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**OCD/OSA ltr, 9 Jun 1967**

USNRDL-TR-834
4 June 1964

Contract No. CDM-SR-59-54
Subtask 1113A





# DEVELOPMENT OF DESIGN CRITERIA FOR ROOF WASHDOWN SYSTEMS: A STUDY OF THE RELATIONSHIP OF SLOPE TO PARTICLE TRANSPORT BY WATER FILMS

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DEVELOPMENT OF DESIGN CRITERIA FOR ROOF WASHDOWN SYSTEMS -
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SUMMARY OF RESEARCH REPORT (Pages A-B, inclusive; for OCD use as detached document)

PURPOSE

The purpose of this report is to summarize studies of the basic principles involved in the transport of particulate matter by water films on an ideally smooth surface.

OBJECTIVE

The objective of these studies is to determine the relationship of surface slope and water flow rate to transport of particulate matter.

SCOPE

The flow characteristics of the water film were determined by measuring the depth of the water film and the surface velocity. The rate of particle transport was studied under the following conditions:

Slope: Horizontal 0.00065 0.02, 0.04, 0.08, and 0.165 (rise in feet).
Water Flow Rate: 0.195 to 7.32 gallons per min/ft of width.
Fallout Particle Simulant: Irregular-shaped silica and spherical glass beads.
Simulant Particle Size: 68 to 1015 μ.

The maximum amount of particulate matter that can be transported at various slopes was determined.

The characteristics of water surface wave development at various conditions was studied in relation to particle transport.

SIGNIFICANT FINDINGS

Fallout particles can be transported by thin films of water on horizontal surfaces only when the water flow rate is sufficient to produce turbulent flow. Water films in laminar flow will transport particulate matter if the surface is given the slightest incline. Surface waves are produced at all slopes at certain water flow rates. These waves increase the particle transport rate. An equation was developed from experimental data for the calculation of velocity of transport for various size particles under various conditions of slope and water flow.

The maximum amount of irregularly shaped particulate matter of the 68 to 1000-μ size range which can be transported under any set of conditions at any slope is much greater than would be expected from a nuclear detonation.

## CONCLUSION

At all slopes the gravity wave action becomes the biggest factor in the transport of particulate matter. As the slope increases, the water film thins out. The thinning out of the film resulted in an increase in the frequency of the waves.

## RECOMMENDATIONS

It is recommended that studies be made of methods of applying wash-down water to roofing surfaces which will produce an abundance of gravity or surface waves.

## ABSTRACT

This is the sixth report on a series of tests designed to study the basic principles involved in transport of particulate matter by water films. The previous reports covered the transport of particulate matter by various water flow rates on an ideal surface at one of five slopes from 0 to 0.165. This report covers the relationship of slope to transport on an ideal surface. On a near-horizontal surface, no transport occurs when the water flow rate is insufficient to produce turbulent flow. The slightest slope causes particles to be transported at low water flow rates in laminar flow. Surface waves, which are present at all slopes under most flow conditions, increase transport rate.

An empirical equation is presented for the computation of the transport velocities of both spherical and irregular shaped particles. The maximum amount of particulate matter that can be transported is presented.

# SUMMARY


## The Problem

To study the basic principles involved in the transport of particulate matter by water films.

## Findings

The rate of transport of various size particles on an ideal surface, inclined at various angles over a wide range of water flow rates, was determined. The maximum amount of material that can be removed as rapidly as deposited was determined for the various slopes under various flow conditions. This was found to be a much larger amount at all slopes studied than would be expected to be deposited on roof surfaces by a nuclear detonation.

CONTENTS

FIGURES

## PREFACE

The experimental work covered by this report was initiated to determine the basic principles involved in the transport of particulate matter by thin water films. The principle objective was to devise more effective washdown systems for the removal of radioactive fallout. These experiments were designed to study the relationship of fallout particle size and shape, water flow rate, and surface slope to rate and efficiency of transport by thin water films. An abundance of information was acquired from these studies that was utilized in the design of a full-scale roof washdown test facility which ultimately assisted in the design of a basic roof washdown system.

An empirical equation for the transport velocity of particles is presented in this report but the practical application of this equation to the design of roof washdown systems is not attempted or is it implied that this equation can be used in the solution of other radiological recovery problems. It is presented as being of possible interest in the general field of hydraulics.

It was discovered in these basic studies that one single factor which contributed most to the effective transport of particles by water films was surface waves which are developed under certain conditions. The development of these waves is discussed in this report and in a subsequent report on roof washdown system design. A method of producing these waves is incorporated into a basic design.

## 1. INTRODUCTION

The flushing of building roofs with water to remove radiological fallout was proposed a number of years ago as a radiological countermeasure, but the first development work on this method was directed towards its application to Navy ships. Development tests were conducted in 1949 with simulants of contaminated seawater sprayed onto vertically mounted plates; 99 % of the liquid simulant was removed when the surface was covered with a sheet of water prior to contamination.[1]

In June 1951, tests were conducted by the Bureau of Ships on a destroyer to determine whether a vessel's salt-water pumping capacity would adequately decontaminate its weather surfaces. Tests then were conducted by NRDL on the USS Worchester (CL-144) during January 1952, using non-radioactive simulants.[2] The results of these Worchester tests confirmed the 99 % effectiveness results obtained in laboratory tests on 1-$ft^2$ plates. The placement of spray nozzles to create a water curtain was accomplished chiefly by visual observation of the effectiveness of surface wetting. Later in July 1952, similar qualitative tests were carried out on the aircraft carrier, USS Shangri-La (CV-38). The same order of effectiveness was reported.[3] At Operation Castle, installed washdown systems were found to be 87 to 94 % effective in removing the radioactive fallout from a thermo-nuclear detonation.[4] The contaminant deposited on the ships during these tests contained a high percentage of insoluble radioactive coral particles as well as liquid contaminant.

Little regard was given to the fundamentals of transporting contaminant by water films in this early development work because there is an unlimited supply of seawater available to ships and the system is limited only by the ship's pumping capacity. When attention was finally focused on washdown for building roofs it was realized that there may be a shortage of water when the system is needed. Thus the use of a recirculating water system may be the only way to be sure of having water when fallout is expected. Further, the volume of water used must be kept at a minimum to reduce the size of the pumping equipment, storage tanks, and auxilliary equipment. Therefore the roof washdown system must be designed for maximum efficiency. A series of studies were conducted to provide a better understanding of the basic principles involved in the transport of particulate matter by water films.

The study of the transport of particulate matter on a near-horizontal ideally smooth surface is reported in Reference 5. The relationship of particle transport to water flow rate and particle diameter on an ideally smooth surface at slopes of 0.02, 0.04, 0.08, and 0.165 (rise in feet) are reported in References 6, 7, 8 and 9 respectively. This report extends these studies to the generalized relationship of slope to particle transport on an ideal surface.

## 2. EXPERIMENTAL DETAILS

### 2.1 Test Apparatus

The test apparatus (Fig. 1) consists of a plane formed by a 4 ft × 26 ft plate glass surface, supported by a rigid I-beam frame which can be adjusted to any desired slope up to 0.25. Details of construction are described in Appendix A. Glass was selected for the test surface because it was considered to be essentially an ideally smooth surface. Therefore the surface variable was essentially eliminated so that other variables could be studied.

### 2.2 Test Procedures

The flow characteristics of the water film were determined by measuring the depth of the water film and the surface velocity. The shape of the waves was drawn on a strip chart recorder connected to an electrical capacitance gauge which was calibrated to film thickness in mils (Appendix A). The water surface velocity was determined by timing small floats between stations.

Two types of particles were used in these water transport studies - irregularly shaped silica particles with rounded corners (sp. gr. 2.63) and spherical glass beads (sp. gr. 2.53 and 4.35). These particles were separated into standard sieve fractions and the tests were conducted on four size-fractions of silica and beads; 500 to 590 μ diameters (mean-545), 250 to 297 (mean-274), 125 to 149 (mean-137) and 62 to 74 (mean-68).

Most of the studies were conducted at the station located 10.9 ft from the entrance to the plane. It was found that the water flow changes in characteristics as it moves down from the water entrance to the plane and the water flowing off the end of the plane produces disturbances that are transmitted back up the plane. The test station at 10.9 ft was chosen because it is approximately midway between these end disturbances.

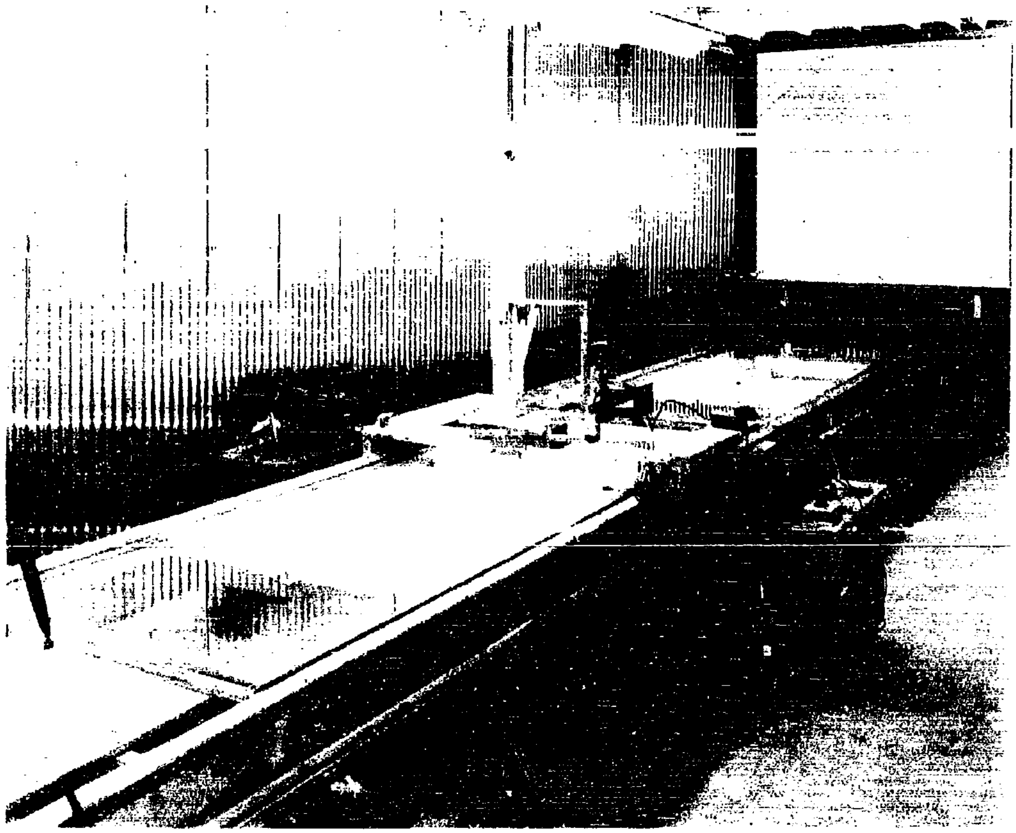


Fig. 1 Test Plane

The particles were deposited onto the test surface from a revolving-disc disperser. This disperser consisted of an 8-in. diameter disc mounted in a horizontal plane onto which particles were fed from a small hopper. A strip of particles was laid onto the disc as it revolved. As the disc completed a revolution the particles were blown off into a collecting hopper as they passed in front of a small air stream. The collecting hopper was connected to a 2 × 2 in. column from which the particles fell onto the plane. This column was fitted with a series of coarse mesh screens which interrupted their free fall to give a uniform fallout pattern on 4 in.$^2$ of test surface. The rate of fallout was varied by changing the rotational speed of the disc, and/or the size of the particle ring that was deposited on the disc, and by moving this ring of particles either closer to or away from the center of the disc.

