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THE REQUIREMENTS FOR A NEW FULL-SCALE SUBSONIC WIND TUNNEL

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THE REQUIREMENTS FOR A NEW FULL-SCALE SUBSONIC WIND TUNNEL

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SUMMARY

This paper summarizes the justification and requirements for a large subsonic wind tunnel capable of testing full-scale aircraft, rotor systems, and advanced V/STOL propulsion systems. The design considerations and constraints for such a facility are reviewed, and the trades between facility test capability and costs are discussed.

INTRODUCTION

The studies reported here were initiated in 1967 when the Aeronautics and Astronautics Coordinating Board (AACB) requested a general study to determine the need for new national aeronautics facilities. The Aeronautics Panel of the AACB organized three working groups to consider facility requirements for three types of aircraft: (a) subsonic and V/STOL; (b) transonic and supersonic; and (c) hypersonic.

In 1968 the Subsonic and V/STOL Working Group presented the Aeronautics Panel a report identifying the need for a large subsonic wind tunnel capable of testing full-scale rotor systems and high performance V/STOL aircraft. Over the next two years the Aeronautics Panel reviewed the justification and technology requirements for the facilities proposed by the Working Groups and, in October 1970, recommended to the AACB that a large engine test facility and the large subsonic wind tunnel described here be constructed. The requirements for this wind tunnel and the design solutions to these requirements have been subjects of considerable study by NASA during the last three years.

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One of the prime factors which motivated the AACB to initiate
the study to determine the need for new aeronautical facilities was
the recognition that improvements in effectiveness and economy of
aeronautical systems have only been achieved by the extensive use of
ground-based facilities. Another important factor was the recognition
by the AACB that the United States had not initiated any new major
aeronautical facilities since the Unitary Wind Tunnel program in 1950.

In their original instructions to the Subsonic and V/STOL Working
Group the Aeronautics Panel of the AACB directed the Working Group to
consider planned future aircraft programs and the facilities required
for the development of these aircraft. To support this effort the
advanced planning groups of the various military services and NASA
submitted requirements for various military and commercial missions.
Several points immediately became clear. First, it was obvious that
the wind tunnel could not be built soon enough to contribute to the
development of specifically planned aircraft developments; so the
Working Group interpreted the more generalized long-range mission
requirements in terms of aircraft for the more distant future. Second,
this exercise showed that the basic aircraft development trends and
technical problems which justify the facility are more fundamental and
more certain than any specific aircraft development programs. And,
third, there was no single absolute requirement in terms of either
aircraft or problem solution which would justify the facility, but
there were numerous technical problems for which the proposed facility
would provide solutions in such an effective and efficient manner that
it could be expected to pay for itself many times over. This situation
makes the presentation and substantiation of the justification a
protracted process. In brief, however, the points which will be made
are as follows:

1. There is a rapidly growing demand for transportation
   based on the growing economy and population of the
   nation. Provision of this transportation will far
   overtax our present transportation systems, and is
   critical for improvement of the quality of life in
   this country. Traffic congestion and aircraft noise
   are a key retardants to the development of adequate
   transportation.

2. The use of STOL, VTOL, and other high lift technology
   aircraft will provide solutions for a significant part of
   the transportation requirement. These same technologies
   are required for a number of military missions.

3. The key problem area in the development of these aircraft
   is the extremely complex interface between aerodynamics
   and structure where the design of sophisticated pieces of
   lightweight flight hardware can be critically dependent
   on details of the aerodynamics and the dynamics of the
   structure. The key justification for the full-scale size
   of the tunnel is the pressing need to test the actual flight
   propulsion systems (including rotors) over their critical
   operating range in the real aerodynamic environment of
   speed, operating conditions, and airframe-induced flow
   distortion; and to do such testing at an early stage in the
   development of the system to prevent catastrophic failures
   in terms of hardware, money, and lives.

