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A PRELIMINARY STUDY OF CONTAINMENT CONCEPTS
FOR AIRCRAFT LANDING ON ELEVATED STOL-PORTS

A TECHNICAL REPORT
SUBMITTED TO:
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SUBMITTED BY:
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TABLE OF CONTENTS

SUMMARY

A preliminary study of containment systems for aircraft landing on
elevated STOL-ports was conducted under NASA Grant NGL 47-005-014, as part
of an overall study of human acceptance problems associated with STOL
operations. The study included a survey and feasibility study of different
concepts and a computer analysis of four arrestment systems. The principal
conclusion of this study was that a system referred to as the FAA system
appears to offer the greatest promise. In this system, standard arresting gear
cables are stretched across the roof-top, at roughly 100-foot intervals,
but are shielded over the 100-foot-wide primary landing strip. Thus a
pilot can land with an arresting hook down, but will not contact the
cable unless he swerves off the landing strip, either because he has made
a bad landing, or because his landing gear has failed. An alternate
system, essentially a modification of a system suggested by NASA, was
shown to be acceptable, but would require considerable development. It
was also noted that a suitable curb or guard rail should be developed.
Presently available arresting gears and nylon net barriers were considered
satisfactory for the overshoot problem.

ACKNOWLEDGMENTS

SECTION I

INTRODUCTION

The University of Virginia has been engaged in a general study of
the operational aspects of short-takeoff-and-landing (STOL) air trans-
portation systems, with particular emphasis on determining criteria for
assessing passenger acceptance of this mode of transportation.

Several STOL systems which have been proposed by various segments
of the air transportation industry incorporate landing on an elevated
structure, often located over a building, railroad yard or highway,
in an area near the city center in order to take full advantage of the
STOL capability in effecting time savings and convenience for the
passenger. Thus the attributes of landings on elevated structures require
serious consideration from the point of view of safety and reliability as
well as of the psychological and esthetic effects on passenger acceptance.

Undoubtedly an elevated STOLport will be required to have emergency
arresting or containment devices to meet federal safety specifications.
There is also the possibility that some advantages may accrue from using
arresting devices routinely in landing operations. Thus in order to
define better those properties of such potential devices which would be
required to make an evaluation of passenger reaction, a group of students,
under the direction of the author, was assigned the task of making a
preliminary study of their operation, use, and performance.

Since several of the results of this initial study appear to be
of some value in the planning of elevated landing structures, it is deem-
ed appropriate to report them at this time.

The individual student task assignments covered herein are:

1. A survey of industry attitudes, suggestion, and
recommendations by Hunter F. Taylor;

2. A feasibility study and evaluation of possible arresting
and containment concepts by J. Wilson; and

3. A study of arrested landing based on models of selected
arresting systems by S. C. Mischen.

The feasibility study was based upon results obtained from the
survey combined with unsolicited ideas and comments received from workers

in the field and with suggestions generated internally. It indicated that four arresting devices appeared particularly promising, and so simplified calculations were made concerning the performance of these four systems under conditions representative of operating situations that might require their use.

The results of the survey and feasibility evaluation are presented in Sections II and III, respectively. Section IV outlines the calculations made for the four particular arresting systems selected for further study. Finally, conclusions and recommendations relating to the overall subject of landing operations on elevated STOLports are presented in Section V.

SECTION II

SURVEY

The survey was conducted both informally, through personal contacts, and formally, by letter to some twenty airlines, manufacturers, or government agencies. Its purpose was primarily to obtain information on existing concepts for the containment of aircraft landing on elevated runways and on existing devices that could possibly be applied to this situation. Information was also requested on the landing environment and on passenger reaction to landing.

The letter of inquiry, a list of the addressees, and excerpts from those responses which provided answers pertinent to the questions raised in the survey letter are attached in the appendix.

Eleven replies were received and the information provided by these replies and by numerous personal discussions may be summarized as follows:

1. Concepts suggested include
   a. Conventional arresting gear (e.g.) as commercially available from All-American Engrg Co.
   b. Side arresting gear - essentially the conventional gear, but recessed in a slot across the active runway portion (FAA)
   c. Overshoot arresting gear
   d. Curbs (unspecified) for lateral containment
   e. Use of open deck gridding to keep runways clear
   f. Sloped apron off side of runway;

2. There is markedly little enthusiasm for use of arresting gear during normal landings;

3. There is considerable concern about the problem of lateral containment in emergencies;

4. Peak g levels of up to .43 have been experienced in normal (unarrested) landings. However, additional passenger constraints, such as foot bars, might be needed if this became a normal level; and

5. Peak g levels of 1.0 to 1.5 might be acceptable under emergency arrestment conditions. (A figure of 1.5 was actually recommended by the ICAO 5th Conference, 1967.)

SECTION III

EVALUATION OF CONCEPTS FOR LATERAL CONTAINMENT

A.   Basic Guidelines

A total of nine concepts were evaluated. Although these were by no means thorough detailed studies, they were of sufficient depth to permit the identification of a limited number of systems which were felt to merit further study. No attempt was made to include any economic analysis, or to forecast the difficulties involved in reducing certain concepts to practice. The performance data claimed for a given concept was accepted as practically achievable if it appeared fundamentally sound.

In establishing a set of guidelines for the evaluation, the following factors or issues are considered important:

- Reliability and Safety
   (a) brake or reversed thrust failure
   (b) landing gear failure
   (c) landing out of line with the runway due
        to turbulence, poor visibility, or strong
        crosswind;
- Pilot acceptance; and
- Passenger Acceptance.

The guidelines which were ultimately selected as compatible with the level of complexity of this evaluation are listed below.

   1. Essential Function - to restrain an aircraft so that it remains
       on the building after a bad landing or a landing accident;
       both overshoots and lateral excursion must be considered.

   2. Essential Constraints
       a. Decelerations must be acceptable to passengers
           (tentatively .5 g for normal conditions and 1.5 g
           for emergency conditions).
       b. The system should be simple, requiring little
           maintenance.

5

c. The system must have a high degree of reliability. This should reduce the hazards of roof-top landings to those of normal field landings. Given appropriate statistics on accidents in normal field landings, a reliability could be determined.

3. High Priority Requirements
   a. The system should be within current technology.
   b. The system should not require resetting for different aircraft.

4. Low Priority Requirements
   a. The system should have a reasonable cost
   b. Appearance of the system should be acceptable to passengers.

B.   Remarks on Concepts Evaluated

1. Standard Arresting Gear

This is essentially the All-American Engineering Co. concept as shown in Figure 2, in which a standard arresting gear is placed at each end of the runway. The pilot has the option of engaging on touch-down, thereby shortening his run and reducing the chance of going over the side. If he does not do this, he still has the chance of engaging at the end of the runway, should he have a brake failure. Failing even this, a nylon net barrier could be available at the far end of the runway. For a pilot who exercises this option, safety is comparable to that experienced in carrier landings, but possibly at the expense of losing future passengers, who may object to arrested landings. Further, it might be necessary to set the arresting gear individually for each air-craft, if the .5 g limit is to be met. If the pilot does not exercise this option, but subsequently makes a bad landing or suffers a landing gear failure, there is no lateral constraint. Thus, it is not possible to meet all of the guidelines set above. Nonetheless, it seems worthy of further study because of its simplicity.

2. Shielded Arresting Gear

This system, hereinafter referred to as the FAA system, is

illustrated in Figure 7. It is basically the one referred to by J. C.
Staples of FAA in letter (f) of the Appendix. It is similar to the
standard arresting gear, but would be shielded across the primary landing
strip so that it would only be engaged if the aircraft had swerved off
this strip. The arresting forces could be at emergency levels (i.e.,
1.5 g according to ICAO fifth conference, 1967) and possibly one setting
could handle all aircraft. However, the system would rely on bringing
an aircraft to a stop before reaching the edge of a building, without
any centering tendency. To work effectively, it would have to be placed
at regular intervals, probably 100 feet, all down the runway, leading to
high cost. Otherwise, it would meet the guidelines.

3. Side Arresting Gear - NASA Concept

This system was suggested by Joyner [2] of NASA, and is
referred to as the NASA system. It is shown in Figure 9. It is restricted
to the prepared surface on either side of the primary landing strip
having water twisters or other brakes along the sides of the building,
and cars moving on tracks alongside the landing strip. Combined with a
hook placed ahead of the c.g., the system tends to return the aircraft
to the center of the runway. This system does not meet the guidelines
for simplicity (it requires a special hook),nor is it within current
technology (the car has not been developed);and it is potentially expensive.
Nevertheless, it is worthy of further study because of its positive
centering tendencies.

4. Side Arresting Gear - UVA-Modified NASA Concept

This is an inversion of the NASA concept, in which the cars
run along the sides of the building. It avoids the requirement for a
special hook and would work with a convential hook arrangement. Otherwise
it has the same disadvantages as the NASA system. It will also receive
further study.

5. Anti-cambered Runway

The idea here is to build an anticambered surface on each side
of the primary landing strip, so that the aircraft will tend to return if

it goes off to one side. However, further analysis, not included here,
shows that, above a certain critical speed, the system becomes unstable,
and makes the aircraft turn away from the centerline.

6. Side Barriers

Although side barriers may at first seem to be an obvious
choice, they could actually increase the hazards of roof top landing if
there was a tendency to hang-up a wing tip or propeller on one, causing
the aircraft to swerve towards the edge of the building. It appears
evident that some sort of barrier will be required to stop slowly-moving
aircraft, but the design of successful high energy side barriers poses
considerable challenges which have not yet been taken up. If anti-cross-
wind screens prove to be necessary, they will also constitute side
barriers, and it will be essential to tackle the aforementioned problems.

7. Artificial Headwinds

It has been suggested that something like an open throat wind
tunnel be placed so that the aircraft can make a very slow touchdown.
However, many objections can be raised to this scheme, which seems to
meet none of the guidelines.

8. Deceleration Strips

Plantings of bushes have been used successfully on highway
centre-strips to decelerate cars, and a similar system used alongside
the primary landings strip might be successful. However, it would have
a decentering tendency, because the off-center wheel would touch it
first. It would also need repairs after each use, and would therefore
fail to meet one of the essential constraints in the guidelines.

9. Deceleration Surfaces

The use of some resilient material such as 'silly putty' or
urea formaldehyde resin (suggested by the British Royal Aircraft
Establishment), in much the same manner as the deceleration strips above,
has been suggested. Problems would be excessive maintenance, susceptibility
to extreme weather conditions, and decentering tendencies.

10. Landing Slot

        The suggestion has been made that some bullet-shaped protrusion
beneath an aircraft could be engaged in a suitably shaped slot in the
runway so that positive centering and deceleration would result. Although
a really positive engagement with the runway would be advantageous, the
suggested system seems to be hazardous and unreliable.

