FEDERAL AVIATION AGENCY

AND

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

JOINT TECHNICAL CONFERENCE

ON

SLUSH DRAG AND BRAKING PROBLEMS

A COPY OF

THE SLIDES TO BE PRESENTED

December 19-20, 1961

Departmental Auditorium
Washington, D. C.

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FAA-NASA JOINT TECHNICAL CONFERENCE

ON SLUSH DRAG AND BRAKING PROBLEMS

December 19-20, 1961

PROGRAM

December 19, 1961

CONFERENCE OPENING - JOSEPH D. BLATT
Director, Aviation Research and Development Service - FAA

A. SLUSH DRAG

Session Chairman - Harold D. Hoekstra

1. Introduction to the Slush Problem - Isaac H. Hoover

2. Experimental Techniques

   Part I - Instrumentation and Procedures -
   Charles M. Middlesworth, John F. Marcy, and
   Daniel E. Sommers

   Part II - Test Area Preparation - Don W. Conley

3. Effect of Slush on Aircraft Drag and Wheel Rotations -
   Eugene P. Klueg

4. Slush Spray Patterns and Slush Damage - Wayne D. Howell
   and Daniel E. Sommers

5. Prediction of Slush Drag on Aircraft Performance -
   Walter B. Horne and Trafford J. W. Leland

6. Operational Methods for Slush Measurements -
   Richard H. Sawyer and B. C. Riddle, Jr.

7. Operations in Slush as Seen by the Pilot - C. E. Richards

8. Summary - Upshur T. Joyner and Isaac H. Hoover

December 20, 1961

B. BRAKING PROBLEMS

Session Chairman - Philip Donely

9. Introduction to the Braking Problem - Upshur T. Joyner and Nicholas S. Dobi

10. Braking Test Program and Results - Jack J. Shrager

11. Correlations of Braking on Slippery Surfaces - Walter B. Horne and Trafford J. W. Leland

12. Operational Methods for Determining Braking Conditions - Richard H. Sawyer

13. Summary - Charles M. Middlesworth and Upshur T. Joyner

C. GENERAL DISCUSSION

Session Chairman - Harold D. Hoekstra

(Exchange of views on significance of Conference results)

HAZARDS OF OPERATIONS IN SLUSH

1. POOR BRAKING
2. DRAG (DISPLACEMENT AND IMPINGEMENT)
3. DAMAGE TO SYSTEMS AND STRUCTURE FROM IMPINGEMENT
4. ENGINE INGESTION (POWER LOSS AND DAMAGE)
5. FREEZING SLUSH, JAMMING AND DAMAGING MECHANICAL UNITS
6. CONTROL PROBLEMS

Figure 1

SPECIFIC GOALS OF SLUSH DRAG PROGRAM

1. MEASURE SLUSH DRAG
2. IDENTIFY INCIPIENT DAMAGE BOUNDARY
3. STUDY SLUSH SPRAY PATTERNS
4. STUDY HYDROPLANING CHARACTERISTICS

Figure 2

TYPES OF TESTS

1.- DECELERATION
   - A. DRY RUNWAY
   - B. SLUSH - COVERED RUNWAY
   - C. SLUSH BED WITH NOSE WHEEL PATH CLEARED

2.- ACCELERATION AND TAKE-OFF

Figure 1

TEST AIRPLANE TAKE-OFF CONFIGURATION

MAX. GROSS WEIGHT = 193,000 LB; V_R = 145 KNOTS

TEST WEIGHT = 150,000 LB; V_R = 124 KNOTS

4 G.E. 805-3B ENGINES; MAX THRUST (TOTAL) 46,600 LB
THRUST AT IDLE (TOTAL) 1600 LB

AIRCRAFT WEIGHT ON NOSE GEAR, 76%

TIRES:	NO.	SIZE, IN.	PRESSURE (PSI)
MAIN	8	39 x 13	130 - 150
NOSE	2	29 x 7.7	110 - 125

Figure 2

LOCATION OF TEST OPERATIONS AND INSTRUMENTATION

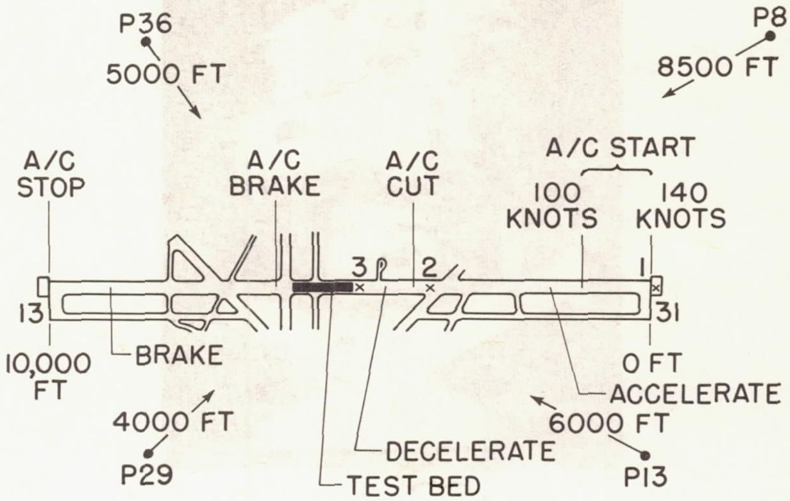


Figure 3

BASIC MEASUREMENTS AND INSTRUMENTS

MEASUREMENT	INSTRUMENTS
1. AIRPLANE GROUND SPEED	a) PHOTOTHEODOLITES b) TAPE SWITCHES c) SPN-12 DOPPLER RADAR d) AIR SPEED INDICATOR
2. AIRPLANE ACCELERATION	a) ACCELEROMETER b) PHOTOTHEODOLITES c) TAPE SWITCHES
3. WHEEL ROTATION	a) WHEEL ROTATION RECORDER
4. TIME	a) CENTRAL TIMING SYSTEM
5. SLUSH SPRAY PATTERN	a) CAMERAS
6. SLUSH DEPTH AND DENSITY	a) SPECIAL SAMPLING SCOOP, SCALES, AND RULER

