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FINAL TECHNICAL REPORT

on

DEFINITION OF THE DUST ENVIRONMENT FOR PURPOSES OF GAS TURBINE INGESTION STUDIES PHASE I

Contract No. DA-44-009-ENG-4542

SwRI Project No. 988-11

to

U. S. Army Engineer Center and Fort Belvoir
Fort Belvoir, Virginia





SwRI Report No. EE-387

SOUTHWEST RESEARCH INSTITUTE
SAN ANTONIO, TEXAS

(9) FINAL TECHNICAL REP[redacted]T.

on

# (6) DEFINITION OF THE DUST ENVIRONMENT FOR PURPOSES OF GAS TURBINE INGESTION STUDIES. PHASE I.

(15) Contract No. DA-44-009-ENG-4542

(16) SwRI [redacted] 988-11

to

U.S. Army Engineer Center and Fort Belvoir
Fort Belvoir, Virginia

Submitted by

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## ABSTRACT

The purpose of this ~~phase of the overall~~ study is to define the dust environment which a gas turbine engine would experience when operating in a dusty terrain or near equipment causing dust to be airborne. A literature review and supplemental data acquired under various dust conditions were used to establish the severity, duration, and other important factors of dust concentration. Features associated with the dust environment are discussed and the limitations of physical measurements are presented. Summarized results are given with dust concentration within prescribed ranges.

A recommended Gas Turbine Dust Evaluation Schedule with dust concentrations and prescribed ranges of definite particle size distribution will be included in the Phase II Final Report. The evaluation schedule will, therefore, be established from both preliminary studies.

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# I. INTRODUCTION

During the past decade an increasing role of importance has been placed on the dust environment in which a vehicle or machine has to operate. Considerable effort has been directed to the measurement and proper identification of the parameters of the dust environment such that tangible results could be utilized for specific purposes. Much of the previous information and data acquired on the dust environment are of little benefit for reasons of inaccuracy, improper technique, and due to the specific narrow purpose for which the data were obtained.

This is a preliminary study to actual physical testing of the effects of abrasive dust when ingested by gas turbine engines. For purposes of acquiring dust concentration data representative of actual field operations on dust producing terrain, this study reviews the various facets of the dust environment and contains additional data verifying and supplementing the information found in published literature. The primary objective of this study is to define the dust environment a gas turbine engine would experience when operating near particular field activities on various military vehicles or in stationary power installations.

The dust environment and the conditions under which they occur are given in this report together with the various factors which influence the dust concentration.

## II. APPROACH

The scope of this study includes review of all information available on dust concentrations found in published literature, and the range of dust concentrations for various types of vehicular operation and industrial processes. Full interpretation of the methods by which the concentration data were obtained is also presented. In general, the basic study is restricted to defining the dust environment which a gas turbine engine would experience when used in the field as a prime mover. The use of the gas turbine engine for several vehicular applications is also considered; therefore, the dust concentration existing at various "points" around a moving vehicle is included from available literature and previous data recorded by SwRI. The range of concentrations for various operations and conditions is tabulated and conclusions are made as to the representative dust concentration cycle and particle size distribution.

Since the study consists of an analysis of published literature where considerable variations in techniques of measuring dust concentrations were found, a sample acquisition study was also conducted under field conditions using military vehicles. Dust samples were obtained under various conditions and in several locations.

# III. DEFINITION OF DUST ENVIRONMENT

The dust environment, consisting of small particulate matter suspended in the air immediately over and sometimes extending to heights of several hundred feet above the ground surface, is usually a result of vehicular or personnel activity on that surface. Minor dust conditions can be a result of climatic conditions, however, the frequency of dust storms is minute compared to man-made dust clouds. Industrial dust production can reach staggering quantities and under certain conditions the concentrations necessitate careful measurement and exhaustive control processes. Dust inhaled by man results in an accumulative effect and can, within a period of exposure, constitute a definite health hazard.

Dust environments also have a physiological effect that is associated with their chemical (solubility, acidity, etc.) and physical activity; small particles appear more severe and are of greater physiological importance than equal quantities of large particles.

These statements are made merely to illustrate the ramifications of the general term "dust environment" and the interpretations which frequently arise. In the main, this report uses the term "dust environment" in the context of man-made dust clouds and the associated effects on military equipment.

Since the factors which affect the dust environment are extremely broad and encompass such a range of phenomena, consideration of these factors will be presented where actual concentration data are given.

A. Dust Particle Size

The size of a dust particle usually is expressed in microns (one micron is equal to $10^{-3}$ millimeters or .00004 inches) and is understood to be the mean or effective diameter of particle. Particle size bears directly on dust formation and airborne dust movement. Particle size, together with the extended profile of the particle, determines the air velocity (forces) necessary to initiate and maintain movement.

Particle size may be expressed as "effective" diameter or as "statistical" diameter. Since most dust particles possess no definite geometric diameter, particle size is usually expressed as some equivalent or effective diameter. The effective diameter is defined as the diameter of a sphere of the same material which would fall at the same velocity as the particle under consideration. The statistical method of determining particle size is based on the physical characteristics of the particle volume, its surface area, or mean diameter. The diameter thus determined, however, is not necessarily indicative of the aerodynamic or hydrodynamic behavior of the particle, but must be modified by a shape correction factor. For instance, a clay (very irregularly shaped) particle may possess a statistical diameter of 10.0 microns but actually falls at a rate of a 7.6 micron particle; therefore, a shape correction factor of .76 must be applied.

Particle size expressed in microns and dust concentration expressed in grams per cubic feet are glaring examples of the misuse of engineering units in accepted usage today. Combination of English and metric units is difficult to interpret, unless the units are reorganized into one system. The definition of the dust environment using the expression of grams per cubic foot must suffice until another relationship is developed which provides better interpretation and acceptance. Direct measurement of particle size is always presented in geometrical terms, i.e., average of two or three of the cross-sectional measurements.

B. Dust Particle Size Distribution

Other factors of particle size distribution indicate the severity of the dust plume as well as terrain and vehicle operation. The size distribution of dust particles is extremely important, because the surface area and the upper and lower limits of particle sizes are clearly defined. Without the distribution of the particles in a given sample, the dust concentration of 0.0001 grams per cubic foot may represent some large particles or millions of small particles. The distribution range of particles in a dust sample is usually presented in diameter versus percent weight less than diameter. Stating this more clearly, particle size distribution is described as the percentage of the dust sample smaller than a given particle diameter. A typical size distribution for a (Yuma) dust sample is therefore shown in the following manner: 90% below 62 microns, 50% below 11 microns, and 10% below 2.7 microns, etc.

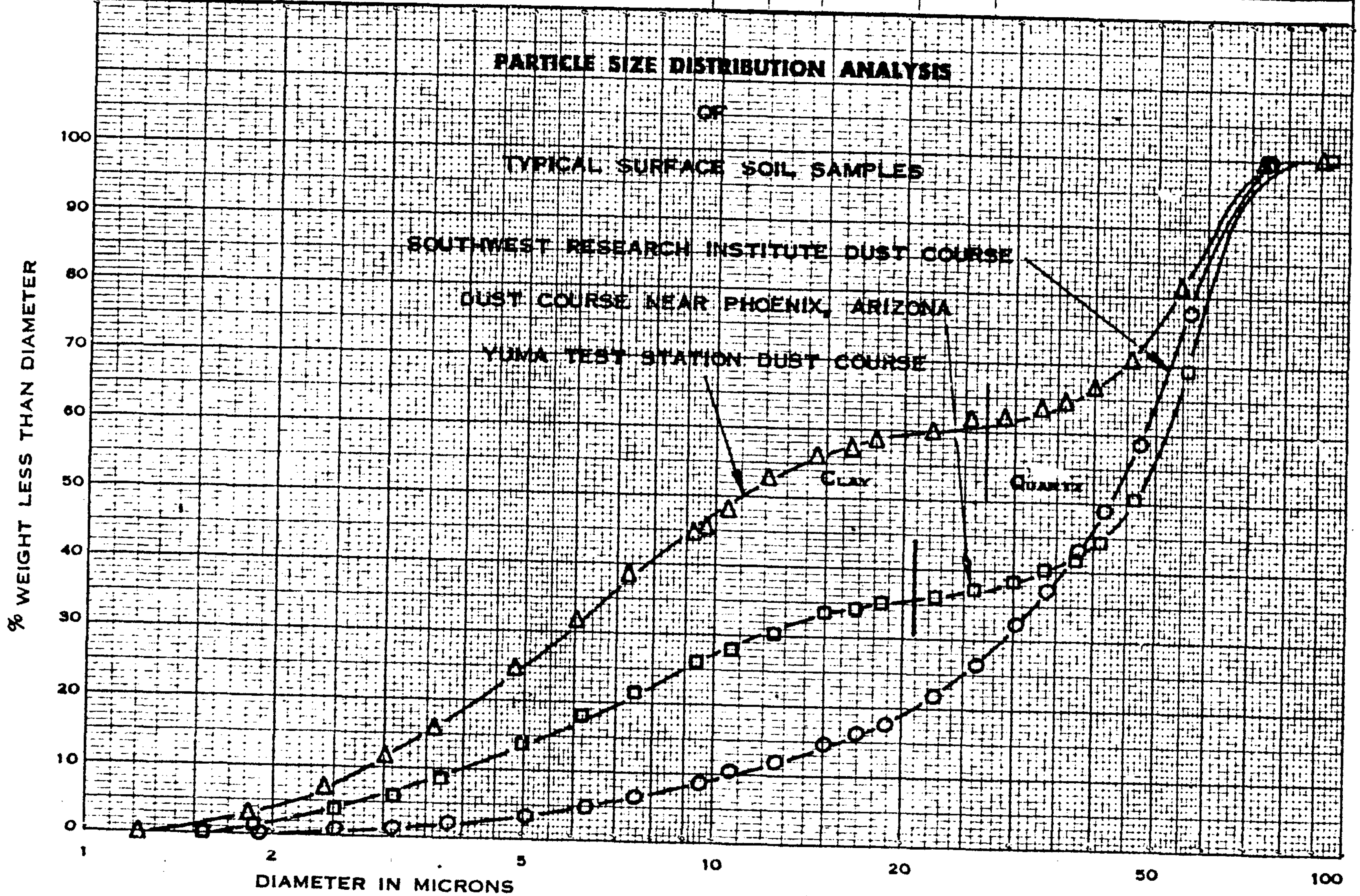
The size distribution is relatively indicative of the composition of the surface soil material since particles of least density and size will become available to the dust plume under moderate conditions. When the surface soil is composed of two or more basic soil materials, the particle size distribution will indicate this composition with a double distribution curve, i.e., for a clay and quartz soil, the distribution below approximately 30 microns is indicative of clay particles with those particles over approximately 30 microns constituting the quartz particles. The type of soil and its associated response to climatic and vehicular exposure are more germane than mere particle size distributions in the establishment of dust generation indices.