C.   General Comments

        The suggestion that landings on elevated runways be made routinely
as arrested landings certainly seems controversial and appears to meet
with little favor from the air carrier industry. However, it seems never
to have received an objective consideration and perhaps it should. In
addition to its contribution to solution of the emergency containment problem
it could also permit shorter runways and allow landing in higher crosswinds,
thus leading to a considerable overall economic advantage.

        An enormous body of experience has been accumulated concerning
arresting landings. According to a study by the National Safety
Foundation, [3] the reliability of arresting gears in land based operations
is better than 99%.

        The main objection to the arrested approach has been that passengers
may not accept the decelerations experienced. There is little information on
this, because the Navy is operating either combat aircraft with fully
restrained crews or passenger aircraft with rearward facing seats.
However, during arrestment tests conducted for the FAA on a Convair 240
(C131B), decelerations of up to 0.65 g were experienced, and, as reported
in Reference (4), "the general consensus of the passengers was that the
deceleration was surprisingly gentle, quieter, and smoother than being
stopped by reversed propellers or reversed thrust." Similar tests were
also carried out on a Boeing 720 with conventional airline seats, as
reported in Reference (5), with decelerations of up to 1.0 g.

        Meanwhile, decelerations in unarrested landings may run over 0.4 g
for example 0.42 g were experienced during landing tests of the Boeing
737 and 0.43 g during test on the Breguet 941 (see letters (d) and (f)
of the Appendix).

D.   Summary of Concepts Evaluation

The problem of overshoot seems to be well under control. Standard arresting gears with nylon net barriers for a backup appear adequate for emergency uses of this type.

The feasibility of routinely arrested landings should be investigated. It appears to have some economic advantages, poses little technological or operating difficulty. However, the major issue is that of passenger and pilot acceptance. A thorough study of the distributions of motions to be expected from arrested landings has never been made - at least under conditions where a reasonable runout after engagement can be permitted to make the operation as smooth as possible. Also, criteria for acceptable motions, the formulation of which is one of the primary objectives of the overall University of Virginia program, do not yet exist.

Returning to emergency arrestments the matter of side containment requires considerable study. Fences or some type of stable edge barrier seems feasible as a last resort for low velocity encounters, but to rely on such devices to be successful at high velocities will require a large advance in the state-of-the-art with little expectation of success at reasonable cost.

The following four hook and cable systems were judged worthy of further analysis, in the order of preference listed, and these are all considered in more detail in the next section.

1.   Standard Arresting System (e.g., All-American Engrg. Co.)
2.   Shielded Arresting System (FAA concept)
3.   Side Arresting System (UVa modified NASA concept)
4.   Side Arresting System (NASA concept)

TABLE I. COMPUTER PROGRAM FOR ARRESTED LANDING STUDY

LANGUAGE

BASIC on Hewlett-Packard (UVA)
and CDC 6400 (UCS Time Sharing)

AIRCRAFT MODEL

Three degrees of freedom in
horizontal plane; no skid or
cornering of main wheels;
no aerodynamic drag.

Data used in analysis:

Mass

Moment of Inertia

Distance, C.G. to main gear

Distance, C.G. to hook

Fixed drag and moment to
simulate gear failure

Two hook options, see below

ARRESTING GEAR MODEL

Water twister with variable drum
radius according to tape thickness;
fixed rotary damping; no drum
inertia or tape stretch; no cable
dynamics.

Data used in analysis:

Tape Thickness

Damping rate

CONFIGURATION

Two options:

(i) Standard − Water twister at
each side of runway

(ii) Side gear − One water twister,
and one traveling car

SECTION IV

ANALYSIS OF SELECTED SIDE ARRESTMENT SYSTEMS

A.   Introduction

Four hook and cable arresting gear systems were studied further
by representing them in a digital computer analysis, using a BASIC
program. The systems studied were those selected from the concept
evaluation reported in the last section. The results of the computer
studies are reported in this section.

Essential features of the computer programs used are given in
Table I. Details are available from the author on request.

The assumed runway, which is based on data supplied by Merrill [6]
and is in line with FAA criteria, is shown in Figure I. It has a total
width of 300 feet, to accommodate landing mishaps, and is equipped with
nylon net crash barriers.

In the simplified model used in making the calculations it was
assumed that there were no pilot inputs such as braking, reverse thrust,
or steering of any form. Very little data exists which would enable
a model of pilot reaction to be formulated. Thus to attempt to include
it would not be valid within the scope of the present study.

B.   Concept I - Standard Arresting Gear Study

The standard system, consisting of two water twisters located 300
feet apart on the edges of the building was studied. A layout of the
system is shown in Figure 2 which conforms generally to suggestions made
by Merrill of All-American Engineering. In the figure, the cables at
each end of the runway are only 300 feet apart, because a minimum length
runway of 1500 feet was shown, assuming an 1800 foot building with 150
foot overshoots at each end. More probably runways will be up to 2000
feet long, and the separation between the cables would then be 800 feet.
However, the purpose of this study was to investigate the action of the
arresting gear, and not to recommend runway layouts.

FIGURE 1. ASSUMED RUNWAY LAYOUT

MODIFICATIONS: INCREASE PRIMARY SURFACE WIDTH TO 300'

ADD 50' TO EACH END

ADD BARRIERS
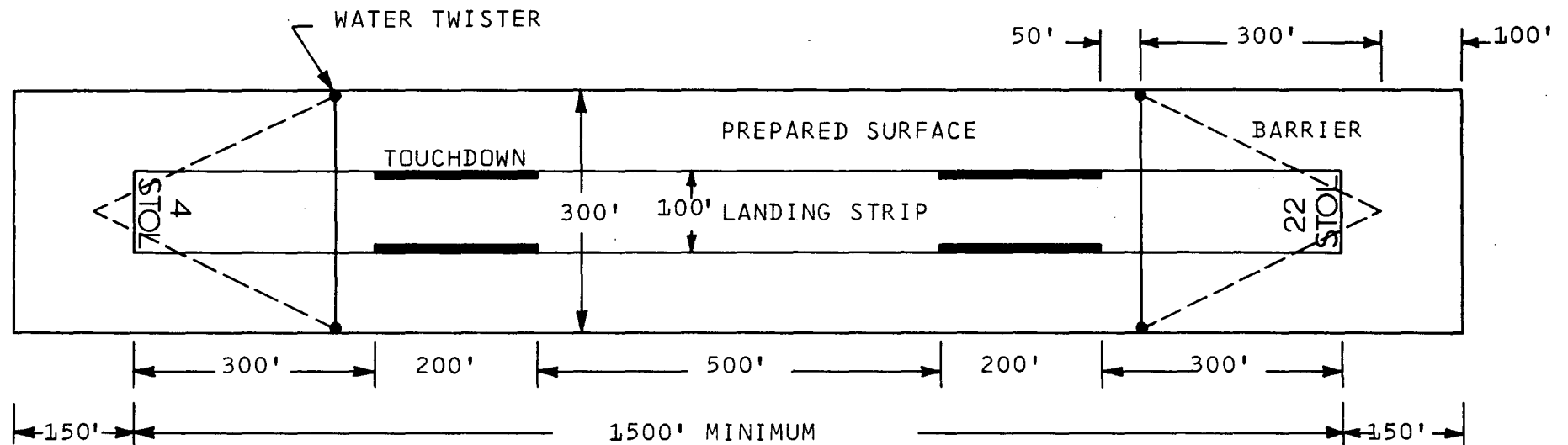
FIGURE 2. CONCEPT I--STANDARD SYSTEM

<u>SOURCE</u>: REFERENCE (6)

<u>ADDITIONAL FEATURES</u>: WARNING STRIPS AND ARRESTING GEAR AT EACH END OF LANDING STRIP.

<u>OPERATIONAL MODES</u>: A. EMERGENCY ONLY--PILOT DROPS HOOK TO ENGAGE SECOND WIRE IN EMERGENCY; BARRIER IS BACKUP.

  B. OPTIONAL--PILOT MAY LAND WITH HOOK DOWN; SECOND WIRE AND BARRIER ARE BOTH BACKUPS.

  C. MANDATORY--PILOT ALWAYS LANDS WITH HOOK DOWN.

<u>DESIGN RESTRICTIONS</u>: DECELERATION MUST BE ACCEPTABLE TO PASSENGERS; OPTIONS ARE:
  (i) FIXED TWISTER SETTING, ACCEPT VARIABLE RUNOUTS TO KEEP HIGHEST g TO ABOUT 0.5
  (ii) SET TWISTER FOR EACH LANDING
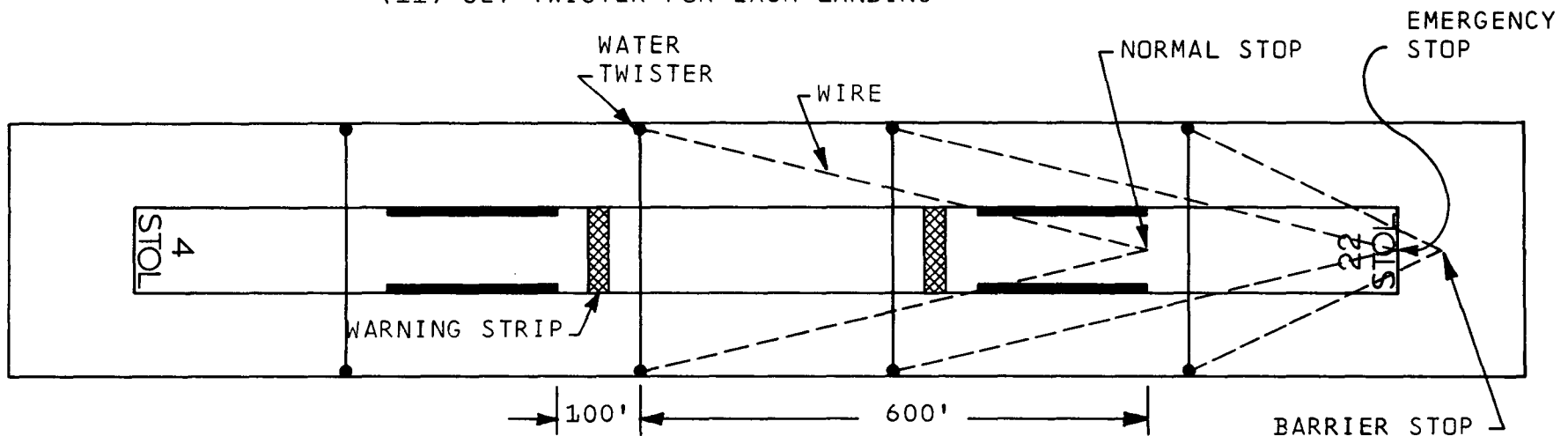
NOTE: 600' STOP CAN BE ACHIEVED WITH LESS THAN 0.4 g PEAK AT 65 KNOTS, ASSUMING TWISTER SET FOR AIRCRAFT SPEED AND WEIGHT

The decelerations computed during a typical arrestment down the center of the runway are shown for a Breguet 941 in Figure 3. The aircraft was assumed to weigh 39,000 lb., and to contact the arresting gear at 57 knots. The damping in the water twisters was iterated until the aircraft came to a stop in 600 feet. This setting was adopted as a standard for later investigations. An efficiency of 73% was computed for this case, based on the peak deceleration of 0.38 g (literally $\dot{V}/g$). This value is shown also on the composite plot in Figure 4, together with curves for 75% efficiency, and point values supplied by Merrill. It must be realized that different water twister settings must be made to achieve these values. For example, to stop a 78,000 lb. aircraft in 600 feet, one would need twice the damping rate used in Figure 3, also for the same setting, the heavier aircraft would run about 862 feet with a lower peak deceleration while a 10,000 lb. aircraft would stop in about 288 feet, but would experience a .87 g deceleration. Calculations were made to determine the stopping point (X,Y), assuming various values for the initial distance (Y_0) from the centerline, and initial heading angle θ_0. Some results are shown plotted in Figure 5 for an aircraft typical of the Breguet 941, whose characteristics are also shown on the figure. Two assumptions were made: (1) that the cable does not slip through the hook; and (2) that it slips freely. Actually, it is subject to a friction force, and does not slip until this reaches the breakout value thus the two assumptions should bracket the more exact solution. It will be noted that there was slightly more decentering tendency when hook slip was assumed.