Figure 4

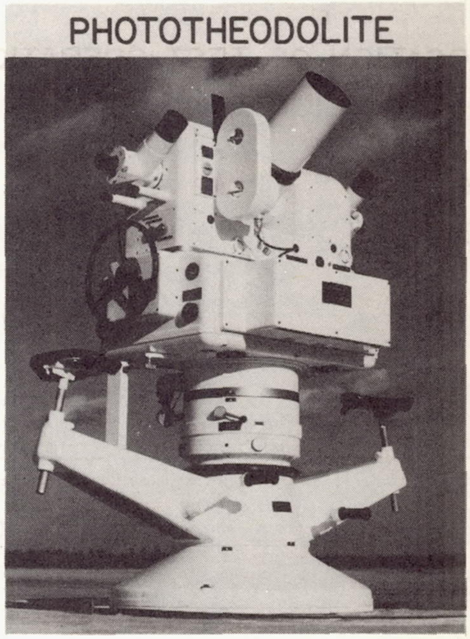


Figure 5

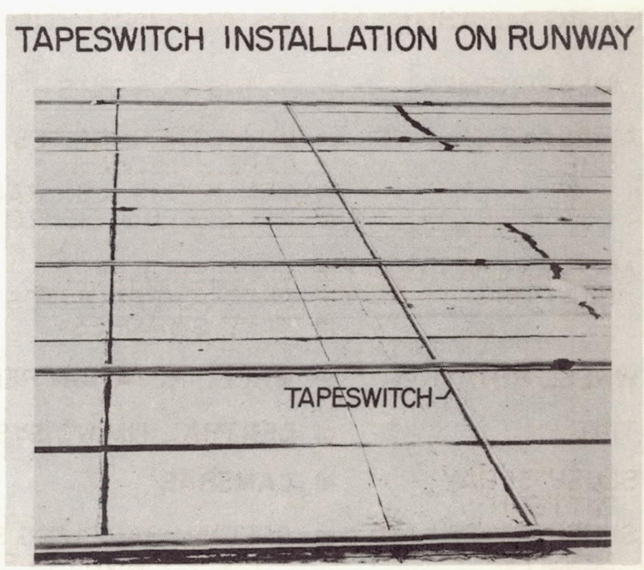


Figure 6

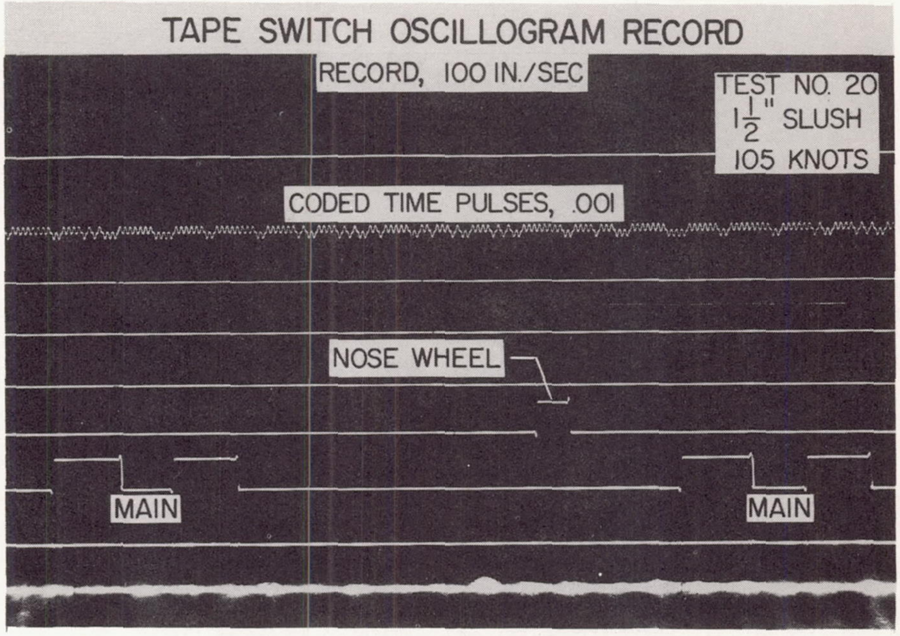


Figure 7

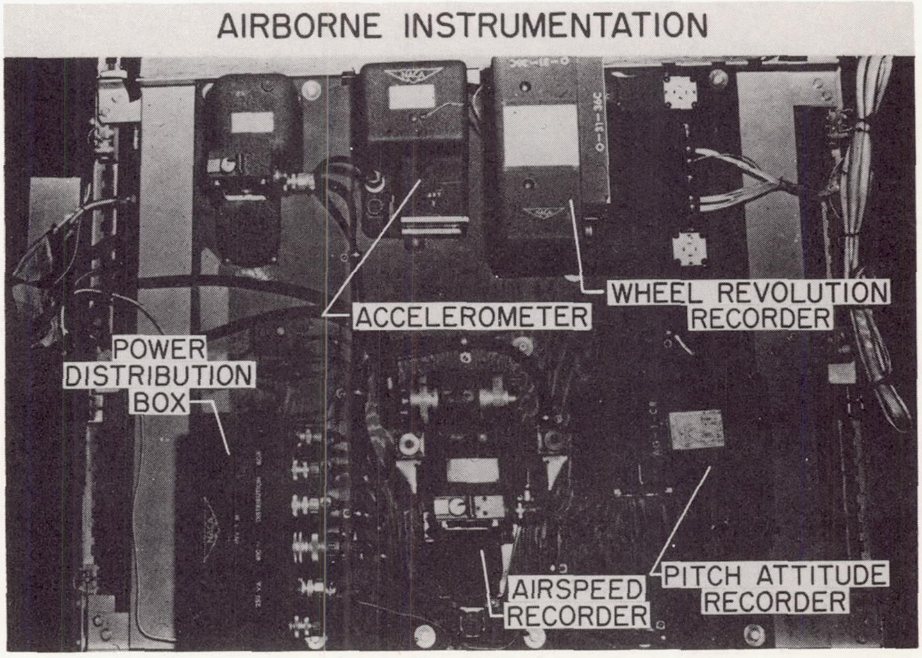


Figure 8

ATTITUDE AND ACCELEROMETER RECORDS

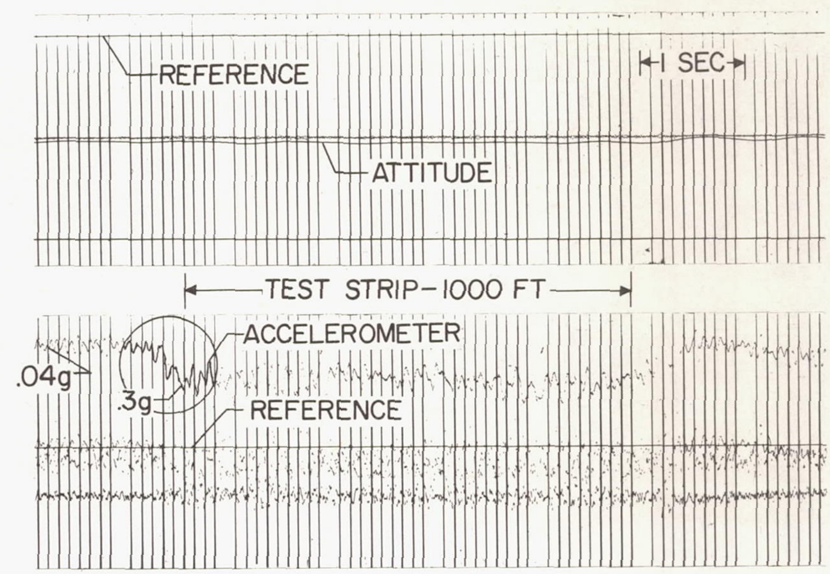


Figure 9

WHEEL ROTATION RECORD

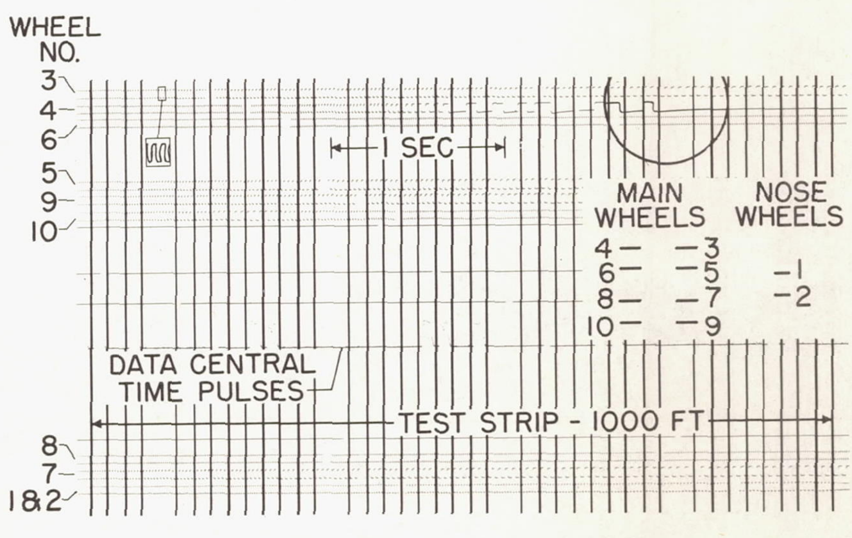


Figure 10

ins 19, 20

CAMERA LOCATIONS ON GROUND

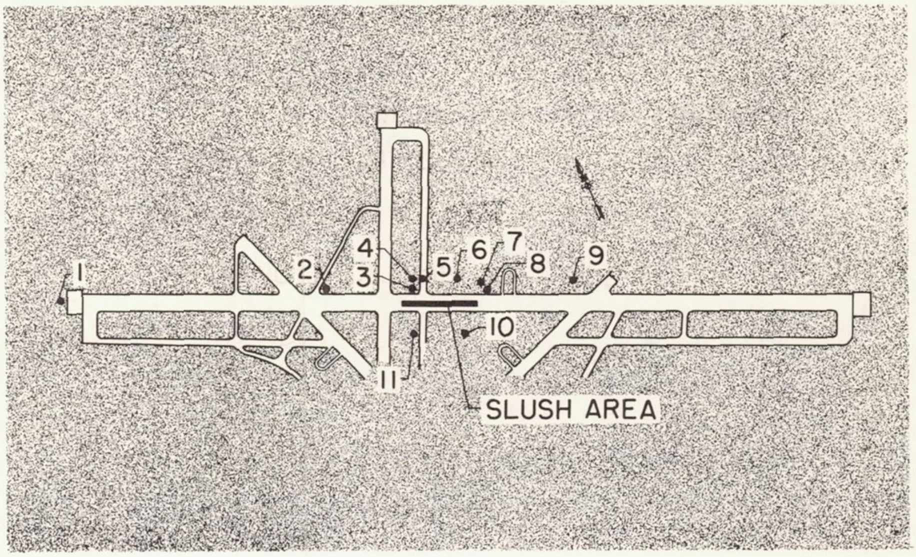


Figure 11

CAMERA LOCATIONS ON AIRCRAFT

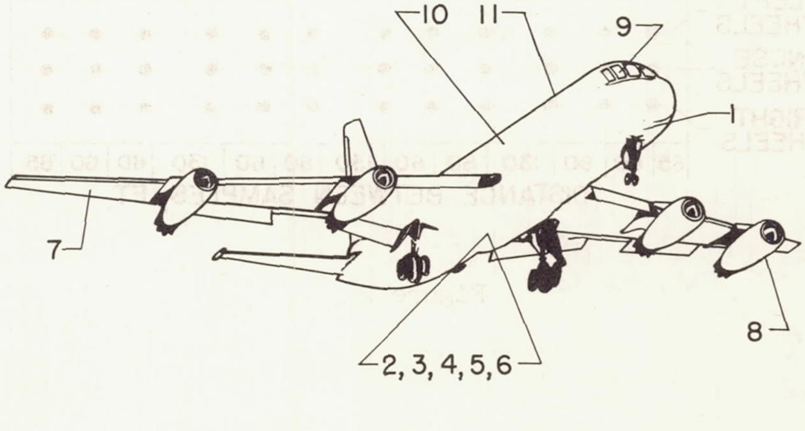


Figure 12

2(b)