FUTURE AIR TRANSPORTATION REQUIREMENTS

Civil Requirements

A number of studies have documented the growing problems in
providing the transportation facilities required to contend with the
estimated growth in population and economy of the United States. For
example, the domestic airlines alone expect the number of passenger
miles flown in 1980 to be more than double that flown in 1970 (see
Ref. 1). An even greater increase is expected in air cargo operations.
When viewed in the context of the current congestion at large airports,
it is clear that a major technical challenge must be met if the
forecasted transportation capability is to be realized.

Figure 1 shows the major problem areas for civil air transportation
as identified by the Joint DOT-NASA Civil Aviation Research and
Development Policy Study (Ref. 1) along with the associated technological
disciplines. With the exception of avionics, all of these disciplines
would benefit from the type of facility proposed in this report.

Application of high-lift aerodynamics to civil air transport
requirements.- Reference 2 discusses the economic impact of high lift
aerodynamics on the economy of commercial air transportation. For
example, Fig. 2 (taken from Ref. 2) shows that a 5 percent increase in
the maximum lift coefficient available for landing can result in 65
percent increase in payload which can be landed in a given field, and
that this can result in a 133 percent increase in trip profit. Similar
statements are made in Ref. 2 concerning the economic impact of maximum
lift coefficient and lift-drag ratio available for takeoff. The above
described economics of high lift are for the situation where high-lift

technology is used to increase the payload that can be lifted into or out of a given size of airport. Alternatively, increases in maximum lift coefficient can be used to reduce the field length requirements of the aircraft, with resulting reductions in airport costs and increases in the number of communities that can be served. The recognition of these factors has led directly to the current interest in short takeoff and landing (STOL) and vertical takeoff and landing (VTOL) aircraft discussed in the next section. In many respects V/STOL aircraft are a logical extension of high-lift technology trends for conventional aircraft.

Application of V/STOL aircraft to civil transport requirements.-
References 3 through 9 show that V/STOL aircraft can be expected to have a major impact on relieving congestion at the major airports by shifting the short-haul traffic away from the major airports to small V/STOL ports. The major transportation demand for all scheduled carriers (both air and surface) is for trips between 50 and 500 miles. The high-speed V/STOL transport can make large savings in the total time required for trips of this stage length. These savings accrue from two factors. First, the takeoff and landing facilities can be closer to the traveler's destination with resulting savings in the time and cost of ground transportation to and from the airport. Second, the V/STOL flight capability of the aircraft makes it possible to reduce the time lost in air and ground maneuvers in the terminal area and thereby to reduce the required airport-to-airport time.

Not only is this reduction in lost time of importance to the passenger, but it also has a first order impact on the economics of air transportation. Figure 3 shows that terminal area delays cost the airlines nearly 160 million dollars in 1969 (Ref. 10). It is estimated in Ref. 10 that the accompanying cost to passengers due to terminal area delays was about 100 million dollars. It is further estimated in Ref. 10 that these losses will grow to 600 million dollars for the airlines and 400 million dollars for passengers by 1980 unless corrective action is taken. This is one of the prime motivations for the development of V/STOL aircraft to alleviate the congestion problem.

Other civil applications of V/STOL aircraft.- The preceding discussion has been directed at the application of V/STOL aircraft to scheduled commercial transport operations. It should be noted, however, that there are many other uses for V/STOL aircraft. For example, the heavy-lift helicopter has already shown its value in many missions, both commercial and military. The helicopter is being used as a utility transport in a variety of commercial applications in spite of its deficiencies. This in itself is a testimony to the economic value of the utility provided by vertical flight capability. For example, the use of helicopters for carrying personnel and equipment to and from the off-shore oil rigs along the Gulf Coast alone has accounted for more than 1 million flight hours.