The distribution curves on the following page illustrate the composite size ranges of clay-quartz soils found at the Yuma Test Station, Dust Course, Yuma, Arizona; a major tractor firm's dust course located near Phoenix, Arizona; and the Southwest Research Institute Dust Course. The curves are for the dust size fraction of the surface soils which represent approximately 60% from the Yuma Dust Course, 20% for the Phoenix Dust Course, and less than 10% for the Southwest Research Institute Dust Course. These distribution arrangements can be interpreted more clearly by observing and comparing microscopically the plate-like clay particles to the angular quartz particles. The clay particles lend themselves to movement with low wind (forces) velocities due to their large surface area. When the curve is not of a smooth "S" shape it can be assumed that the dust is composed of particles from two different materials. In both Yuma and Phoenix distribution curves the clay particles have influence in the area below the 27 and 21 micron range, respectively.

As a matter of interest, virtually all dust samples analyzed in our laboratory indicate a combination of soil particles rather than specific type particles.

| | | | |
|---|---|---|---|
| DEPARTMENT | | | |
| MATERIAL | SURFACE SOILS-3 DUST COURSES | | |
| SPECIFIC GRAVITY | 2.51 G/CC<br>2.79 G/CC<br>2/73 G/CC | DATE | 8/4/60 |
| COMMENT | | | |

| RUN | SYMB | DEAGLM. | PRES. | COMMENT |
|---|---|---|---|---|
| | O | 150 | 100 | San Antonio Dust Course |
| | □ | 150 | 100 | Phoenix Dust Course |
| | Δ | 150 | 100 | Yuma Dust Course |



The following table gives the partial distribution of particles collected at various heights at four locations. The data for the Southwest Research gravel road course, San Antonio Texas, represent iso-kinetic collected samples while the other three are for samples collected in stationary collection pans.

## DISTRIBUTION (% BY WEIGHT) OF SAMPLE BELOW 74 MICRONS DIAMETER

| Sample Collection Height, Feet | 5 microns | 10 microns | 20 microns | 40 microns | 74 microns |
|---|---|---|---|---|---|
| **Yuma Test Station Dust Course** | | | | | |
| 0 | 21 | 38 | 51 | 66 | 99 |
| 1 | 21 | 40 | 56 | 69 | 99 |
| 2 | 22 | 35 | 51 | 66 | 99 |
| 3 | 21 | 43 | 59 | 73 | 99 |
| 4 | 19 | 33 | 46 | 67 | 99 |
| 5 | 16 | 37 | 53 | 62 | 96 |
| 6 | 24 | 42 | 56 | 67 | 92 |
| **Yuma Test Station Gravel Road** | | | | | |
| 0 | 4 | 10 | 17 | 30 | 95 |
| 1 | 2 | 4 | 7 | 19 | 93 |
| 2 | 3 | 5 | 9 | 22 | 95 |
| **Dust Course Near Phoenix, Arizona** | | | | | |
| 1 | 14 | 28 | 43 | 66 | 99 |
| 2 | 11 | 28 | 47 | 73 | 99 |
| 3 | 10 | 23 | 43 | 69 | 99 |
| 4 | 11 | 26 | 47 | 73 | 99 |
| 5 | 13 | 28 | 47 | 75 | 99 |
| 6 | 14 | 31 | 50 | 67 | 93 |
| **San Antonio, Texas, Gravel Road* (Iso-Kinetic Samples)** | | | | | |
| 1.5 | 17 | 40 | 58 | 75 | 96 |
| 2.7 | 18 | 45 | 68 | 87 | 99 |
| 4.0 | 22 | 61 | 92 | 99 | 100 |
| 6.0 | 14 | 53 | 84 | 94 | 100 |
| 8.5 | 15 | 54 | 83 | 93 | 100 |

*Reference 1

## C. Dust Particle Shape

The shape of a dust particle, when viewed under a microscope, is usually a small replica of that material from which the particle originated. Prior chemical attack and physical stress to which dust particles were subjected can influence the shape of the particles. The general shapes of the particles or aggregates are classified as follows:

| | | |
|---|---|---|
| Angular | - | having sharp corners |
| Sub-Angular | - | having some partially round corners |
| Round | - | spherical |
| Sub-Round | - | having most of the corners fairly well rounded |
| Lath-Shaped | - | having thin, narrow strips |
| Pod-Shaped | - | having alternate large and small dimensions |
| Tabular | - | flat surfaces |
| Lens-Sahped | - | having two opposite curved or one curved and one plane surface |

Particle shape has a direct influence on dust formation due to the exposed surface area and arrangement of the particle with reference to the adjacent particles. The angular particles usually break off along a definite cleavage plane. The percent void ratio and consequent in situ density is a function of both compaction and particle shape. It is believed that particle shape has direct influence on the rate of wear on metal surfaces when exposed to repeated abrasive action of the particle.

## D. Dust Concentration

The most important features to keep in mind during discussion of dust concentration are the methods by which the data were obtained and are presented, i.e., concentration based on a weight per volume of air or number of particles per volume of air. For the dust size particles in the range of 1 to 100 microns

(1 micron = approximately 0.00004 inches) a concentration by count appears very high compared with a concentration by weight. The two methods should be clearly understood and documented. For virtually all engineering purposes a dust concentration by weight has more meaning because in most dust control systems a quantity of dust is interpreted instead of a number of dust particles. Dust concentration reported on a surface area per weight basis ($cm^2/gm$) is coming into acceptance. This system combines particle size with weight distributions.

Following are actual dust concentrations found in the literature. The conditions of measurements are presented where indicated.

Reference 15

The concentrations measured at 17 positions around a tractor varied between 0.000931 grams per cubic foot obtained at 111 inches above ground level to 0.00607 grams per cubic foot obtained at 54 inches above ground level. The other concentrations were:

| Concentration Grams/Cubic Foot | Height above Ground Level, Inches |
|---|---|
| .003771 | 40 |
| .003993 | 44 |
| .002338 | 49 |
| .001631 | 49 |
| .004290 | 52 |
| .004599 | 54 |
| .002095 | 54 |
| .001366 | 54 |
| .003834 | 57 |
| .002847 | 64 |
| .002385 | 64 |
| .001476 | 68 |
| .001428 | 81 |
| .001478 | 84 |
| .002771 | 85 |
| .001364 | 94 |
| .001329 | 100 |

The above concentrations were measured on a rectangular dust course owned by a major tractor firm in the Phoenix, Arizona area. Four sample positions were measured together. The concentrations measured were those taken on an operating tractor, therefore, the concentration is higher when compared to stationary sampling near, instead of on, the vehicle. Although the airflows were uniform during the sampling operations, no control of the air-dust flow at the entrance of the sampler is mentioned, and thus the samples cannot be assumed to be true iso-kinetic samples. That is, the flow of the air-dust mixture into the sampler may have been different than a natural flow existing in zones of minimum external influence. Dust particle size is given as 100% less than 40 microns in size with 90% less than 29 microns. It is assumed this is on a weight basis.

Reference 2

The following statement is made in the report: "Actual dust concentrations around a track laying vehicle depend on several factors: namely, shape, size, speed of vehicle, and wind direction and velocity, and the composition of the terrain." Other factors such as single or convoy operation and the point of measurement must be taken into consideration. Following are dust concentration measurements obtained:

Average Dust Concentration Around a M48 Tank
While Operating On Cross Country Desert Terrain

| Position | Dust Concentration (Grams/Cubic Foot) Single | Convoy |
|---|---|---|
| Crew Compartment (Hatches Open) | 0.006 | 0.008 |
| Crew Compartment (Hatches Closed) | 0.018 | --- |
| Engine Compartment | 0.017 | --- |
| Four Feet Above Carburetor | 0.004 | 0.013 |
| Eight Feet Above Carburetor | 0.0012 | 0.004 |

The method used to measure the above concentrations was not defined; however, they can be assumed as samples taken at a stationary location within the area described. The concentrations were a result of periodic sampling, such that a valid figure could be obtained to establish the amount of dust that surrounds a vehicle during operation.