PHYSICAL PROPERTIES OF FRESH SNOW-ICE

1. SPECIFIC WEIGHT 37 LB/FT^3

2. PARTICLE SIZE (% BY WEIGHT)

   85 % LESS THAN .25 IN. DIAMETER

   12 % BETWEEN .25 IN. AND .50 IN. DIAMETER

   3 % GREATER THAN .50 IN. DIAMETER

Figure 1

DENSITY - SAMPLE LOCATIONS

TEST BED, 50 FT BY 1,000 FT

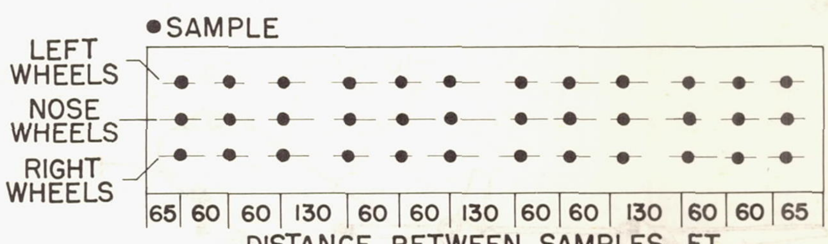


Figure 2

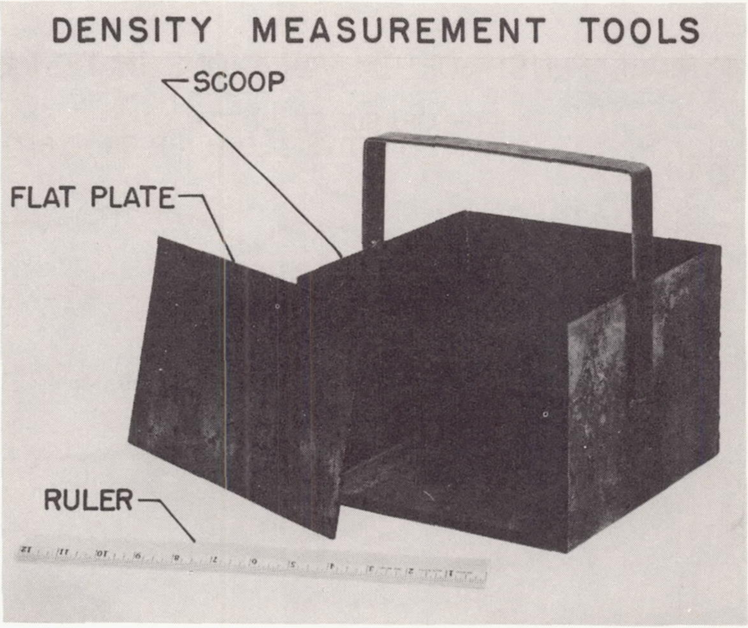


Figure 3

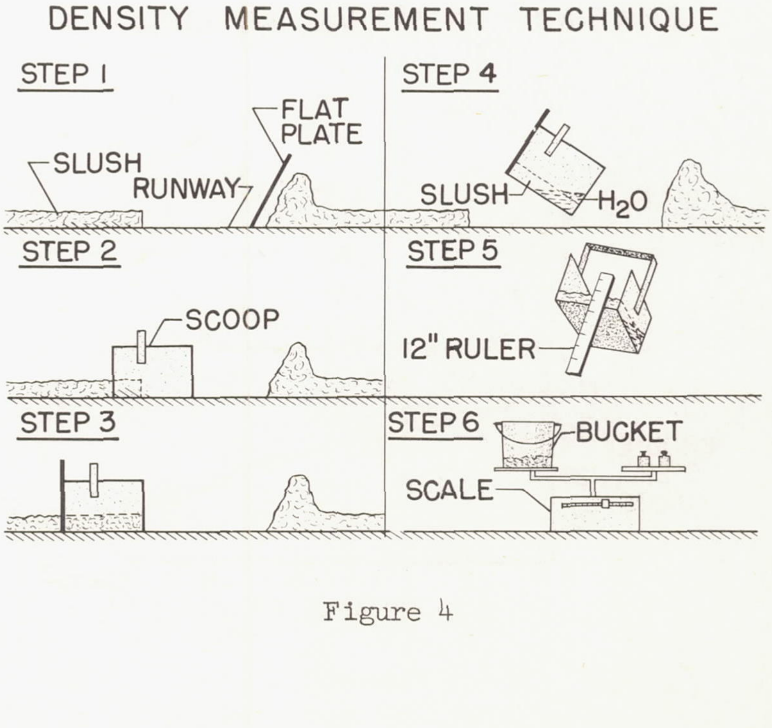


Figure 4

3

TYPICAL SLUSH-DEPTH VARIATIONS IN TEST BED

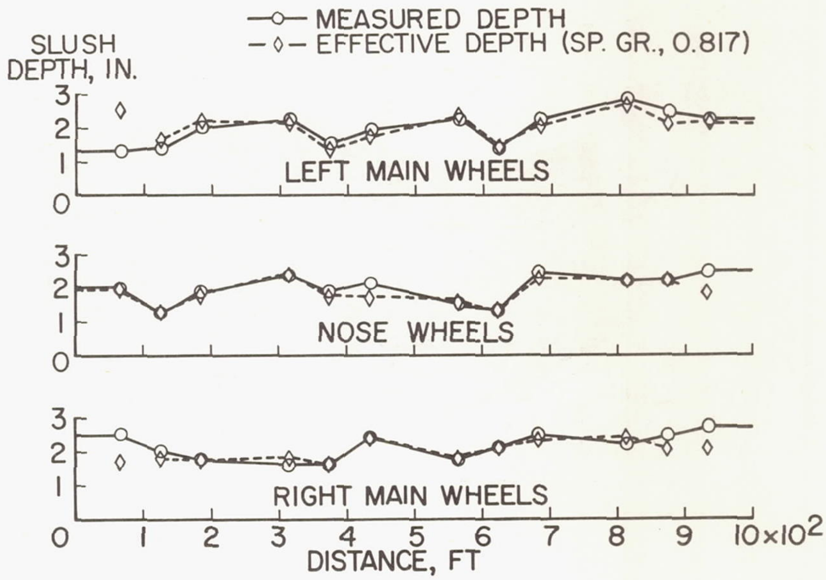


Figure 1

TYPICAL DECELERATION DATA

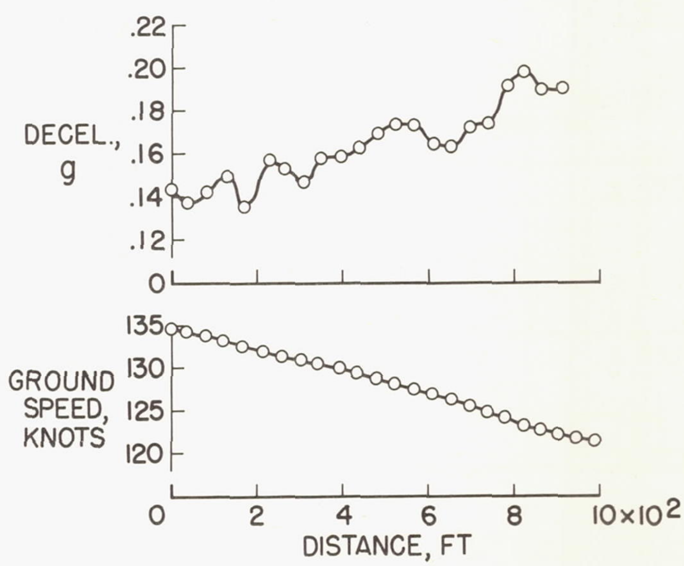


Figure 2

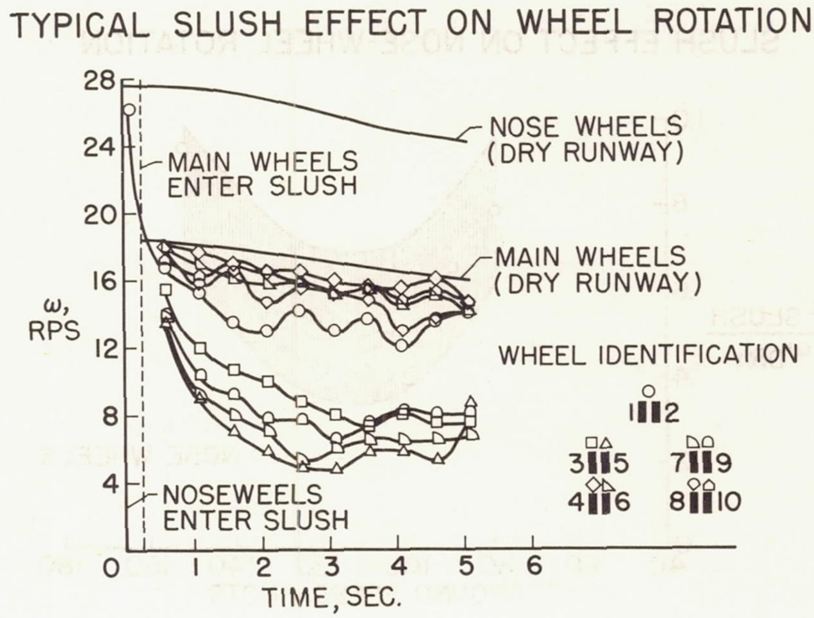


Figure 3

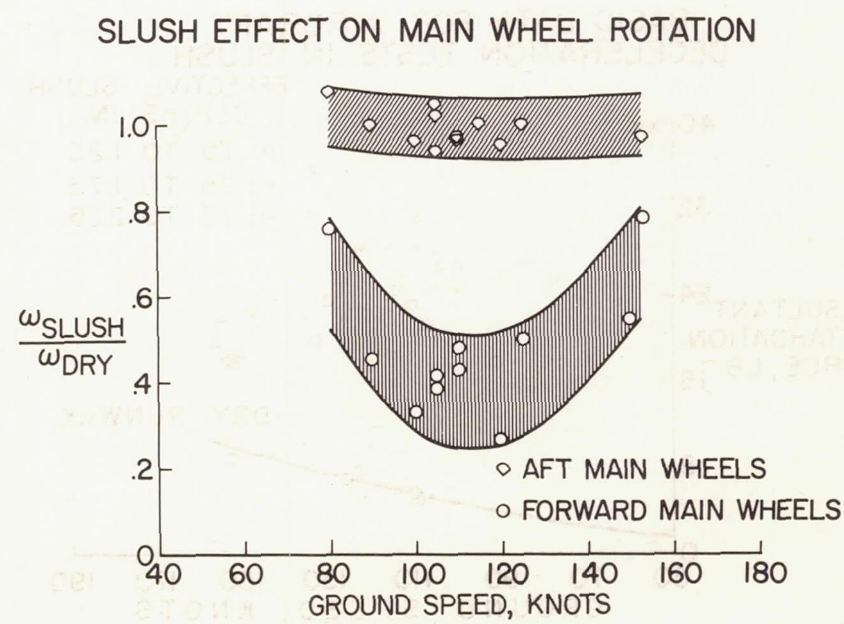


Figure 4

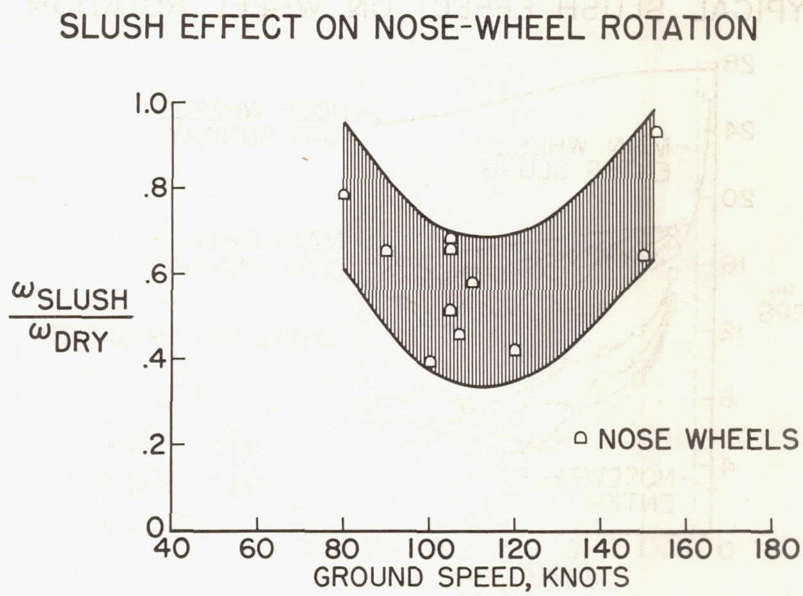


Figure 5

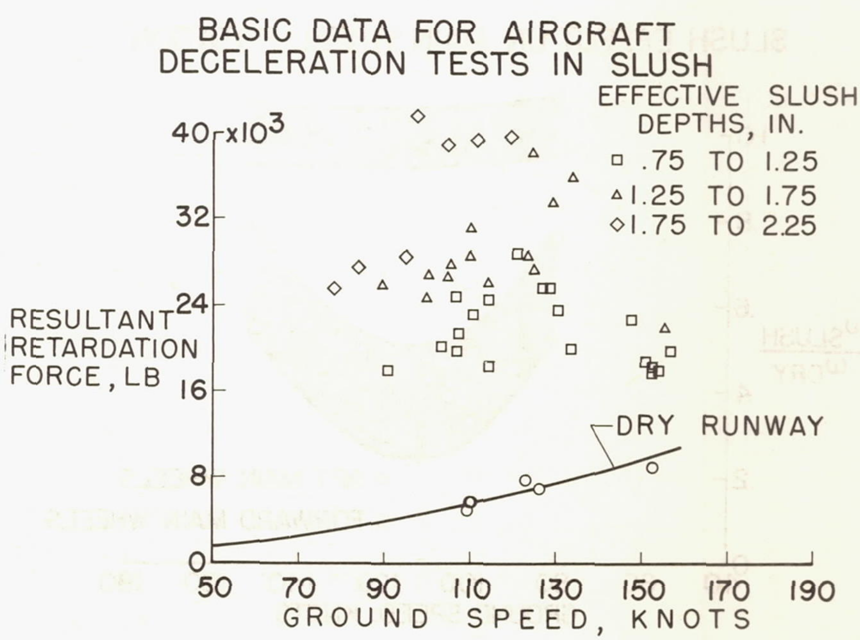


Figure 6

AIRCRAFT RETARDATION DUE TO SLUSH

$D_S \approx \rho d V^2$, $V < 110$ KNOTS

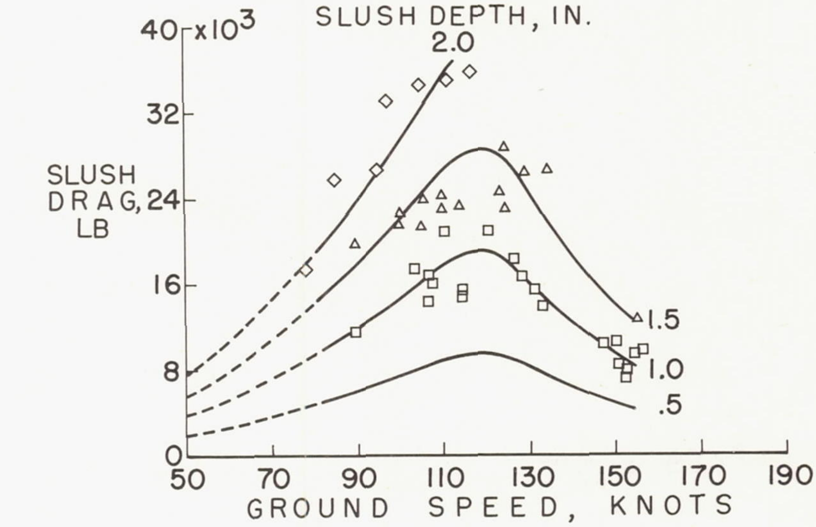


Figure 7

EFFECT OF SLUSH ON TAKE-OFF ACCELERATION OF AIRCRAFT

SPECIFIC GRAVITY, 0.817

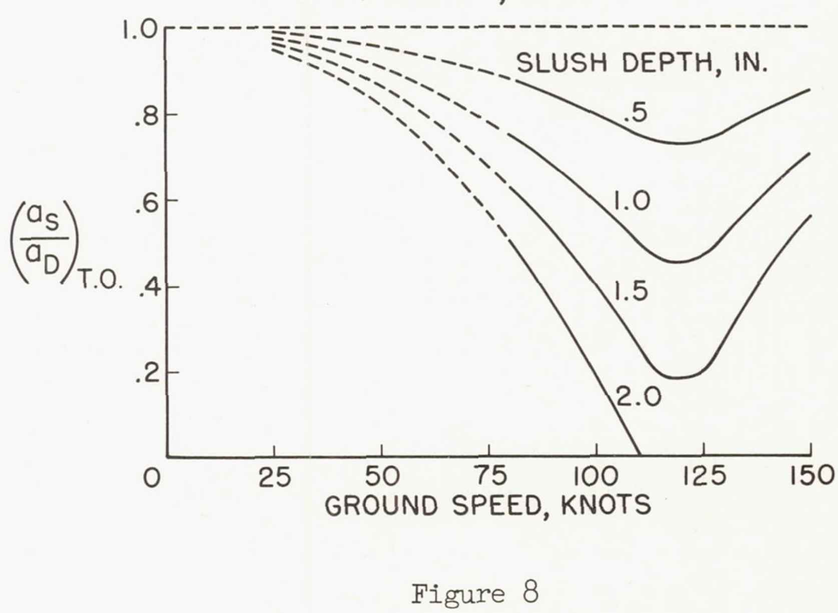


Figure 8

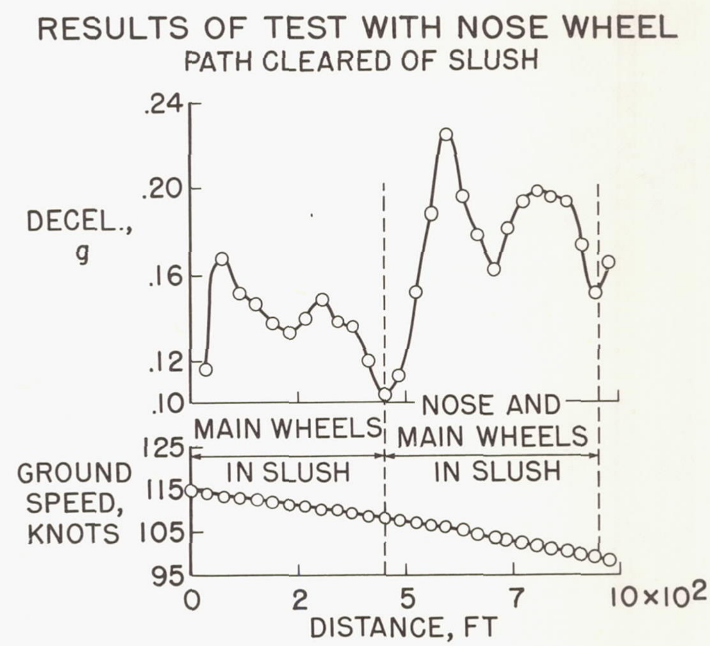

RESULTS OF TEST WITH NOSE WHEEL
PATH CLEARED OF SLUSH
DECEL., g
.24
.20
.16
.12
.10
MAIN WHEELS IN SLUSH
NOSE AND MAIN WHEELS IN SLUSH
GROUND SPEED, KNOTS
125
115
105
95
0
2
5
7
10×10^2
DISTANCE, FT

Figure 9

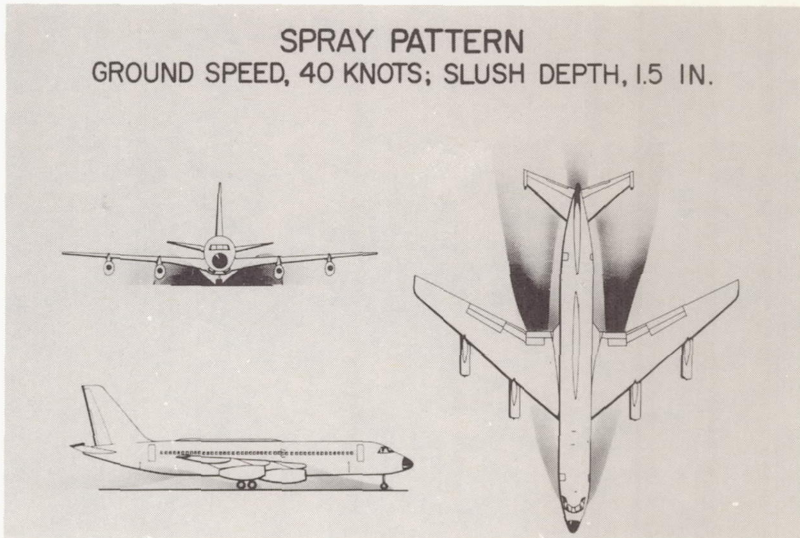


Figure 1

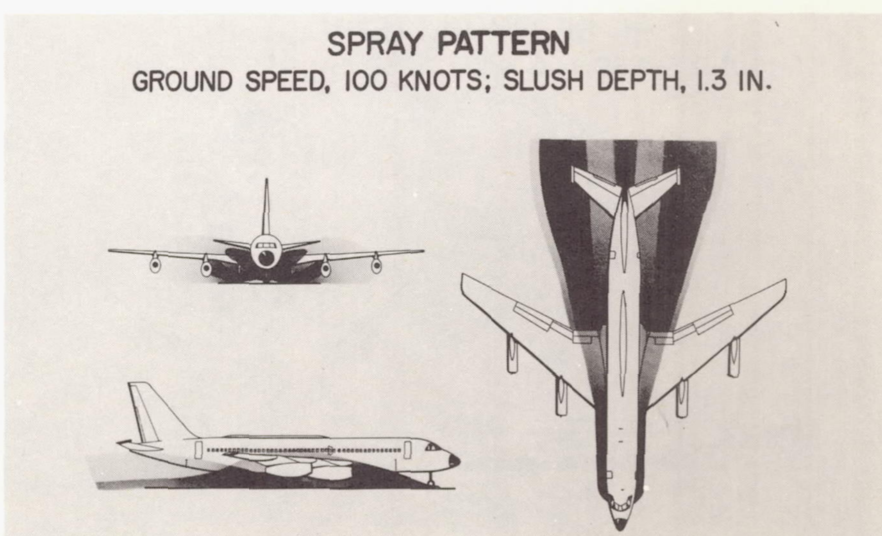


Figure 2

4

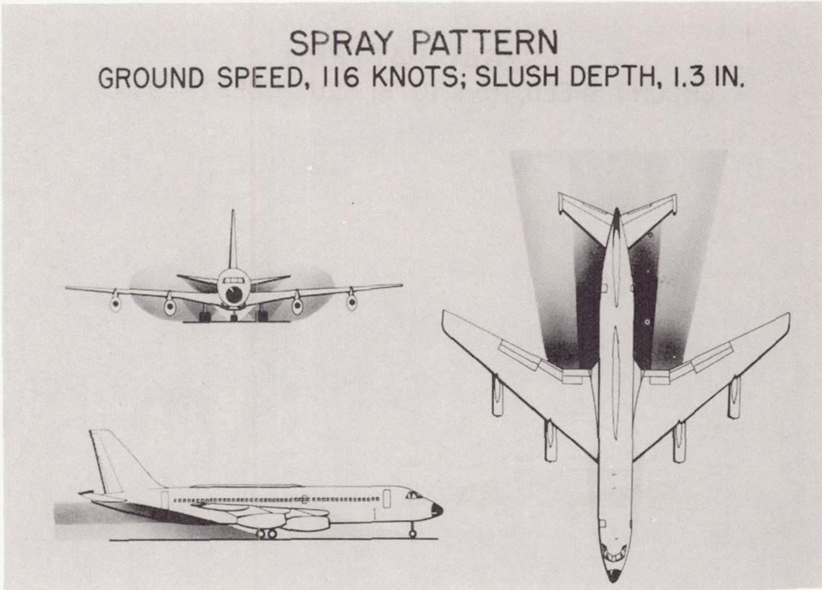


Figure 3

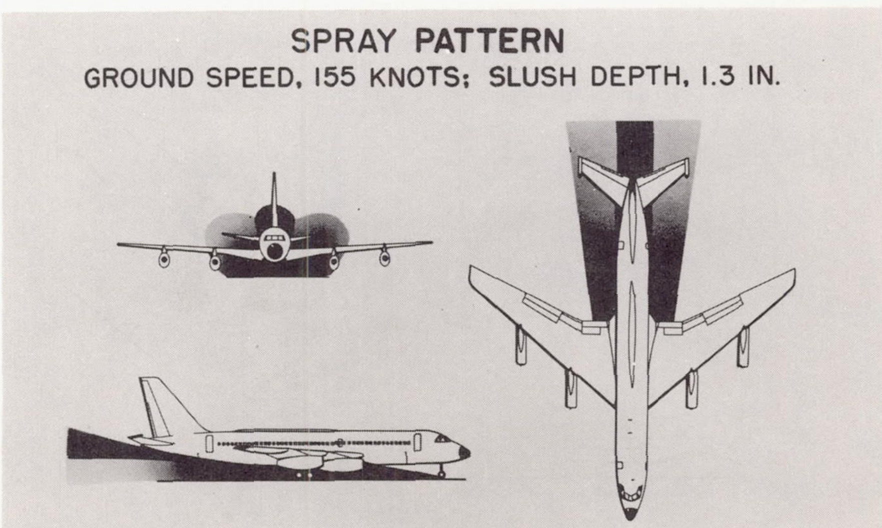
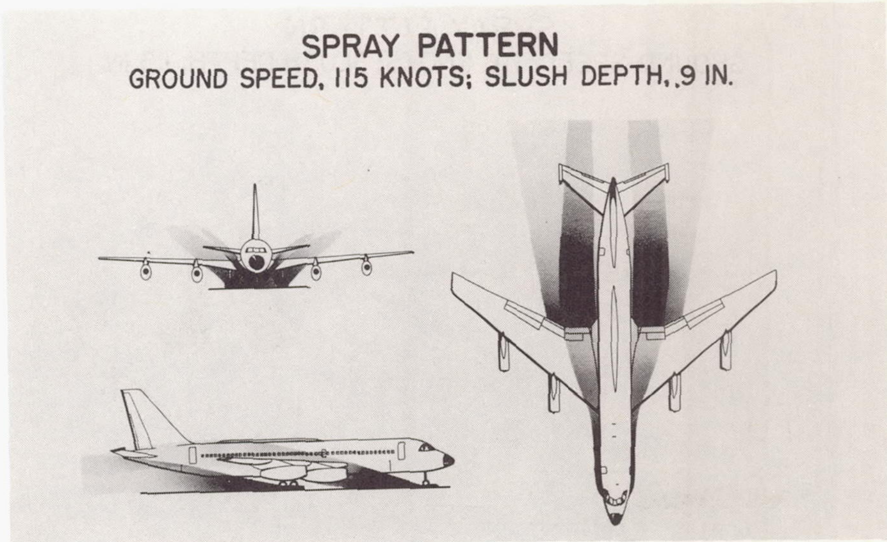