It is interesting to compare these results with what would happen if the aircraft stopped in 600 feet in a straight line. In this case, we would have

$$X = 600 \cos \theta_0 \qquad\qquad\qquad (1)$$

$$Y = 600 \sin \theta_0 + Y_0 \qquad\qquad\qquad (2)$$

(see Figure 5 for definitions)

15

FIGURE 3. CONCEPT I - g VS. RUNOUT

DATA SHOWN: DECELERATION IN g'S FOR A 39000 LB. AIRCRAFT AT 57 KNOTS STOPPED IN 600 FEET DOWN CENTER OF RUNWAY (OFF-CENTER AND OUT-OF-LINE LANDINGS INTO SAME GEAR SHOWED SLIGHTLY HIGHER)

$$\text{EFFICIENCY} = \frac{(V\ \text{KNOTS} \times 0.298)^2}{2 \times \text{RUNOUT (FT.)} \times (\dot{V}/g)_{MAX}} = 63\%$$

$(\dot{V}/g)_{MAX} = 0.38$

$\dot{V}/g$

BREGUET 941
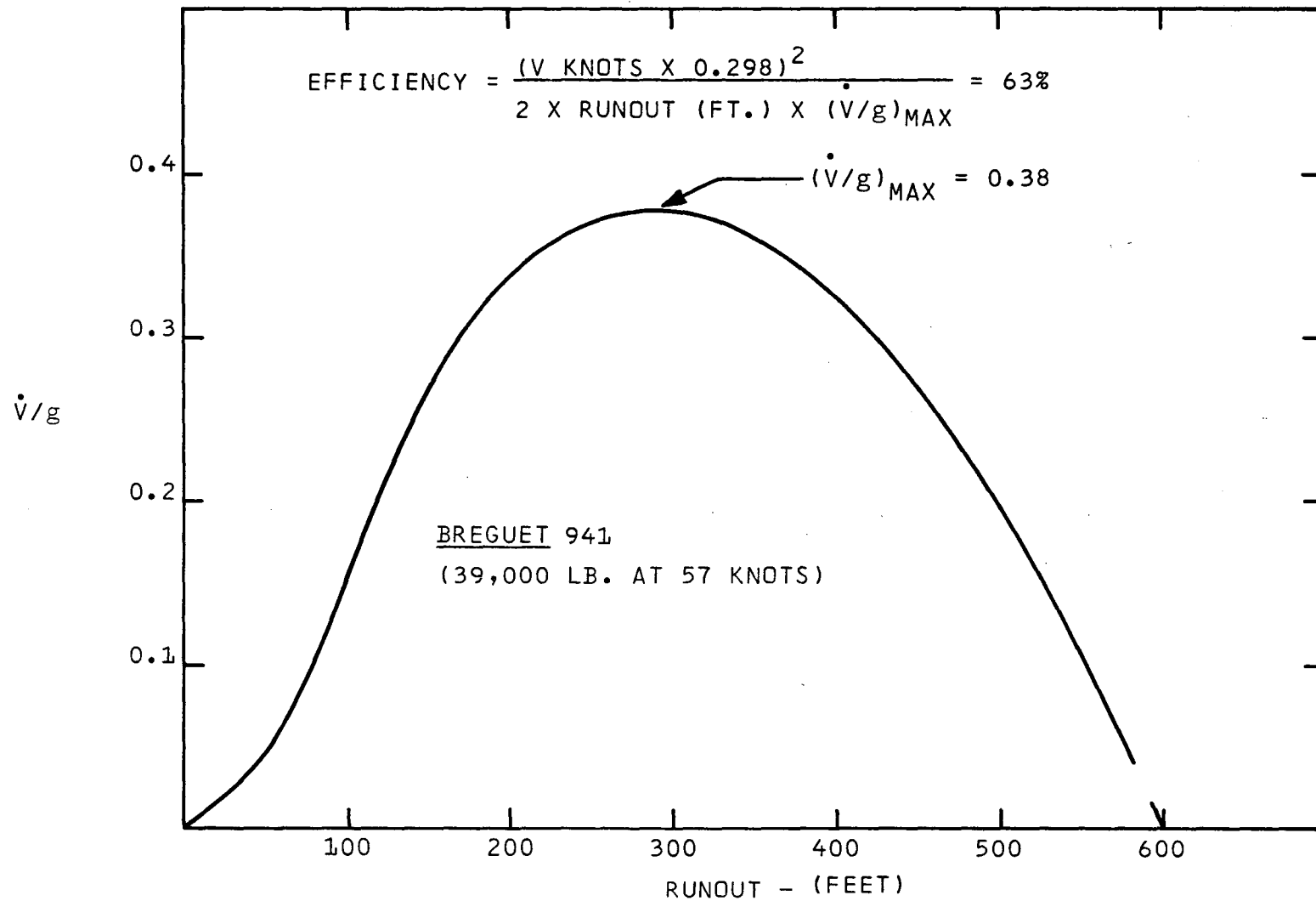(39,000 LB. AT 57 KNOTS)

RUNOUT - (FEET)

FIGURE 4.   CONCEPT I – PEAK g VS. RUNOUT FOR VARIOUS SYSTEMS
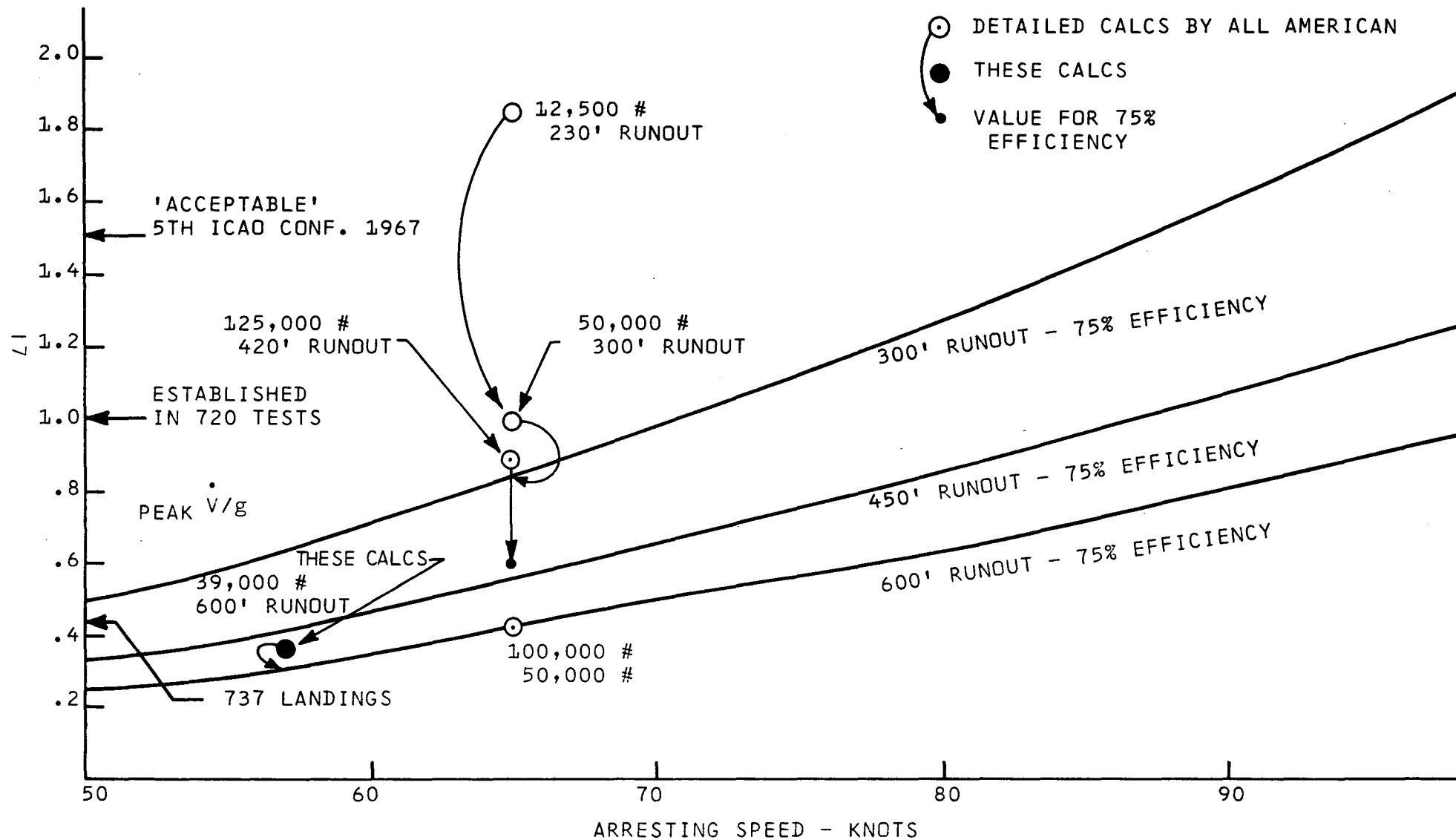
FIGURE 5. CONCEPT I - OFF-LINE TOUCHDOWNS

<u>DATA SHOWN</u>: CALCULATIONS OF STOPPING POINTS FOR VARIOUS INITIAL HEADINGS AND DISTANCES OF
HOOK ENGAGEMENT POINT FROM CENTERLINE

<u>ASSUMPTIONS</u>: LANDING SPEED   57 KNOTS
  WEIGHT   39,000 LB.
  M OF I   400,000 SLUG FT^2
  DISTANCE, C.G. TO MAIN GEAR   1.00 FT.
  C.G. TO HOOK   3.24 FT.