## 2.3 Particle Velocity Measurements

### 2.3.1 Photographic Method

Multiple exposure photographs were taken of the moving particles lighted by a stroboscopic light source which was controlled by an adjustable vibrating reed. Each photograph showed a series of images of the particles. The distance between the first and last image of the particle was measured and divided by the time lapse to obtain the velocity of the particle. Figure 2 shows a typical photograph used to determine particle velocities.

### 2.3.2 Gross Method

A small group of particles was dispersed on the plane approximately 6 ft from the entrance. The time for the particles to move from a point 8 ft from the entrance to a point 18.5 ft from the entrance was measured. Particle velocity was determined by dividing the distance traveled by the average time of travel. If the particles remained in a group it was a simple matter to estimate the center of the group by eye and easily obtain the average particle velocity. However, if the particles tended to become distributed over some distance, the task of estimating the average velocity was somewhat complicated. Generally, some of the particles were caught in a wave crest and remained on the surface of the entire length of the plane. These were the fastest moving particles or "floaters". The majority of the particles would drop to the glass surface and be moved along at a rhythmical rate by the action of the waves. These slower particles or "rollers" trailed far behind the fastest particles and seemed to roll along the plane surface at a steady speed. Stopwatches were used to time the travel of the fastest, middle, and slowest groups of particles. Since most of the particles were of the middle group, it was weighted by a factor of 2. The average time, was calculated as

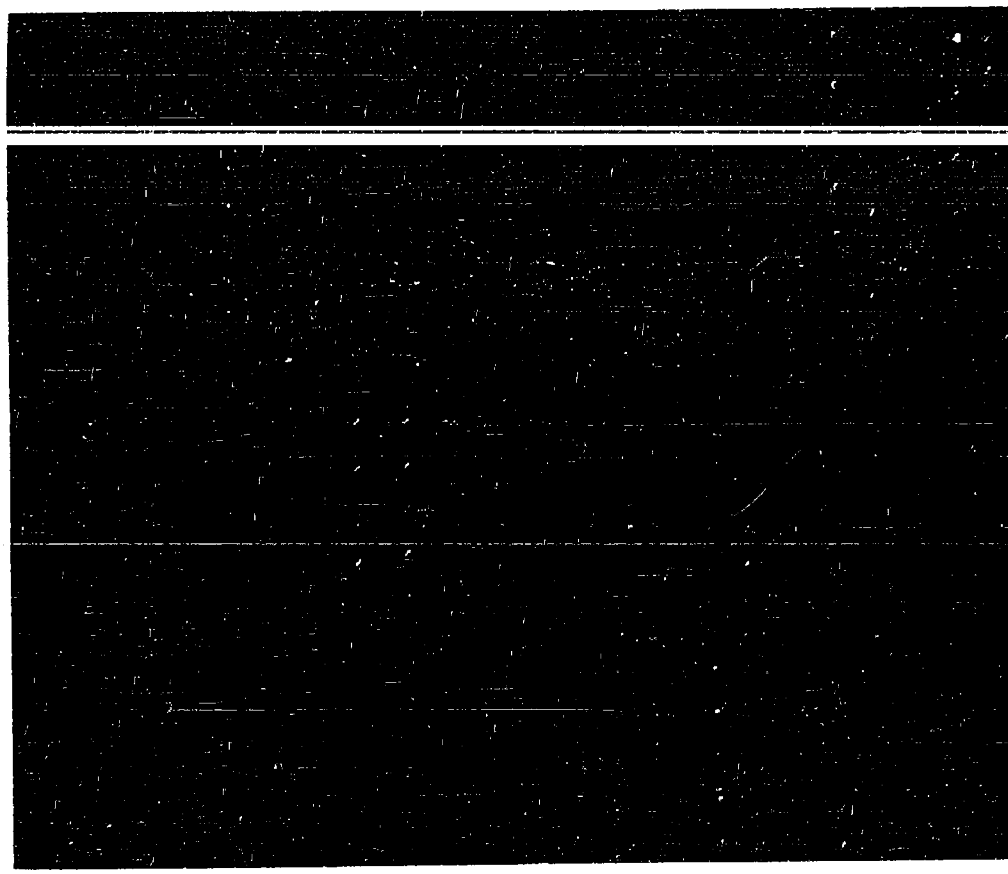


Fig. 2 Typical Particle Velocity-Measurement Photograph

$$T_{ave} = \frac{T_1 + 2T_2 + T_3}{4}$$

where $T_1$ = time of travel of the fastest group
$T_2$ = time of travel of the middle group. This portion was weighted in proximate ratio to the percentage of particles present.
$T_3$ = time of travel of the slowest group

The particle velocities obtained by the gross method for the higher slopes were much greater than those obtained by the photographic method. This discrepancy is greater as the ratio of floaters to rollers increases. The floaters and other fast-moving particles move across the field of view of the camera so quickly that their velocity could not be obtained with the flash rate used.

### 2.4 Mass Transport Effectiveness

The maximum mass loading rate is a measure of the maximum amount of particulate matter that can be transported as fast as deposited by a given flow of water at a particular slope. It does not, however, give any indication of the amount of material that will remain as residual after the washdown is shut down. The amount of residual will vary with roughness and irregularities of the roofing surface.

As the mass rate of deposition was increased, a point was reached where a long non-moving mass built up beneath the disperser.

The time this took after starting the disperser varied with the water flow rate, slope, and particle size. The time required for the build-up to occur under a set of test conditions was recorded and the disperser adjusted to give a build-up in a different length of time. The time at which build-up began was determined by visual observation. The mass loadings were then plotted against reciprocal time. When this curve was extrapolated to infinite time or $1/T = 0$, the maximum amount of deposition that would give no build-up was obtained,

## 3. RESULTS AND DISCUSSION

### 3.1 Water Film Flow Characteristics

The average film depth at various slopes is shown in Fig. 3. It will be noted that at a near-horizontal slope ($6.5 \times 10^{-4}$) a break in

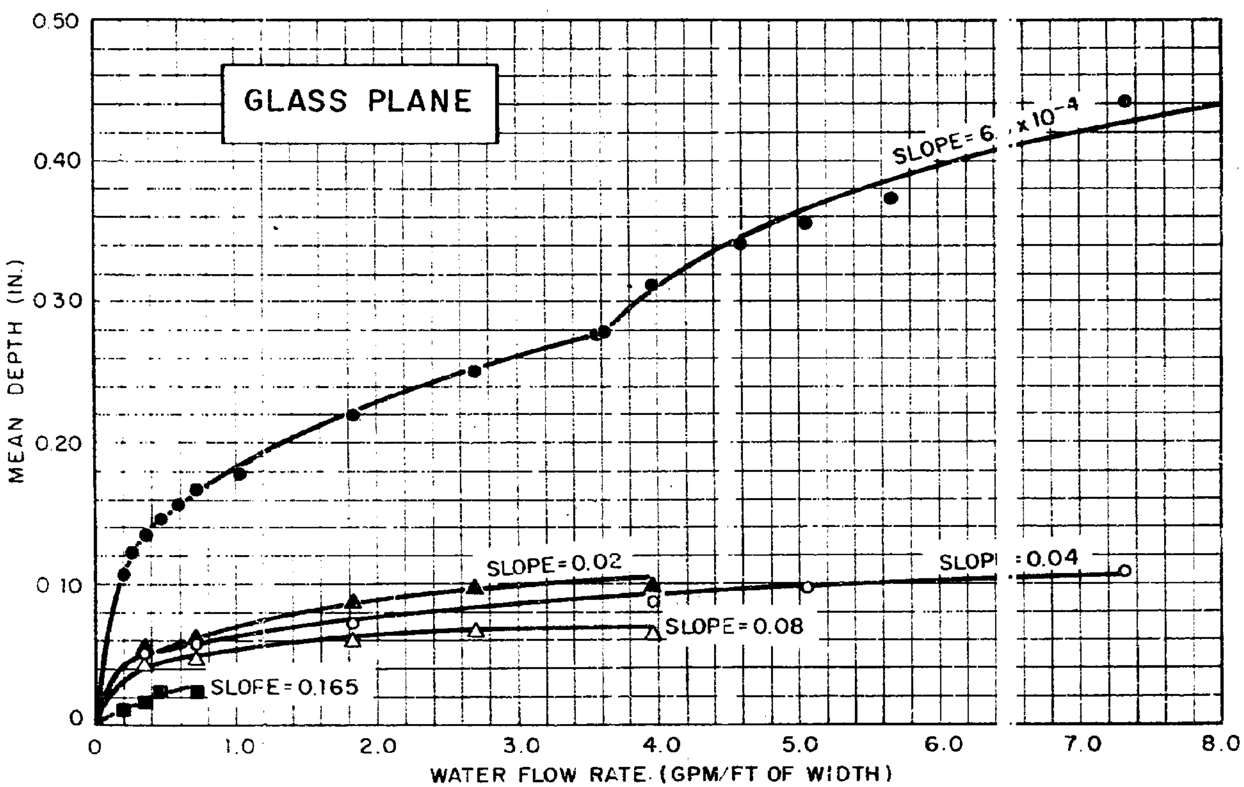



Fig. 3 Mean Water Depth vs Water Flow Rate for Different Slopes, a : 10.9 ft From Entrance to Plane

the depth curve occurs at a flow rate of 3.6 gpm/ft of width. This is the point at which the Reynold's Number approaches 3000. Below this point the film flow follows laminar film flow theory, where the friction factor is equal to 96 divided by the Reynold's Number (F = 96/Re). At Reynolds' Numbers over 3000, turbulent flow occurs. Figure 4 shows the variation of the calculated average water film velocity with change in slope. This velocity; U, was calculated from U = Q/DW, where Q = cu ft of water/sec, D = depth of film in ft, and W = width of plane in ft. The data for a flow rate of 0.195 gpm/ft of width was limited to the 0.00065 and 0.165 slopes. An estimated curve between these two points is shown in Fig. 4 by a dotted line.

A hot-wire anemometer (Appendix A) was used to measure the relative velocity of the water film on the near-horizontal slope only. The velocity profile for three flow rates is shown in Fig. 5. These curves show only the change of velocity with depth as indicated by the temperature differential between the hot wire and the water. It is observed that the water film is in laminar flow at all three water flow rates. In the case of flow of approximately 0.2 gpm per ft of width (curve A) the entire film depth is in laminar flow. With a flow rate of approximately 4.0 gpm/ft of width, curve B, the water film is in turbulent flow from a depth of 100 mils to 240 mils from the bottom while a flow of 9.0 gpm/ft of width (curve C) gives a turbulent film from a depth of 80 mils from the bottom up to a depth of 400 mils from the bottom.

## 3.2 The Mechanics of Particle Transport

A section of the glass plane was projected onto a screen to study the movement of the particles. It was observed on the near-horizontal test plane that the spherical particles moved uniformly as if rolling while the irregularly shaped silica particles moved with starts and stops, with pauses of various lengths of time. There was no apparent pattern in the length of the pauses or the distance traveled while in motion. The particles moved in a similar manner at each of the slopes but on all the slopes the gravity wave action becomes the biggest factor in the transport of the particles.

The surface or gravity waves appeared to move down the plane with a rolling over or folding under action. These waves were not continuous across the width of the plane but were semi-elliptical in shape (Fig. 6) and the shape or form was changed constantly as the water film flowed down the plane. The waves induced a pulsing action on the particles as they passed over them. The particles at rest were jarred loose by the waves and were moved along at the same velocity as the wave for a short distance. The transport velocity of the particles which were in motion at the time a wave passed over was increased to the velocity of the wave. After the particles were given a boost for a short distance by the wave passing over, they continued to move as previously described.