Figure 4



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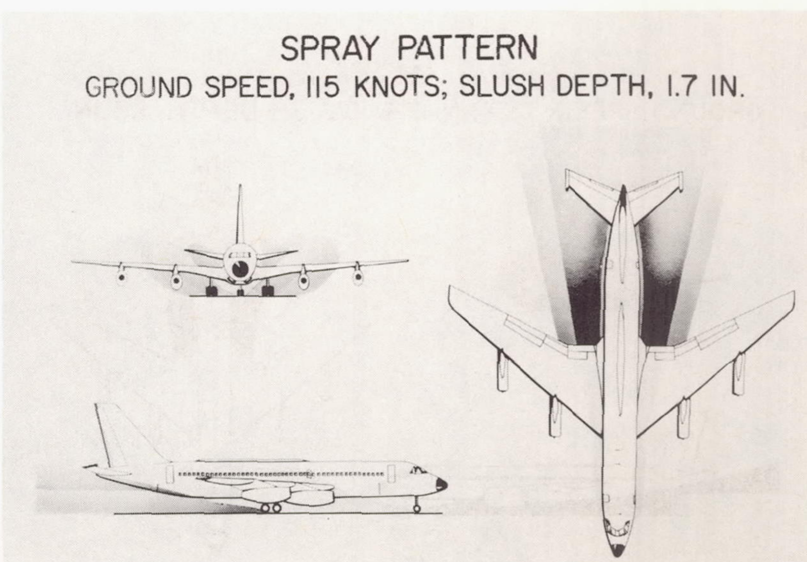

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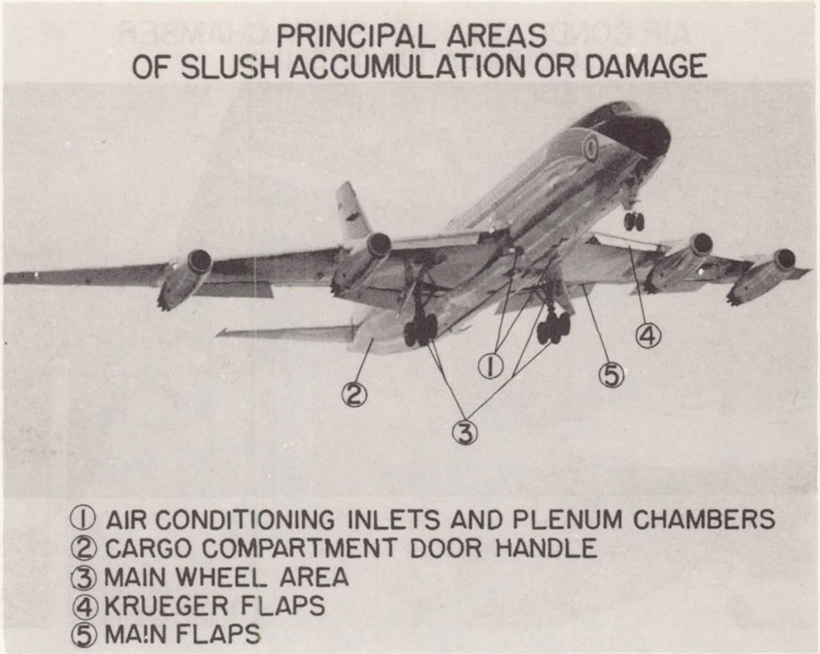

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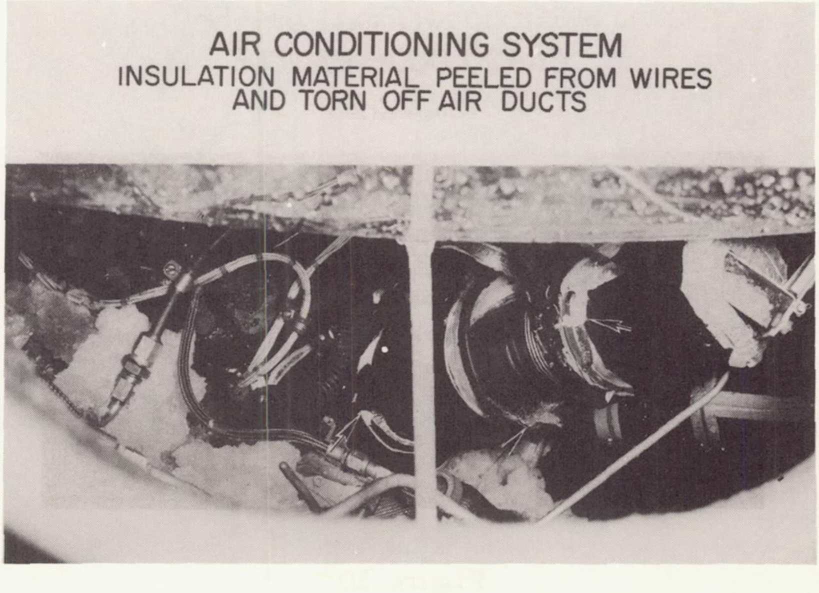


Figure 8

Figure 9

Figure 10

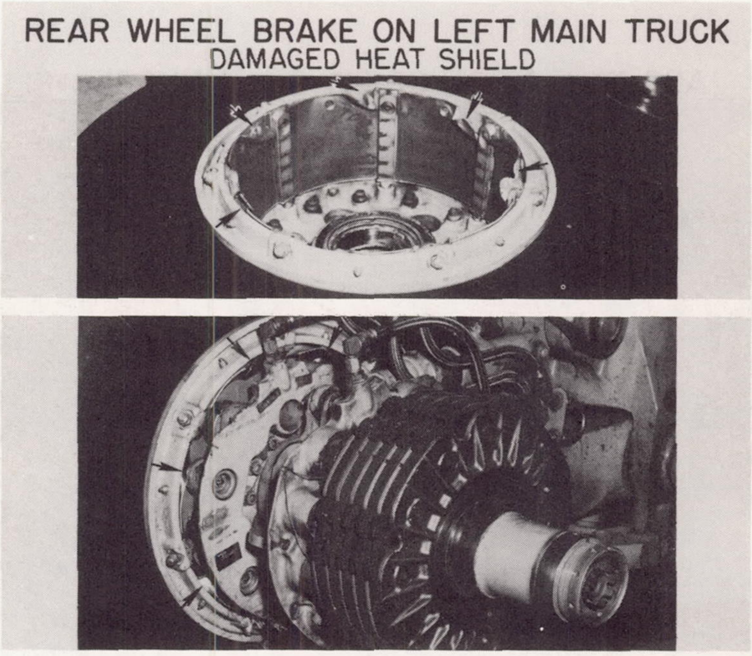


Figure 11

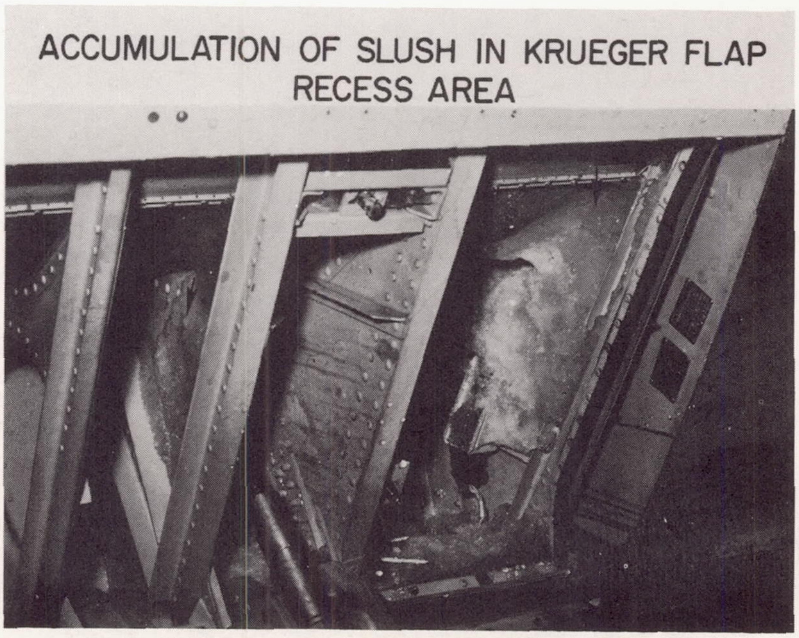


Figure 12

ACCUMULATION OF SLUSH IN WHEEL WELL

Figure 13

ACCUMULATION OF SLUSH ON MAIN BOGEY STRUCTURE

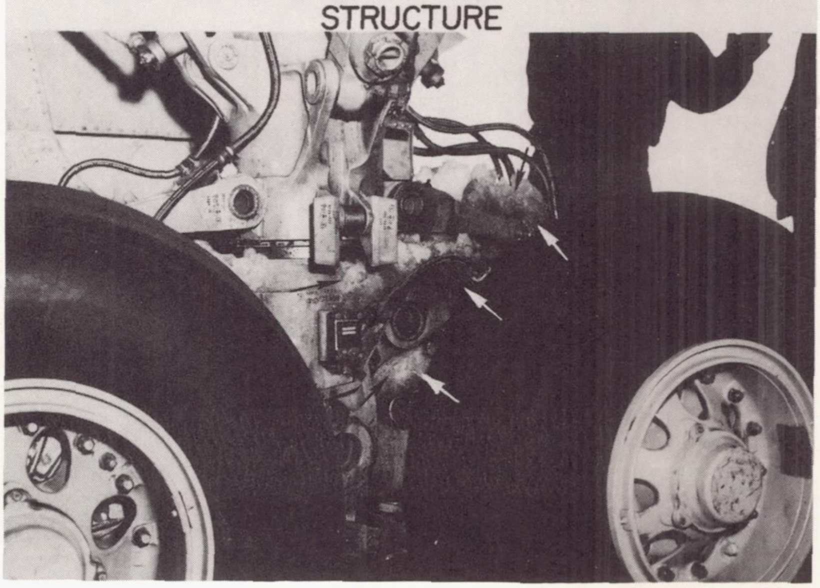


Figure 14

SLUSH DRAG ON TEST AIRCRAFT

SLUSH SPECIFIC GRAVITY, 0.82

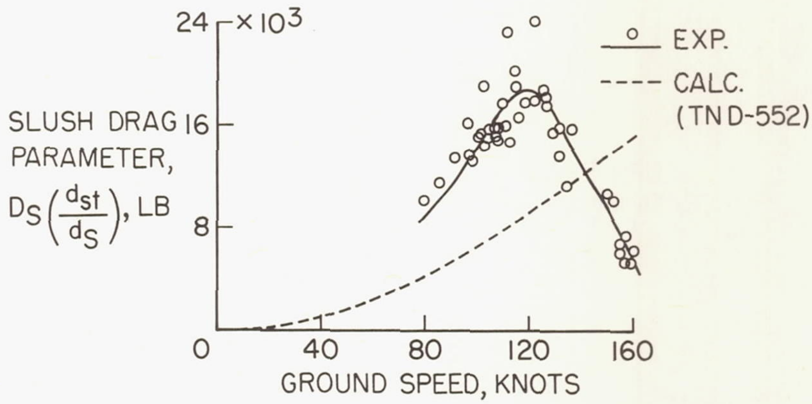


Figure 1

SLUSH DRAG COEFFICIENT

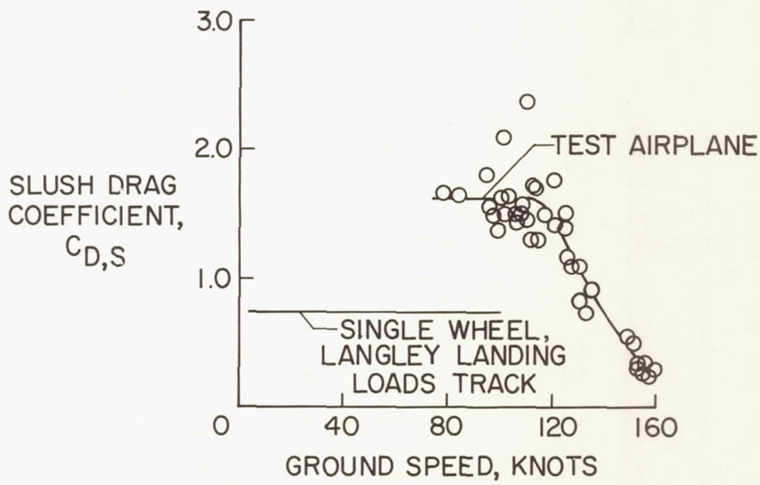


Figure 2

5

Aus 22-25

NORMALIZED AIRPLANE SLUSH DRAG COEFFICIENT

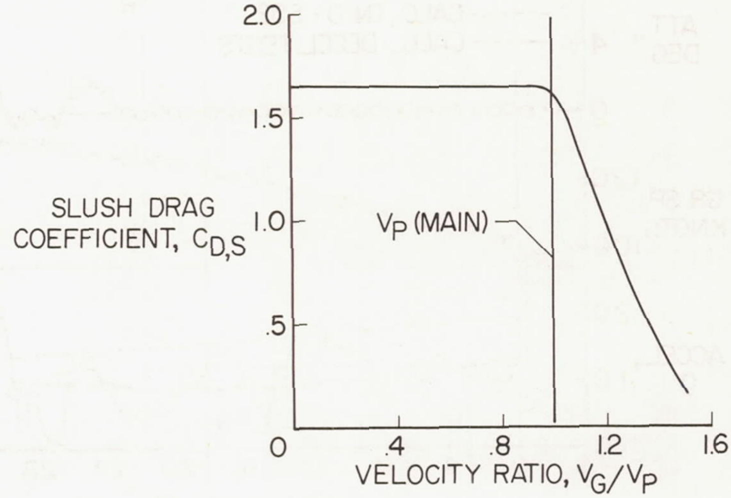


Figure 3

EFFECT OF VERTICAL LOAD
ON SLUSH DRAG COEFFICIENT

MAIN WHEEL TIRE PRESSURE = 160 LB/SQ IN.