Reference 14

The author of this paper reported that the visibility during a severe dust storm can range from fifty feet (a concentration of 0.035 to 0.065 grams per cubic foot) to only twenty feet, or a dust concentration of 0.25 to 0.50* grams per cubic foot. Other information concerning sand and dust storms included such facts as: blowing sand is generated when the wind velocity at ground level is approximately 11mph. The relatively large (100 microns or greater) sand particles rarely rise over three feet above the surface, with an average height of only four inches (MunitionsBoard Aircraft Committee, Bulletin ANC-22, U.S. Government Printing Office, Washington, D. C., June 1952, 65 pp.)

The net effect of sand and dust storms on the majority of land surfaces is minute, and only specific land areas warrant their full definition. The severity of sand and dust storms on dust concentration lies in the fact that there exists a cumulative effect, i.e., the dust concentration is a sum of the natural and externally generated dust of the dust storm and of the vehicular or other activity.

* These figures of 0.25 to 0.50 grams per cubic foot appear very high, since dust concentration of less than 0.20 grams per cubic foot in a dust chamber reduce visibility to approximately one foot.

Reference 19

The author reported that during World War II the amount of dust around a military vehicle could be as high as 0.17 grams per cubic foot near the ground and 0.035 to 0.055 grams per cubic foot at six to eight feet above the ground. The methods used in obtaining these figures are not included, therefore the concentrations could be indicative of either iso-kinetic samples (taken aboard a moving vehicle) or from some stationary place near vehicular activity.

Reference 11

This source is one of the first and perhaps the simplest of all investigations on measuring dust concentrations. Mr. Hoffman states: In 1925 oil-wetted cloth strips were hung on a small farm tractor which was operated under dusty conditions. The dust, in proportion to the amount, adhered to the cloth, and a graphic, if not quantitative, picture of the concentration was obtained. This practice, although crude in nature, should provide valuable information if the sample collection time, sample area, and other important factors are accurately controlled and recorded.

Reference 8

The following table contains a tabulated list of the concentrations obtained by the Armored Medical Research Laboratory. The data was originally presented on a count basis and was later converted by Mr. James Pauly (Southwest Research Institute) to a weight basis, i.e., from millions of particles per cubic foot to grams of dust per cubic foot of air. The dust concentrations for the various activities are give for air-floated material in the California Desert Training Center Area. In the conversion of the data from a count to a weight basis, the assumption was made that for a particular operation there exists a certain number of particles per gram. This basis was drawn from the author's vast experience in previous dust studies. These assumptions were largely based on like operations conducted in Yuma, Arizona, where concentration data were measured on a weight basis.

DUST CONCENTRATIONS TO WHICH ARMORED PERSONNEL ARE EXPOSED

| Operations | Dust Concentration By Count $10^6$ particles/cu. ft. | Dust Concentration By Weight Grams/cu. ft. |
|---|---|---|
| **MINIMUM ACTIVITY** | | |
| Airborne dust from infantry camp; some from a road grader | 9.0 | .000350 |
| Motor pool of a medical battalion; slow traffic | 12.0 | .000467 |
| Bivouac area, Sunday afternoon; fresh breeze | 15.4 | .000600 |
| Div. Sug. Tent, Hdqrs., camp area | 21.0 | .000878 |
| Air base; planes taking off clean runway | 21.7 | .000845 |
| Motor pool; ambulance driving in loose sand | 22.5 | .000876 |
| Infantry training on regt. parade ground | 25.0 | .000973 |
| Ordnance unloading depot, only 3 vehicles moving | 27.7 | .001078 |
| Army truck road, dust raised by staff car | 27.7 | .001078 |
| Regimental area of camp; normal traffic | 29.0 | .001129 |
| Gas dump, no vehicular movement, light to no breeze | 29.2 | .001137 |
| Railhead with light traffic, no convoy movements | 31.0 | .001207 |
| Repeated passage of 1/4 ton truck on tank trail | 29.2 | .001137 |
| Railhead with little traffic | 32.0 | .001246 |
| Hdqrs. camp, light traffic, fresh breeze | 32.2 | .001254 |
| Ordnance unloading depot; heavy wind storm;no traffic | 34.5 | .001343 |
| **MODERATE ACTIVITY** | | |
| Infantry column, 4 companies ahead of sampler | 41.0 | .001596 |
| In convoy behind half-track | 41.2 | .001604 |
| Asst. driver's seat; light tank midway of column of tanks (co) | 42.7 | .001662 |
| Evacuation hospital area; sandy surface, fresh breeze | 44.2 | .001721 |
| Corner tank battalion motor pool; 16 tanks and 1 truck moved | 48.7 | .001896 |
| Entrance to railhead; almost continuous truck traffic | 51.0 | .001985 |
| Troops drilling -- no traffic | 51.7 | .002013 |

| Operations | Dust Concentration By Count $10^6$ particles/cu. ft. | Dust Concentration By Weight Grams/cu. ft. |
|---|---|---|
| **HIGH ACTIVITY** | | |
| Maneuver road; dust raised by staff car | 75.0 | .002920 |
| Convoy of cargo trucks spaced 100 yards | 79.0 | .003075 |
| From 1/4 ton truck and wind-blown dust | 104.0 | .004049 |
| Deliberate dust disturbance by 1/4 ton truck | 113.0 | .004399 |
| Convoy of trucks and towed 75 mm guns | 131.0 | .005100 |
| Repeated passage of 1/4 ton truck through pulverized silt bed | 160.0 | .006229 |
| Alongside moving tank column | 187.0 | .007280 |
| Inside tank following another 150 yards | 219.0 | .008526 |
| Convoy of trucks passing by | 250.0 | .009733 |
| Following 1/4 ton truck | 472.0 | .018375 |
| Thirty feet behind half track; loose sand | 750.0 | .029198 |
| **EXTREME ACTIVITY** Conditions Deliberately Fixed for Maximum Dustiness | | |
| Medium tank operating alone on dry driving range, 10 mph | 145.0 | .005645 |
| Medium tank operating alone on dry driving range, 10 mph | 350.0 | .013626 |
| One tank trailing another, dry driving range, 10 mph | 610.0 | .023747 |
| One tank trailing another, dry driving range, 10 mph | 700.0 | .027251 |
| End of column of 5 light tanks, 10-15 mph | 250.0 | .009733 |
| Five tanks in wedge, sampled in 6th center tank | 450.0 | .017519 |
| Midway of column of 6 light tanks, driving into wind | 1250.0 | .048663 |
| Midway of column of 6 light tanks, driving into wind | 1500.0 | .058395 |

Reference 9

The following conclusions are made by the author. "In summation, it may be calculated that the maximum theoretical dust concentration or suspension density for Stokes' Law to remain valid is approximately five grams of particles per one gram of air. However, actual suspension densities of less than $6 \times 10^{-3}$ grams of particles per one gram of air (0.2 grams per cubic foot) were the maximum measured near the ground. The concentration measured at six to eight feet heights were approximately $1.8 \times 10^{-4}$ grams of particles per gram of air (.006 grams per cubic foot)."

Reference 21

In this report, entitled "Petrographic and Particle Size Analysis of Terrain Samples Taken from Vehicle Test Courses at Yuma Test Station, Arizona, and Aberdeen Proving Ground, Maryland," are presented the results of a measurement program involving identification of rock samples, determination of petrographic characteristics, and particle size distribution of terrain samples taken from vehicle test courses. From this study it was learned that four trends in the data are immediately evident:

(1) Abrasive content in the dust fraction increases conspicuously with particle size at all test courses, but the increase is not necessarily in the same proportion at all test sites.

(2) Except for nonabrasive, platy mica particles, which remained relatively constant in configuration, particle shape is completely independent of size, range, and mineral constituents.

(3) Although other abrasive minerals were found, when dust particles are seriously abrasive, quartz, possessing a Moh hardness number of 7, predominates at all three test sites.

(4) The dustiness or detrimental character of a terrain cannot be absolutely determined by particle size and petrographic analysis alone. Some indication of the packed or agglomerated condition must also be known in order to predict the possibility of particle dislodgement from the parent surface.

Reference 12

In this report a paragraph entitled "Character of the Railroad Dust Getting to the Engine Filter" presents the following information:

Particle size distribution of the road dust as determined from the dust impinged on the microscopic slides held in front of the filters varied with atmospheric conditions and with slide position. The following particle size distribution on rail dust was reported on a count basis:

| Particle Size Range | Percent by Number Max. | Min. | Avg. |
|---|---|---|---|
| 80-200 microns | 0.1 | 0 | 0 |
| 40-80 microns | 1.4 | 0 | (0.4) |
| 20-40 microns | 9.0 | 1.0 | 3 |
| 10-20 microns | 14.0 | 1.0 | 6 |
| 5-10 microns | 20.0 | 4.0 | 9 |
| 1-5 microns | 94.0 | 61.0 | 82 |

Reference 5

The two authors give the following values for normal atmospheric dust concentration for various localities.

| Locality | Average Dust Concentration Grams per Cubic Foot After Clower | After Kayser |
|---|---|---|
| Rural and Suburban | .0002 to .0004 | .0000013 to .0000032 |
| Metropolitan | .0004 to .0008 | .0000032 to .000013 |
| Industrial | .0008 to .0015 | .00004 to .0000485 |

Reference 7

The authors present a chart of various dust concentrations derived in their studies. Only general information is presented and only those significant concentration values are given.

| Condition or Dusty Trade | Concentration Grams per Cubic Foot | |
|---|---|---|
| Dust Storm | .015 | to .30 |
| Mine Air (coal cutting) | .0005 | to .01 |
| Foundry | .00004 | to .001 |
| Fog and Mist | .00006 | to .001 |
| Industrial District Air | .000008 | to .00005 |
| City Air | .000004 | to .00004 |
| Rural and Suburban Air | .000002 | to .00002 |

These average values were obtained with various sampling methods and the figures should be used with caution. An interesting figure was adapted for converting weight of particles to number of particles. This figure is: 0.1 mg as equivalent to 5 million particles. This figure is for minute (1 to 5 microns average, by count) particles with measurement by the konimeter.