APPROXIMATES BREGUET 941

OPTIONS   ⊙ WITH HOOK SLIP

 ✕ NO HOOK SLIP

y_0 = DISTANCE-ENGAGEMENT PT.
TO CENTERLINE (FEET)

INITIAL HEADING=θ_0=0°

RUNWAY
CENTERLINE

EDGE OF
LANDING
STRIP

EDGE OF
PREPARED
SURFACE

10°

20°

x = RUNOUT DOWN RUNWAY

y = LATERAL RUNOUT (FEET)
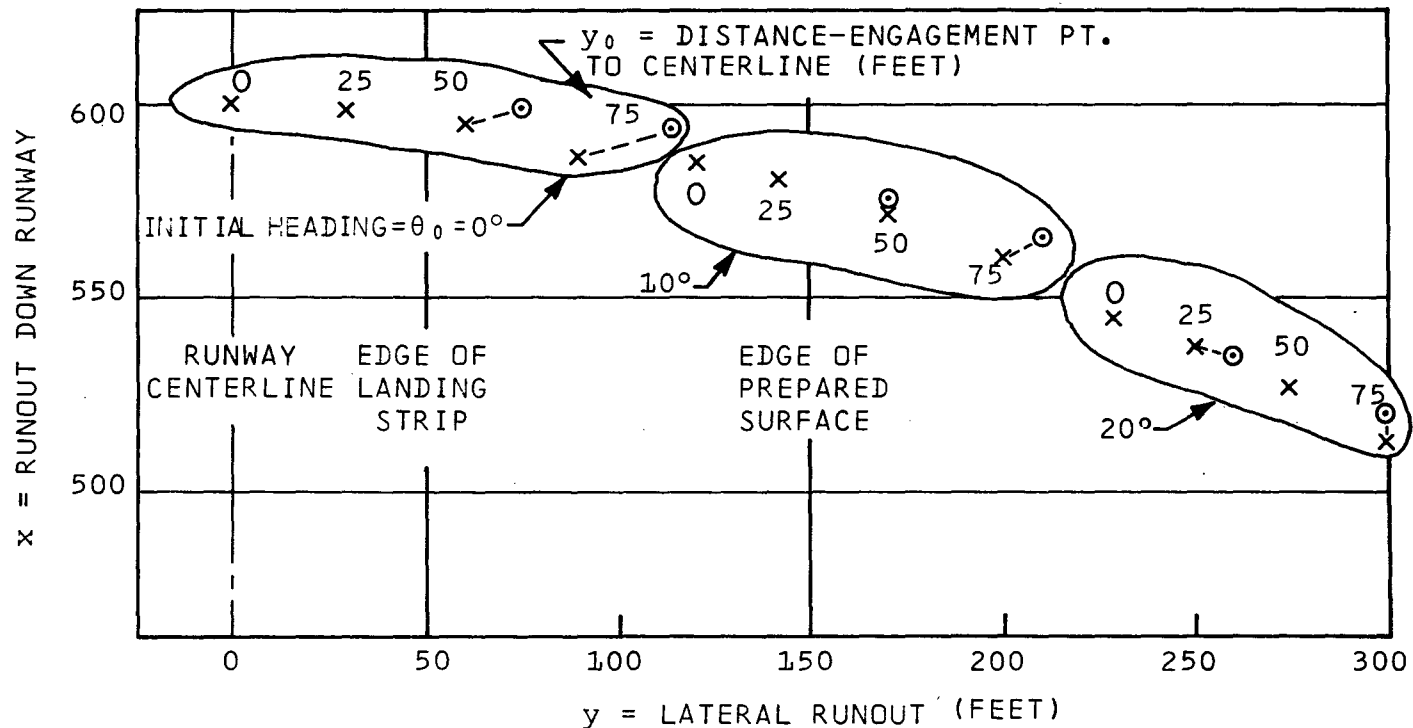
For small angles, Eq. (2) can be approximated by:

$$Y = 10.5 \, \theta_0 + Y_0 \tag{3}$$

The results of the calculations shown previously, for no hook slip, but including more initial heading angles, are shown in Figure 6. These approximately fit the formula:

$$Y = 11.73 \, \theta_0 + 1.16 \, Y_0 \tag{4}$$

It is therefore apparent that there is a small decentering tendency with the standard gear. For example, touchdown (Y_0) at 75 feet from the centerline at a 10° angle (θ_0) results in a final stop (Y) at 204 feet from the centerline, whereas a straight stop would give 180 feet, which is 24 feet less.

C.   Concept II - FAA (Shielded) Arresting Gear

This system resembles the standard system except that it is shielded over the primary landing strip, which is 100 feet wide, so that the aircraft can land with hook down, but will not engage the cable so long as it stays on the strip. It is shown in Figure 7. Note that many cables are required, and that the water twister is set higher than normal, actually a value of three times higher was used in the calculations.

Results of calculations for the previously mentioned Breguet 941 are shown in Figure 8, but with the additional assumption that various degrees of landing gear damage had occurred, represented by equivalent values of the coefficient of friction between one wheel and the runway, the other being assumed to be normal. It will be noted that all landings were contained, and that the peak deceleration was 0.76 g in the undamaged case. In the latter case, the aircraft stopped at 80 feet from the centerline (Y) and 320 feet from engagement (X), whereas a straight stop would have occurred 78 feet from the centerline. Some variations on these conditions are summarized in Table II below.

FIGURE 6. CONCEPT I - CORRELATION OF OFF-LINE TOUCHDOWNS

<u>AIRCRAFT</u>: APPROXIMATES BREGUET 941

<u>CONDITIONS</u>: NO HOOK SLIP
ENGAGEMENT AT 57 KNOTS

y_0 = DISTANCE ENGAGEMENT

POINT TO CENTERLINE (FEET)
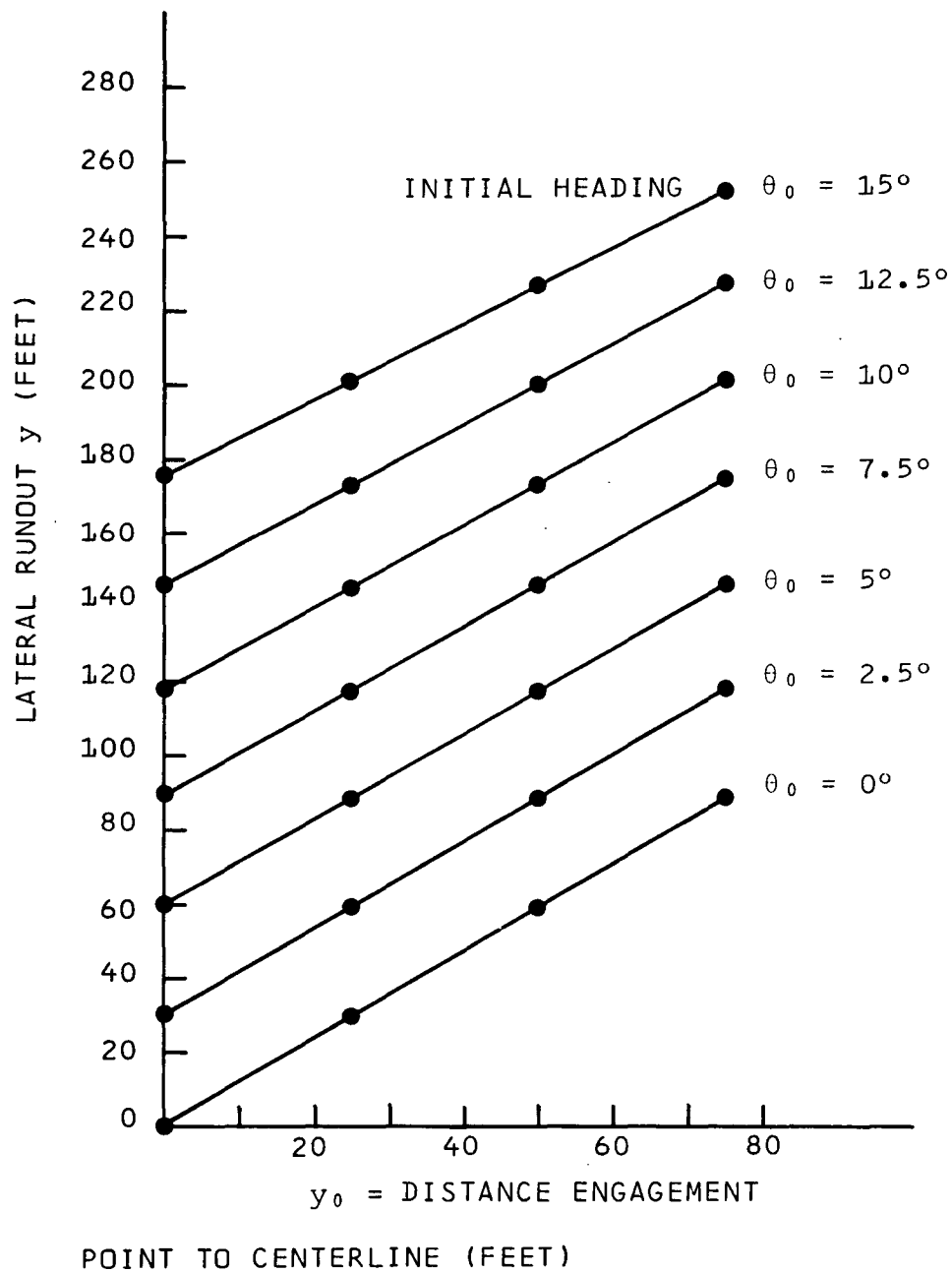
FIGURE 7. CONCEPT II — FAA ARRESTING SYSTEM

ADDITIONAL FEATURES: NUMBER (UNDETERMINED) OF ARRESTING WIRES DOWN RUNWAY, BUT SHIELDED
ACROSS LANDING STRIP.

WATER TWISTER SETTINGS FOR ARRESTMENT IN ABOUT 300'(3 TIMES NORMAL SETTINGS)

OPERATIONAL MODE: PILOT ALWAYS LANDS WITH HOOK DOWN. WIRE ONLY ENGAGED IF AIRCRAFT
LEAVES LANDING STRIP.

DESIGN RESTRICTIONS: LIMITED TO ACCEPTABLE EMERGENCY DECELERATION--ABOUT 1.5 g.
SINGLE SETTING WOULD ACCOMMODATE UP TO 85 KNOTS FOR 300' RUNOUT,
WIDE RANGE OF AIRCRAFT WEIGHTS AT LOWER SPEEDS.

