This report describes an investigation to determine the uplift characteristics of M19 welded aluminum landing mat when it is subjected to the high-velocity exhaust blast of a jet engine. The investigation consisted of two phases. The first phase was a wind tunnel test of a half-scale section of the M19 mat panel which consisted of making pressure measurements on the upper and lower surfaces of the M19 landing mat model. The pressures were then integrated to (Continued)
20. ABSTRACT (Continued).

yield the uplift force and overturning moment acting on the model. This test
gave information on the effect of the landing mat connector and angle of attack
on the aerodynamic characteristics of the model. The second phase consisted of
subjecting a panel of M19 landing mat to the exhaust blast of a J-35 jet engine
and measuring the uplift forces on the panel created by the high-velocity blast
of J-35 jet engine exhaust. The uplift forces on the mat panel were measured
using bolts instrumented with strain gages which anchored the test panel to the
concrete surfaced test area. The results of these tests indicated that the
M19 landing mat panel, when subjected to high velocities, will have imposed on
it aerodynamic loads which will lift the mat panel from the ground. The mat
panels need to be anchored to the ground surface along edges of runways, taxi
strips, aprons, etc., where the mat may be subjected to engine blast exceeding
80 fps.
The investigation reported herein was conducted by personnel of the Soils and Pavements Laboratory, U. S. Army Engineer Waterways Experiment Station (WES), for the Directorate of Facilities Engineering (formerly Directorate of Military Engineering and Topography), Office, Chief of Engineers, Department of the Army, as part of "Air Line Communication Facilities," Research and Development Project 4Al62121AT31-02.

The study was accomplished during the period July 1972 through June 1973 under the general supervision of Messrs. J. P. Sale and A. H. Joseph, and under the immediate supervision of Mr. G. W. Leese, who prepared this report.

Directors of WES during the investigation and the preparation and publication of this report were BG E. D. Peixotto, CE, and COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.
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FIGURES 1-18

APPENDIX A: NOTATION
CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI)
UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

<table>
<thead>
<tr>
<th>Multiply</th>
<th>By</th>
<th>To Obtain</th>
</tr>
</thead>
<tbody>
<tr>
<td>inches</td>
<td>0.0254</td>
<td>meters</td>
</tr>
<tr>
<td>feet</td>
<td>0.3048</td>
<td>meters</td>
</tr>
<tr>
<td>square feet</td>
<td>0.09290304</td>
<td>square meters</td>
</tr>
<tr>
<td>pounds (mass)</td>
<td>0.4535924</td>
<td>kilograms</td>
</tr>
<tr>
<td>pounds (force) per foot</td>
<td>14.5939</td>
<td>newtons per meter</td>
</tr>
<tr>
<td>pounds (force) per square foot</td>
<td>47.88026</td>
<td>pascals</td>
</tr>
<tr>
<td>slugs per cubic foot</td>
<td>515.3788</td>
<td>kilograms per cubic meter</td>
</tr>
<tr>
<td>feet per second</td>
<td>0.3048</td>
<td>meters per second</td>
</tr>
<tr>
<td>foot-pounds</td>
<td>1.355818</td>
<td>newton-meters</td>
</tr>
<tr>
<td>Fahrenheit degrees</td>
<td>5/9</td>
<td>Celsius degrees or Kelvins*</td>
</tr>
</tbody>
</table>

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: \( C = \frac{5}{9}(F - 32) \). To obtain Kelvin (K) readings, use: \( K = \frac{5}{9}(F - 32) + 273.15 \).
PART I: INTRODUCTION

Background

1. Rapidly prepared runway surfaces in forward areas commonly involve prefabricated landing mat panels. The panels are placed on a prepared smooth subgrade and joined with built-in side and end connectors which interlock to provide a continuous surface. There are several types of landing mat panels in use which vary in size, shape, construction, and material. Landing mat panels are subjected to aerodynamic loads developed by the high-velocity blast from the propellers or engine exhaust of taking-off or taxiing aircraft. These aerodynamic forces on the landing mat very often reach magnitudes large enough to cause it to lift from the ground and move downstream in the aircraft blast.

Purpose and Scope

2. The purpose of the study reported herein was to determine the dynamically created uplift forces developed on the M19 landing mat when subjected to high-velocity blast. The objective was accomplished in two phases: (a) model tests conducted in a wind tunnel and (b) full-scale tests using actual M19 landing mat panels in the exhaust blast impingement area of a J-35 jet engine. These studies were conducted in the Surface Blast Effects Research Facility of the U. S. Army Engineer Waterways Experiment Station (WES).
PART II: WIND TUNNEL TESTS

Wind Tunnel Facility

3. The wind tunnel test facility is of the open-circuit type with a test section 18 by 18 in.* in cross section and 48 in. in length. A variable-speed hydraulic motor is used to drive a 4-ft-diam propeller, providing velocities up to 200 fps.