E. Supplementary Sample Acquisition Data

Supplemental data of dust concentrations found in various locations near Yuma and Phoenix, Arizona, and under several conditions of sampling height and distances from vehicle operation are given in the following table. Additional iso-kinetic concentration data from San Antonio, Texas Dust Courses are given. The data are summarized to illustrate the range of dust concentrations which can and do exist near different activities.

| Vehicle (s) | Terrain | No. Samples | Sample Height | Concentration |
|---|---|---|---|---|
| Various | Unpaved Road | 8 | 4.0 feet | .00196 to .00987 grams/ft$^3$ |
| Various | Unpaved Road | 7 | 2.5 feet | .00226 to .00591 grams/ft$^3$ |
| Various | Unpaved Road | 2 | 6.0 feet | .00306 to .00313 grams/ft$^3$ |
| Helicopter | Landing, Hovering, Take-Off from Sandy Unpaved Road | 5 | 4.0 feet | .00290 to .00740 grams/ft$^3$ |
| Tank M60 | Desert Pavement | 6 | 5.0 feet | .00989 to .13950 grams/ft$^3$ |
| Road Grader | Desert Pavement | 4 | 4.0 feet | .01160 to .04650 grams/ft$^3$ |
| Scraper | Sandy | 2 | 5.0 feet | .00387 to .00574 grams/ft$^3$ |
| 20 Ton Tractor | Dust Course | 1 | 3.0 feet | .01074 grams/ft$^3$ |
| 20 Ton Tractor | Dust Course | 2 | 4.0 feet | .00257 to .0104 grams/ft$^3$ |
| 20 Ton Tractor | Dust Course | 3 | 5.0 feet | .00224 to .0205 grams/ft$^3$ |
| 20 Ton Tractor | Dust Course | 2 | 6.5 feet | .00287 to .00991 grams/ft$^3$ |
| 8 Ton Tractor | Dust Course | 1 | 4.0 feet | .00517 grams/ft$^3$ |
| 8 Ton Tractor | Dust Course | 1 | 5.0 feet | .01175 grams/ft$^3$ |
| 20 Ton Tractor | Sandy-Clay Soil | 1 | 6.0 feet | .00104 grams/ft$^3$ |
| 20 Ton Tractor | Sandy-Clay Soil | 1 | 5.0 feet | .0461 grams/ft$^3$ |
| 20 Ton Tractor | Sandy-Clay Soil | 1 | 7.0 feet | .0256 grams/ft$^3$ |
| 20 Ton Tractor | Sandy-Clay Soil | 1 | 8.0 feet | .00154 grams/ft$^3$ |

| Vehicle(s) | Terrain | No. Samples | Sample Height | Concentration |
|---|---|---|---|---|
| M34 10 mph | Southwest Research Dust Course | -- | 1.5 feet | .015 grams/ft$^3$ |
| | | | 2.0 feet | .007 grams/ft$^3$ |
| | | | 4.0 feet | .003 grams/ft$^3$ |
| | | | 6.0 feet | .003 grams/ft$^3$ |
| M34 30 mph | Southwest Research Dust Course | -- | 1.5 feet | .085 grams/ft$^3$ |
| | | | 2.0 feet | .075 grams/ft$^3$ |
| | | | 4.0 feet | .025 grams/ft$^3$ |
| | | | 6.0 feet | .020 grams/ft$^3$ |
| M34 10 mph | Gravel Road San Antonio, Texas | -- | 1.5 feet | .015 grams/ft$^3$ |
| | | | 2.0 feet | .008 grams/ft$^3$ |
| | | | 4.0 feet | .004 grams/ft$^3$ |
| | | | 6.0 feet | .003 grams/ft$^3$ |
| M34 30 mph | Gravel Road San Antonio, Texas | -- | 1.5 feet | .050 grams/ft$^3$ |
| | | | 2.0 feet | .030 grams/ft$^3$ |
| | | | 4.0 feet | .015 grams/ft$^3$ |
| | | | 6.0 feet | .007 grams/ft$^3$ |

# IV. FACTORS WHICH AFFECT THE DUST ENVIRONMENT

The dust concentration measured near or directly on a moving vehicle is primarily a function of terrain, vehicle type, vehicle speed, and the climatic conditions. Each of these factors necessitate exhaustive definition and may result in consequent incomplete understanding. Interrelations of the factors accounts for a dynamic dust environment, and, at best, the environment and dust conditions can be interpreted only on an average basis. Instantaneous dust concentrations are impractical except for specific purposes, such as filter loading, etc. In the following paragraphs several of the more important phenomena associated with the measurement, variation, and trends in dust concentration will be outlined.

Dust concentration is usually reported on a number (millions) or quantity (weight) of particles per unit volume. A third method consists of a surface area per unit weight ($cm^2/gm$). For engineering purposes it has been ascertained that reporting of dust particle concentration on a weight per volume of air has maximum usefulness. Capacity of air cleaning equipment is given as quantity rather than number of particles. The obvious reason for this, of course, is due to the fact that for large (100 micron ) particles, 1 million small (1.0 micron) particles weigh the same.

The methods and techniques employed in obtaining and measuring dust concentration are responsible for the accuracy of dust concentration data. Since both sampling methods and sample analysis techniques can be variable it is possible for deviations from standard practices to result in misleading and useless data. Several of the more important factors include sampling period, location of samples, type of filter, handling of filter, and recording of all pertinent climatic and observation data. A sampling period of 15 instead of 20 seconds can easily give twice the concentration. If there is a change in humidity or if filters are allowed to age for more than one week, serious errors are introduced because of changes in weights of dust-laden filters.

The practice of obtaining dust samples and analyses requires practice and understanding, which are enhanced most readily through concerted effort. Using a sampling period which is consistent for identical wind conditions and controlled vehicular operation is the best method of obtaining true representative samples.

In summation, the factors which affect dust concentration and the dust environment are not detrimental as long as they are adequately recorded, so that proper control measures can be effected. Apparent inconsistencies in data can usually be interpreted if all of the conditions of measurement are available.

## A. Dust and Terrain

The ability of a vehicle to generate a dust plume is highly dependent on terrain features such as slope configuration, vegetation, soil composition, and compaction of the surface soil. The terrain, in part, governs the maximum speed at which a vehicle can traverse over the surface, and, therefore, places limits on the forces subjected onto the soil by the suspension system of the vehicle. The exceptionally high surface contact per unit time for normal vehicular motion on soils may be held accountable for the large volume of soil displacement with subsequent generation of large dust plumes.

Seldom is natural terrain closely comparable to surfaced roads and as such does not possess an evenly compacted and distributed surface soil composition. Vegetation is primarily responsible for maintaining an aerated productive soil. (The mere fact that a soil is capable of sustaining vegetation does not indicate that large dust plumes cannot be generated from the soil.) Particle size distribution of a soil is the best index of the available dust particles which may become a dust plume.

Slope of a terrain can be influential to the dust plume due to the removal of the finer particles during periods of rainfall. Literature contains very limited data on the correlation of surface soils on sloped terrain and level terrain. The effect of slope on the dust generation potential of a terrain has two possible combinations, i.e., more than normal quantities of particles would be motivated by the vehicle traction media due to slip, or, secondly, due to the large decrease in vehicle speed while negotiating a sloped terrain, the aerodynamic forces on the suspended dust particles are insignificantly small with consequent minor dust plume manufacture.

Only the surface soil layer is responsible for the dust environment. Any mechanical or aerodynamic force which causes this surface layer of soil to be agitated or moved may be assumed as a dust generating mechanism. The combination of soil minerals is so broad that only a cursory review can be directed toward the soil system.

## B. Dust and Moisture

One of the most influential factors governing the availability of dust particles to the dust plume is that of moisture. Moisture in any form has a negative effect on the concentration to be found during operation on a normal dusty terrain. Both the soil moisture and ambient relative humidity are dynamic in nature and vary from hour to hour. The moisture between particles causes the particles to agglomerate and therefore they become less prone to be moved by normal dust generating forces.

The cohesion forces of moisture films between particles are dependent on particle shape. Cohesion decreases with increasing thickness of water film, and maximum cohesion occurs at the moisture content at which the moisture film is present at all points of contact. Particles exhibiting tabular and lath shapes have higher bonding characteristics than do round or angular-shaped particles primarily as a result of their large-surface contact area. Clay particles with crystalline (tabular) structures are an excellent example of large-surface, high bonding strength particles.

The cohesion force of a water film between two particles is given by the equation (Baver-Soil Physics)

$$F_c = \frac{k2\ d\ T_s \cos 0}{t}$$

where

$F_c$ = Cohesion force, grams

k = Constant

d = Diameter of the particles, microns

$T_s$ = Surface tension, gm/cm$^2$

t = Thickness of water film, cm

For a soil consisting of 2/3 sand and 1/3 clay with approximately 13% moisture content, the cohesive force is 2.33 grams per square centimeter; for a soil mixture of 1/3 sand, 2/3 clay, and having 13% moisture content, the cohesion is 3/5 grams per square centimeter (Nichols 1931, as quoted by Baver-Soil Physics). Dust may be produced from highly plastic soils at a high absolute water content; however, it must be less than 10% in order for free dust particles to be available (personal communications with Freitag and Joseph). Where clay is present in soils, a humidity change will cause small particles to "fluff-off" due to contraction or expansion (Pickett). Soil specialists contend that the moisture content and the organic composition are perhaps the two most important aspects of the soil boundary surface.