├── 300' ──┤

SHIELDED OVER
LANDING STRIP

FIGURE 8. CONCEPT II — ONE GEAR DAMAGED

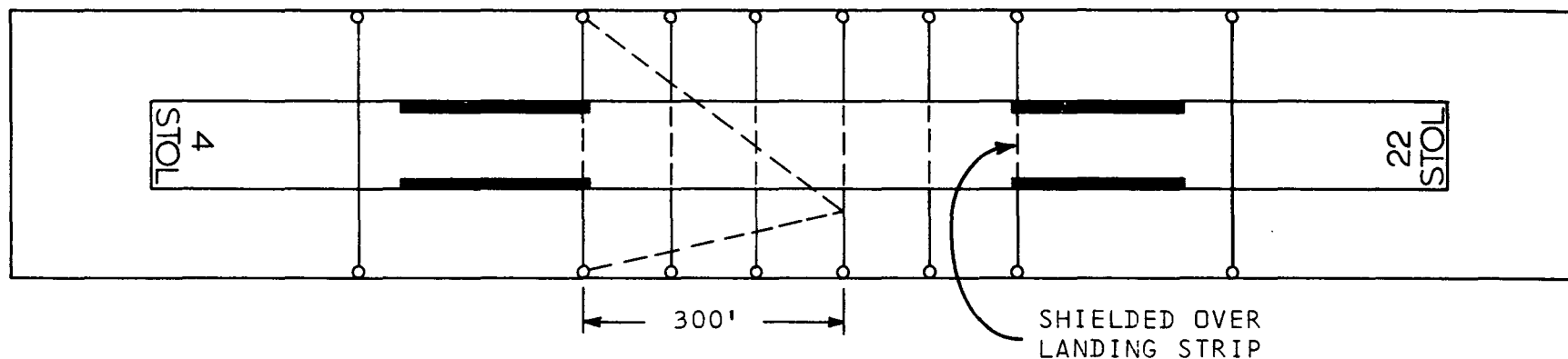DATA SHOWN: CALCULATIONS OF STOPPING POINTS FOR AN AIRCRAFT ENGAGING GEAR AT EDGE OF LANDING STRIP (50 FT. FROM CENTERLINE) AND 5° HEADING; ONE GEAR DAMAGED; VARIOUS VALUES FOR COEFFICIENT OF FRICTION μ.

ASSUMPTIONS: BREGUET AT 57 KNOTS.
WATER TWISTER SETTING 3 TIMES VALUE FOR CONCEPT I.
WHEELS 5.9 FEET FROM AIRCRAFT CENTERLINE. (11.8 FT. TRACK.)
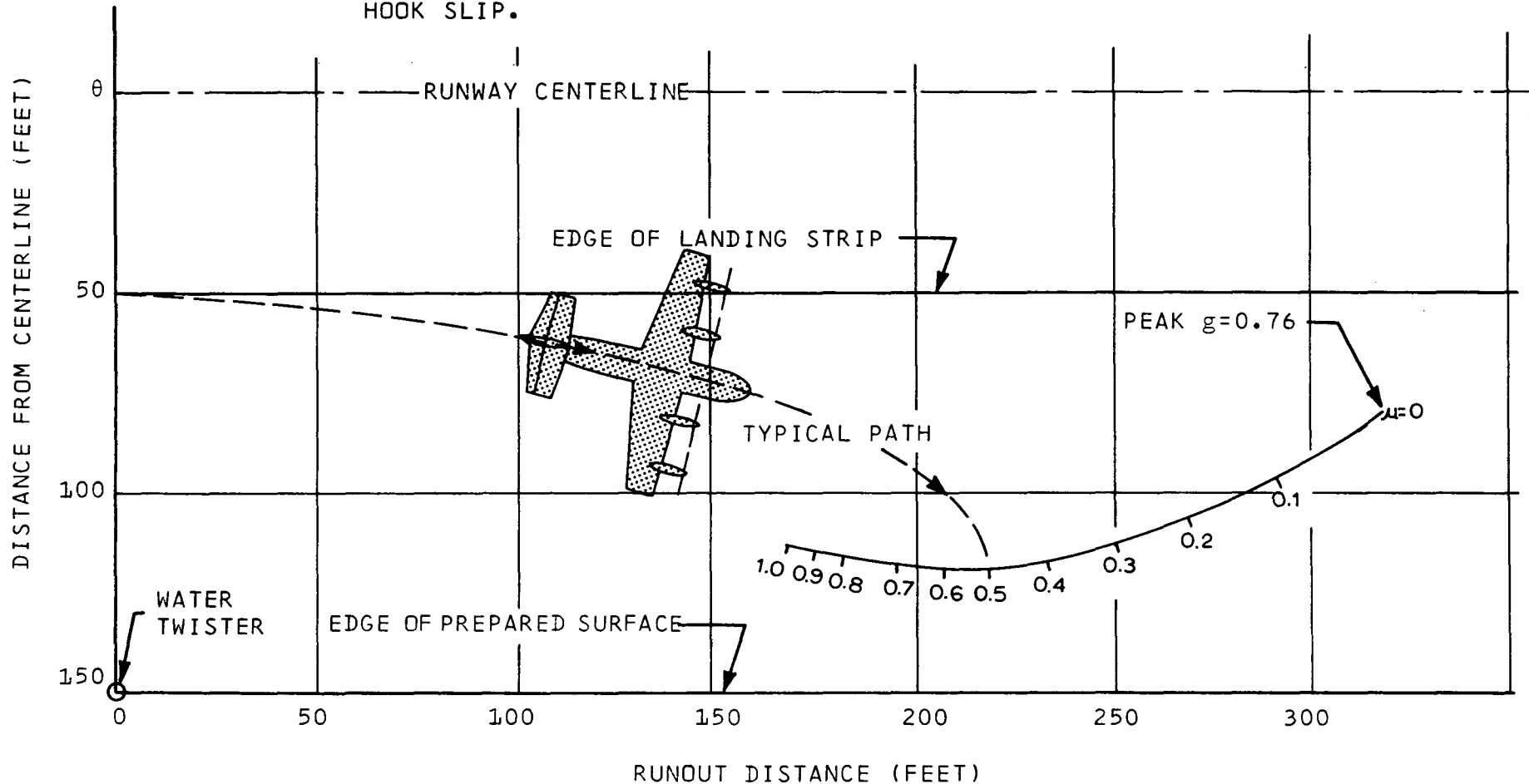HOOK SLIP.

TABLE II. STOPPING POINTS FOR AIRCRAFT USING CONCEPT II

$$(\Theta_0 = 5, \quad Y_0 = 50 \text{ ft.})$$

Aircraft Weight	Initial Velocity Knots	Runout X ft.	Lateral Runout Y ft.	Max $\dot{V}/g$
19500	80.6	266	74	1.8
19500	40.3	189	67	.68
39000	57	320	80	.76
78000	80.6	567	118	.78
78000	40.3	383	92	.31

All of these landings were contained satisfactorily, and only one exceeded the tentative deceleration limit of 1.5 g.

Because the Breguet 941 landing gear is unusually close to the center-line, the damaged gear calculations were repeated with twice the wheel track. The results, which showed the aircraft just reaching the edge of the building under the worst conditions, are plotted in Figure 13, where they are compared with the results of similar calculations for Concept IV.

D.   Concept III - NASA/Langley (Side) Arresting Gear

This system is shown in Figure 9, and is largely conceptual, in that no such system is known to have been developed to date. It relies on a car running on a track alongside the landing strip to maintain a laterally directed cable load. In conjunction with a hook mounted ahead of the C.G., this results in a centering force. A typical computer landing is shown in Figure 10, resulting in the aircraft crossing over the building, and running off the far side. Similar, though less violent, results were obtained when the hook was moved back towards the C.G.

E.   Concept IV - UVA-Modified NASA (Side) Arresting Gear

This system, which is essentially an inversion of the NASA system, is

FIGURE 9.   CONCEPT III - NASA/LANGLEY SIDE ARRESTING SYSTEM

SOURCE: REFERENCE (2).

ADDITIONAL FEATURES: NUMBER (UNDETERMINED) OF ARRESTING WIRES TO EITHER SIDE OF RUNWAY;
                      WATER TWISTER ON OUTER EDGE; CAR RUNNING ON TRACK ON SIDE OF LAND-
                      ING STRIP; PROVISION FOR CARS TO PASS EACH OTHER.

OPERATIONAL MODE: REQUIRES SPECIAL HOOK AHEAD OF C.G.
                   PILOT LANDS WITH HOOK DOWN.
                   WIRE ONLY ENGAGED IF AIRCRAFT LEAVES LANDING STRIP.

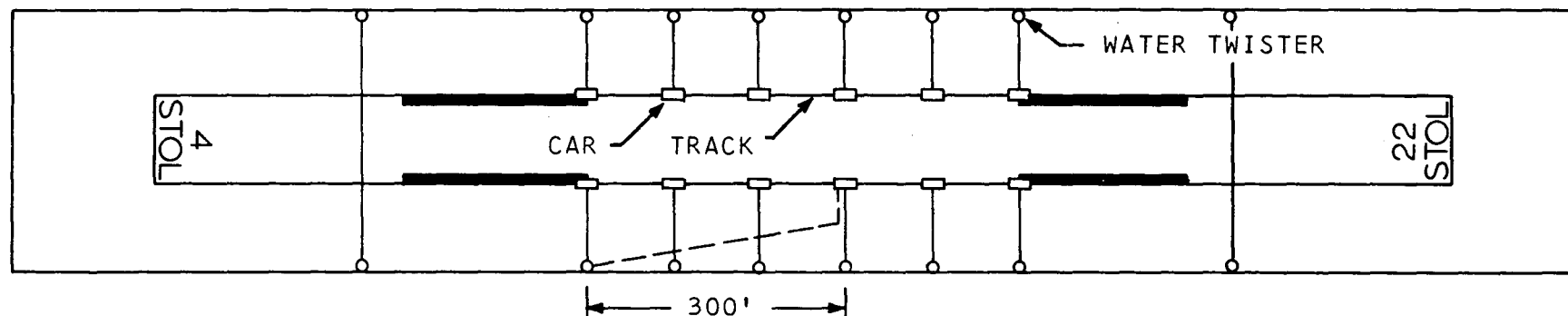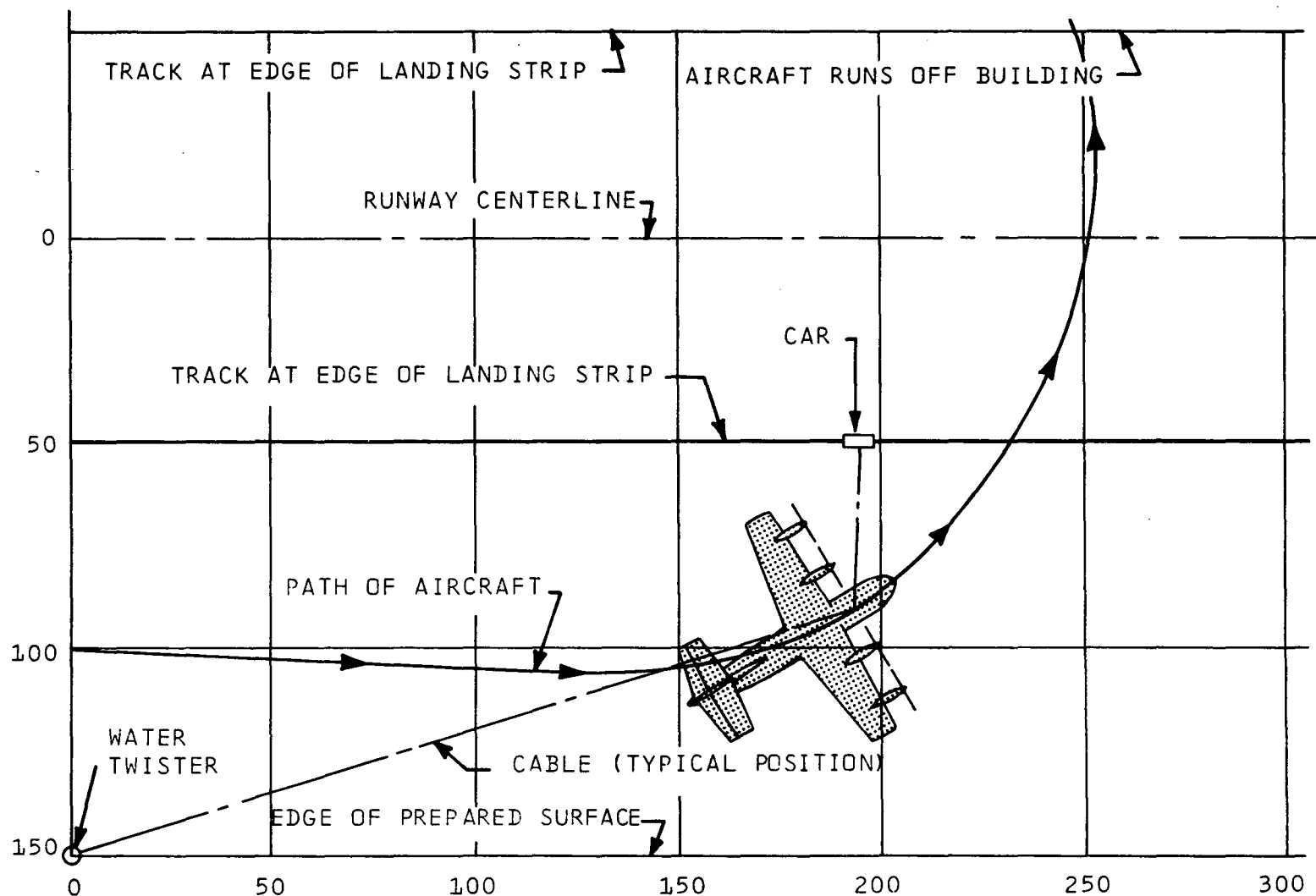DESIGN RESTRICTIONS: AS FOR FAA CONCEPT II.