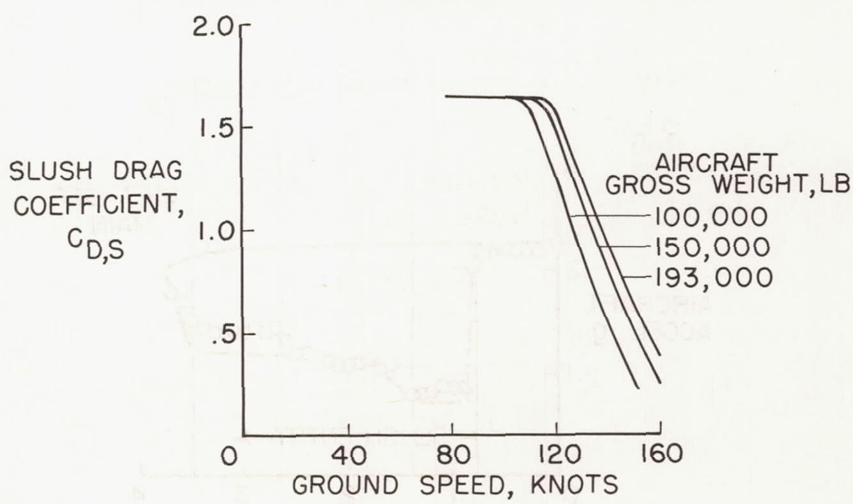


Figure 4

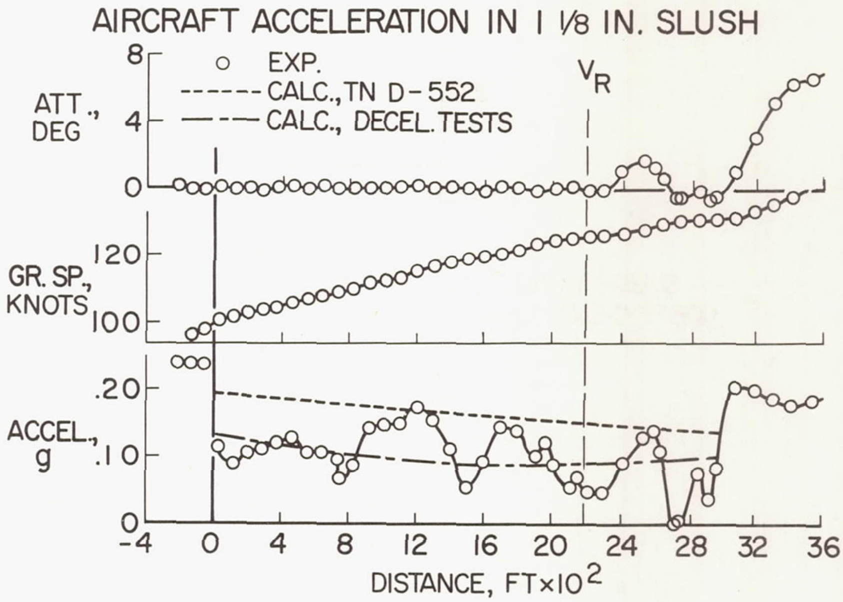


Figure 5

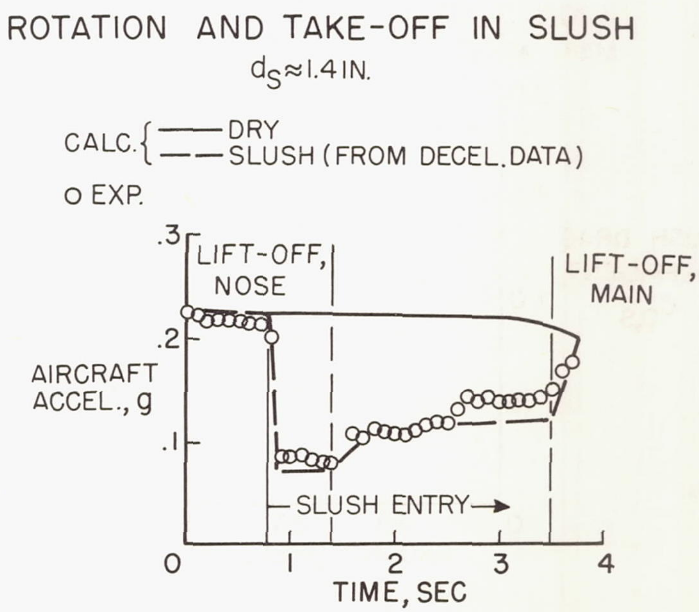


Figure 6

SLUSH MEASUREMENT

1. SPOT MANUAL
2. SPOT VEHICULAR
3. CONTINUOUS VEHICULAR

Figure 1

AUTOMOBILE DECELERATION IN SLUSH

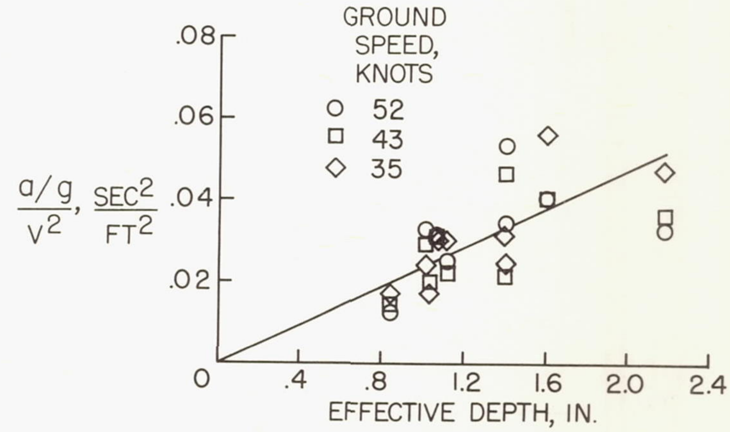


Figure 2

6

SLUSH DRAG ON SINGLE WHEEL

LANGLEY LANDING LOADS TRACK;
GROUND SPEED, 65 TO 105 KNOTS

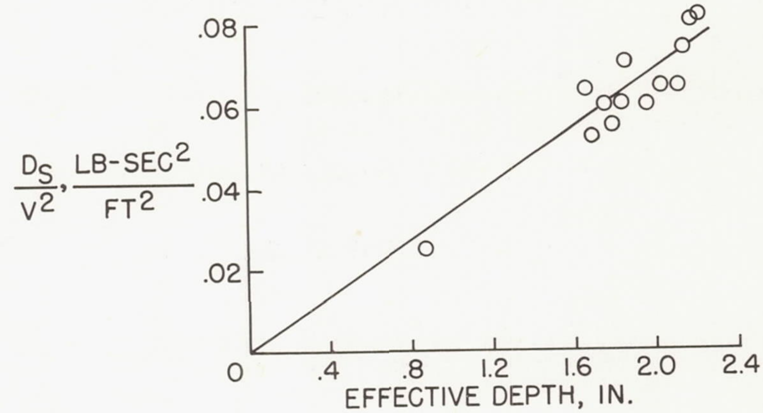


Figure 3

MEASUREMENT - ERROR EFFECT
ON DISTANCE TO ROTATIONAL SPEED

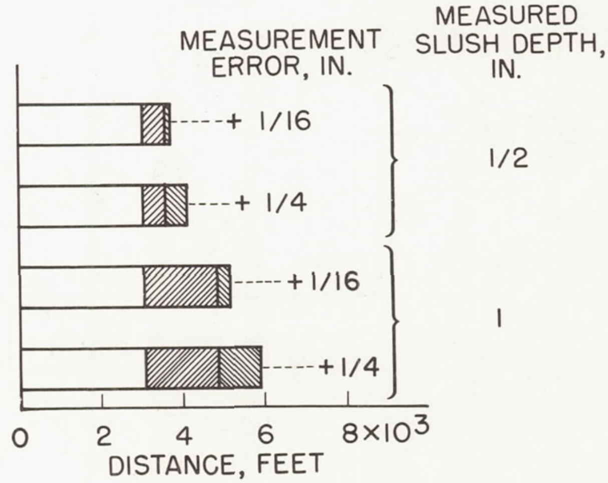


Figure 4

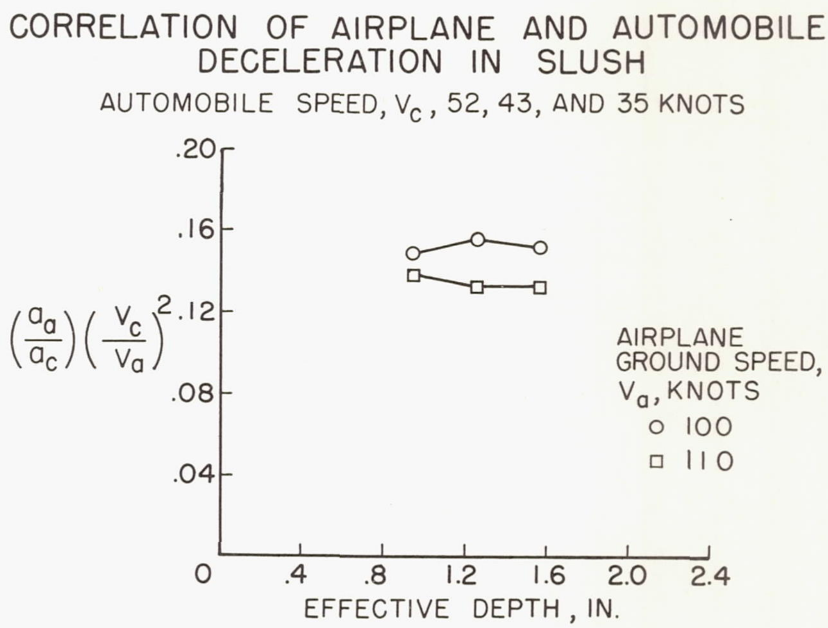

CORRELATION OF AIRPLANE AND AUTOMOBILE DECELERATION IN SLUSH
AUTOMOBILE SPEED, V_c, 52, 43, AND 35 KNOTS
$\left(\frac{a_a}{a_c}\right)\left(\frac{V_c}{V_a}\right)^2$
.20
.16
.12
.08
.04
0
.4
.8
1.2
1.6
2.0
2.4
EFFECTIVE DEPTH, IN.
AIRPLANE GROUND SPEED, V_a, KNOTS
○ 100
□ 110

Figure 5

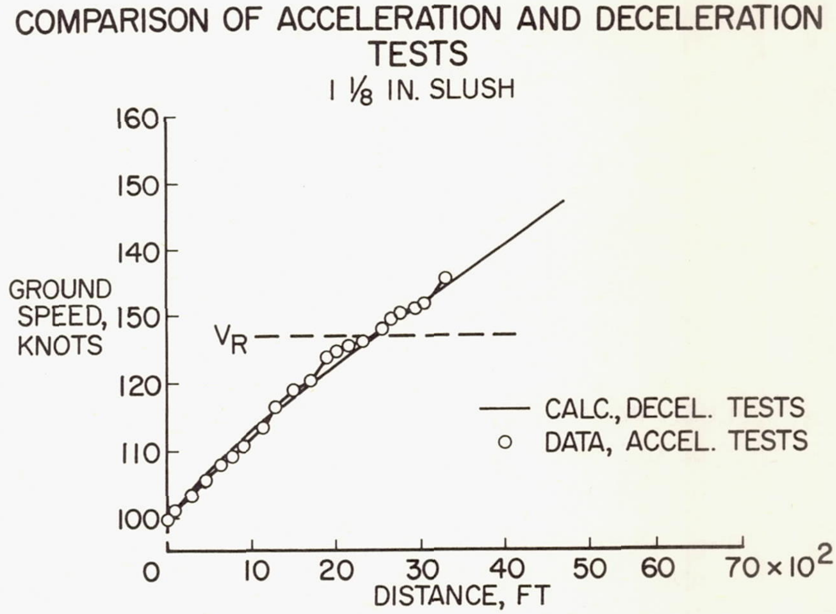


Figure 1.

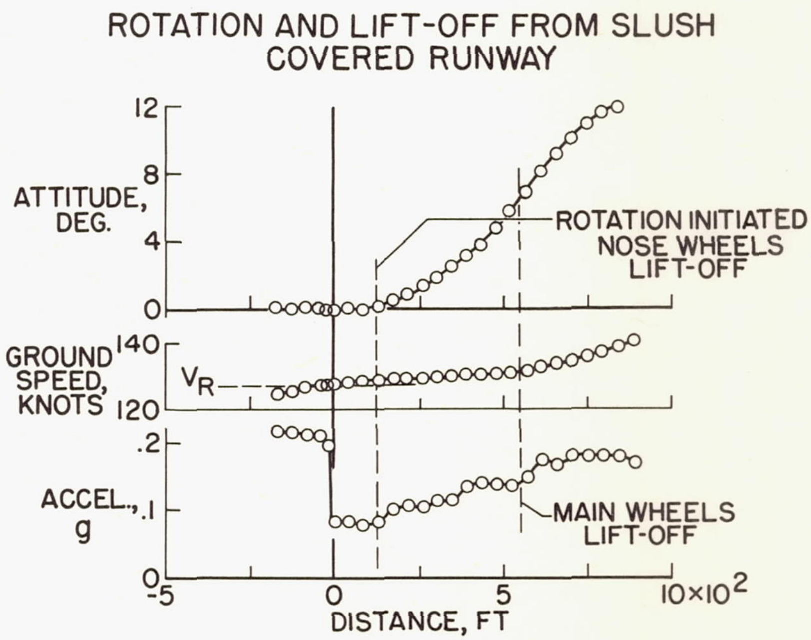


Figure 2

CONCLUSIONS

1. SLUSH IMPINGEMENT AND INGESTION CAN BE SERIOUS PROBLEMS DEPENDING ON AIRPLANE GEOMETRY
2. HIGH SPEED BRAKING IS ALMOST NONEXISTENT AND CAN INCREASE "ACCELERATE-STOP" AND LANDING DISTANCES TO IMPRACTICABLE VALUES
3. AIRCRAFT PERFORMANCE SUFFERS TO SUCH A DEGREE FROM SLUSH DRAG FORCES AS TO MAKE TAKE-OFFS IN DEEP SLUSH IMPOSSIBLE