Model Landing Mat Tests

4. A half-scale model of a section of the M19 landing mat was made from 3/4-in. plywood. The model section (Figure 1) was 18 in. wide and 24 in. long. The width of the model was such that it would completely span the test section of the wind tunnel. A wood model of the mat connector was made from a separate piece, thus allowing easy removal and replacing of the connector model. The model connector approximated the shape of that on the actual mat panel.

5. Static pressure taps made of 1/16-in. brass tubing were embedded in the upper and lower surfaces of the model. Corresponding taps on the upper and lower surfaces of the model were located at equal distances from the leading edge so that the pressure difference between the upper and lower surfaces could be measured. A total of 24 taps were used, 12 on each surface. The pressure taps exited the model at the trailing edge and were connected to flexible tubing which ran outside the tunnel to an inclined manometer board.

6. The model was mounted in the wind tunnel on a ground board 8 in. above the bottom of the wind tunnel's test section. By doing this, the boundary layer along the wind tunnel floor was eliminated from the tests. (Figure 2 identifies the nomenclature of the model.)

7. Angle of attack was controlled by adjusting screws at the

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.
model’s leading edge. The trailing edge was fixed to the ground board by hinges. Rubber gaskets were used to completely seal the lower surface for the tests at 0-deg angle of attack, thereby preventing flow between the lower surface of the model and the ground board.

8. Three different configurations of the model panel were tested: (a) without the connector, (b) with the connector, and (c) with the connector inverted to simulate mat placement parameters. Figure 3 shows the model panel with the connector attached. Each configuration was tested at velocities ranging from 80 to 120 fps. Data were taken at angles of attack from 0 to about 8 deg.

Results and Analysis of Model Tests

9. The pressure distributions for the three model configurations tested at several different angles of attack are shown in Figures 4-6. Figure 7 shows the effect of the connector on the pressure distribution of the model at 0-deg angle of attack.

10. The section lift coefficients for the three model configurations tested were obtained by integrating the pressure distribution in Figures 4-6 for each angle of attack as follows.* For a two-dimensional section, the lift per unit length can be written

$$L' = - \int_{0}^{C} (P_\mu - P_\lambda) \, dx$$

The subscripts \( \mu \) and \( \lambda \) refer to the upper and lower surfaces, respectively. By defining the pressure coefficient as

$$C_p = \frac{P - P_0}{\frac{1}{2} \rho v_0^2}$$

* For convenience, a Notation defining all symbols found in this report is given in Appendix A.
and the section lift coefficient as

\[ C_\lambda = \frac{L'}{\frac{1}{2} \rho V_0^2 c} \quad (3) \]

Equation 1 can be rewritten in nondimensional form as

\[ C_\lambda = -\int_0^1 \Delta C_p \ d \left( \frac{x}{c} \right) \quad (4) \]

where

\[ C_p = C_\lambda - C_\lambda \]

11. The section moment coefficient about the trailing edge was obtained by determining the center of pressure of each pressure distribution by the area moment method and then using Equation 7 below. The section pitching moment coefficient is defined as

\[ C_M = \frac{M'}{\frac{1}{2} \rho V_0^2 c^2} \quad (5) \]

where \( M' \) is the moment per unit span. The moment about the trailing edge can be written in terms of lift as

\[ M' = L' \overline{x} \quad (6) \]

where \( \overline{x} \) is the distance from the trailing edge to the center of pressure. In nondimensionalized form, Equation 5 can be written

\[ C_{M_{TE}} = C_\lambda \frac{\overline{x}}{c} \quad (7) \]

12. Consequently, both the section lift and pitching moments can be determined from the pressure distribution. The section lift and moment coefficients versus angles of attack are shown in Figure 8.