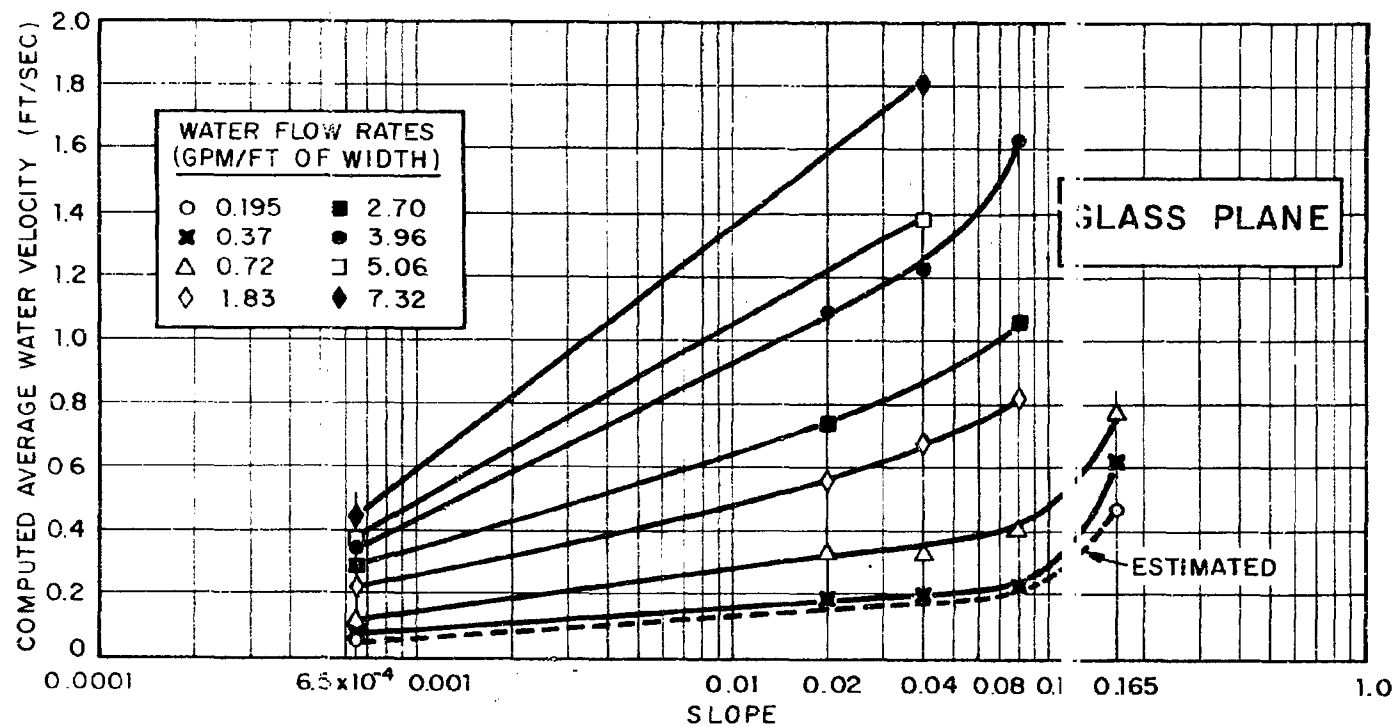



Fig. 4 Average Velocity of Water Film vs. Slope. Velocities computed f m $U = Q/DW$, where $U$ = velocity (ft/sec, $Q$ = water flow rate (gpm/ft of width , $D$ = depth of water (ft), $W$ = width of plane (ft)

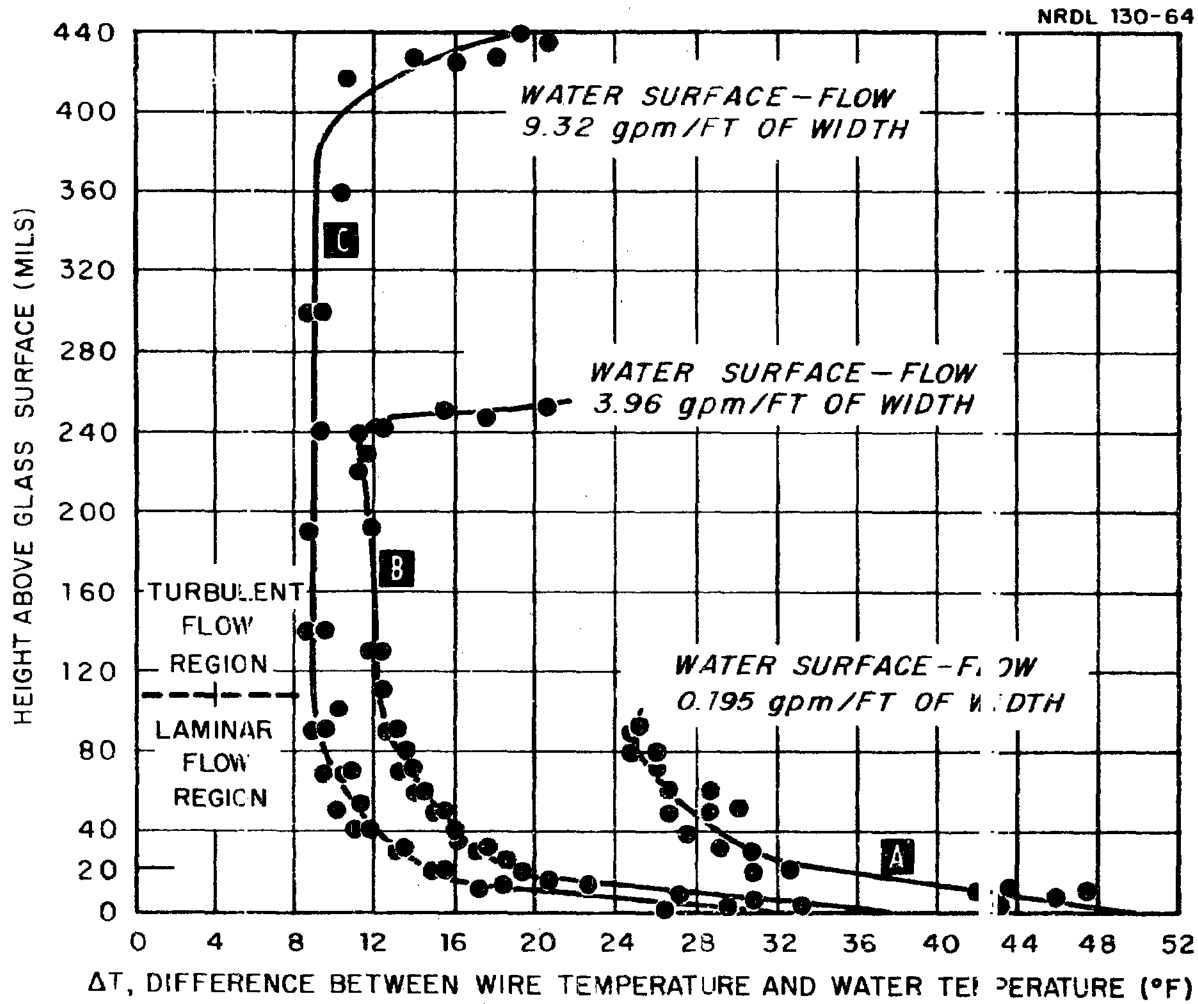



Fig. 5 Relationship of Hot Wire Temperature Difference to Depth. (Indicates the change of velocity with depth; lower temperature differential indicates higher water velocity.)

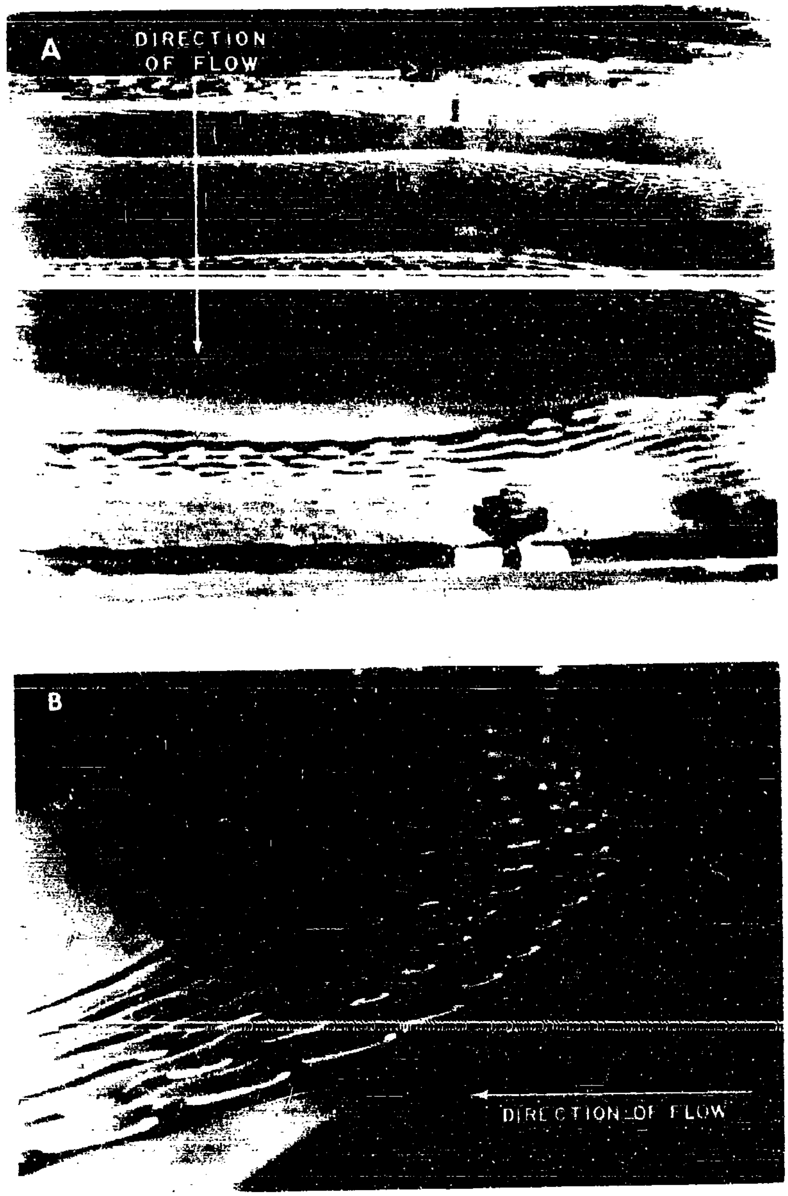



Fig. 6 Typical Wave Patterns

A study of the wave pattern was made at each slope with various water flow rates. A complete set of plots are presented in References 5 to 9. Typical plots are shown in Figs. 7 to 10 for a flow rate of 0.72 gpm/ft of width for a slope of 0.02, 0.04, 0.08, and 0.165. These figures show that as the slope increases the water film thins out. The mean depth was reduced from 0.080 in. at an 0.02 slope to 0.027 in. at a slope of 0.165. The thinning of film resulted in an increase of the frequency of the waves as shown by the time lapse reduction from 2.6 to 1.0 sec from slope 0.02 to 0.165. The development of waves becomes more pronounced as one moves down the plane. Figure 7 shows the waves just starting to develop at the 9 and 10 ft distance on the [illegible] and continuing to increase in height down to the end of the plane. At the 0.04, 0.08, and 0.165 slope (Figs. 8, 9 and 10) the waves start to develop at the 5 or 6 ft distance and increase in number as the water flows down the plane. Changing the water flow on a particular slope also changes the wave action as can be seen by comparing Fig. 9 with Fig. 11.

### 3.3 Rate of Particle Transport

The rate of transport of the various sizes of both the spherical and irregularly shaped particles are presented in Tables 1, 2, and 3. Table 1 gives the transport velocity of irregular silica particles with a specific gravity of 2.63 at various flow rates on a variety of slopes. Table 2 gives the velocity of spherical glass beads with a sp. gr. of 2.53 and Table 3 gives the velocity of glass beads with a sp. gr. of 4.35. For the 0.165 slope the figures for particle velocities are, for the most part, slower than those taken on the 0.04 and 0.08 slopes. However, for the 0.00065, 0.02, 0.04, and 0.08 slopes, the particle velocity increased with slope. At the 0.165 slope a large percentage of the particles were "floaters", so the previously mentioned discrepancies occurred in measuring their velocities.