24

FIGURE 10. CONCEPT III - LANDING RUNOUT

DATA SHOWN: CALCULATION OF LANDING RUNOUT FOR AN AIRCRAFT ENGAGING GEAR AT CENTER OF PREPARED SURFACE (100 FT. FROM CENTERLINE) AND 5° HEADING.

ASSUMPTIONS: BREGUET AT 57 KNOTS; HOOK 7.52 FT. AHEAD OF C.G.
WATER TWISTER SET AS FOR CONCEPT II CALCS.

shown in Figure II. Calculations were made for an aircraft reaching the edge of the primary landing strip at a 5° heading angle with varying gear damage, and also for an undamaged aircraft assuming other initial conditions. These are all shown plotted in Figure 12. It will be noted that all landings were contained, but that the final aircraft heading reached about 60° to the centerline. It would be interesting to see what effect applications of brakes would have on this.

Because of the rather narrow track on this type of aircraft, calculations on both this concept, and on Concept II, were repeated assuming twice the track, but similar landing gear damage. The results are shown comparatively in Figure 13. They indicate nearly identical lateral runouts at coefficients of friction of 0.5, but much greater centering for smaller coefficients of friction with the UVA Concept IV than with the FAA Concept II. A tentative conclusion would be that the UVA system provides excess centering when it is not needed. However, neither system was optimized.

A further point, which did not show up here, is that should both gears be damaged, the UVA concept IV system would tend to throw aircraft off the building. The centering tendency noted is due to the cornering force on the tires, but at least one must be intact for this to occur.

F.   Summary of Analyses

It is concluded that the FAA system should be adequate to handle most contingencies that might arise, and that there is a distinct promise that it can handle all types of aircraft with one setting, since it is only required in emergencies. A 300 foot wide prepared surface seems to be essential.

By comparison, the UVA-Modified NASA system, with self centering features, does not appear to offer any other great advantage, although it might be considered a backup system.

The standard arresting gear system does not contain aircraft as efficiently as the FAA system, mainly because it must be set to lower decelerations. It appears unlikely that a satisfactory single setting could be found for the standard system acceptable to the passengers of all the types of aircraft which might land.

These and other points are summarized in Table III.

26

FIGURE 11. CONCEPT IV - UVA-MODIFIED NASA/LANGLEY ARRESTING SYSTEM

SOURCE: ADAPTATION OF NASA CONCEPT.

ADDITIONAL FEATURES: AS IN NASA SCHEME, BUT WITH CARS AND WATER TWISTERS EXCHANGED.

OPERATIONAL MODE: REQUIRES NORMAL HOOK.
PILOT LAND WITH HOOK DOWN.
WIRE ONLY ENGAGED IF AIRCRAFT LEAVES LANDING STRIP.

DESIGN RESTRICTIONS: AS FOR FAA CONCEPT II.
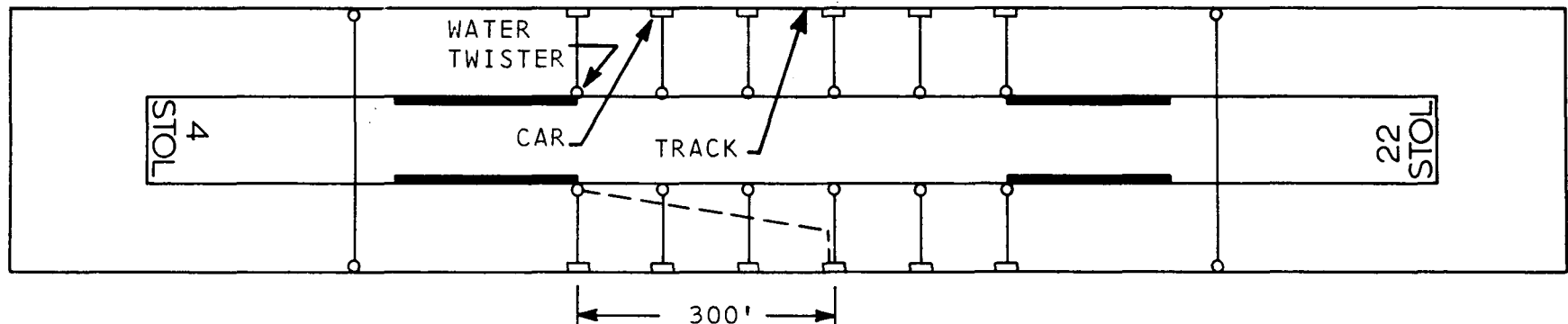
FIGURE 12. CONCEPT IV - LANDING RUNOUT

DATA SHOWN: CALCULATION OF PATHS FOR SEVERAL ENGAGEMENT POINTS AND INITIAL HEADINGS; ALSO, STOPPING POINTS FOR AIRCRAFT FOR VARIOUS VALUES OF COEFFICIENT OF FRICTION μ.

ASSUMPTIONS: BREGUET 941 AT 57 KNOTS.
WATER TWISTER SETTING AS FOR CONCEPT II.

RUNWAY CENTERLINE

DISTANCE FROM CENTERLINE (FEET)