13. The data taken from the model tests can be extrapolated to
the full-scale landing mat by Equations 3 and 5. Since the lift and moment coefficients are nondimensional, the lift in pounds and moment in foot-pounds for the full-scale mat can be obtained as follows:

\[ L = \frac{1}{2} C_L \rho V_o^2 cb \]  

(8)

\[ M = \frac{1}{2} C_M \rho V_o^2 c^2 b \]  

(9)

It should be noted here that two-dimensional data from the model are being used to predict the three-dimensional characteristics of the full-scale landing mat. Consequently, there is an inherent error involved in the calculations. This error is expected to be small for the 0-deg angle of attack and is expected to become greater with increasing angle of attack. The lift in pounds and pitching moment in foot-pounds for the full-scale mat panel derived from Equations 8 and 9 are shown versus velocity in Figure 9. The points marked critical on these curves are the lift and moment needed to pick up and/or pitch up, respectively. These points are based on a mat weight of 4 psf. From this figure, it can be seen that the pitch up of the mat will occur at a lower blast velocity than that associated with lift-off. Consequently, the mat panel will begin to rotate its leading edge up before it lifts off. Once the leading edge of the mat has moved off the ground, the mat then attains an angle of attack for which the lift is sufficient to pick it up vertically. Once this occurs, areas of mat can be floated on a cushion of air created by the blast.
PART III: FULL-SCALE BLAST TESTS

Jet Engine Test Facility

14. The full-scale mat panel tests were conducted at the jet engine blast test facility of the WES. This facility is designed to accept a wide variety of jet engines. When mounted in the facility, the engines can be raised to heights of 20 ft from the ground plane, and the engine can be positioned at any angle between the horizontal and vertical. For this study, a J-35 turbojet engine was mounted in the facility with the engine center line placed 4 ft above the ground plane and positioned with a 2-deg tail-down tilt. Figure 10 is a general view of the test facility.

M19 Landing Mat Panel

15. The aluminum sandwich-type M19 landing mat panel used in this study consisted of a honeycomb core of aluminum foil bonded to top and bottom aluminum sheets with a fiber-film epoxy adhesive. Edge connecting members are welded to the top and bottom sheets and bonded to the core with a potting compound. The core is formed from 5096-H19 aluminum alloy foil. The foil is 0.0027 in. thick and is formed into 1/8-in. hexagons. All surface pieces of the panels are formed from 6061-T6 aluminum alloy. A composite view of a full panel is shown in Figure 11. Physical dimensions of the full landing mat panel and its weight are 50.1 in. in length, 49.5 in. in width, 1.5 in. in depth, and 68.0 lb in weight. It is classed as a medium-duty landing mat.

Blast Test Area

16. The M19 landing mat panel used in the full-scale tests was mounted on four studs located at the four corners of the mat. These studs were made of 6061-T6 aluminum and were instrumented with strain gages such that the load on the panel could be measured (see Figure 12).
The instrumented bolts were anchored into the concrete surface of the test area, and the mat panel was positioned on them slightly off the concrete surface of the test area so that compression or tensile aerodynamic loads could be measured. The rear connector of the instrumented test panel rested against mat panels which were anchored to the concrete, thereby preventing horizontal loading of the instrumented studs. The outputs of the instrumented studs were fed through amplifiers and recorded using a multichannel oscillograph. Each instrumented stud bolt was calibrated prior to the test. Figure 13 shows a general view of the jet engine blast test area. The test panel was positioned 40 ft from the jet engine exhaust exit which insured that the test panel would be completely immersed in the exhaust blast.

Full-Scale Mat Panel Tests and Results

17. Aerodynamic data were collected with the mat panel at angles of attack of 0.33, 0.55, 1.65, and 3.12 deg. Mounting restraints did not allow for a test to be conducted at exactly 0-deg angle of attack. Blast velocities ranged from about 60 to 345 fps over the mat panel.

18. The aerodynamic lift and moments on the mat panel were measured by the instrumented stud bolts. The total lift was taken to be the sum of the measurements indicated by the four stud bolts. The moment about the trailing edge was taken to be simply the sum of the products of the load in each bolt multiplied by the respective distance to the trailing edge of the mat panel. The measured lift and moment on the mat at each angle of attack are plotted versus velocity in Figures 14-17. The points marked critical on these plots represent the lift and moment needed to pick up and pitch up the mat panel, respectively.

19. Since velocities over the mat panel were measured by a pilot-static probe, it was necessary to correct the reading because of temperature effects. The temperature at the mat panel was measured to be 200°F for all power settings of the engine. Assuming that the flow at the mat consists entirely of air, the air density at that point can be
calculated from the ideal gas equation to be 0.00188 slug per cu ft. Hence, the air speed was corrected by

\[ V_{\text{TRUE}} = \sqrt{\frac{\rho}{\rho_o}} V_{\text{ind}} \]  \hspace{1cm} (11)

where

- \( V_{\text{TRUE}} \) = true air speed
- \( V_{\text{ind}} \) = indicated air speed
- \( \rho_o = 0.0024 \) slug per cu ft or the standard day density of air

The velocities in Figures 14-17 are true rather than indicated velocities.