The following equations were developed from the experimental data given in references 5-9 for the calculation of the particle transport velocities:

$$U = AS^{a}D\,(Q^{b}-B) + C$$

where U is the particle velocity in ft/sec
Q is the water flow rate in gpm/ft of width
D is the particle diameter in microns
S is the sine of the slope angle
A, B, C, a and b - Constants derived from experimental data.

The constants vary for both slope and particle shape as follows: for spherical particles at 0.00065 slope

$$U = 0.00280S^{2/3}\,D(Q^{1/2}-1.094) + 0.0007$$

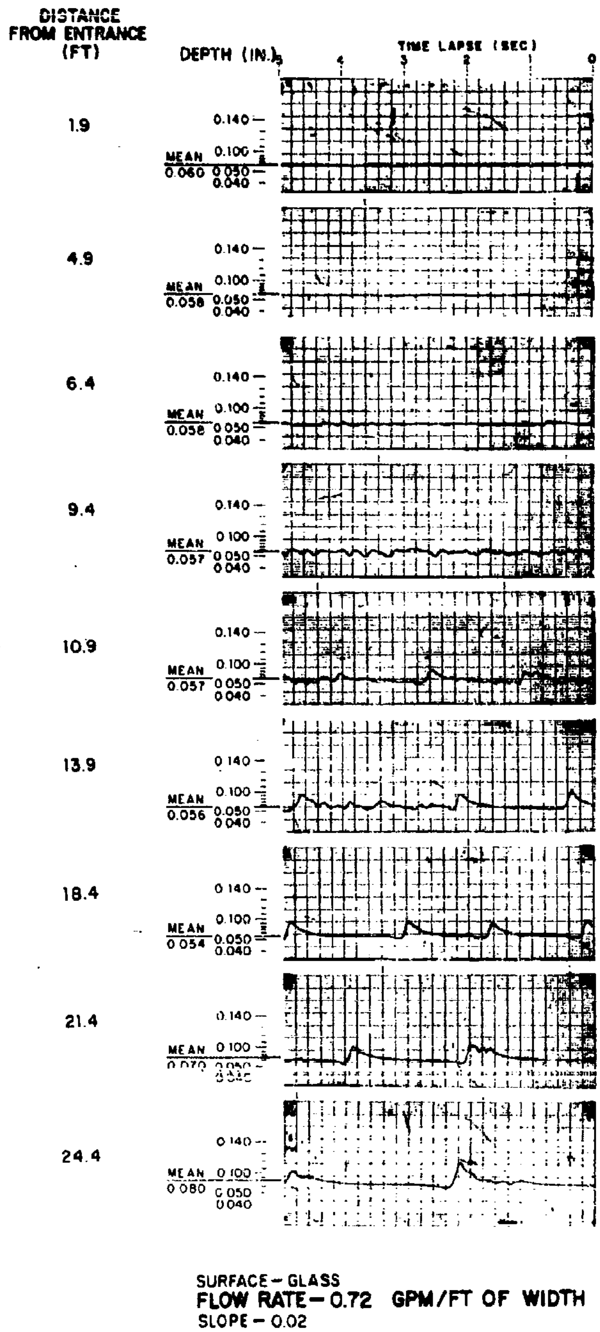



Fig. 7 Water Surface Profiles

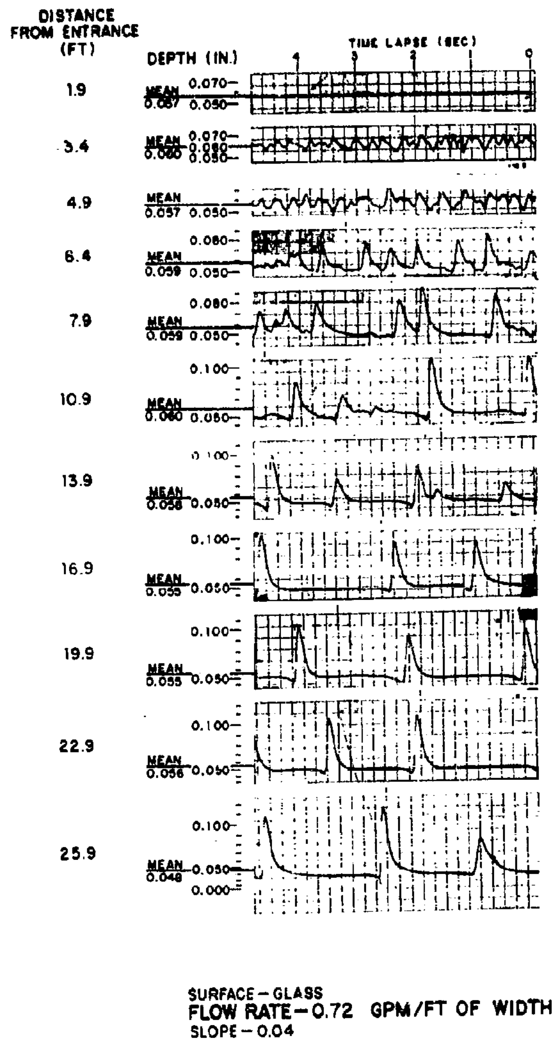
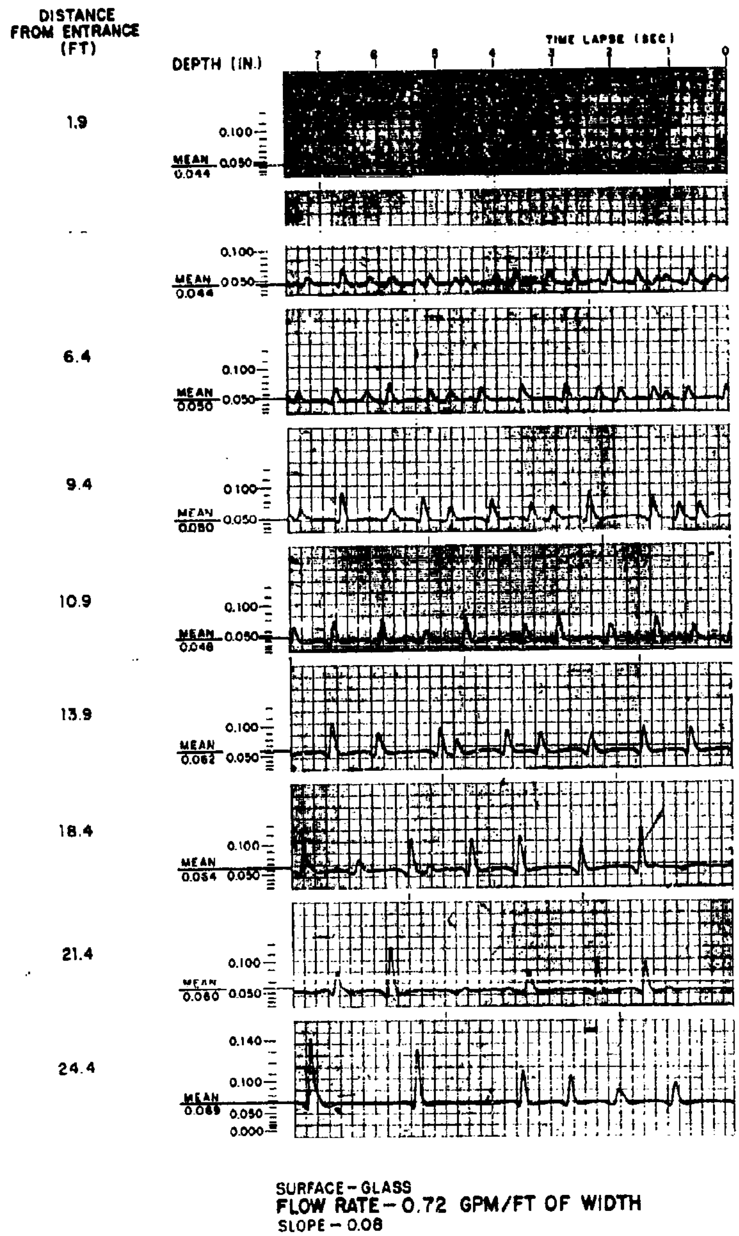



