scattered low shrubs and grasses. Grasses, where relatively dense, are important factors in the entrapment of dust and also in the rate of emission. The loess deposits are light tones on aerial imagery and uniform in texture. Where dissected vertical exposures are evident, they reveal a fine texture, even on large-scale imagery. Surface expression, except for occasional gullies, is generally lacking.

h. Sand plains and low dunes. Sand plains are nearly level to undulating desert surfaces consisting predominantly of wind-blown sands locally enriched with alluvially transported sands and silts from adjacent upland sources during times of heavy rainfall. The plains are frequently associated with active or stabilized dune fields. Textures are fine on aerial imagery, and tones vary from white to medium grey depending on whether the color of the sand grains is white or red.

(1) Geometry. Slopes are nearly level, almost always less than 2 percent. Local relief is lacking except where dunes are present and then may vary from several to tens of feet. The surface of the plain is often characterized by patterns of small sand ripples generally less than several inches from crest to trough.

(2) Drainage. Drainage patterns are usually absent since most of the surface drainage is internal. Where patterns are present, they are poorly developed and are usually relict, having been developed prior to deposition of the sand.

(3) Parent materials. Parent materials for sand plains and dunes are diverse. They have been transported by aeolian processes for great distances or alluvially transported from adjacent uplands. Since the vase majority of the surface sand and silt is composed of quartz, source materials are most commonly sandstone, quartzite, granite, and related igneous rocks.

(4) Soils. Soils are predominantly sandy with generally less than 10-percent silt. They are classified as SP, SP-SM, and SM. Where stabilized or partially stabilized dunes occur on the surface of the plains, the percentage of fines is higher due partly to entrapment by the shrub and grass vegetation that surmounts the dunes.

(5) Vegetation. Overall vegetation is sparse consisting of thin grasses and low shrubs. The stabilized dunes are frequently surmounted by shrubs, usually sage and creosote. When the foliage turns brown, it is difficult to distinguish shrubs from the background on aerial imagery.

i. Hills and mountains. Hills and mountains are relief features that rise prominently above the surrounding plains. The distinction between hills and mountains is that hills are generally considered as having less than 1,000 ft of relief (from base to summit). They are most often composed of bedrock and its weathered products. Some hills are actually composed of unconsolidated materials that were weathered and transported from adjacent uplands and later dissected. At YPG, they are composed of a wide variety of rock types, often found in the same outcrop, and further complicated by folding, faulting, igneous intrusions, and outpouring of extrusive rocks. With only generalized source materials available, hills are impossible to delineate into individual types and as a result are grouped into complexes with similar characteristics. Volcanic hills are further distinguished on the basis of slopes, being divided into those with slopes less than 15 percent and those with slopes greater than 15 percent. The latter distinction is significant from a mobility standpoint, since it has been concluded that vehicle traffic in hills and mountains with slopes greater than 15 percent, high local relief, and high incidence of surface boulders and stones would not be possible except where roads and improved trails are present.