RUNOUT DISTANCE (FEET)
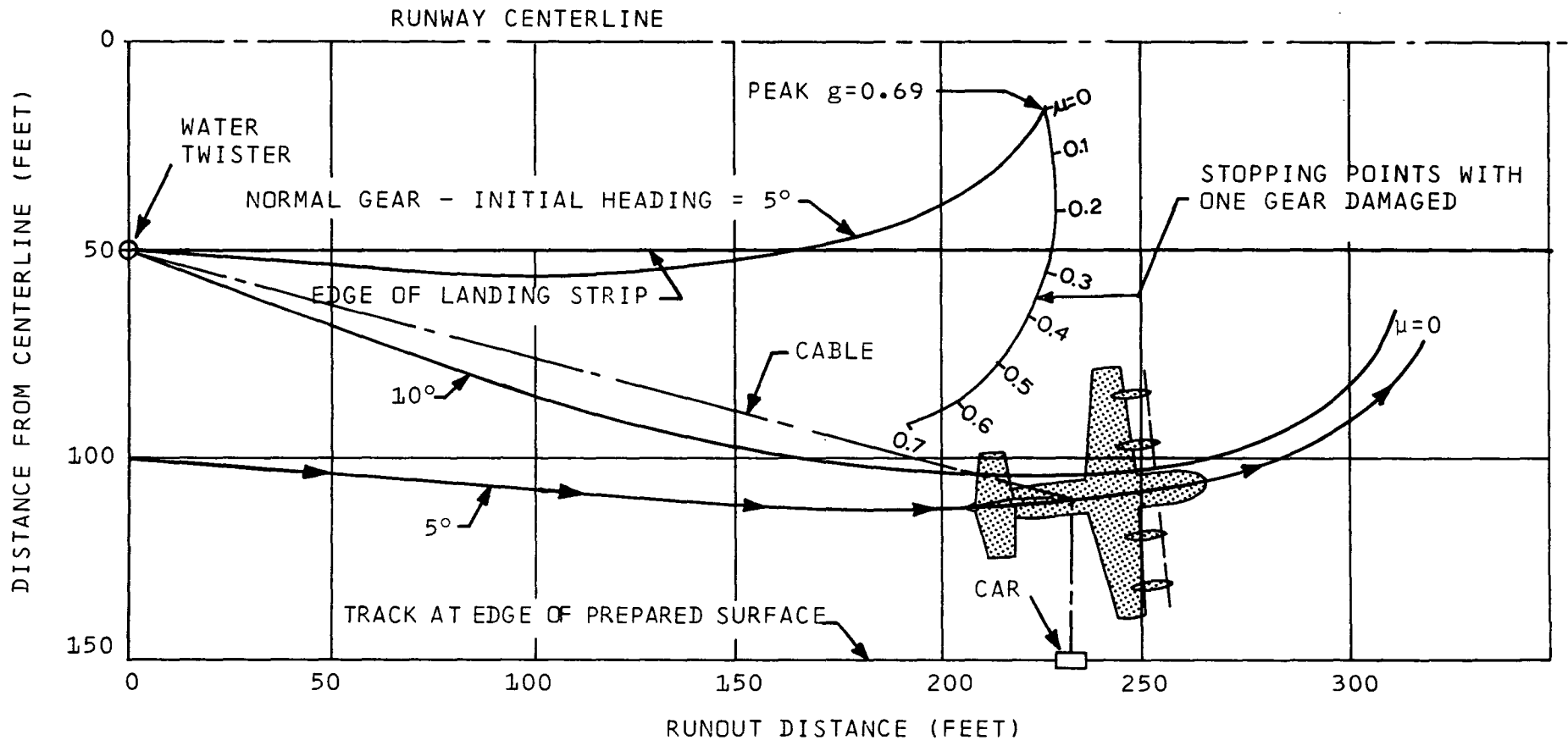
FIGURE 13.   CONCEPTS II & IV COMPARISON

ASSUMPTIONS: BREGUET AS IN FIGURE 8 BUT WITH 23.6 FT. TRACK
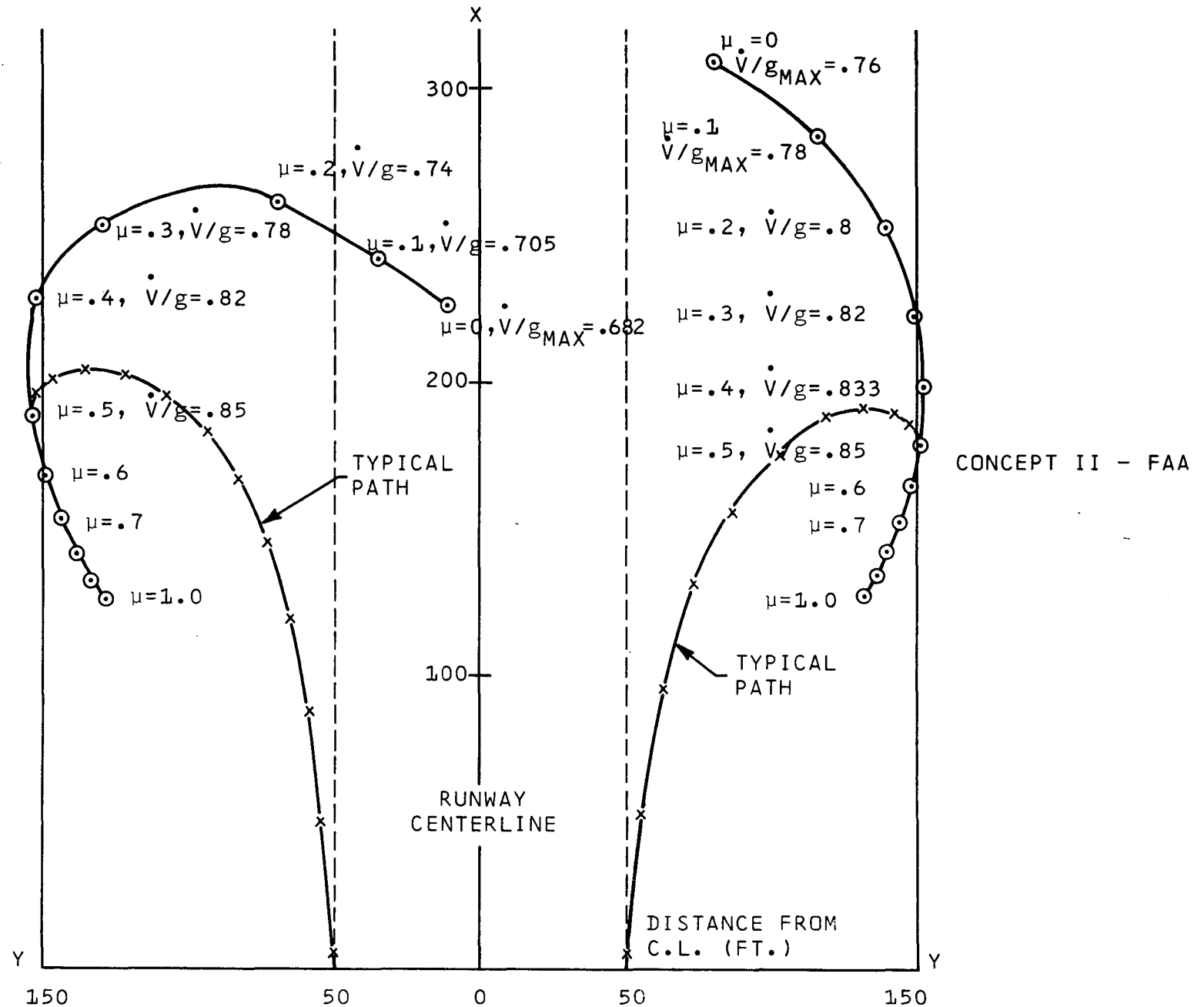
TABLE III. SUMMARY OF ARRESTED LANDING STUDIES

Concept	Advantages	Disadvantages
I Standard	Proven state of the art	No centering Limited by passenger acceptance to about 0.4g. About 600 ft runout at 57 knots if water twister set for each aircraft More than 600 foot runout to accommodate all aircraft without setting change.
II FAA	Little change in state of art Could be designed to accommodate wide range of aircraft without setting Would handle all types of gear damage	No centering
III NASA	Would handle aircraft with both gears damaged	Needs special hook installation on aircraft Excessive centering – may throw aircraft off opposite side Car concept not developed
IV UVA	Uses standard hook installation Good centering Effective control of aircraft with one gear damaged	May not control aircraft with both gears damaged Car concept not developed

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

A.   Conclusions

The following conclusions were reached as a result of the studies reported here and subject to the priority arbitrarily assigned to each characteristic.

1. The FAA proposed system as shown in Fig. 7, appears to
    be the superior system, for the following reasons:

    a. In comparison with the standard system, it has a greater
        arresting capability because considerably higher decelera-
        tions can be imposed when it only operates under emergency
        conditions;

    b. It appears possible to meet most weight and landing speed
        conditions with one setting, whereas the standard system
        would require resetting for each aircraft type; and

    c. In comparison with the UVA-modified NASA system, it shows
        equal capability under extreme landing gear damage conditions,
        as demonstrated in Fig. 8, although with little or no
        centering tendencies under normal conditions.

One serious disadvantage compared to the standard system is its greater cost, because an arresting cable would be required every 100 feet or so.

2. Despite the foregoing, it is believed that the UVA-modified
    NASA system is sufficiently promising that it should be retained
    as a conceptual backup system, until a definite decision is
    reached. More sophisticated studies, particularly including pilot
    reactions, may demonstrate the importance of its tendency to
    center.

3. Some form of curb is required. Development of an effective
    system, which will be more than a safety rail designed to
    reassure passengers, offers a serious challenge.

4. It has been more or less assumed a priori that existing arresting gear and nylon net barrier systems are adequate for the overshoot case. These would have to be designed so as to be readily adaptable to approaches from either end of the runway.

B.   Recommendations

It is recommended that future programs of study cover the following steps:

1. That a more comprehensive computer program be developed, in FORTRAN language. This program should meet the requirements set out in Table IV below.

TABLE IV. IMPROVEMENTS REQUIRED IN COMPUTER PROGRAM

ESSENTIAL	DESIRABLE
FORTRAN	
Aerodynamic Drag	Landing gear dynamics
Wheel Cornering and skid	Cable dynamics
Pilot model to apply brakes and steering	Hook dynamics
Cable stretch	
Water twister and car inertia	
Pick up cable at correct place	
Drop slack cable	
More realistic damage conditions	
Hook slip with friction	

ULTIMATE PROGRAM

Combine with flight approach model
Incorporate into statistical dispersion program.

2. That a FORTRAN computer program be developed to predict the landing approach path of an aircraft subject to lateral gusts and wind gradients, and including the control inputs from a

simulated pilot. Such a program has been under development
at UVA, but using BASIC language. Results would be used to
determine the statistical distribution of touchdown points.

3. That a flight test program of simulated roof-top landings be
    performed, using aircraft equipped with hooks operating on a
    ground runway marked to represent a roof-top STOLport. Such
    a program might be in two parts, as follows:

    a. Tests with any suitable aircraft to confirm the predicted
        behavior of the aircraft when arrested. Results of these
        tests could also be used to verify and refine the computer
        program.
    b. Taxi tests with a passenger aircraft, with passengers, to
        determine passenger reactions to the selected system, and
        thus to determine necessary limitations which must be
        imposed on various system characteristics to determine
        passenger acceptance.

4. That a comprehensive evaluation be made of the safety, economy
    and current technology aspects of different concepts, to
    aid in the final selection of a suitable system. This should
    include a survey, considerably enlarged over the survey reported
    here Safety standards should then be defined, and preliminary
    engineering with each concept should proceed to the stage that
    compliance with the safety standards is met or the concept
    is dropped. Finally, the overall costs and development time
    schedules of each of the systems should be obtained and used
    in making a final selection.

        This evaluation program should run concurrently with the
    others mentioned, so that the final selection of a system would be
    made with the advantage of having considered all suggested
    concepts, as well as all existing systems which might be available
    for the simulated landings.

        An example of the type of answer which might be obtained
    from this evaluation would be the required spacing for arresting
    gear cables using the FAA system.

5. That the approach and arrested landing computer programs be
    combined and used in a Monte Carlo analysis of the selected
    system. This would be a final safety evaluation, and would
    attempt to simulate day-to-day operations from a hypothetical
    STOLport. Its main purpose would be to provide a final
    safety evaluation of the selected system, as well as to
    provide necessary information on operational requirements for
    assistance in final layout and design of a runway and its
    safety equipment.

6. That the foregoing analyses be confirmed by laying out a
    completely simulated STOLport, and making landings with a
    suitable passenger aircraft, as a final evaluation of the
    system selected.

Information gained from the above program elements when combined with
quantitative data on passenger reactions to motion under various enviro-
mental and psychological conditions should provide new insight into the
feasibility of emergency or routine arrested landings on elevated structures.

REFERENCES

1. FAA, "Planning and Design Criteria for Metropolitan STOL Ports, A.C. No. IDS/5325, July 1970.

2. U. T. Joyner, Consultant, NASA Langley Research Center, Communication

3. "Survey and Evaluation of the Need for Runway Arresting Mechanisms for Commercial Air Carrier Operations," Flight Safety Foundation, Inc., April 1969.

4. FAA Report M-657A, "The Use of A Sheaffer Spring Type Arresting Hook as an Engagement Method for Arresting Large Jet Transports," prepared by All American Engineering Company, January 1962.

5. FAA Report M-788, Part I, "Development of Model 3500 Arresting Gear and Continued Development of Spring Hook for Commercial Aircraft," prepared by All American Engineering Company, January 1963.