Fig. 8 Water Surface Profiles




SURFACE – GLASS
**FLOW RATE – 0.72 GPM/FT OF WIDTH**
SLOPE – 0.08

Fig. 9 Water Surface Profiles

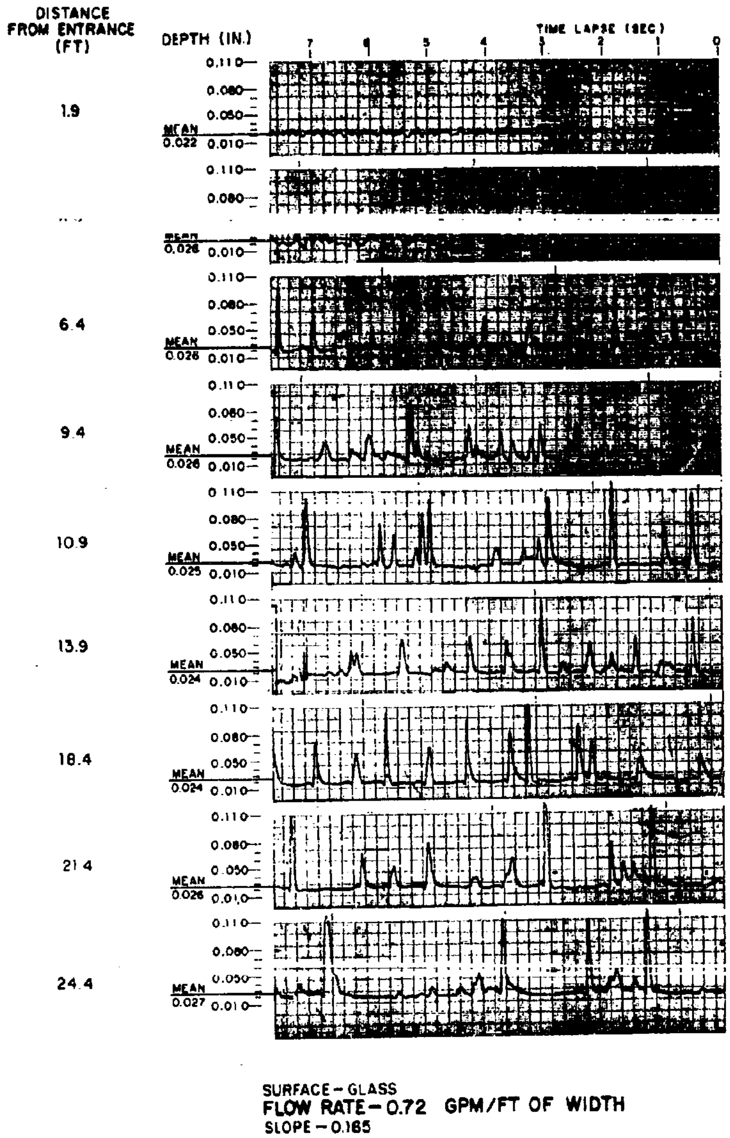



Fig. 10 Water Surface Profiles

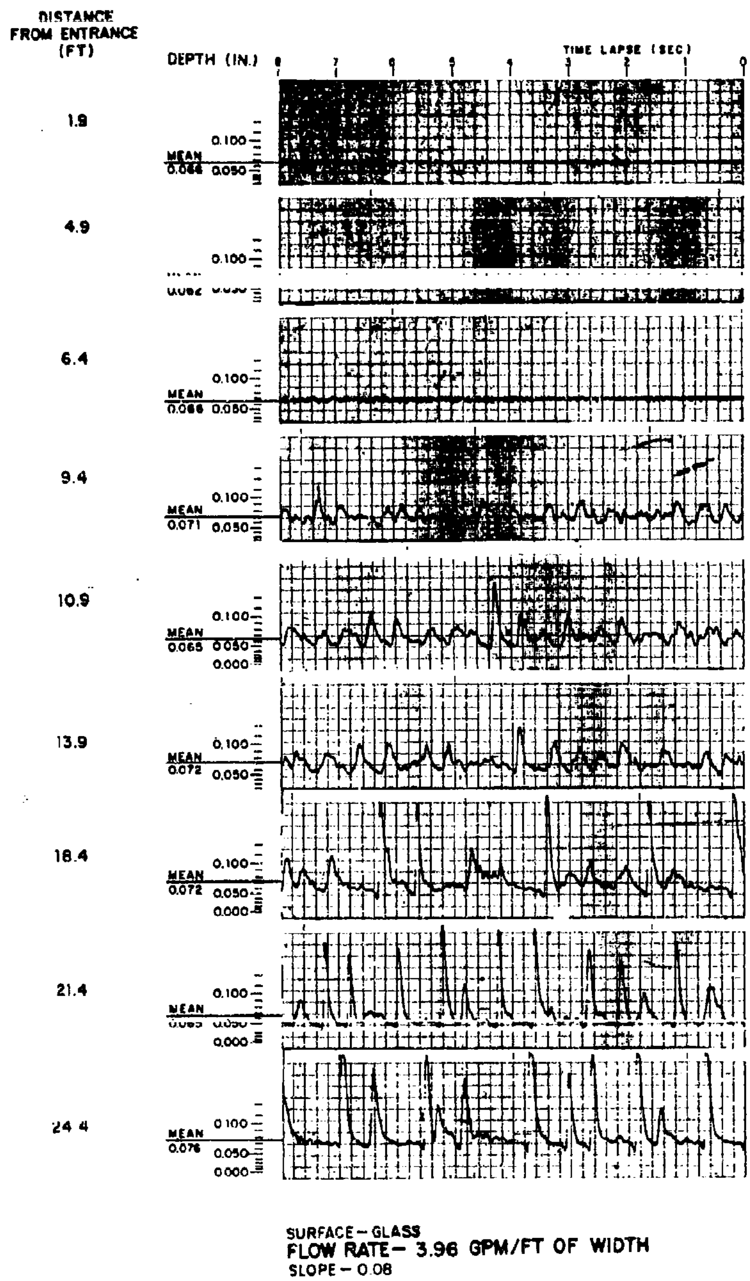



Fig. 11 Water Surface Profiles

TABLE 1

Transport Rate of Irregular Shaped Silica Particles (sp. gr. 2. 3)
Point of Measurement - 10 to 11 ft from Entrance to Plane

| Slope | Water Flow Rate (GPM/ft of width) / Mean Particle Diameter (microns) | 0 (Dry Plane) | 0.195 | 0.37 | 0.72 | 0.133 | 2.70 | 3.96 | 5.06 | 7.32 | 9.32 | 11.2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Particle Velocities in Feet per Second | | | | | | | | | | |
| 0.0035 | 1015 | - | - | - | - | - | - | - | 0 | - | - | 0.0072 |
| | 545 | - | - | - | - | - | - | 0 | - | 0.0043 | 0.0083 | 0.0038 |
| | 274 | - | - | - | - | - | - | 0 | 0.0006 to 0 .13 | 0.0022 | 0.0024 | 0.0060 |
| | 230 | - | - | - | - | - | - | - | 0.001 to 0 .19 | - | - | - |
| | 194 | - | - | - | - | - | - | - | 0.0013 | 0.0027 | 0.0043 | 0.0064 |
| | 137 | - | - | - | - | - | - | - | 0.0013 | 0.0033 | 0.0053 | 0.0051 |
| | 68 | - | - | - | - | - | - | - | 0.0022 | 0.0038 | - | 0.0053 |
| 0.02 | 545 | 0 | - | - | 0.113 ± 0.028 | 0.10 ± 0.029 | 0.344 ± 0.078 | 0.457 ± 0.070 | - | - | - | - |
| | 274 | 0 | - | - | 0.056 ± 0.008 | - | 0.148 ± 0.027 | 0.184 ± 0.040 | - | - | - | - |
| | 137 | 0 | - | - | 0.027 ± 0.005 | 0.056 ± 0.008 | 0.072 ± 0.018 | 0.105 ± 0.025 | - | - | - | - |
| | 68 | 0 | - | - | - | - | - | - | - | - | - | - |
| 0.04 | 545 | 0 | - | 0.12 ± 0.004 | 0.18 ± 0.10 | 0.30 ± 0.10 | - | 0.82 ± 0.07 | 0.93 ± 0.0 | 1.1 ± 0.3 | - | - |
| | 274 | 0 | - | 0.062 ± 0.025 | 0.060 ± 0.019 | 0.24 ± 0.10 | - | 0.31 ± 0.07 | 0.31 ± 0.0 | 0.44 ± 0.13 | - | - |
| | 194 | - | - | - | - | - | - | - | - | - | - | - |
| | 137 | - | - | 0.055 ± 0.010 | 0.060 ± 0.018 | 0.076 ± 0.023 | - | 0.17 ± 0.05 | 0.17 ± 0.0 | 0.26 ± 0.02 | - | - |
| | 68 | 0 | - | 0.013 ± 0.003 | - | - | - | 0.093 ± 0.016 | 0.093 ± 0.0 | - | - | - |
| 0.07 | 545 | - | - | 0.19 ± 0.16 | 0.52 ± 0.19 | 0.57 ± 0.41 | 0.84 ± 0.27 | - | - | - | - | - |
| | 274 | - | - | 0.17 ± 0.07 | 0.12 ± 0.05 | 0.40 ± 0.15 | 0.49 ± 0.32 | - | - | - | - | - |
| | 137 | - | - | 0.07 ± 0.02 | 0.12 ± 0.05 | 0.20 ± 0.09 | 0.30 ± 0.10 | - | - | - | - | - |
| | 68 | - | - | - | - | - | - | - | - | - | - | - |
| 0.155 | 545 | - | 0.050 ± 0.052 | 0.129 ± 0.030 | 0.573 ± 0.015 | 0.257 ± 0.092 | - | - | - | - | - | - |
| | 274 | - | 0.086 ± 0.030 | 0.164 ± 0.078 | 0.132 ± 0.045 | 0.31 ± 0.12 | - | - | - | - | - | - |
| | 137 | - | 0.080 ± 0.012 | 0.050 ± 0.011 | 0.047 ± 0.018 | 0.047 ± 0.018 | - | - | - | - | - | - |
| | 68 | - | - | - | - | - | - | - | - | - | - | - |

Note. Values given are average with maximum and minimum limits

# TABLE 2

## Transport Rate of Spherical Glass Beads (sp. gr. 2.53)
## Point of Measurement - 10 to 11 ft from Entrance to Plane

| Slope | Water Flow Rate (GPM/ft of width) | 0 (Dry Plane) | 0.195 | 0.37 | 0.72 | 1.83 | 2.70 | 3.96 | 5.06 | 7.32 | 9.32 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean Particle Diameter (microns) | Particle Velocities in Feet per Second | | | | | | | | | |
| 0.00065 | 1015 | - | - | - | - | - | - | - | - | - | - |
| | 545 | - | - | - | - | - | - | 0.0098 | 0.0137 | 0.0215 | 0.0221 |
| | 274 | - | - | - | - | - | - | 0.0058 | 0.0092 | - | 0.0145 |
| | 230 | - | - | - | - | - | - | - | - | - | - |
| | 194 | - | - | - | - | - | - | - | - | - | - |
| | 137 | - | - | - | - | - | - | 0.0027 | 0.0038 | 0.0046 | 0.0057 |
| | 68 | - | - | - | - | - | - | 0.0015 | 0.0025 | 0.0032 | 0.0041 |
| 0.02 | 545 | 0 | 0.041 | - | 0.071 ± 0.011 | 0.170 ± 0.025 | 0.131 ± 0.025 | 0.231 ± 0.021 | - | - | - |
| | 274 | 0 | 0.025 | - | 0.054 ± 0.005 | 0.080 ± 0.008 | 0.095 ± 0.007 | 0.117 ± 0.012 | - | - | - |
| | 137 | 0 | - | - | 0.024 ± 0.002 | 0.040 ± 0.003 | 0.045 ± 0.005 | 0.055 ± 0.005 | - | - | - |
| | 68 | 0 | - | - | - | - | - | - | - | - | - |
| 0.04 | 545 | 0.26 ± 0.03 | - | | 0.15 ± 0.04 | 0.26 ± 0.03 | - | 0.42 ± 0.12 | 0.42 ± [illegible] | 0.68 ± 0.30 | - |
| | 274 | - | - | - | - | - | - | 0.15 ± 0.04 | 0.15 ± [illegible] | - | - |
| | 194 | 0.038 ± 0.003 | - | 0.028 ± 0.006 | 0.050 ± 0.011 | 0.30 ± 0.05 | - | 0.12 ± 0.04 | 0.12 ± [illegible] | 0.18 ± 0.07 | - |
| | 137 | 0.021 ± 0.003 | - | 0.014 ± 0.003 | 0.041 ± 0.006 | 0.049 ± 0.013 | - | 0.095 ± 0.021 | 0.095 ± [illegible] | 0.14 ± 0.05 | - |
| | 68 | 0 | - | 0.0049 ± 0.0013 | - | - | - | - | - | - | - |
| 0.08 | 545 | - | - | 0.13 ± 0.08 | 0.19 ± 0.06 | 0.27 ± 0.10 | 0.57 ± 0.15 | - | - | - | - |
| | 274 | - | - | 0.08 ± 0.03 | 0.14 ± 0.08 | 0.27 ± 0.09 | 0.37 ± 0.14 | - | - | - | - |
| | 137 | - | - | 0.03 ± 0.01 | 0.08 ± 0.03 | 0.07 ± 0.02 | 0.18 ± 0.05 | - | - | - | - |
| | 68 | - | - | - | - | - | - | - | - | - | - |
| 0.165 | 545 | - | 0.353 ± 0.054 | 0.067 ± 0.019 | 0.105 ± 0.037 | 0.285 ± 0.081 | - | - | - | - | - |
| | 274 | - | 0.331 ± 0.074 | 0.110 ± 0.040 | 0.139 ± 0.016 | 0.209 ± 0.061 | - | - | - | - | - |
| | 137 | - | - | 0.049 ± 0.088 | 0.091 ± 0.024 | 0.092 ± 0.024 | - | - | - | - | - |
| | 68 | - | 0.348 ± 0.008 | - | - | - | - | - | - | - | - |

Note. Values given are average with maximum and minimum limits.