Figure 3

SLUSH DRAG ON TEST AIRCRAFT

SLUSH SPECIFIC GRAVITY, 0.817

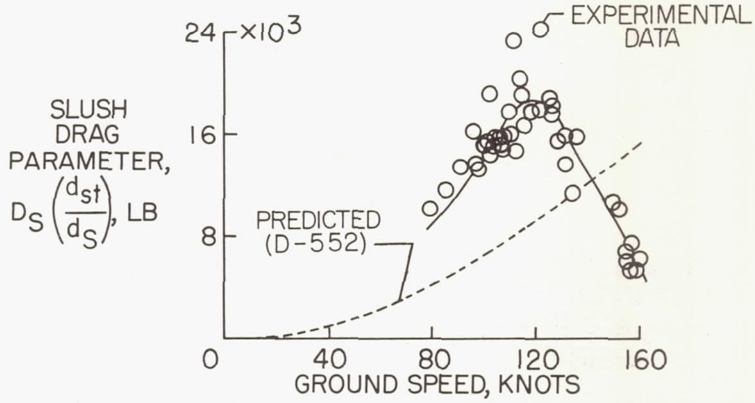


Figure 1

AIRPLANE TAKE-OFF DISTANCE

T/W = .232; W = 193,000 LB

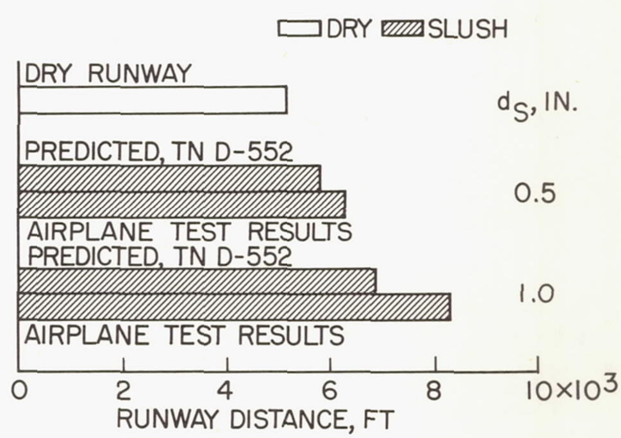


Figure 2

8

POSSIBLE FUTURE STUDIES

1. DEVELOPMENT OF OPERATIONAL METHODS FOR MEASURING SLUSH.
2. POSSIBLE CONTROL OF SLUSH AND WATER SPRAY PATTERNS.
3. "ROOSTER TAIL" AND SPRAY INTERFERENCE ON TRUCK-TYPE GEARS (GEOMETRY, SPACING, ETC.).
4. HYDROPLANING, HOW TO AVOID OR USE TO ADVANTAGE
5. PROGRAM SIMILAR TO CURRENT TESTS ON OTHER AIRCRAFT TYPES.

Figure 3

INCIDENTS AND ACCIDENTS ON SLICK RUNWAYS
U. S. SCHEDULED PASSENGER OPERATIONS

INCIDENT	1956	1957	1958	1959	1960	1961	TOTAL
LANDING							
VEERED OFF RUNWAY	1	4	4	3	5+1[a]	2+1[a]	21
OVERRAN	3	—	2	3	3[a]	2+1[a]	14
TAKE-OFF							
VEERED OFF RUNWAY	—	—	—	—	1	1[a]	2
OVERRAN	—	—	2	—	1	1[a]	4
TOTAL	4	4	8	6	11	8	41

[a] JET AIRCRAFT

Figure 1

RUNOUT DISTANCE FOR 4-ENGINE JET TRANSPORT
W=160, 000 LB; 50 PERCENT OF IDEAL BRAKING

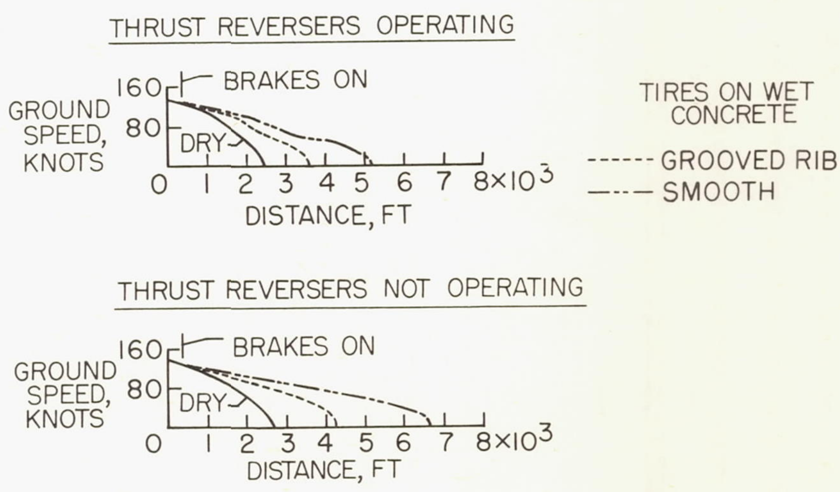


Figure 2

OBJECTIVE OF BRAKING PROGRAM

TO ASSIST IN THE IMPROVEMENT OF FULL-SCALE AIRPLANE LANDING PERFORMANCE ON SLICK RUNWAYS AS FOLLOWS:

1. INVESTIGATE METHODS FOR OPERATIONAL DETERMINATION OF RUNWAY BRAKING CONDITIONS.
2. ESTABLISH A REPRODUCIBLE LOW-COEFFICIENT-OF-FRICTION TEST-RUNWAY SURFACE.
3. CORRELATE FULL-SCALE BRAKING RESULTS AND THOSE FROM THE LANGLEY LANDING LOADS TRACK.

Figure 3

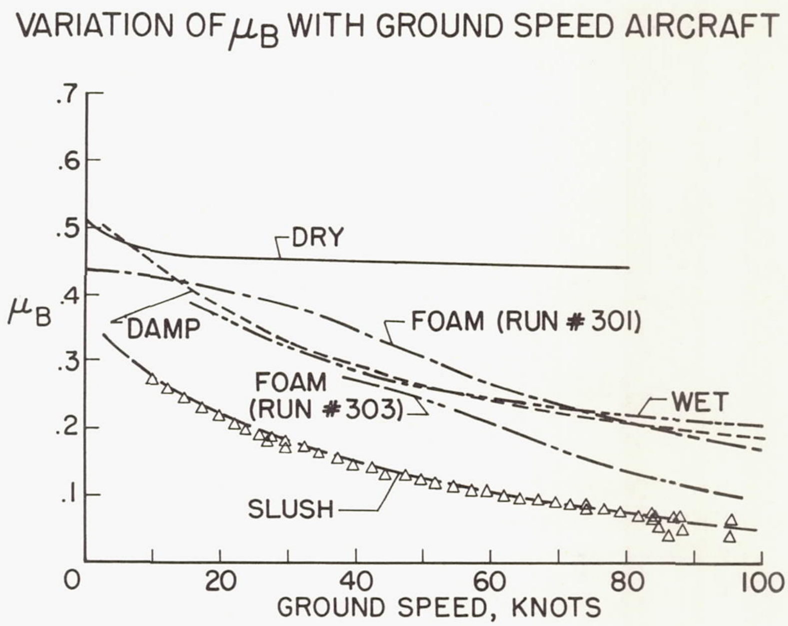


Figure 1

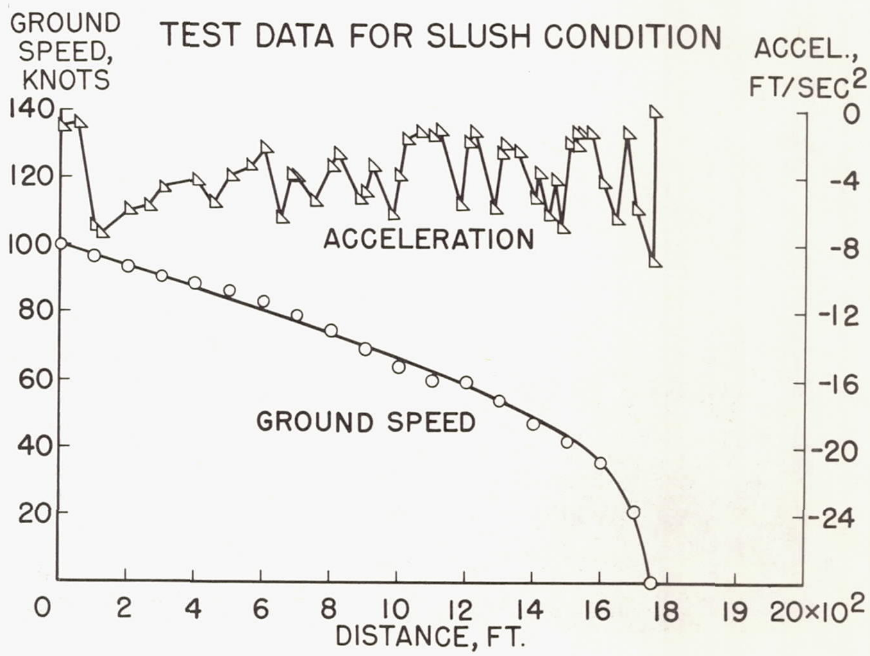


Figure 2

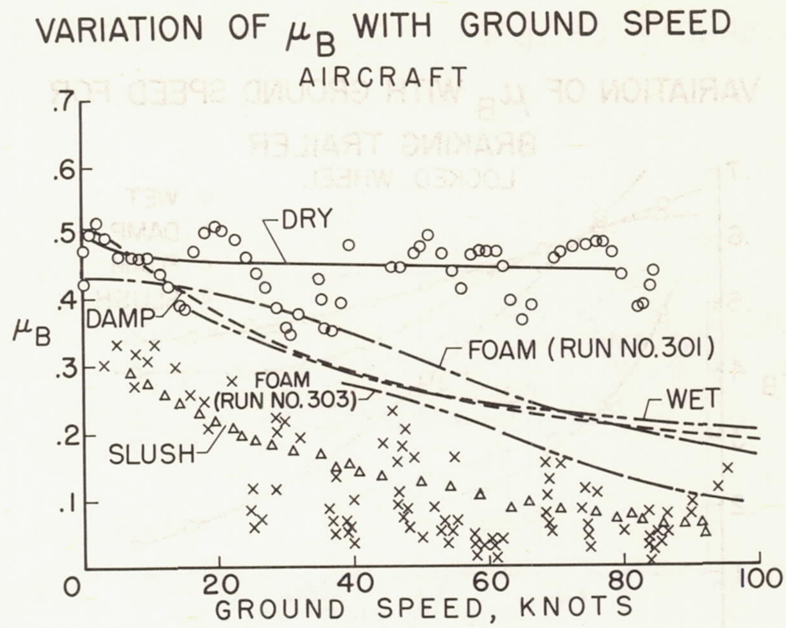


Figure 3

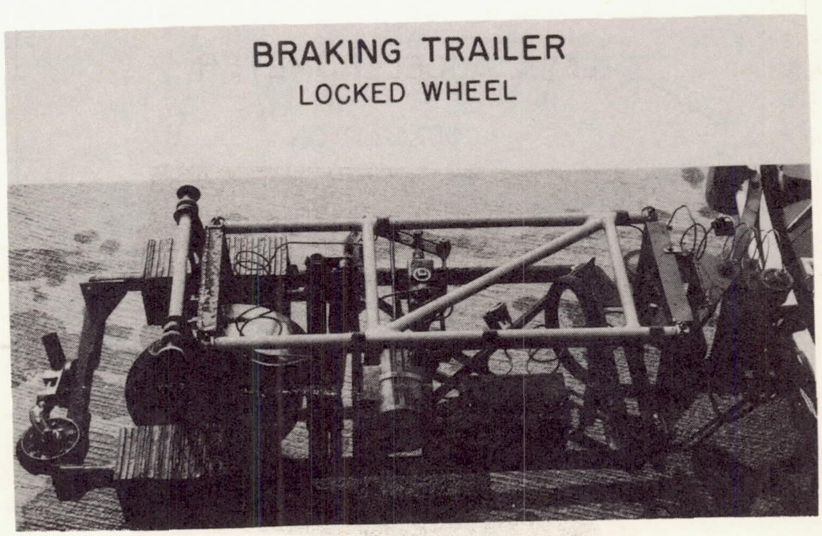


Figure 4

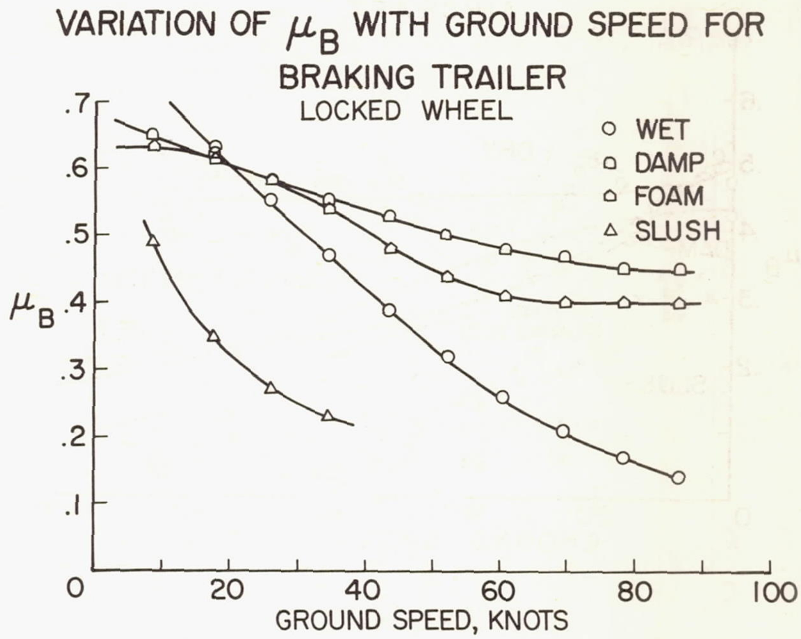
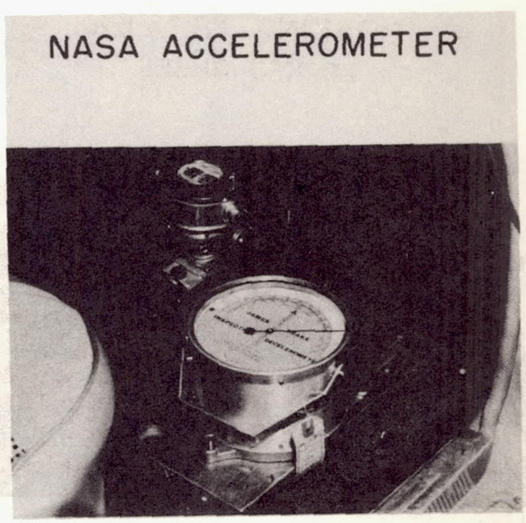