During the extensive dust concentration measurements on two dust courses at Southwest Research Institute an attempt was made to correlate the soil moisture content with particle size and dust concentration. A relationship was developed by Robinson as follows:

$$d_m = \frac{K}{(100M)^n}$$

and

$$C = K_1 \, d_m^3 + K_2$$

where

$d_m$ = Median particle size, microns

$K$ = $\left(\frac{\rho_p \pi}{6k}\right)^3$

$M$ = Percent free moisture (expressed as a decimal)

$n$ = An exponential power

$C$ = Dust concentration, $gm/ft^3$

$K_1, K_2, k$ = Constants (6.82, $88.3(10)^{-9}$, 73.2)

$\rho_p$ = Particle density, $gm/cm^3$

From past experience it appears that optimum dust conditions prevail when the soil moisture content is less than 2% or 3%. Additional research is required before accurate correlation can be obtained concerning the relationships of particle size, concentration, and moisture content.

## V. METHODS AND TECHNIQUES EMPLOYED IN SAMPLING OF AIRBORNE DUST PARTICLES

The collection of airborne dust samples has been a primary objective in all dust concentration experiments. The airborne dust concentration is constantly changing because no activity produces a constant quantity of dust. There can be no doubt that a large number of samples taken at various times define the dust environment with greater accuracy than single samples, even if taken over a period of several hours. The human element, as well as variables in the dust producing processes, changes from one period tc the next. Samples collected over long periods of time lead to results which do not correctly picture the dust generated by a short-lived activity.

Peak concentrations occur shortly after a vehicle passes over the soil, and, depending on the particle size distribution, the dust plume concentration diminishes as a function of the square of the particle diameter. Relatively large particles (40 to 74 microns) descend some twelve feet within a matter of ten seconds, whereas particles below 5 microns fall less than one foot in 100 seconds. The wide variation in the descent velocity of different size particles is therefore highly important to dust sampling. Distance of the dust sampler from the area of dust generation, height of the sampler inlet, and the duration of sampling time after the departure of the dust generating mechanism are but a few of the factors that are involved in the accuracy of the dust concentration values obtained. The various factors having influence on the airborne dust cample will be presented in detail in some of the following paragraphs. Full knowledge of these factors is necessary in developing full understanding of the dust environment.

A. Types of Dust Samples

Airborne dust samples can be obtained in a number of ways using various methods and techniques. The final measure of dust concentration provides design engineering data to persons interested in the understanding and control or elimination of the dust environment.

The types of dust samples obtained depend on the type of sampler used to collect the dust particles. A sampling device usually consists of the following parts:

1. A tube or nozzle for insertion into the gas stream through which the sample is withdrawn.

2. A filtering or separating device for removing the dust from the gas sample.

3. Means for checking the approximate equality of the velocity of the gas entering the nozzle and the velocity of the gas in the flue at the point of withdrawing the sample.

4. Means for measuring the quantity of gas sampled.

5. An exhausting device for withdrawing the gas through the sampling nozzle filter, and metering device.

The above components describe a system for testing air cleaners or for measuring the particles in a known quantity of gas. The general description of such filters is high volume or high flow samplers. The major fallacy of such a system is that the actual air filtered is drawn into the sampler head at velocities completely different from the natural air flow, and, consequently, inaccurate concentrations are obtained. This is true, because the change of flow at or near the filter or sampler inlet causes large particles to be centrifuged out of the air stream, thus eliminating their entering the sampler. A similar effect is encountered when the inlet dust-laden air stream is at a higher velocity than the inlet of the sampler, thus producing a ram effect wherein large particles are impacted onto the filter head resulting in an inaccurate dust concentration.

Dust samples are usually obtained by passing a known quantity of dust laden air through a filter whereon the particles are trapped and quantitatively measured. Dust particles can also be trapped onto some viscous media and retrieved for purposes of measurement. Another very practical method consists of collecting particles in a suitable receptacle. The particles thus collected can be studied primarily on a size basis. Many other methods of obtaining dust concentration exist, each having both favorable and unfavorable merits. As with most engineering methods, a dust concentration measurement system that offers accurate results at a reasonable cost is the system most likely to be chosen.

The static surface impact sampler consists of a smooth surface slide coated with a suitable adhesive agent so that any particles falling onto the surface are retained. The "fall-out" can then be counted and the particle sizes measured to give a count per unit area. This method has little engineering significance and is usually associated with the biological field.

Other types of dust samples consist of naturally deposited dust particles collected in a suitable receiver positioned so that minimal external influence is placed on the sample. An important particle size distribution can be obtained in a sample obtained less than fifty feet from the source of the dust plume and during very low wind velocities.

The type of sample is dependent largely on the future uses desired of the sample and the specific analyses to be made of the sample. Retrieval of particles from filter media is difficult and in many cases impossible. Sufficient quantities of particles are required for weight measurements. Microscopic analyses can be made on most particulate matter collected on filter media; however, distinction must be made between the filter material and the deposited dust material.

Utilization of most precise measuring apparatus and techniques of collecting dust samples indicates variations exist and is therefore less illustrative of technique or methods. This same process exists in soil density measurements--with utilization of most precise methods of measuring soil density it was learned that the density actually varies, even for samples taken from adjoining locations.

B. Sampler Location

The location of the dust sampler is usually a compromise between vehicle path or the dust generating source, prevailing wind, terrain configuration, and terrain type. The height of the dust sampler inlet and the distance of the sampler from the dust generating source are parameters that must receive extensive consideration. The placement of a gas turbine engine in a field system (generator unit, pump, etc.) is considered to include extreme dust environments, i.e., minimum air intake heights, and close proximity to moving vehicles.

However, it is not understood to include those particles which are mechanically thrown into the air intake of the turbine compressor. Permitting sand to be dumped into the engine intake due to close vehicle maneuvering completely alleviates control of the dust environment and departs from the realm of dust environment.

Ambient wind conditions govern the dispersion of the dust plume and thus dictate the location of the dust sampler. It is well known from observing motion pictures that low (three to five mph) wind speeds provide the optimum sampling conditions. Higher velocities result in the rapid dispersion of dust particles with consequent critical sampling periods. The sampling period may be 15 to 20 seconds in ambient winds of less than 3 mph while the most effective sampling period during 8 to 9 mph winds may be in the order of 5 seconds. Since most prevailing winds over a dust producing terrain are variable in direction at a specific location (sample point) the effective sample period is necessarily an observable phenomena and must be controlled by the good judgment of the operator.

Sampler location is usually changed and distances to the dust generation source are varied to provide a "range" instead of point concentrations. The maximum dust collection points are usually chosen to give maximum concentration data. Capacity of air cleaning systems is usually specified on either a total (accumulative) separation of particles or on a removal "rate" which designates the ability of the cleaning system to cope with a specific maximum concentration. The critical location of the dust sampler unit must be continually observed and maintained at optimum positions.

C. Collection of Dust Samples for Concentration Measurements

To properly define the dust environment, critical interpretation of the observed data is necessary. Collection of dust particles for purposes of measuring concentration can be accomplished by using various methods. The most popular and convenient technique is to employ a weight gain of the collecting filter. This procedure consists of weighing a clean filter, then exposing the filter in the dust environment during a fixed time. A known quantity of ambient air will be drawn through the filter. The weight gain of the filter in grams divided by the total cubic feet of ambient air drawn through the filter during the sampling period is a measure of the dust concentration.

The sample of dust collected on a filter is only representative of average conditions existing during the measurement, and a careful interpretation of these conditions is mandatory. As mentioned previously, the distance of the sampler from the dust generating source, the height of the sampler inlet, and the ambient climatic conditions effect the weight of the dust sample, hence the dust concentration. In addition, the vehicle selected for generating of the dust is important because the forces producing the airborne dust environment are directly related to the surface agitation (wheel or tracked) and the aerodynamic influences on the available dust particles.

Dispersion of the dust plume occurs very quickly and within seconds the larger particles descend to the surface. Smaller particles remain suspended in the air and appear to float with the ambient wind. The concentration density varies accordingly and the peak concentrations are measured during periods of the lowest visibility near the point of generation of the dust plume. Collection of the average dust sample can be made with greater confidence by including part of the periods preceding and succeeding the maximum concentration. That is, a sample including the buildup, peak, and diminishing dust plume is most practical. Extended sampling periods generate a close "average" concentration; however, peak concentrations have greater importance in establishing most dust handling requirements.

The height at which a sample is collected can contribute directly to the specific particle size distribution and the concentration. Together with correlation of sample collection height is proximity of sample collection zone to the dust generating source. The necessity for this consideration is that equal concentrations are easily obtained for a high collection point at a small distance from the vehicle and a low collection height at a greater distance from the vehicle. The difference in the two samples can be found in the particle size distribution instead of the dust concentration.

Although the collection of a sample is fixed for a general sample collection program, i.e., the heights and distances from the dust generating sources are held within limits, the dust concentration is greatly influenced by the vehicle type, weight, speed, suspension mechanism, unsprung mass, and aerodynamic characteristics of the vehicle responsible for the dust plume.

The following examples are presented for clarification of the above consideration; the dust concentrations are not average values but represent individual samples obtained using identical methods.