20. In order to nondimensionalize the data, the measured values of lift and moments for each angle of attack were reduced to lift and moment coefficients where the lift coefficient is

\[ C_L = \frac{L}{\frac{1}{2} \rho V_o^2 S} \]  \hspace{1cm} (12)

and the pitching moment coefficient about the trailing edge is

\[ C_{M_{\text{TE}}} = \frac{M}{\frac{1}{2} \rho V_o^2 S c} \]  \hspace{1cm} (13)

Figure 18 shows the lift and pitching moment coefficients versus angle of attack.
PART IV: CONCLUSIONS

21. The results of this study demonstrated that an M19 landing mat panel, when subjected to the exhaust blast of a jet engine, will have imposed on it aerodynamic loads which will lift the mat from the ground. Summarized below are data that were taken for the velocities needed at the mat panel to cause it to lift up at various angles of attack.

<table>
<thead>
<tr>
<th>Angle of Attack (deg)</th>
<th>Uplift Velocity (fps)</th>
</tr>
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<tbody>
<tr>
<td>0.33</td>
<td>97</td>
</tr>
<tr>
<td>0.55</td>
<td>95</td>
</tr>
<tr>
<td>1.65</td>
<td>86</td>
</tr>
<tr>
<td>3.12</td>
<td>80</td>
</tr>
</tbody>
</table>

22. The results of the study indicate the need for the mat panels to be anchored to the ground along the edges of taxiways, runways, and aprons where the mat may be subjected to blast velocities from aircraft that exceed 80 fps. Care should be taken to place the mat as flush with the ground surface as possible.

23. Airfield layout will dictate those areas where mat anchorage is necessary; thus, no blanket statement can be made as to what percentage of mat anchorage will be required for an airfield.
Figure 1. Half-scale model, M19 landing mat without connectors
Figure 2. M19 model mat nomenclature

Figure 3. Half-scale model M19 landing mat with connector
Figure 4. Effect of angle of attack on pressure distribution of M19 landing mat with connector inverted
Figure 5. Effect of angle of attack on pressure distribution of M19 landing mat with connector
Figure 6. Effect of angle of attack on pressure distribution of M19 landing mat without connector
Figure 7. Effect of connector at leading edge of M19 landing mat on pressure distribution at 0-deg angle of attack
Figure 8. Lift and pitching moment coefficients versus angle of attack
Figure 9. Lift and moment characteristics of M19 landing mat at 0-deg angle of attack
Figure 10. Blast test facility
Figure 11. Airplane landing mat, aluminum, sandwich type, M19
Figure 12. Instrumented anchor stud

Figure 13. Blast test area
Figure 14. Full-scale lift and moment on
M19 landing mat, $\alpha = 0.33$
Figure 15. Full-scale lift and moment on M19 landing mat, $\alpha = 0.55$
Figure 16. Full-scale lift and moment on M19 landing mat, $\alpha = 1.65$
Figure 17. Full-scale lift and moment on M19 landing mat, $\alpha = 3.12$
Figure 18. Full-scale lift and pitching moment coefficients versus angle of attack
APPENDIX A: NOTATION

b  
Span, ft

c  
Distance from leading edge to trailing edge, ft

$C_L$  
Three-dimensional lift coefficient (nondimensional)

$C_M$  
Two-dimensional (section) pitching moment coefficient about the trailing edge (nondimensional)

$C_{M_{TE}}$  
Three-dimensional pitching moment coefficient about trailing edge (nondimensional)

$C_P$  
Pressure coefficient (nondimensional)

$C_{\lambda}$  
Two-dimensional (section) lift coefficient (nondimensional)

L  
Lift force, lb

$L'$  
Lift force per unit span, lb/ft

M  
Moment, ft-lb

$M_{TE}$  
Moment about trailing edge, ft-lb

$M'$  
Moment per unit span, ft-lb/ft

$M'_{TE}$  
Moment about trailing edge per unit span, ft-lb/ft

P  
Static pressure, lb/ft$^2$

$P_o$  
Static pressure in free stream, lb/ft$^2$

S  
Lifting surface, ft$^2$

$V_{ind}$  
Indicated air speed, fps

$V_o$  
Free stream velocity, fps

$V_{TRUE}$  
True air speed, fps.

x  
Distance from trailing edge to center of pressure, ft

$\alpha$  
Angle of attack, deg

$\Delta C_p$  
Change in pressure coefficient between upper and lower surfaces (nondimensional)

$\rho$  
Free stream air density (0.0024 lb-sec$^2$/ft$^4$).