Figure 5



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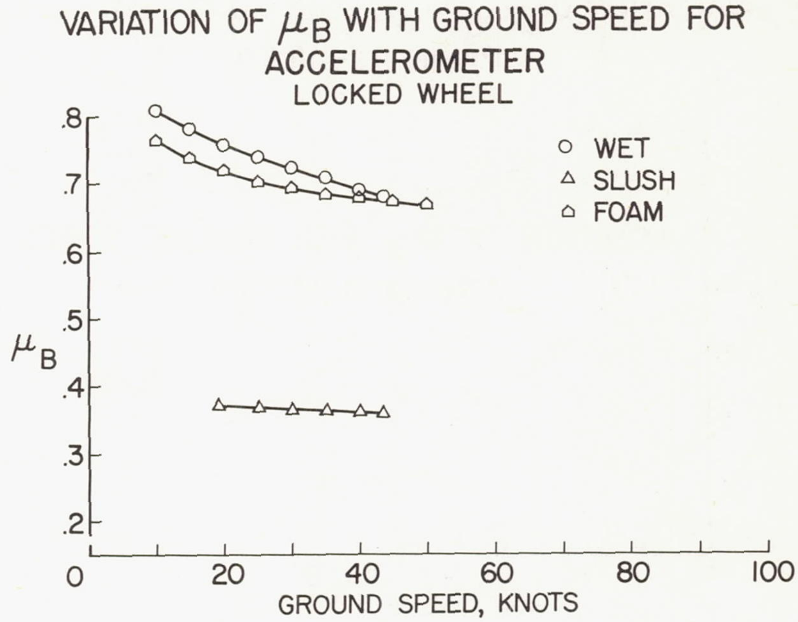

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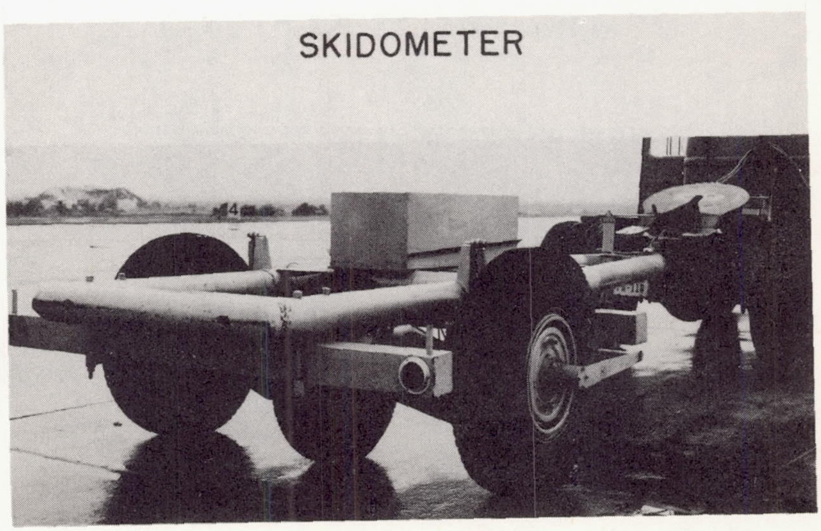