Summary of civil aircraft requirements.- It is clear that basic factors such as the growth of the population and economy of this country will create a rapidly growing demand for transportation; and it is equally clear that the quality of life in the United States will be determined in a large part by how well these transportation requirements are dealt with. While there is room for debate about the level of growth in the transportation requirement, there can be no doubt that transportation capabilities will be taxed to the utmost. This is already evident in terms of the air and ground congestion in and around metropolitan areas. The potential of aircraft utilizing V/STOL technology to provide solutions for a significant part of this transportation requirement has been documented in a number of studies. The solution of the technical problems associated with the development of such aircraft constitutes a large part of the requirement for the proposed full-scale wind tunnel, as will be shown in a subsequent discussion of V/STOL aircraft technology.

Military Requirements

Conventional aircraft.- Many of the aircraft mission requirements dictated by military operations impose stringent requirements on landing and takeoff performance, low-speed flight characteristics, stall and spin characteristics, etc. For example, the achievement of satisfactory landing and takeoff characteristics for carrier-based aircraft without penalizing high speed performance requires a careful compromise between high-lift aerodynamics, high-speed aerodynamics, structural weight, and complexity. A similar situation exists for most tactical aircraft since they are required to use small unprepared fields which place a premium on landing and takeoff characteristics. Even large, long range military transports have generally quite stringent takeoff and landing specifications compared to their commercial counterparts. For example, the C5-A military transport is required to operate out of 4000 ft. fields with a 100,000 lb. payload.

V/STOL aircraft.- The value of V/STOL aircraft in a limited war situation has been proven by the widespread use of the helicopter in Vietnam for such missions as transportation, air-rescue operations, reconnaissance, tactical support of ground forces, and recovery of downed aircraft and other equipment from hostile territory. In a less constrained military situation where the enemy may be able to attack large air bases with either conventional or nuclear weapons, dispersal of aircraft to a number of small sites will be mandatory for survival. The vulnerability of large air bases (and aircraft that need long runways) has been demonstrated on a number of occasions, one of the most recent being the destruction of the Egyptian Air Force on the ground by the Israeli Air Force at the outset of the 1967 conflict.

As mentioned previously, the AACB requested the military services to review their long-range requirements for aeronautical weapons systems to help determine the ground-based facilities required to develop these systems. The requirements included a heavy-lift helicopter, a variety of V/STOL transports, anti-submarine warfare aircraft, rescue aircraft, and V/STOL fighters and tactical aircraft. The aircraft performance requirements for many of these missions dictate V/STOL aircraft with considerably higher speed capability than is available from conventional helicopters.

BASIC TECHNOLOGY PROBLEMS

Conventional Aircraft

A fundamental problem encountered in all aircraft design is the prediction of full-scale flight characteristics from data obtained from wind tunnel tests of small-scale models. This is particularly true when flow separation is involved. There are two aspects to this problem. First, the model tests are conducted at considerably lower Reynolds numbers than those for full-scale flight conditions. Second, there may exist subtle, but important, differences between the model and the full-scale aircraft. Typical of these differences are leakage through the structure, deformation of flaps and slats under load, exhausting cooling air in regions of marginal flow stability, surface discontinuities, roughness, brackets, etc., all of which are details of the full-scale structure which cannot be duplicated at model scale. When discrepancies occur between predicted and actual flight characteristics, it is usually impossible to tell whether the cause is due to the difference in Reynolds number or to detailed differences between the model and the actual aircraft. The full-scale wind tunnel is a valuable tool in developing satisfactory high-lift systems and in defining discrepancies between predicted and actual performance, so that design procedures can be improved.

Low-Disk Loading V/STOL Aircraft

The main technical problem areas for low-disk loading aircraft are rotor control, dynamic stability, dynamic loads, and performance at high flight speeds. These characteristics are highly dependent on the unsteady aerodynamic force inputs to the rotor and the dynamic characteristics of the rotor and its control system (including such real-world factors as backlash, break-out forces, and nonlinear effects).

The unsteady aerodynamic forces on the rotor system are critically dependent on Mach number, Reynolds number, and advance ratio. Therefore, wind tunnel tests must be conducted at flight values of these parameters if they are to be meaningful.