Identical Vehicle Operation
(3/4 ton, 4 x 4 truck, Yuma)

| Sample Collection Height | Distance from Vehicle Path | Concentration |
|---|---|---|
| 2.5 feet | 18 feet | .00581 g/ft$^3$ |
| 4.0 feet | 18 feet | .00214 g/ft$^3$ |

Different Vehicle Type
(Personnel Carrier and 2.5 ton, 4 x 4 trucks)

| | | |
|---|---|---|
| 4.0 feet | 25 feet (1 PC and 1 Truck) | .00692 g/ft$^3$ |
| 4.0 feet | 25 feet (2 Trucks) | .00349 g/ft$^3$ |

These values illustrate the variation which can be obtained when either the sample collection height or the vehicle type are different. In nearly all dust sample collection programs, the scatter of dust concentration values appear unrealistic; however, full interpretation of the terrain, climatic, and vehicle operation reveals discrete information which combines all factors into one final dust concentration. Application of the side data such as distances, heights, wind directions, velocities, important factors of surface soil compaction, and of the dust generation mechanism (vehicle) must be included in the collection of a dust sample for an accurate determination of dust concentrations.

## D. Collection of Dust Samples for Particle Size Distribution Measurements

The collection of sufficient quantities of dust particles for measurement of particle size distribution by weight requires refined techniques of retrieving the sample particles from the filter media. When cellulose fiber filters are employed, full recovery is possible by dissolving the filter paper. Certain fibrous filters can be ignited with full recovery of sample. Each method requires careful laboratory practice. A very practical method, which can be used in areas of low (less than 3 mph) ambient wind, consists of suspending collection pans at different heights and allowing the particles to float into the pans over a period of time so that sufficient quantities of particles are collected in the pans. In most cases, the resulting distribution will indicate a shift to the larger particles. The reason is that the minute particles are continually moved from the pan by any wind acting on the pans.

Particle size distribution is controlled by the basic soil composition and the forces acting upon the soil. Density plays an important role in the size particles which make up the dust plume. It was found that the particles collected in airborne sampling operations consisted primarily of particles of the lower density material, whereas the surface soil particles consisted of greater compositions of higher density particles.

Presentation of particle size distribution is usually made on a percent by weight less than diameter versus effective particle diameter, i.e., for example 78% of the sample by weight are less than 24 microns diameter. For critical interpretation, a curve of the distribution is drawn on semi-logarithmic paper and from this curve individual particle size ranges can be studied. The particle size distribution curve illustrates any change in material and often minute variations can be delineated to define conditions of soil, climate, and vehicular operation.

# VI. DUST CONCENTRATION DATA AND CONDITIONS UNDER WHICH THEY EXIST

Following are summarized the concentration measurements and various conditions during which they occur. The list includes the important types of samples from various distances and heights with respect to the source of dust particles. The conditions will be further summarized in order to develop a useful turbine dust ingestion program representative of different field applications. These are airborne samples, and, in general, the particle size is in the range below 74 microns.

| Terrain | Vehicle | Climate | | Sampler Ht., feet | Sampler Dist. from Vehicle path, feet | Concentration grams/ft$^3$ |
|---|---|---|---|---|---|---|
| | | Temp. °F | Wind, mph | | | |
| 1. Non-Paved Gravel Rd. stationary sampler | 3/4 ton truck (20-30 mph) | 100+ | 3-8 | 2.5 | 8-15 | .0021 to .0031 |
| 2. Non-Paved Gravel Rd. stationary sampler | 2.5 ton truck (30 mph) | 100+ | 3-8 | 2.5 | 12-18 | .0023 to .0058 |
| 3. Non-Paved Gravel Rd. stationary sampler | 3/4 ton truck (30 mph) | 100+ | 3-8 | 4.0 | 20-25 | .0019 to .0032 |
| 4. Non-Paved Gravel Rd. stationary sampler | Tracked Vehicle (PC) 20mph | 100+ | 5-8 | 4.0 | 20 | .0050 to .0070 |
| 5. Desert Pavement (very dusty) | M60 Tank | 100+ | 3 | 5.0 | 20 | .0690 to .1395 |
| 6. Desert Pavement (very dusty) | M60 Tank | 100+ | 2-5 | 5.0 | 20-40 | .0325 to .0447 |
| 7. Desert Pavement (very dusty) | M60 Tank | 100+ | 3 | 5.0 | 30-50 | .0322 |
| 8. Desert Pavement (very dusty) | Grader | 100+ | 2-4 | 4.0 | 20 | .0116 to .0465 |
| 9. Desert Pavement (very dusty) | Grader | 100+ | 2-4 | 4.0 | 25 | .0152 |
| 10. Clay-Gravel Road | 20 ton tracked vehicle | 90+ | 3-5 | 6.0 | 50 | .0010 |
| 11. Dust Course | 20 ton tracked vehicle | 90+ | 1-3 | 3.0 | 22 | .0107 |
| 12. Dust Course | 20 ton tracked vehicle | 90+ | 1-3 | 4.0 | 15-25 | .0026 to .0104 |

| Terrain | Vehicle | Climate Temp, °F | Climate Wind, mph | Sampler Ht, feet | Sampler Dist. from Vehicle path, feet | Concentration grams/ft$^3$ |
|---|---|---|---|---|---|---|
| 13. Dust Course | 20 ton tracked vehicle | 90+ | 2-5 | 5.0 | 20 | .0022 to .0205 |
| 14. Dust Course | 20 ton tracked vehicle | 90+ | 2-5 | 6.5 | 18-24 | .0029 to .0099 |
| 15. Dust Course | 8 ton tracked vehicle | 90+ | 1-2 | 4.0 | 20 | .0052 |
| 16. Dust Course | 8 ton tracked vehicle | 90+ | 1-2 | 5.0 | 20 | .0117 (sampling period = 55% of above (4) passes) |
| 17. Clay-Gravel | 20 ton tracked vehicle | 100+ | 1-2 | 5.0 | to 25 | .001 (damp subsoil) |
| 18. Driving Range Road | Single tank (10 mph) | -- | -- | -- | -- | .0056 to .0136 |
| 19. Driving Range Road | Multiple tanks (10 mph) | -- | -- | -- | -- | .0175 to .0584 |
| 20. Driving Range Road | Multiple Tank Operation (end of convoy) | -- | -- | -- | -- | .0097 |
| 21. Dusty Road | Staff Car | -- | -- | -- | -- | .0029 |
| 22. Dusty Road | 1/4 ton truck | -- | -- | -- | -- | .0044 to .0062 |
| 23. Dusty Road | Truck convoy | -- | -- | -- | -- | .0097 to .0184 |
| 24. Dust Course | Military traffic (severe) | -- | -- | 0.2 | -- | .1700 |
| 25. Dust Course | Military traffic | -- | -- | 6.8 | -- | .035 to .055 |
| 26. Sandy Surface | Normal traffic | -- | -- | -- | -- | .0015 to .0019 |
| 27. Rural & Suburban | -- | -- | -- | -- | -- | .0002 to .0004 |

| Terrain | Vehicle | Climate Temp, °F | Climate Wind, mph | Sampler Ht, feet | Sampler Dist. from Vehicle path, feet | Concentration grams/ft³ |
|---|---|---|---|---|---|---|
| 28. Dust Storm (San Antonio, Texas vicinity) | -- | -- | -- | -- | -- | .0002 to .003<br>.0005 |
| (Place Unknown) | -- | -- | -- | -- | (20' visibility)<br>(50' visibility) | .250 to .500<br>.035 to .065<br>.015 to .3 |
| 29. Metropolitan | -- | -- | -- | -- | -- | .0004 to .0008<br>.0000032 to .000013<br>.000004 to .00004 |
| 30. Industrial | -- | -- | -- | -- | -- | .0008 to .0015<br>.00004 to .0000485<br>.000008 to .00005 |
| 31. Fog and Mist | -- | -- | -- | -- | -- | .00006 to .001 |
| ISO-KINETIC SAMPLES | | | | | | |
| 32. Sandy Clay Road | 2-1/2 ton truck (10 mph) | -- | -- | 6 | 0 | .00025 |
| 33. Sandy Clay Road | 2-1/2 ton truck (20 mph) | -- | -- | 1.5 | 0 | .015 |
| 34. Sandy Clay | 2-1/2 ton truck (20 mph) | variable | | 6.0 | -- | .007 |
| 35. Sandy Clay | 2-1/2 ton truck (20 mph) | variable | | 1.0 | -- | .05 |
| 36. Sandy Clay | 2-1/2 ton truck (30 mph) | variable | | 8.5 | -- | .015 |
| 37. Sandy Clay | 2-1/2 ton truck (30 mph) | variable | | 1.0 | -- | .085 |
| 38. Gravel Road | 2-1/2 ton truck (10 mph) | variable | | 8.5 | -- | .00075 |

| | Terrain | Vehicle | Climate Temp, °F | Climate Wind, mph | Sampler Ht, feet | Sampler Dist. from Vehicle path, feet | Concentration grams/ft$^3$ |
|---|---|---|---|---|---|---|---|
| 39. | Gravel Road | 2-1/2 ton truck (10 mph) | variable | | 1.5 | -- | .015 |
| 40. | Gravel Road | 2-1/2 ton truck (20 mph) | variable | | 8.5 | -- | .0035 |
| 41. | Gravel Road | 2-1/2 ton truck (20 mph) | variable | | 2.3 | -- | .025 |
| 42. | Gravel Road | 2-1/2 ton truck (30 mph) | variable | | 8.5 | -- | .0035 |
| 43. | Gravel Road | 2-1/2 ton truck (30 mph) | variable | | 2.0 | -- | .05 |
| | | **NON-ISO KINETIC SAMPLES** Sampler Placed on Vehicle at Different Heights | | | | | |
| 44. | Sandy Clay | 20 ton tracked vehicle-dozer (near rear of tractor) | 90+ | 3-4 | 5.0 | -- | .046 |
| 45. | Sandy Clay | 20 ton tracked vehicle-dozer (near rear of tractor) | 90+ | 3-4 | 7.0 | -- | .026 |
| 46. | Sandy Clay | 20 ton tracked vehicle-dozer (front center on vehicle hood) | 90+ | 3-4 | 8.0 | -- | .00154 to .00208 |
| 47. | Cross-Country Desert Terrain | M48 Tank Crew Compartment (hatches open) | 90+ | 3-4 | -- | -- | (single) .006 (convoy) .008 |
| 48. | Cross-Country Desert Terrain | M48 Tank Crew Compartment (hatches closed) | 90+ | 3-4 | -- | -- | .018 |
| 49. | Cross-Country Desert Terrain | M48 Tank Crew Compartment | -- | -- | -- | -- | .017 |