## TABLE 3

Transport Rate of Spherical Glass Beads (sp. gr. 4.35)
Point of Measurement - 10 to 11 ft From Entrance to Plan

| Slope | Water Flow Rate (GPM/ft of width) → Mean Particle Diameter (microns) | 0 (Dry Plane) | 0.195 | 0.37 | 0.72 | 1.83 | 2.70 | 3.96 | [illegible].06 | 7.32 | 9.32 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Particle Velocities in Feet per Second | | | | | | | | | |
| 0.00065 | 1015 | - | - | - | - | - | - | - | - | - | - |
| | 545 | - | - | - | - | - | - | 0 | 0.0[illegible]4 | 0.026 | 0.0306 |
| | 274 | - | - | - | - | - | - | 0 | 0.0[illegible]1 | 0.0123 | 0.0148 |
| | 230 | - | - | - | - | - | - | - | - | - | - |
| | 194 | - | - | - | - | - | - | - | - | - | - |
| | 137 | - | - | - | - | - | - | 0.0027 | 0.0[illegible]2 | 0.0056 | 0.0064 |
| | 68 | - | - | - | - | - | - | 0.0018 | 0.0[illegible] | 0.0040 | - |
| 0.02 | 545 | 0 | 0.049 | - | 0.085 ± 0.015 | 0.154 ± 0.024 | 0.184 ± 0.028 | 0.248 ± 0.013 | - | - | - |
| | 274 | 0 | 0.027 | - | 0.044 ± 0.005 | 0.070 ± 0.008 | 0.085 ± 0.005 | 0.102 ± 0.025 | - | - | - |
| | 137 | 0 | 0.014 | - | 0.023 ± 0.002 | 0.036 ± 0.003 | 0.042 ± 0.003 | 0.049 ± 0.006 | - | - | - |
| | 68 | 0 | - | - | - | - | - | - | - | - | - |
| 0.04 | 545 | 0.46 ± 0.07 | - | 0.083 ± 0.056 | 0.21 ± 0.16 | 0.28 ± 0.05 | - | 0.35 ± 0.01 | 0.[illegible] ± 0.01 | 0.53 ± 0.13 | - |
| | 274 | 0.13 ± 0.03 | - | 0.045 ± 0.005 | 0.078 ± 0.014 | 0.10 ± 0.02 | - | 0.17 ± 0.02 | 0.[illegible] ± 0.02 | 0.18 ± 0.01 | - |
| | 194 | - | - | - | - | - | - | - | - | - | - |
| | 137 | 0.037 ± 0.004 | - | 0.014 ± 0 | 0.035 ± 0.004 | 0.041 ± 0.006 | - | 0.066 ± 0.006 | 0.0[illegible] ± 0.006 | 0.079 ± 0.00[illegible] | - |
| | 68 | 0 | - | 0.0077 ± 0.0010 | - | - | - | 0.042 ± 0.005 | 0.0[illegible] ± 0.005 | 0.072 ± 0.013 | - |
| 0.08 | 545 | - | - | 0.19 ± 0.09 | 0.25 ± 0.21 | 0.53 ± 0.11 | 0.65 ± 0.13 | - | - | - | - |
| | 274 | - | - | 0.11 ± 0.03 | 0.12 ± 0.05 | 0.20 ± 0.05 | 0.33 ± 0.08 | - | - | - | - |
| | 137 | - | - | 0.06 ± 0.01 | 0.06 ± 0.002 | 0.07 ± 0.03 | 0.15 ± 0.03 | - | - | - | - |
| | 68 | - | - | - | - | - | - | - | - | - | - |
| 0.265 | 545 | - | 0.06[illegible] ± 0.093 | 0.188 ± 0.063 | 0.162 ± 0.117 | 0.43 ± 0.023 | - | - | - | - | - |
| | 274 | - | 0.093 ± 0.095 | 0.117 ± 0.022 | 0.239 ± 0.056 | 0.19 ± 0.17 | - | - | - | - | - |
| | 137 | - | 0.045 ± 0.008 | 0.350 ± 0.01 | 0.081 ± 0.124 | 0.51 ± 0.124 | - | - | - | - | - |
| | 68 | - | - | - | - | - | - | - | - | - | - |

Note. Values given are average with maximum and minimum limits.

for spherical particles at 0.02, 0.04, and 0.08 slope

$$U = 0.00280S^{2/3}D(Q^{1/2}-0.069) + 0.30S^{4/3}$$

for irregulAr silica particles at 0.02, 0.04 and 0.08 slopes

$$U = 0.00688S^{2/3}D(Q^{1/2}-0.480) + 1.5S^{4/3}$$

A nomograph is presented in Fig. B.1 of Appendix B for finding the velocities of various sizes of spherical particles for a given slope and water flow rate. Figure [illegible] particles. The particle velocity equations cannot be used for the horizontal slope or the 0.165 slope, but should be accurate within the 0.01 to 0.10 slope range shown on the nomographs.

### 3.4 Mass Transport Effectiveness

The maximum mass loading rate for various particle sizes at the different slopes studied are given in Table 4 for spherical particles and Table 5 for irregular particles. These maximum mass loadings show that if an ideally smooth surface can be approached on a roof, almost any water flow rate on any slope is capable of transporting much more particulate matter than will ever be encountered in a radioactive fallout from a nuclear detonation. A reasonable maximum from a nuclear detonation may be on the order of 2 gr/ft$^2$/min. A flow rate of 0.37 gpm/ft of width was capable of transporting high masses of spherical particles on all slopes studied except 0.02.

A flow rate of 2.70 gpm/ft of width or higher was required on the 0.02 slope to transport the 68-μ spherical particles, while a flow of only 0.72 gpm/ft transported 150 gr/ft$^2$/min of the 460 μ particles.

A flow rate of only 0.37 gpm/ft of width is capable of transporting much higher mass loadings of all sizes of irregularly shaped particles at all slopes than would be encountered from a nuclear detonation. It is also noted in Table 5 that much higher mass loadings of both the 274-μ and 68-μ particles can be transported under any set of conditions than the 137-μ size. This is believed to be due to the characteristic movement of the irregular particles. These particles move by hopping and sliding on the surface, so that part of the time they are suspended in the turbulent layer of the water film. The higher mass 274 μ and 137 μ particles are suspended for shorter periods than the 68 μ particles. These 68 μ particles are of such mass that they probably are suspended most of the time. A sharp increase in the periods of suspension of the 68 μ particles would account for their more efficient transport. The particles while not in suspension are in the laminar layer. This laminar layer is sufficiently thick to completely cover the 137 μ particles, most of the time, so they are being transported principally by the

TABLE 4

Maximum Mass Loading Rate of Spherical Particles on an Ideal Surface

| Flow Rate (gpm/ft of width) | [illegible] | | | |
|---|---|---|---|---|
| | Average Particle Diameter | | | |
| | 460 μ | 274 μ | 137 μ | 68 μ |
| | | **0.02 Slope** | | |
| 0.72 | 150 | - | - | 0 |
| 1.83 | 215 | - | - | 0 |
| 2.70 | 335 | - | - | 10 |
| 3.96 | 445 | - | - | 20 |
| | | **0.04 Slope** | | |
| 0.37 | 180 | 60 | 20 | 20 |
| 0.72 | 430 | 90 | 50 | - |
| 1.83 | 560 | 160 | 110 | 90 |
| 2.70 | - | 300 | 160 | 140 |
| 3.96 | 700 | - | - | - |
| | | **0.08 Slope** | | |
| 0.37 | 810 | 240 | 60 | 60 |
| 0.72 | 1080 | 530 | 340 | 380 |
| 1.83 | 2820 | 2150 | 1880 | 1630 |
| | | **0.165 Slope** | | |
| 0.195 | 1290 | - | - | 300 |
| 0.37 | 2080 | - | - | 1940 |
| 0.47 | 3720 | - | - | 2340 |
| 0.59 | - | - | - | 5000 |

TABLE 5

Maximum Mass Loading Rate of Irregular Particles on an Ideal Surface

| Flow Rate (gpm/ft of width) | Maximum Mass Loading Rate (gr/ft/min) Average Particle Diameter 460 μ | 274 μ | 137 μ | 68 μ |
|---|---|---|---|---|
| | | 0.02 Slope | | |
| 0.72 | 60 | 22 | 14 | 49 |
| 1.83 | 260 | 79 | 38 | 105 |
| 2.70 | 440 | 107 | 63 | 215 |
| 3.96 | 850 | 160 | 97 | 285 |
| | | 0.04 Slope | | |
| 0.37 | 90 | 60 | 30 | 60 |
| 0.72 | 340 | 110 | 70 | 130 |
| 1.83 | 940 | 320 | 240 | 450 |
| 3.96 | 2400 | 1380 | 800 | 2150 |
| | | 0.08 Slope | | |
| 0.37 | 750 | 340 | 150 | 260 |
| 0.72 | 1680 | 710 | 600 | 810 |
| 1.83 | 3900 | 2100 | 1600 | - |
| 2.70 | 7250 | 4300 | 2450 | - |
| | | 0.165 Slope | | |
| 0.195 | 600 | 435 | 450 | 405 |
| 0.37 | 1840 | 1470 | 1130 | 1550 |
| 0.47 | 3100 | 2200 | 1780 | 2650 |
| 0.72 | 4500 | 4040 | 4300 | 4500 |

slower moving laminar flow. The 274 μ particles are sufficiently large to protrude through the laminar layer when they are on the bottom, so they are picked up more frequently by the faster moving turbulent layer. Consequently they move at a faster rate than the smaller diameter, lower mass, 137 μ particles.

The following empirical equation was developed from experimental data (References 5-9) for calculation of the maximum mass loading rate (MMLR) of irregular particles.

$$\text{MMIR} = S^{2.5}\, Q^{1.4} \left(5 \times 10^{7} \frac{1}{d + 5 \times D^{2}}\right)$$

where MMLR is Maximum Mass Loading Rate in grams/ft$^2$/min
S is slope of plane
Q is water flow rate in gpm/ft of width
D is diameter of particles in microns

## 4. CONCLUSIONS

Particles are transported on a horizontal ideal surface only when flow rate is sufficient to produce turbulent flow. Particles may be transported, however, by a film in laminar flow, at a lower water flow rate if the surface is given the slightest incline. Surface waves increase particle transport rate by inducing a pulsing action. These waves are produced at all slopes at certain water flow rates.

The velocities of particle transport by thin films can be computed from the empirical equation

$$U = AS^{a}D(Q^{b} - B) + C$$

where U = particle velocity in ft/sec
D = particle diameter in microns
Q = water flow rate in gpm/ft of width
S = sine of the slope angle

The maximum amount of particulate matter which can be transported under any set of conditions at any slope is much greater than would be expected from a nuclear detonation. This maximum mass loading can be computed from the empirical equation

$$\text{MMLR} = S^{2.5}\, Q^{1.4} \left(5 \times 10^{7} \frac{1}{D + 5 \times D^{2}}\right)$$

where MMLR = Maximum Mass Loading Rate in grams per square foot per minute.

At all slopes the gravity wave action becomes the biggest factor in the transport of particulate matter. As the slope increases, the water film thins out. The thinning out of the film resulted in an increase in the frequency of the waves.

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# APPENDIX A

## DETAILS OF TEST APPARATUS

### TEST PLANE

This glass (Fig. A.1) rests on a series of leveling screws which are spaced approximately 30 in. apart on a center line running lengthwise and lines 6 in. in from each side. The plane is leveled to within $\pm$ 0.010 in. with the aid of a transit and a water manometer. This water manometer consists of a bottle connected with flexible hose to a sight-gauge anchored to the plane support. The bottle is placed over the leveling points, and the height of the water is measured to the nearest 1/1000 in. with a point gauge in the sight-glass anchored to the plane supports. The water stilling basin shown in Fig. A.2 admits water to the lead end of the plane in a smooth uniform manner. This stilling basin consists of a series of rectangular compartments which extend to within approximately 2 in. of the bottom. Thus the water can be admitted to the plane only from the bottom of the tank. The rectangular partitions are designed so that they do not touch each other, thus eliminating the transmittal of disturbances from the incoming water and pump vibration. The water comes into the stilling basin from a distributor resting on sponge rubber on top of the tank.

Water flow rates are accurately maintained by an overflow system, which maintains a constant head, and a series of removable calibrated orifices. Figure A.2 diagrams the water system.

### WATER FILM DEPTH GAUGE

The depth of the water was measured with a capacity depth gauge, especially developed for this purpose. This instrument utilized the electrical capacity between a fixed metal plate and the water surface to sense the air gap and by difference gave a measure of the water depth to an accuracy of $\pm$ 0.003 in. The details of construction are described in Reference 10.