The implications of these requirements are shown on the rotor velocity diagram (Fig. 4). The ordinate on this figure is the corrected rotor tip speed, and the abscissa is corrected flight speed. (Tip speed and flight speed corrected for temperature effects are used since these parameters are directly proportional to tip Mach number and flight Mach number, respectively.) The solid lines extending from the origin (lines of constant advance ratio) indicate the degree of flow asymmetry that the rotor must cope with. (This is graphically illustrated by the shaded circles on this figure. The lightly shaded circles represent the rotor disk viewed from above, and the dark circles show the region of reversed flow in the rotor disk at the corresponding advance ratio.) The dashed lines represent values of constant advancing tip Mach number. This parameter has important effects on rotor power requirements, dynamic loads, and noise.

The point labeled "flight" on Fig. 4 represents the operating conditions for a high-performance compound helicopter flying at 300 knots. For these conditions the advancing tip Mach number is 0.91, the advance ratio is 1.0, and the whole retreating blade is in the reversed flow region. In order to simulate the flight advance ratio in the Ames 40- by 80-foot wind tunnel, which has a maximum corrected free-stream speed of about 190 knots, the rotor rotational speed must be reduced, since the advance ratio must be held at the correct value. This results in a reduction of the advancing tip Mach number from 0.91 to 0.58. Similar differences in Mach number exist at other locations on the rotor. Therefore, compressibility effects on the rotor characteristics at the proper advance ratio cannot be determined. Thus, it is essential to test the rotor at full-scale flight speeds and rotational speeds to determine compressibility effects.

The discussion thus far has emphasized the importance of achieving test conditions that accurately simulate the aerodynamic forces on the rotor system. However, the mechanical characteristics of the rotor and its control system must be accurately simulated as well, since they determine to a large degree the blade angle of attack and resulting air loads. The blade itself is a complex mechanical system with coupling between torsional and bending deflections through aerodynamic, structural, and inertial effects. These may be quite subtle until they are manifested in terms of high loads or instabilities. For these reasons, it is essential to conduct tests with rotor hardware that duplicates the flight hardware in terms of stiffness, inertia, damping (structural, viscous, and bearing friction), backlash, etc. If this is done with dynamically scaled models, the cost is usually comparable to full-scale rotor hardware.

Further, it is generally not possible to duplicate faithfully all of the parameters of interest, and some compromise in the simulation is required.

In summary, the main technical problems of low-disk loading aircraft are rotor control, dynamic stability, vibration and performance. These problems are accentuated by the fact that the rotor blades cycle in and out of flow regions where the aerodynamic forces are sensitive to variations in local blade section Reynolds number and Mach number. In addition, the possible modes of motion are coupled by combinations of aerodynamic, elastic, inertial, and damping terms that are often subtle and difficult to predict or simulate reliably in scale model tests. Therefore, full-scale wind-tunnel tests of advanced rotor systems prior to flight test at high speeds are an essential step in the development of high-performance rotary-wing aircraft. However, the performance levels of some existing and many forecasted advanced rotary-wing aircraft are beyond the capabilities of the 40- by 80-foot wind tunnel, which is the only facility available for this work at present.

High-Disk Loading V/STOL Aircraft

Effect of inlet distortion and Reynolds number on propulsion system performance and engine stall.- One of the critical problems for fan or jet V/STOL propulsion systems is a distorted inlet flow. The effects on the engine of distortion is shown schematically in Fig. 5. Modest amounts of distortion cause modest though important degradations in engine thrust and efficiency. Some critical level of distortion will cause engine stall with a resulting large loss in thrust, unsteady flows through the engine, blade vibration with attendant high blade stresses, turbine over temperatures, and attendant risk of damage to the engine. For the VTOL airplane the entire airplane weight is supported by the propulsion system at takeoff and landing. The STOL airplane also derives a large measure of its lift from the propulsion system at low speeds. Thus, the thrust loss due to engine stall can be catastrophic. In general, it is mandatory to avoid engine stall, and it is desirable to minimize the performance losses associated with lower levels of distortion.