Figure 8

VARIATION OF μ_B WITH GROUND SPEED FOR SKIDOMETER

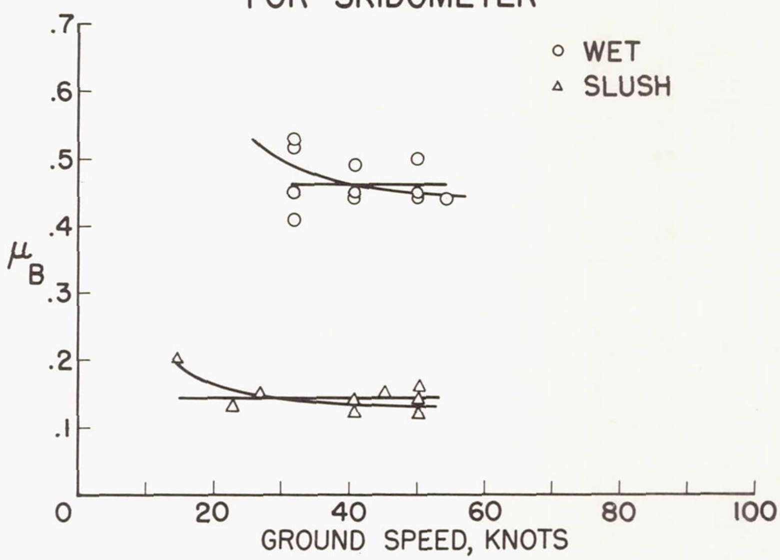

Figure 9

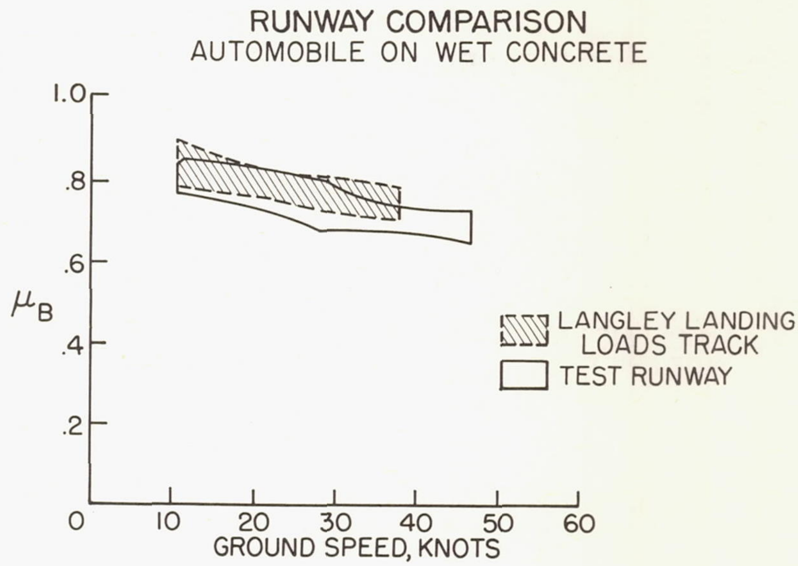

Figure 1

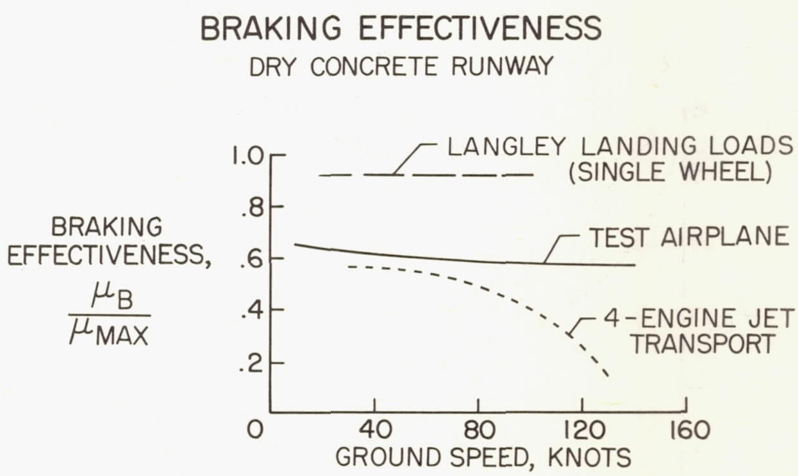

Figure 2

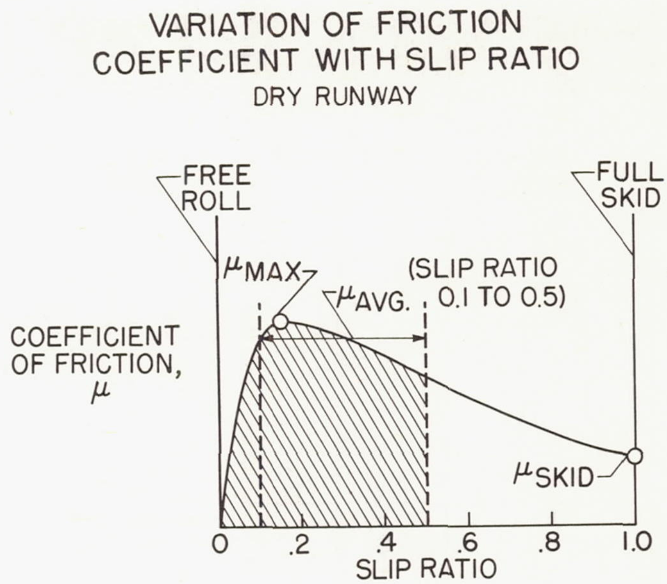

Figure 3

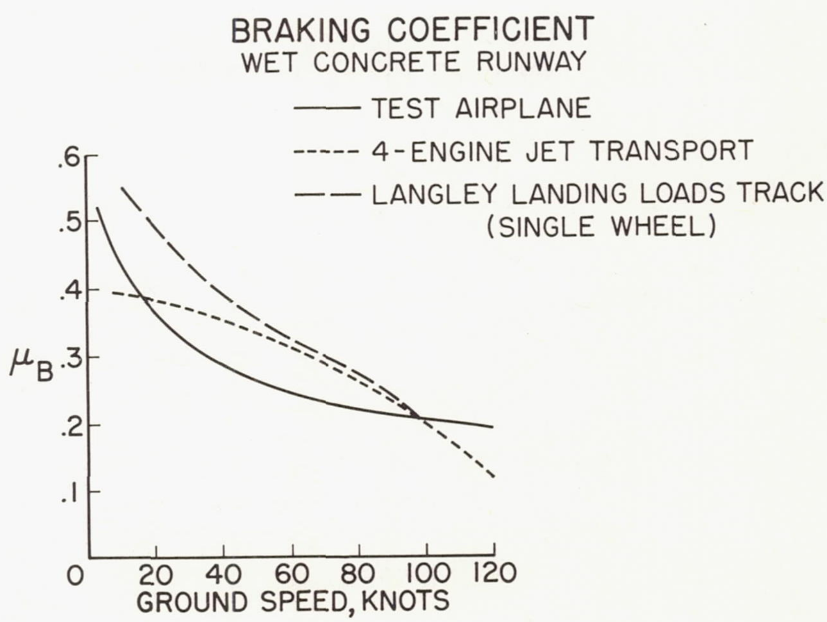

Figure 4

VARIATION OF FRICTION COEFFICIENT WITH SLIP RATIO

WET RUNWAY

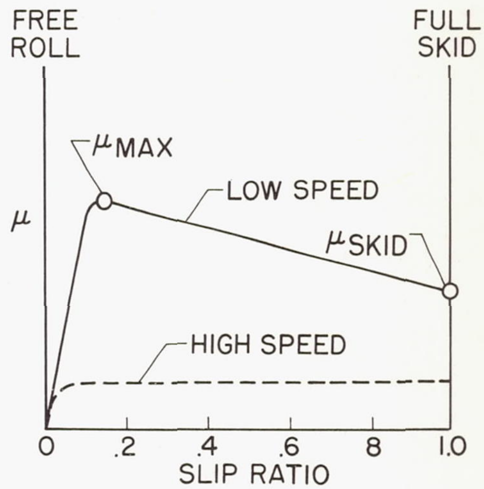

Figure 5

TEST AIRPLANE BRAKING IN SLUSH

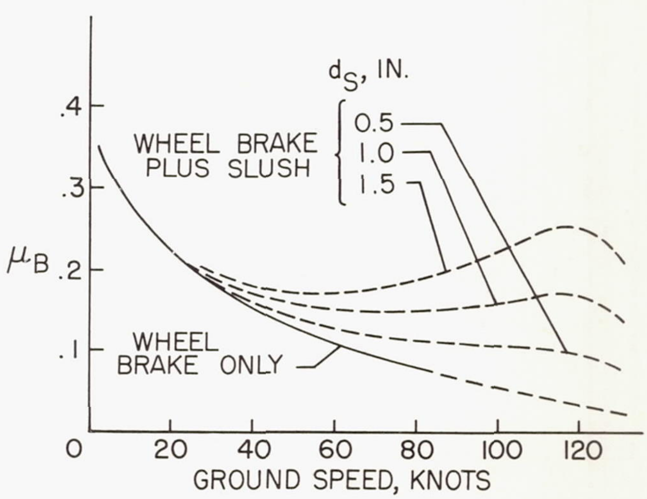

Figure 6

COMPARATIVE BRAKING IN SLUSH
$d_S = 1.5$ INCH

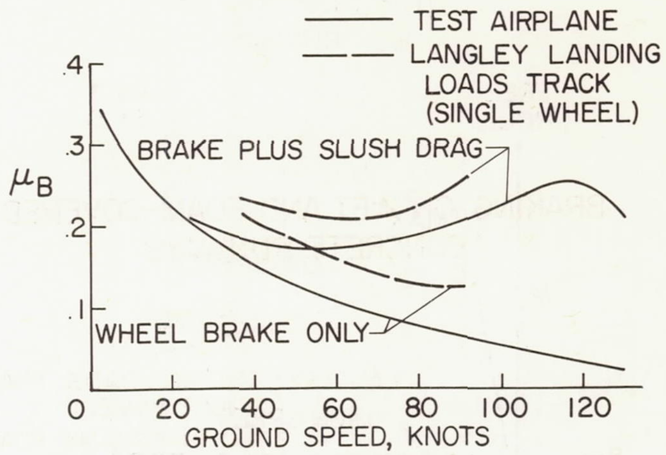

Figure 7

TEST AIRPLANE BRAKING ON CONCRETE RUNWAY

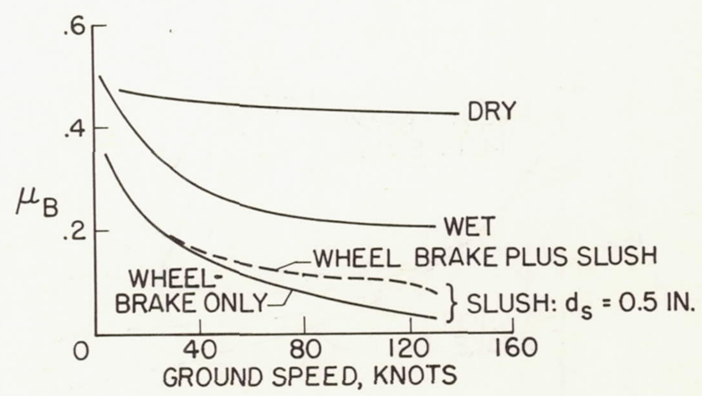

Figure 8

BRAKING ON WET AND FOAM-COVERED CONCRETE RUNWAYS

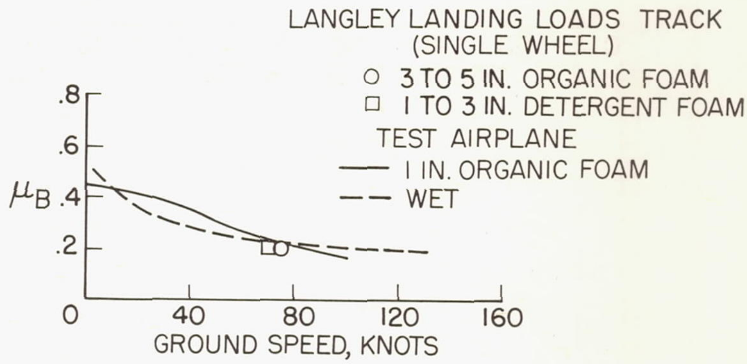

Figure 9

COMPARISON OF BRAKING RESULTS
WET CONCRETE

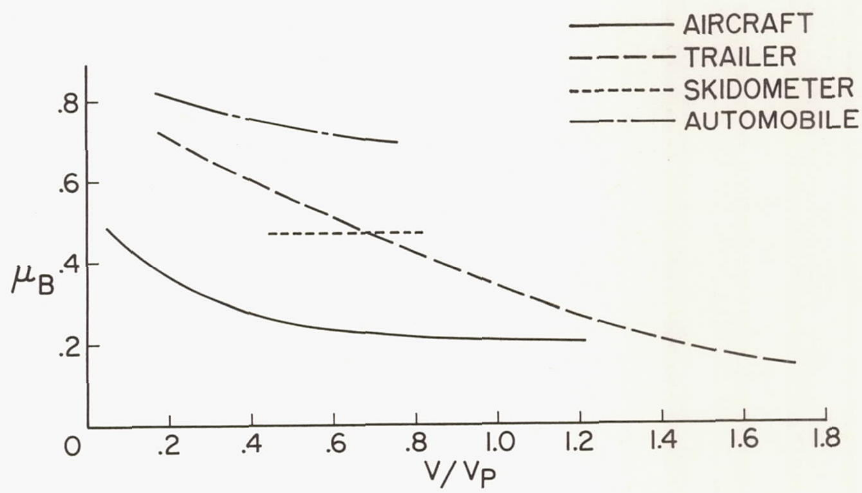

Figure 1

RATIO OF AIRPLANE TO VEHICLE BRAKING FRICTION
BRITISH TRAILER

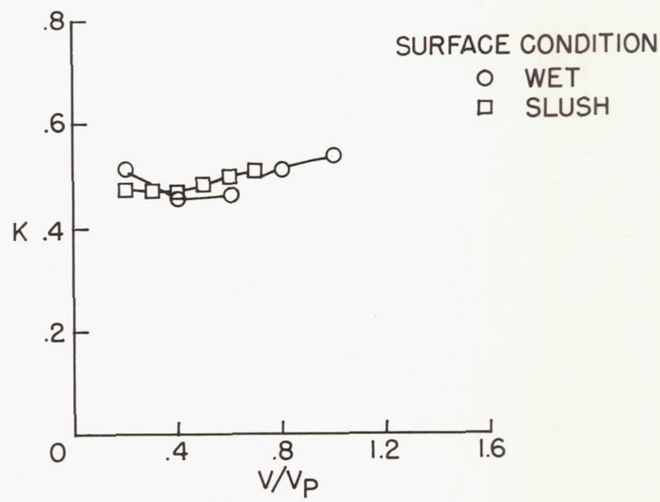

Figure 2

RATIO OF AIRPLANE TO VEHICLE BRAKING FRICTION

AUTOMOBILE

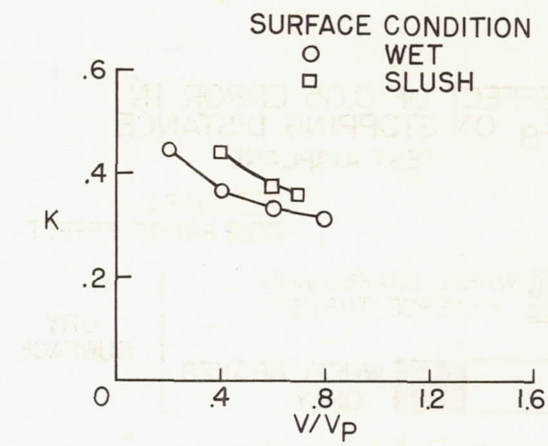

Figure 3

RATIO OF AIRPLANE TO VEHICLE BRAKING FRICTION

SWEDISH SKIDOMETER

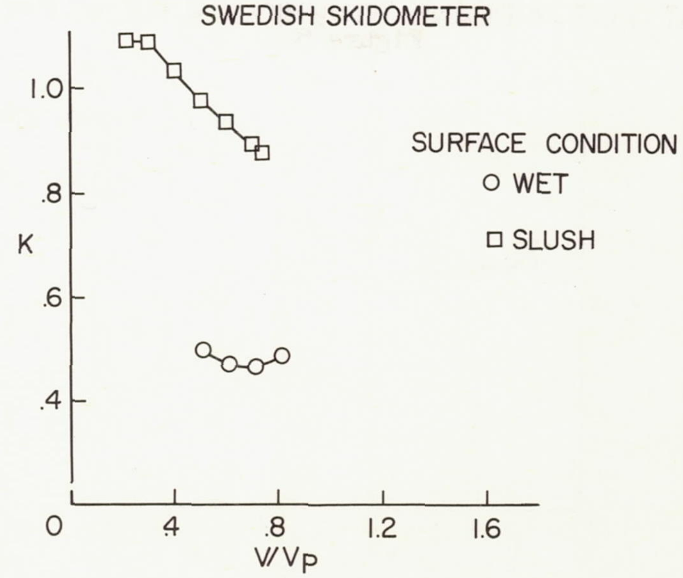

Figure 4

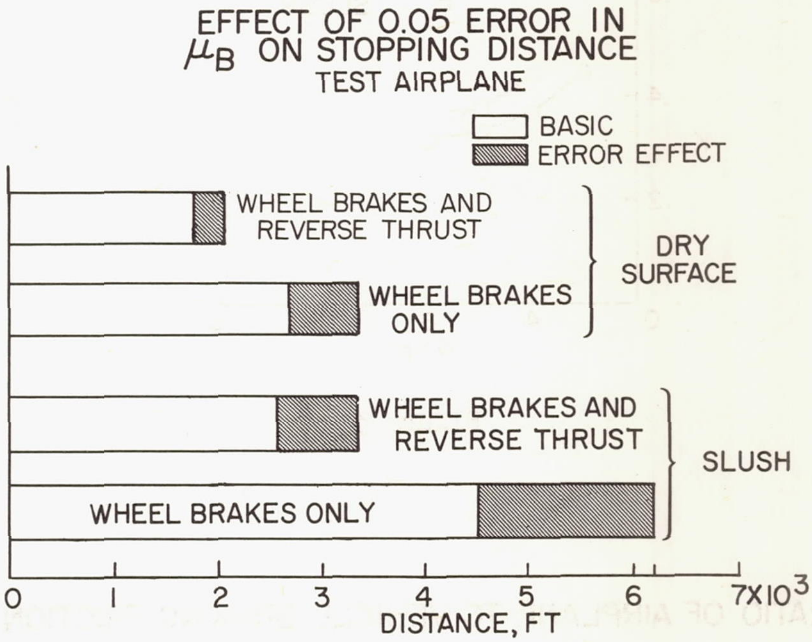
EFFECT OF 0.05 ERROR IN
μ_B ON STOPPING DISTANCE
TEST AIRPLANE
BASIC
ERROR EFFECT
WHEEL BRAKES AND
REVERSE THRUST
WHEEL BRAKES
ONLY
DRY
SURFACE
WHEEL BRAKES AND
REVERSE THRUST
WHEEL BRAKES ONLY
SLUSH
0
1
2
3
4
5
6
7X10^3
DISTANCE, FT

Figure 5

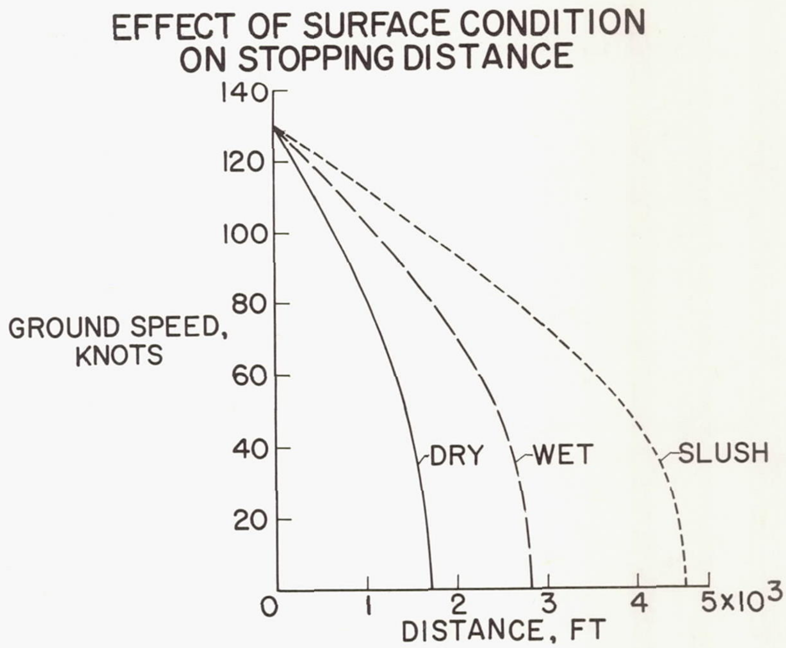

Figure 1

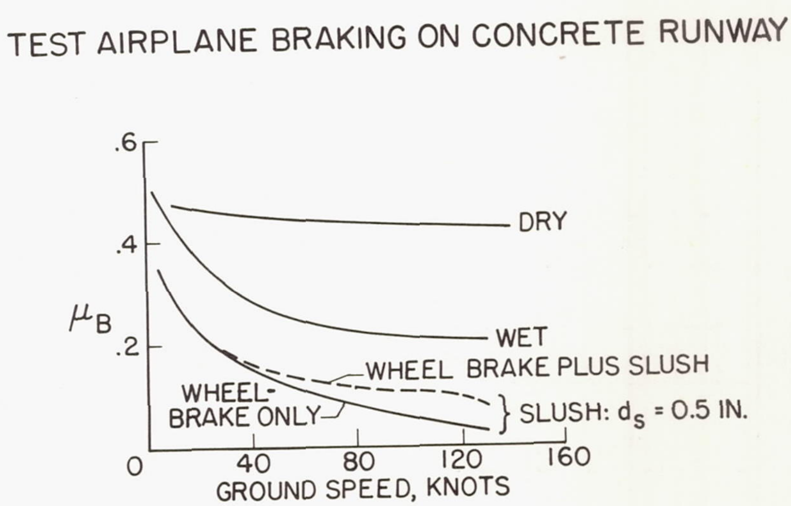

Figure 2

VARIATION OF FRICTION COEFFICIENT
WITH SLIP RATIO
WET RUNWAY

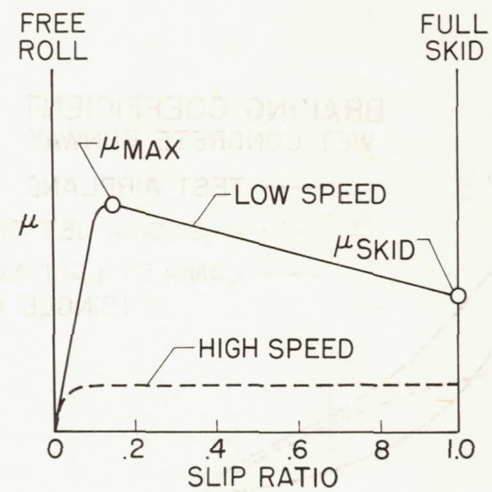

Figure 3

EFFECT OF 0.05 ERROR IN
μ_B ON STOPPING DISTANCE
TEST AIRPLANE

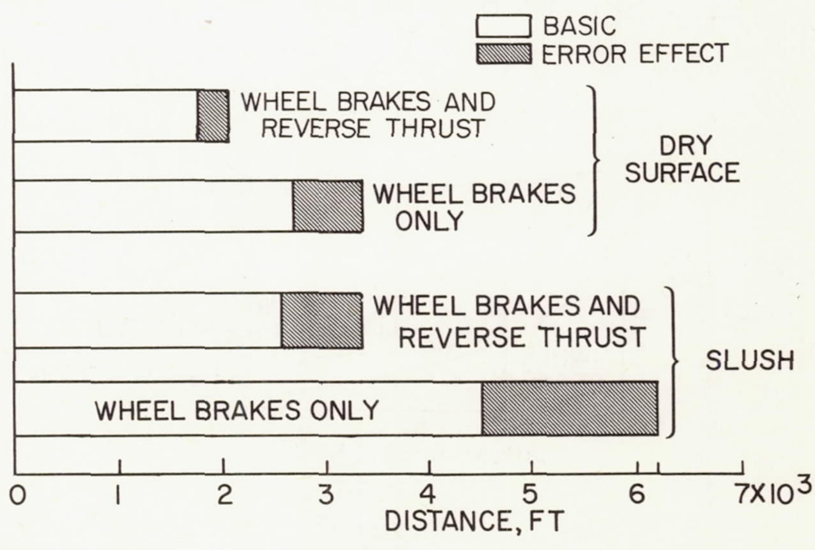

Figure 4

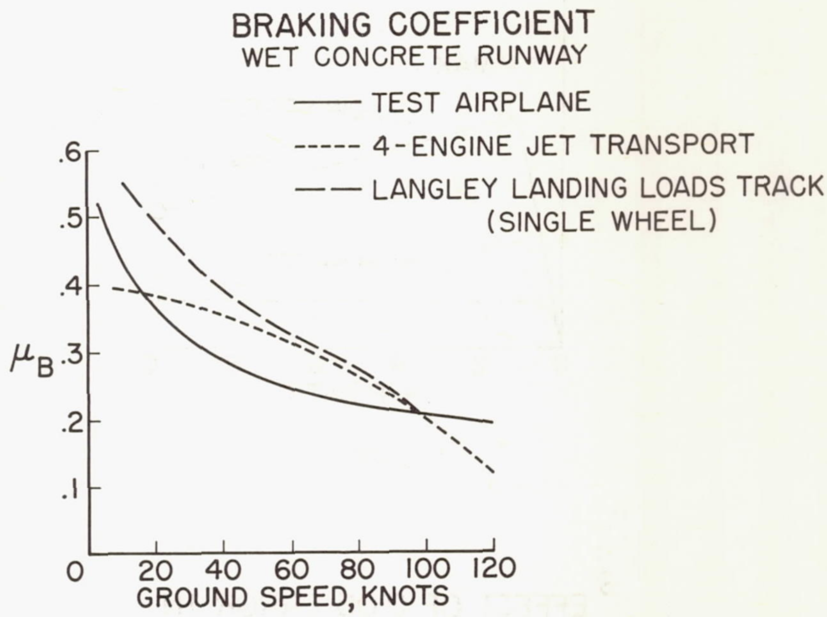

Figure 5

NASA-Langley, 1961