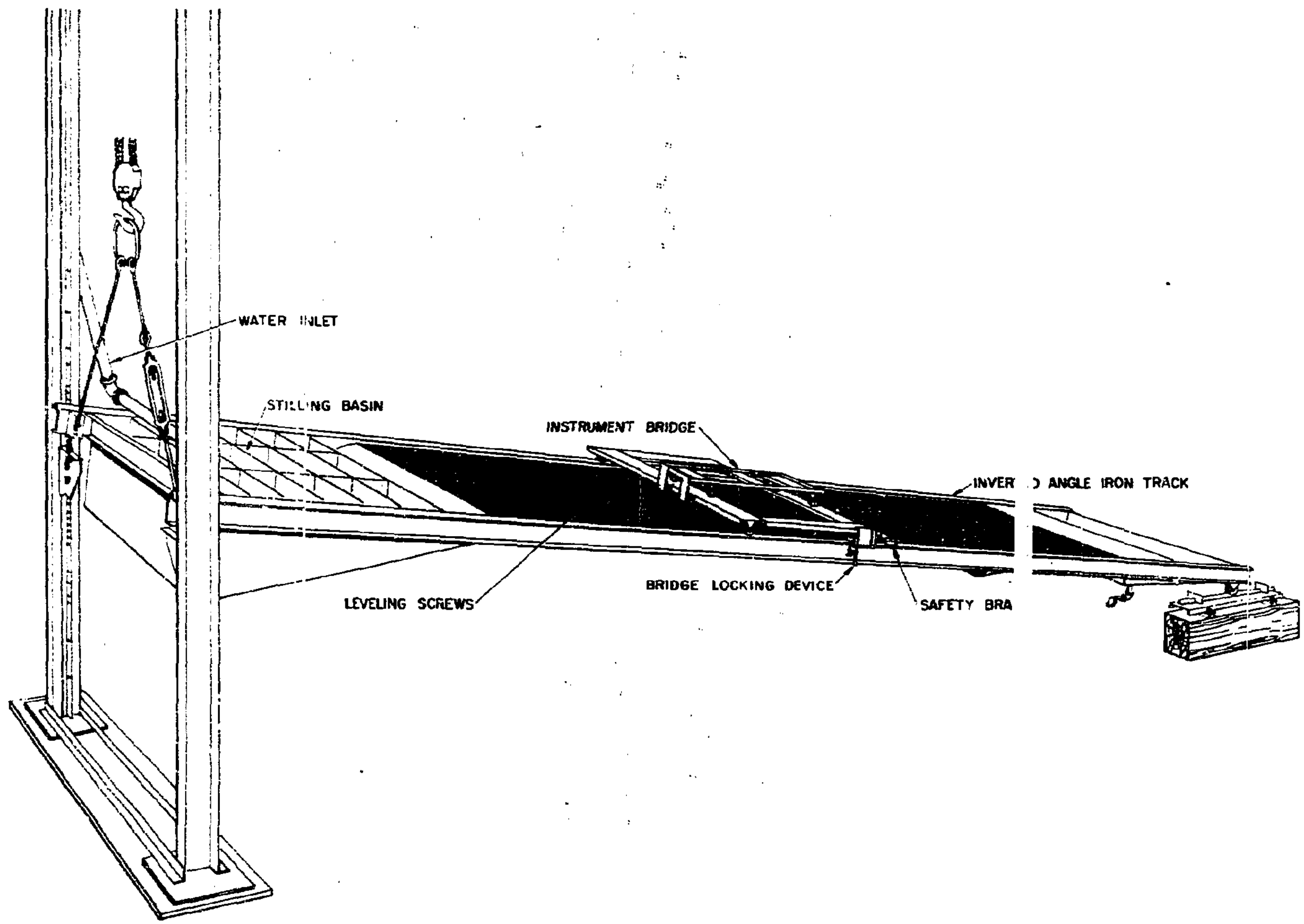



Fig. A.1 Diagram of Test Plane

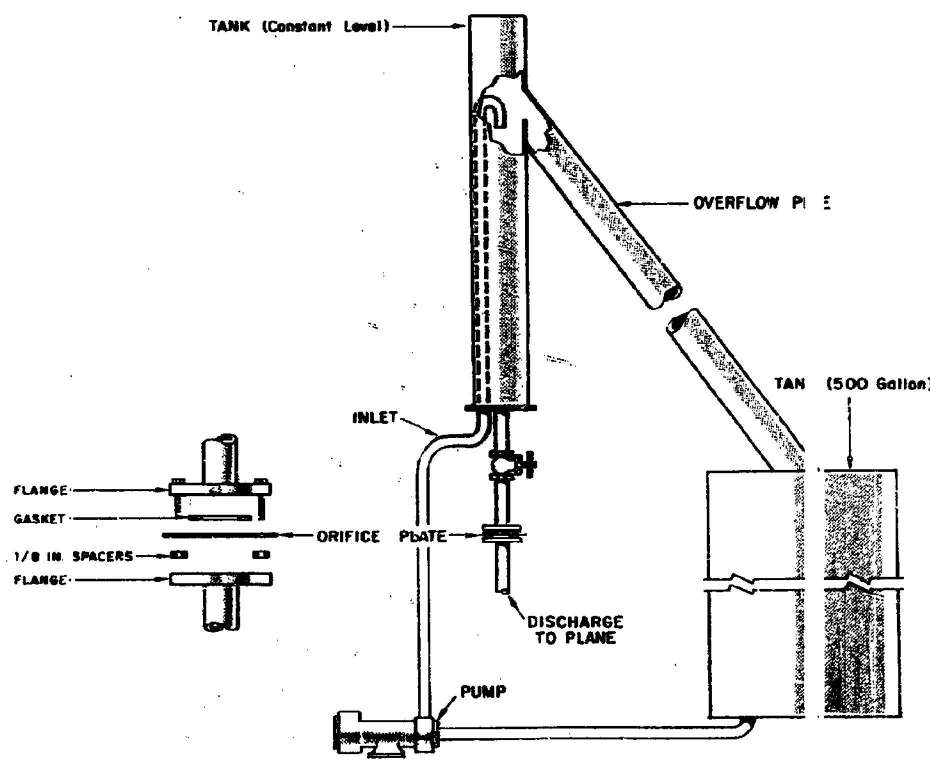



Fig. A.2 Diagram of Water System

HOT-WIRE ANEMOMETER

A hot-wire anemometer was designed to determine the water velocity at various depths. The apparatus consisted of a one-mil wire, 4 in. long, attached to a milling attachment graduated into thousandths of an inch. The wire was positioned horizontal and perpendicular to the water flow. A known current was applied to this wire which was one leg of a wheat-stone bridge. The hot wire was cooled by the water flowing over it and the heat loss was determined by balancing the bridge. The calculated heat loss was then calibrated to give the velocity of the fluid.

# APPENDIX B

## NOMOGRAPHS FOR DETERMINING PARTICLE TRANSPORT VELOCITIES

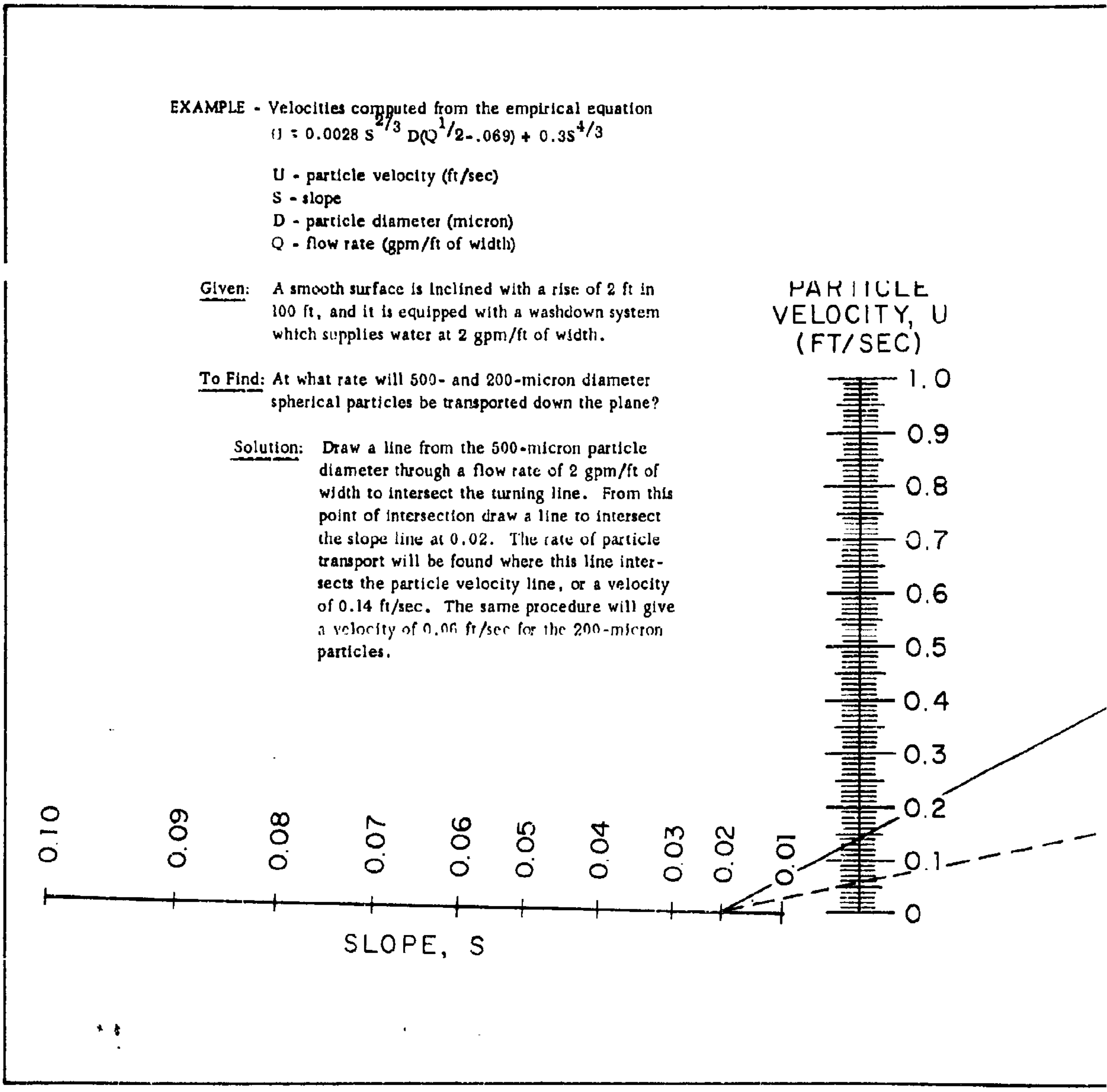
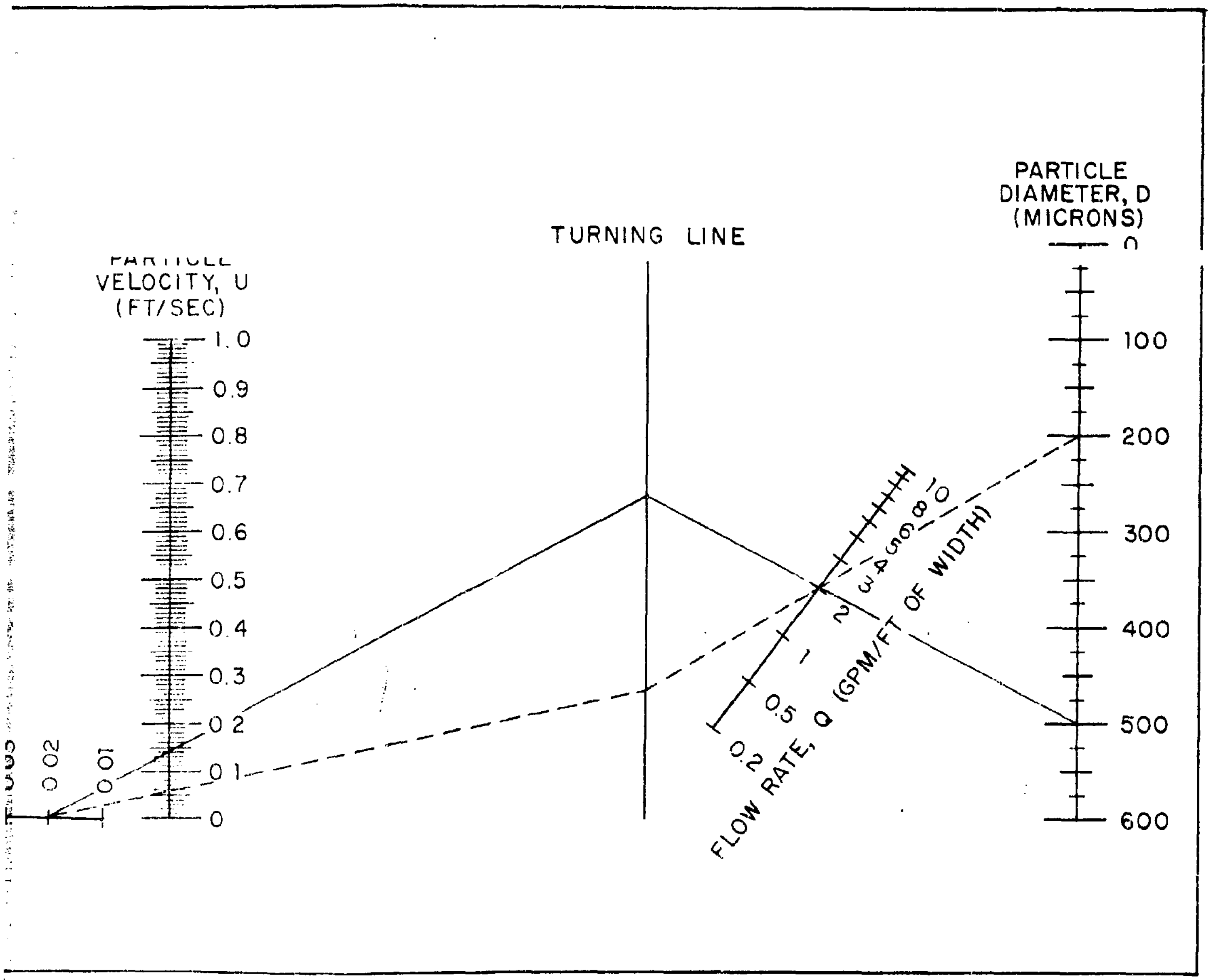