| Terrain | Vehicle | Climate | | Sampler Ht, feet | Sampler Dist. from Vehicle path, feet | Concentration grams/ft$^3$ |
|---|---|---|---|---|---|---|
| | | Temp, °F | Wind, mph | | | |
| 50. Cross-Country Desert Terrain | M48 Tank | -- | -- | 4.0' above carburetor | -- | (single) .004<br>(convoy) .013 |
| 51. Cross-Country Desert Terrain | M48 Tank | -- | -- | 8.0' above carburetor | -- | (single) .0012<br>(convoy) .004 |

# VII. CONCLUSIONS AND RECOMMENDATIONS

The following are five general dust (environments) concentration ranges and the conditions under which they exist. These size ranges are developed from the data presented in the report, together with information from previous investigations. The concentration ranges are believed to be within the accuracy of present methods and techniques of measurement and representative of the various dust producing terrains.

From the condensed list it can be seen that data on concentrations are highly variable and through necessity must be interpreted with caution. The number of variables must be interpreted to gain useful data which describe any particular dust environment. It is believed that approximately five concentration ranges can be categorized to include the major vehicular operations, general dust producing terrain, sample height, and plume duration.

Of the many methods of presenting dust environment, the concentration ranges with respective types of operation are deemed most representative and useful for application to a program which includes normal vehicular activity.

## 0.10 to 0.20 Grams per Cubic Foot

Heavy wheeled vehicle traffic on desert pavement.

20-30 mph at 5-10' distances and 3-5' heights.

Concentration duration: 5-10 seconds with singular operation; continuous with convoy operation.

Tracked vehicle on desert pavement.

20-30 mph at 20' distance and 5' high.

Concentration duration: 10-20 seconds with singular operation.

<u>0.05 to 0.10 Grams Per Cubic Foot</u>

Light tracked vehicle traffic on desert pavement.

10 mph at 20' distances and 4' heights.

Concentration duration 10-15 seconds.

Military traffic (troop movement by truck convoy) on desert pavement.

10-20 mph at approximately 15-25' distances from the vehicle path.

Concentration duration: continuous.

Heavy wheeled vehicle traffic on sandy clay soil.

10-20 mph at 15-20' distances and 2-3' heights.

Concentration duration: 10-15 seconds.

Heavy wheeled vehicle traffic on gravel road.

30 mph at 5-10' distances and 2-4' heights.

Concentration duration: 10 seconds.

Heavy tracked vehicle traffic on desert pavement.

10 mph at 20' distance and 5-6' heights.

Concentration duration: 15-20 seconds.

<u>0.005 to 0.05 Grams Per Cubic Foot</u>

Heavy tracked vehicle on desert pavement.

10 mph at 20-40' distances at 5' height.

Concentration duration: 20 seconds.

Heavy tracked vehicle on cross country unpaved road.

10-20 mph at 20 to 40' distance at 5' height.

Concentration duration: 20 seconds.

Truck convoy on sandy clay soil.

10 mph at 20' to 40' distance at 2' height.

Concentration duration: continuous.

<u>0.0005 to 0.005 Grams Per Cubic Foot</u>

Light tracked vehicle on gravel road.

20 mph at 20' distances at 4' height.

Concentration duration: 15 - 20 seconds.

Wheeled vehicle on gravel or sandy clay road.

10 mph at 5' distances at 5-8' heights.

Concentration duration: 10 seconds.

Wheeled vehicle on gravel road convoy operation.

20 mph at 5' distance and 6-8' heights.

Concentration duration: continuous.

Severe dust storm.

20-40 mph at 5'.

Concentration duration: (usually 1-10 hours).

Heavy tracked vehicle on clay gravel road.

10-20 mph at 50' distance at 6' height.

Light wheeled vehicles on desert pavement (dusty roads).

20-30 mph at 30' distance at 3-4' height.

<u>Below .0005 Grams Per Cubic Foot</u>

Fog and mist.

Industrial areas (excluding plants with stacks).

Metropolitan areas.

Wheeled vehicle traffic on sandy clay road.

10 mph at 10-20' at 6' heights.

Concentration duration: 15-20 seconds.

General dust storms.

10-30 mph.

Concentration duration: 1-10 hours.

The second report "The Effect of Abrasive Dust Particles on Gas Turbine Engine Components" is presently being prepared. On completion of this report recommendations for a test schedule will be made for the dust ingestion studies to be conducted on the Solar turbine engines.

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2. Blackburne, Edward, and Denton, C.R., "Air Cleaners for Military Vehicles," presented at the SAE Automotive Ordnance Day, Detroit Arsenal, Center Line, Michigan, February 28, 1955, 5 pp/photos, curves, and schematics. The pertinent information from this source is included on page 10 in the body of the report.

3. Brooks, F. A., "Tractor Air-Cleaner Performance in Dust Clouds," SAE Journal, Vol 58, No 3, p. 68, March 1950.

This article deals with the relationship between the type of dust encountered and the efficiency of air cleaners. It discusses the difficulty of sampling dust and describes a technique by which the analysis was made. A series of tests was made to determine the dust retention of an engine. When this engine was motored it was found to retain 92% of both the coarse and California No. 3 dust. Medium fine dust showed 88% retention and it was assumed that 75% of the ultra fine dust would be retained. An attempt to correlate the dust analysis by weight to analyze by count was done by assuming equal shapes and densities.

4. Chernov, A. P., "The Effect of Solid Admixtures on the Velocity of

Motion of a Free Dusty Air Jet," Technical Memo 1430, National Advisory Committee for Aeronautics, 5 pp/curve, April 1957 (English translation of Russian report).

This translation describes the effect on the aerodynamics of the air jet by dust concentrations. Chernov concludes that mass concentrations of 1 (1 gram particles/1 gram air) and less have no appreciable effect on the air stream provided the initial velocity is less than 30 meters per second.

5. Clower, J. I., "Oil Filters in Public Utility Fleet Operation," SAE Journal Transactions, Vol 41, No 2, p 381, September 1937.

This paper has to do mainly with the care of the oil while in service and which care is considered as important, or more so, than its selection. The author points out that at present there is no reliable scientific method or test for determining whether or not an oil is suitable for further use, and the author expresses the opinion that oils do not wear out but simply become contaminated with various impurities. These oil impurities are classified as "inherent" (those formed during service, those present in the crude and those introduced in refining, and as "foreign" (those from dust in the air, from combustion processes and from the engine itself). Of interest concerning dust (particles from 1.0 to 150 microns in size) is a tabulation of average dust concentrations in various localities. In addition, the requirements for a good oil filter are enumerated along with a discussion of filter and oil changes. Numerical data are presented on page 16.

Kayse, J.R., "Graphical Selector for Air Cleaners," Heating and Ventilating, Vol 50, No 7, p 80, July 1953.

A table (giving dust concentrations and particle sizes associated with commercial application) and graph (which is useable in the selection of air filters) are presented to aid anyone encountering a dust control problem in answering two questions: What am I dealing with? and What do I want the collection equipment to do? Particle size and concentration will answer the former question, and required collection efficiency, the latter. Numerical data are presented on page 16.

"Desert Testing of Air Cleaners on M48 Tank, Summer 1953," Engine and Power Train Section, Detroit Arsenal, Michigan, 125 pp/appendix, November 1954.

At Yuma Test Station during the summer of 1953 a complete investigation of performance characteristics of air cleaners installed in an M48 tank operating under extreme dust conditions was determined. The dust concentration was found to be 0.006 to 0.018 grams per cubic foot in the crew compartment and 0.170 grams per cubic foot in the engine compartment. The composition of the dust, as measured in both locations, was similar to Standardized Coarse and Fine Dust. It was concluded that servicing of the air cleaners as specified by Lubrication Orders and Technical Manuals resulted in needless waste of engine oil and that a service procedure based on vehicle miles or engine hours would be more realistic. Other conclusions reached were that the engine airflow was considerably less than the factory rating, that OE50 oil was not satisfactory for use in air cleaners as it will lower their efficiency, and that external dust leakage into the engine was strongly indicated. To determine and detect engine wear, spectrographic analyses of used

engine oil were made.

7. Drinker, P. and Hatch, T., "Industrial Dust, Hygienic Significance, Measurement, and Control," (Text book), Second Edition, McGraw-Hill Book Company, Inc., 1954, 401 pp.

This text emphasizes the problem of industrial dust from both the engineering and medical aspects. The text is primarily written from an engineer's standpoint with presentation of control measures for minimizing the problem of industrially originated dust. The pertinent information from this source is included on page 16 in the body of the report.