6. Peter Merrill, All American Engineering. Co, Communication.

APPENDIX

A.   List of Recipients of Survey Letter

1. *Mr. F. deJersey
    The deHavilland Aircraft of Canada, Ltd.
    Downsview, Ontario

2.   Mr. J. W. Hughes
    Canadair Ltd.
    P.O. Box 6087
    Montreal, 9, PQ

3. *Robertson Aircraft Corporation
    Bellevue Airfield
    15400 Sunset Highway
    Bellevue, Washington 98004

4.   Mr. John B. Rettaliata
    Grumman Aircraft Engineering Corporation
    Bethpage, Long Island, New York 11714

5. *Wren Aircraft Corporation
    Meacham Field
    P.O. Box 4115
    Fort Worth, Texas 76106

6. *Custer Channel Wing Corporation
    604 North Grand
    Enid, Oklahoma 73701

7.   Richard J. Davis
    McDonnell Douglas Corporation
    P.O. Box 516
    St. Lousi, Missouri 63166

8. *Eastern Air Lines, Inc.
    10 Rockefeller Plaza
    New York, New York 10020

9.   New York Airways, Inc.
    P.O. Box 426
    La Gaurdia Airport Station
    Flushing, New York 11371

10. *United Air Lines, Inc.
    P.O. Box 66100
    Chicago, Illinois 60666

11. *American Airlines, Inc.
    633 Third Avenue
    New York, New York 10017

12.   National Airlines, Inc.
    P.O. Box 2055
    Airport Mail Facility
    Miami, Florida 33159

13. *Richard D. FitzSimmons
    The Boeing Company
    Commercial Airplane Div.
    P.O. Box 707-BDF
    Renton, Washington 98055

14. *All American Engineering Co.
    Wilmington, Delaware

15.   Aerazur Construction
    Aeronautique of Paris
    Paris, France

16. *Mr. Harry Scott
    5546 West 122nd Street
    Hawthorne, California 90250

17. *Dr. Gilbert De Vore, Pres.
    De Vore Aviation Service Corp.
    125 Mineola Ave.
    Roslyn Heights, N.Y. 11577

18.   Dr. Edward F. Blick, Prof.
    Aerospace and Mechanical Engr.
    School of Aero. and Mech. Engr.
    University of Oklahoma

19. *Federal Aviation Adm.
    800 Independence Avenue
    Washington, D.C. 20590

20.   Capt. C. Ewing
    Bio. Engineering
    N.A.M.R.L.
    Pensacola, Florida 32512

        *   Reply Received

B.   Contents of Survey Letter

Gentlemen:

Under an existing National Aeronautics and Space Administration Grant, the University of Virginia is undertaking a study of the ride qualities of STOL aircraft, and their influence on passenger acceptance of this mode of transportation. The NASA Program Monitor for this grant is Mr. Harleth Wiley, of the NASA Langley Research Center.

I am working with Professor John Kenneth Haviland of the University's Department of Aerospace Engineering and Engineering Physics on a project entitled "Elevated STOL-Port Landing Studies." The project is concerned with the extent to which ride-comfort requirements in STOL aircraft might influence the design of elevated STOL-Ports. Since safety requirements will doubtless have a major impact on this, it is highly probable that safety and ride comfort will interact. For example, if a decision were made that all landings were to be arrested to solve the containment problem (i.e., to avoid accidents in which the aircraft might fall off the side of a building), then the tolerance of the typical passenger to deceleration would have an effect on runway dimensions, hence on the design fo the STOL-Port.

Because the method of containment is not yet known, we intend to consider as many concepts as possible. The studies we plan should help to select it. We are therefore soliciting ideas on which landing system concepts might be based, in order that no promising idea might be over-looked. We plan to evaluate each of them as to safety, practicality, and economics, and then to carry out more detailed analyses on the most attractive of them.

It would be greatly appreciated if you would advise us of any concepts pertaining to the containment problem on elevated landings, and also any relevant references....actual copies if possible.

In addition to concepts, we are in desperate need of measured and qualitative data relative to the landing environment. In particular, mean and peak decelerations during heavy braking on arrested landings are needed. Also data regarding passenger reaction to this environment (i.e., high deceleration) is needed so that an upper limit may be set for arrested landings.

In summary, we are seeking information concerning:

a.   contained or arrested landing concept
b.   data relative to landing environment
c.   data relative to passenger reaction

Your help in this matter will be greatly appreciated, and will lead to an impartial study of this critical phase of STOL operations.

Sincerely yours,

Hunter F. Taylor
Graduate Research Assistant
University of Virginia

Please advise me of any sources you think would be beneficial to us in this matter.

C.   Typical Responses to Survey Letter

Extracts from some of the letters received are given below, together with relevant comments.

(a)   Reply by addressee no. I from Mr. T. G. Dunkin, De Havilland Aircraft of Canada, Ltd.

"With reference to the second paragraph of your letter, may I suggest that if a decision was made that "all landings were to be arrested," I think that we might agree that this would certainly be the end of STOL inter-city service. You may note, however, reference the brochure entitled "Principles of STOLport Operation" page 3, that we would also consider the use of an arrester cable as a last resort, but have it arranged in such a way that, under any normal landing, such restraint devices would never be necessary. Along the sides of any elevated STOLport, however, we do anticipate the use of curbs and such containment devices. At the present time we have a Twin Otter specially modified for such conditions and complying with pertinent operating and safety regulations.

If you have flown in Twin Otters, of which there are probably 135 or so in use with commuter airlines in the U.S.A., I think you will agree that it is a very normal sort of an experience. Even when flown in a STOL mode the deceleration after touch-down is very modest and does not upset passengers in any way. With brakes fully applied and propellers disking, its deceleration is very similar to conventional jet transport deceleration.

It is the general opinion among well-informed carriers who have studied the subject of STOL that side and end arrestment are required for emergency operation only. End arrestment could be by a pilot-operated aircraft tailhook and cable system resulting in average deceleration levels up to 1.0 g (1.3g peak)."

(b)   Reply by addressee no. 10, from Mr. R. C. Collins, Vice President Engineering, United Air Lines

"We see STOL operations in a rather conventional light; the nature of commercial operations makes this necessarily so.

Consequently, we would view installations like arresting systems as strictly for emergency backup and not for primary operational usage.

Actually, we are considerably more concerned about lateral containment. STOL operations, particularly if only a single runway is available, will present much higher frequencies of crosswind exposure. Coupled with the requirement for all-weather capability, this means that particular attention has to be given to the likelihood of lateral movement on the runway and beyond. There are two ideas in this subject area that need study. One deals with the suitability of an open grid decking for the runway to keep it clear, improve steering friction, and affort fuel drainage benefits in the event of crash fire. The other concerns sloped or curled aprons for the sides of the runway dynamically designed to redirect lateral movement of the aircraft. This, of course, involves landing gear side loads, and itself might constitute an obstruction. Provision would have to be made for egress of the aircraft after landing.

Regarding passenger reaction, I think that normal decelerations of the order of 0.2 to 0.3 g might be marketable, if a smoothly programmed autobraking system were available. It is questionable if this could ever be raised to 0.5 g, which is achievable by aircraft under maximum stopping conditions. For design of back-up arresting gear, 1.5 g appears limiting for medical reasons. I must state that we have no measured or qualitative data which examines conventional deceleration loads and passenger reaction."

(c) Reply by addressee no. 11, from Mr. R. K. Ransone, Development Engineering, VSTOL Technology, American Airlines

"We would prefer that arrestment be made only during emergency situations, and would therefore accept higher decelerations (1.0 g average, 1.3 g peak) than are desirable for normal STOL landings (0.33 g). This is discussed further on page 3 of the AIAA paper No. 70-1240.

Arrestment should be controllable by the pilot, without
having to call the tower to request the barrier. The concept of
a pilot-operated tail hook to engage a cable has merit. Perhaps
the tail hook should be deployed automatically with thrust reversal.

The only reason I can see now for near-end arrestment might
be for directional stability when operating in very high crosswinds."

(d)   Reply by addressee no. 13, from Mr. Howard C. Tinney, Manager,
      STOL Exploratory Development, The Boeing Company

"Recent Boeing tests on its advanced 737 did not involve a
controlled human test sample to indicate passenger acceptance of
ground deceleration. However, with maximum braking (coefficient
of about .42) applied and maintained steady until low speed,
casual observers along on many of the flights felt that a foot
rest for bracing would have relieved their discomfort. Attachment
2 shows some of the typical traces of the 737 tests."

(e)   Reply by addressee no. 14, from Mr. R. L. Merrill, Project
      Manager, Catapult and Arresting Gear Programs, All American
      Engineering Co.

"To again emphasize one or two important points: Approach
end engagement is now a standard operating procedure for U.S.A. F.
pilots flying operational jets in S.E.A. This is a safety procedure
that virtually eliminates any accidents that could be attributed
to runway deviations after touch down. This is a known, proven
technique and should be incorporated on elevated STOL-ports.
Secondly, by using this technique, the ride-comfort qualities
during landing are increased by virtue of the smoothly applied
low "g" deceleration the passengers will feel without all the
attendant high noise/vibration which is prevalent in high-power
reverse-thrust stopping techniques. Further, marked reductions
in costs of brake maintenance and power plant and propeller pilot
report discrepancies will decrease turn-around times and delay
rates. (Power plant, landing gear and propeller system write-ups
form the majority of the pireps.)

As you probably know, the energy absorbers of arresting gear can be engineered to give any deceleration (hookload) desired and the enclosure only illustrates one set of loads for a given runout. This set of calculations shows that the energy absorbers do give less deceleration loads than what is shown in the American Airlines Report (January 1970) as longitudinal forces (typical) for STOL aircraft for the same landing roll (runout).

Passenger reaction will be hard to predict but to dispet the fears of the meek yes men in various circles, I suggest very strongly that actual tests be performed with STOL aircraft to prove the values of arrested landings. All American Engineering is ready and willing to participate in any test program that will further the aims of inter-metropolitan STOL Transportation Systems."

(f) Reply from addressee no. 18, from J. Clay Staples, Program Manager, Flight Operations, RD-742, Department of Transportation, Federal Aviation Administration.

"The lateral containment or arresting concepts for elevated STOLports have not been firmed-up. At the moment, we are proceeding on the assumption that we will have emergency arresting cables at the ends of the STOLport and that the lateral containment problem will be solved without having to make every landing an arrestment; however, how this can be done has not yet been determined. One of the possible lateral containment methods would be to stretch a cable from one side of the roof across to the other side with the cable recessed where it crosses the active runway portion. Thus, there would be no arrestment if on the runway, but arrestment if there is an excursion off to the side.

Nets have been considered at the runway end instead of arrestment cables, however, because this must be raised and lowered between takeoff and landing or kept recessed until triggered by some method that has questionable reliability, we are leaning toward arrestment cables. Considerable research will

42

be necessary before decisions are made in this area. However, assuming we only have emergency arrestment at the end of the runway which means no normal arrestment, we anticipate deceleration levels of approximately .4G. On the Breguet 941 tests peak accelerations were approximately 14ft/sec^{2}*, and averaged about 10ft/sec^{2} over the high deceleration period. On takeoff the maximum accelerations were approximately 12ft/sec^{2}. We have no information at this time on passenger reaction, however, we expect to pick up this information on the Twin Otter on the next phase of our tests at NAFEC. McDonnell Douglas at St. Louis may have gathered information on passenger reaction during the Breguet 941 demonstrations in the United States."

* i.e. 0.43 g (author)

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