Fig. B.1 Nomograph for Finding Rate of Transport of Spherical Particle




of Transport of Spherical Particles on an Ideal Surface With a Moving Water Film

2

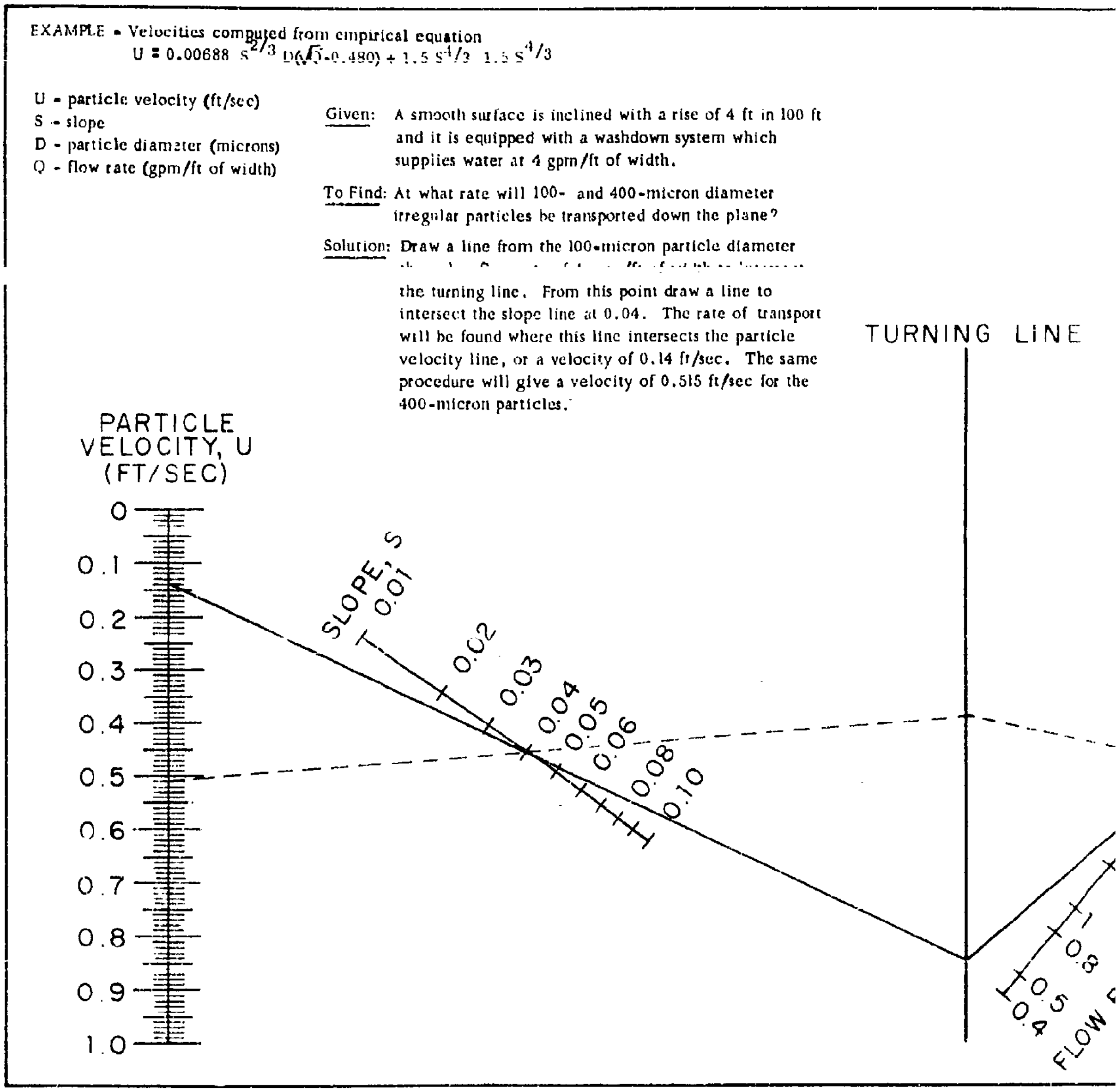
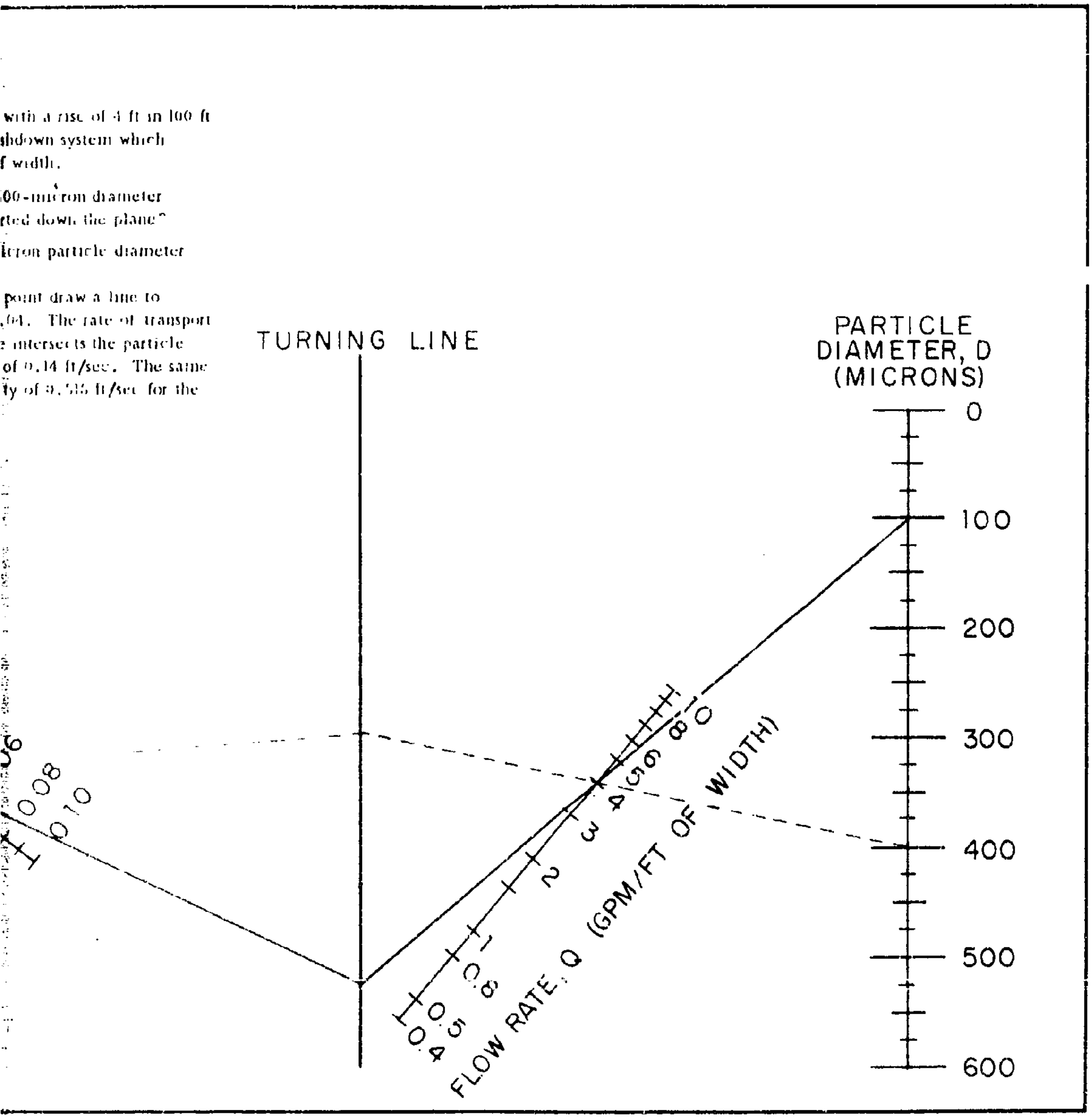



Fig. B.2 Nomograph for Finding Rate of Transport of Irregular Partic

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U. S. Naval Radiological Defense Laboratory
San Francisco, California 94135

**2a. REPORT SECURITY CLASSIFICATION**

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None

**3. REPORT TITLE**

DEVELOPMENT OF DESIGN CRITERIA FOR ROOF WASHDOWN SYSTEM: A STUDY OF THE RELATIONSHIP OF SLOPE TO PARTICLE TRANSPORT BY WATER FILMS

**4. DESCRIPTIVE NOTES** *(Type of report and inclusive dates)*

**5. AUTHOR(S)** *(Last name, first name, initial)*

Heiskell, Raymond H.
Crew, Robert J.
Vella, Noah J.

| 6. REPORT DATE | 7a. TOTAL NO. OF PAGES | 7b. NO. OF REFS |
|---|---|---|
| 25 May 1965 | 44 | 10 |

**8a. CONTRACT OR GRANT NO.** Contract CDM-SR-59-54

**b. PROJECT NO.** Subtask 1113A

**c.**

**d.**

**9a. ORIGINATOR'S REPORT NUMBER(S)**

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**13. ABSTRACT** This is the sixth report on a series of tests designed to study the basic principles involved in transport of particulate matter by water films. The previous reports covered the transport of particulate matter by various water flow rates on an ideal surface at one of five slopes from 0 to 0.165. This report covers the relationship of slope to transport on an ideal surface. On a near-horizontal surface, no transport occurs when the water flow rate is insufficient to produce turbulent flow. The slightest slope causes particles to be transported at low water flow rates in laminar flow. Surface waves, which are present at all slopes under most flow conditions, increase transport rate.

An empirical equation is presented for the computation of the transport velocities of both spherical and irregular shaped particles. The maximum amount of particulate matter that can be transported is presented.

| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
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| Water flow vs slope | | | | | | |
| Water waves | | | | | | |
| Particle transport by water | | | | | | |
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