8. "Dust Exposure in Armored Vehicles, Determinations of Dust Loads and Characteristics of Dust Encountered in Operation of Armored Vehicles," Project 4, Sub-project 4-1, Armored Medical Research Laboratory, Ft. Knox, Kentucky, 1 p/appendix, September 1945. The pertinent information from this source is included on page 12 in the body of the report.

9. Hafer, Carl A., "A Survey and Study of the Factors Which Affect the Dust Environment Created by a Vehicle Operating over Unsurfaced Terrain," Contract DA-23-072-ORD-1210, Supplemental Agreement No. 2, Southwest Research Institute, San Antonio, Texas, 31 pp/appendix.

The pertinent information from this source is included on page 14 in the body of the report.

10. "Handbook of Yuma Environment," Environmental Protection Branch, Report 200, Research and Development Division, Office of the Quartermaster General, 14 p/appendix, February 1953.

This report summarizes and reviews the environmental features of the Yuma Test Station area. Heat and drought are the major climatic controls over desert testing in Yuma Test area. About one-half the days of the year have maximum temperatures of 90°F or above, and nearly one-third the days have maximum temperatures of 100°F or over. The low rainfall of the Yuma region is indicated by its mean annual precipitation of 3.83 inches. Meteorological factors of dew points, wind speeds, and cloud cover, as well as surface materials and terrain forms, are included.

11. Hoffman, A. H., "Mapping the Dust Concentration Around Small Tractors," Agriculture Engineering, Vol 7, No 1, p 12, January 1926.

The pertinent information from this source is included on page 12 in the body of the report.

12. Kangas, Pell, "Air Filtration and Diesel Engine Wear (A Progress Report)," Baltimore and Ohio Railroad, Presented at the SAE Golden Anniversay Diesel Engine Meeting, the Chase Hotel, St. Louis, Missouri, November 2-4, 1955.

The pertinent information from this source is included on page 15 in the body of the report.

13. Keeble, T. S., and Pavia, R. V., "The Dust Problem in Australia from the Standpoint of Aircraft Engine Operation," Report M. E. 82, Department of Supply, Research and Development Branch, Aeronautical Research Laboratories, Melbourne, Australia, 75 pp/tables, curves, and photos, July 1956. ASTIA AD No. 127400 (unclassified).

This document contains six reports on the various aspects of dust encountered by aircraft in Australia. The reports were composed between

August 1943 and July 1947. General descriptions of ten airfields are given, together with screen analyses of the surfacing material of each. Various type aircraft, the position of air intake, and type of dust control equipment are presented. The air velocities necessary to "float" small dust particles are discussed. The particle size distribution of dust from a dust storm and from various aircraft are analyzed. Methods of testing air cleaners are also given. The amount of dust picked up in the air filter depends on the ground level dustiness and the position of the air intake.

14. Koffman, J. L., "The Cleaning of Engine Air; Dust and Its Effect on Engine Wear," Gas and Oil Power, Vol 48, No 572, p 60, March 1953.

The pertinent information from this source is included on page 11 in the body of the report.

15. Larson, R. E., "Advantages of a Well-Chosen Air Cleaner Inlet System," Presented at the SAE National Tractor Meeting, Hotel Schroeder, Milwaukee, Wisconsin, September 1952, 5 pp/data.

The pertinent information from this source is included on page 9 in the body of the report.

16. Lincoln, R. L., "Dust Laboratory Studies, Fan-Abrasion Problem," Power, Vol 84, No 11, p 100 (735), November 1940.

This article describes briefly laboratory methods to study the prevention of fan blade erosion by dust. From small laboratory bench-testing of small scale models to field installation is the technique used to develop means of preventing abrasion. It was found that, in general, the rate of metal loss increases with greater static pressure requirements involving necessarily high fan-wheel tip speeds and with high velocity of ash laden gas across the face of the blade. Certain blade shapes are affected more than others. To avoid abrasion the solids must be removed from the gas stream before the gas enters the fan wheel, and while high (collection) efficiency is desirable, elimination of three-quarters or more of the solids by a practical, not-too-costly collector is a first consideration.

17. Martlew, D. L., "The Distribution of Impacted Particles of Various Sizes on the Blades of a Turbine Cascade," Memo No. M274, October 1956, Ministry of Supply, National Gas Turbine Establishment, Pyestock, Hants, England, AD No. 114642 (Unclassified).

This report describes an experimental study wherein a turbine blade cascade was exposed to an airstream laden with droplets of paraffin wax. Particles in various size groups were counted and the variation of deposition rate with particle size and position on the blade surface estimated. The airflow in the cascade was calculated and the equation of motion of small particles moving initially with the air were integrated to give their paths. The relative deposition rates were calculated and compared with the measurements; good general agreement was obtained. The velocities and directions of impact were also estimated.

18. McCullough, Bruce, "Evaluation of Airborne Contaminants' Effects on the Performance and Service Life of an XT 51-T-1 Shaft Turbine Engine," Contract AF 33(600)-27767, Item 1, SAE Report No. 578, Continental Aviation and Engineering Corporation, Detroit, Michigan, September 30, 1955.

This report describes the performance of an XT 51-T-1 shaft turbine engine operated in a controlled 25-hour sand and dust environment. The performance of the XT 51-T-1 shaft turbine engine was mechanically satisfactory, and the engine completed the test without major component failure. However, the post-test calibration of the engine revealed a decrease of 22.5 percent in the rated maximum power output of the engine. The specific fuel consumption of the engine had increased from 1.01 to 1.11 pounds per horsepower hour, and the air flow was reduced from 4.11 to 3.83 pounds per second. The disassembly inspection of the engine revealed that the compressor-inducer and the radial diffuser were severely eroded and the compressor casting was worn and badly pitted.

19. Overholt, L. F., "Dust Problems in Military Vehicle Operation," SAE Journal Transactions, Vol 51, No 10, p 381, October 1943.

The pertinent information from this source is included on page 12 in the body of the report.

20. Pauly, James G., "A Study of the Effects of Dust on Ordnance Automotive Materiel," Final Report, Contract DA-23-072-ORD-836, Task Order No. 9, Environmental Research Section, Southwest Research Institute, San Antonio, Texas, 204 p/tables, curves, schematics, photos, and bibliography, February 1956. ASTIA AD No. 89530 (Unclassified).

The author concludes, after extensive study and survey of published literature concerning dust and its effect on equipment, that dust creates more of a maintenance problem than the more obvious one of engine wear. This conclusion is based on the high efficiency of present day air cleaners. The problems of fire control, obscuration, position revealment, and crew efficiency arising from the dust created by the vehicle are ones for which additional work is necessary.

21. "Petrographic and Particle Size Analysis of Terrain Samples Taken from Vehicle Test Courses at Yuma Testion Station, Arizona, and Aberdeen Proving Ground, Maryland, " Contract DA-23-072-ORD-1210, Task Orders 1 and 4, OCO, R & D Division, Project No. TB5-1401, Department of Army, Project No. 598-09-004, Southwest Research Institute, March 1959, 33pp/tables and schematics.

The pertinent information from this source is included on page 15 in the body of the report.

22. Whittet, D. R., "Some Tests on a High Efficiency Air Cleaner," Report R-139, National Gas Turbine Establishment, London, England, 19 pp/appendix, July 1953. ASTIA AD 19514 (Unclassified).

From previous work it was found that the performance of axial compressors operating in an industrial atmosphere deteriorates quite rapidly because of deposits fouling the blades. The work reported in this paper describes laboratory tests conducted on an electronic precipitator for possible use as an air cleaner for the compressors. The electron precipitator was chosen because of its extremely high efficiency in filtering the minute particles in the atmosphere, which usually do not exceed a mean diameter of one micron. It was concluded that such a cleaner using a moving film of water as the aerosol receiver was admirably adapted for the purpose of cleaning the intake air for industrial axial compressors.

23. Wickerham, F. A , "Abrasive Resistance of a Low-Alloy Steel (Medium Manganese)," Metal Progress, Vol 30, No 1, p 64, July 1936.

This article deals first with the general problem of abrasive wear and then describes an abrasion-resisting steel, designated as "AR", which has been used quite successfully in a number of applications. The author quotes the abrasive-wear theory of W. A. Wissler, which states that, "the mechanism of wear may be partly explained by saying that the molecules or atoms forming the surface or edge become softened by heat (formed either by cutting or friction with temperature as high as 1100°F) and are torn or worn away while in a relatively soft condition." Among the materials used to resist abrasion are chilled and alloy cast irons, high manganese and other alloy steels, and hard non-ferrous alloys and carbides sintered or welded together. Parts made of common and alloy steels may be prepared by various heat treatments, by hand facing with hard materials such as stellite, by nitriding, or by case hardening. Special alloy steels (principally high carbon-high chromium steels) with or without heat treatment have solved some problem of abrasion.

24. "Winter Test, 1960, of GMT-305-B6 Gas Turbine Engine in an M56 Tracked Vehicle, Report No. DPS/OTA-25, OMS Code 5610.11.701, OMS Code 5510.11.274 (DA Project No. 598-09-004 and No. 549-11-003), Ordnance Test Activity, Yuma, Arizona, August 1960.

A GMT-305-B6 gas turbine engine was installed for test purposes in a modified M56 self-propelled gun chassis for operation at Fort Churchill, Manitoba, Canada. The vehicle was operated a total of 1110 miles on snow-covered roads, trails, and cross-country courses at that site. Cold storage, performance and fuel consumption tests were conducted. Cold starting was very good in ambient air temperatures as low as -41°F. Performance was generally satisfactory, but could be improved by matching to a more suitable transmission. Durability was adversely affected by lack of an air cleaner and design weaknesses in the cooling fan drive. Durther testing under Arctic conditions is recommended after modification of the engine.