There are several kinds of inlet flow distortions: nonuniform velocity magnitudes, nonuniform velocity directions, and nonuniform temperatures. The engine is further sensitive to the radial and circumferential distribution of these distortions at the compressor or fan face, and to their temporal variation; that is, the general turbulence level and the rates of temperature change.

Figure 6 shows the circumstances that lead to velocity and angularity distortions. After the VTOL airplane leaves the ground, the airplane accelerates forward to achieve wing supported flight. During this transition the lift engines must operate in a highly distorted flow caused by the requirement that the velocity approaching the wing must turn approximately ninety degrees to enter the engine inlet. This large turning may induce flow separation at the inlet lip and fan hub which causes further distortions.

For a STOL airplane the angle of attack and high wing lift can induce very large local flow angles at the engine inlet and consequently large flow angularities at the fan face. The inlet lip flow angles can cause flow separation at the inlet lip which causes an unsteady velocity distortion at the compressor face. The high lift flap system may induce still further distortions which are fed upstream through the subsonic fan flow.

Stall in a compressor is associated with the stall of the individual rotor blades. The stall of the blades is directly analogous to the stall of a wing section or helicopter blade and is strongly Reynolds number and Mach number dependent as previously discussed.

The performance of many blades in rows and stages as they occur in a compressor infinitely complicates the prediction of compressor stall, and it has been found that each engine design exhibits its own unique characteristics. Thus, the testing of full-scale engines is the only satisfactory way known of determining its stall characteristics.

Another serious consequence of inlet flow distortions can be local hot spots in the flow through the engine turbine. The fuel injection system and combustor are generally designed for a uniform flow into the combustor and, hence, a uniform fuel distribution. An inlet distortion which causes deficiency of airflow on one region of the combustor will cause a local over temperature because of the local increase in the fuel-to-air ratio. If the hot spot is unanticipated, an early and possibly catastrophic turbine failure can occur. If the hot spot is anticipated, or found to exist, a degradation in engine performance may be accepted or the fuel distribution redesigned to accommodate it. The problem of local hot spots is one that can only be solved on the full-scale engine installed on the airplane at actual flight conditions.

Another undesirable consequence of engine inlet flow distortion is the generation of noise. While the engine fan and compressor stages generate noise in a uniform flow, the noise generated by these rotating aerodynamic surfaces is increased in the presence of a flow distortion. The noise constraints to be imposed on commercial STOL airplanes are very stringent. The precise determination of engine noise and the design of efficient noise suppression systems will depend on tests of full-scale

engines in the environment generated by the full-scale airplane at flight conditions.

The economics of full-scale engine testing warrants some comments. It is generally accepted that the building and testing of small-scale, external aerodynamic airplane models is far less expensive than the testing of a full-size model. This, however, is not the case with engines. Once a commitment has been made to design and build an engine for an aircraft application, it is usually less expensive to buy demonstrator versions of that engine for research and development purposes than it is to build a half- or quarter-scale model of the engine. This is because changing the scale of the engine by factors of two or four requires an extensive redesign and redevelopment effort to insure satisfactory operation. These factors account for a major portion of an engine model cost and usually exceed the cost of a full-scale engine for which the cost of design and development is spread over many engines. Thus, the use of full-scale engine tests in contrast to tests of model engines is the more economical approach, and, in fact, is the only cost-effective way to study problems such as engine stall which were described in the preceding paragraphs.

AIRCRAFT SIZE AND SPEED TRENDS RELATING TO FACILITY REQUIREMENTS

Conventional Aircraft

Over the years the increasing demands of mission requirements and economics have dictated a long term trend toward larger aircraft. A result of this is that the existing full-scale wind tunnels are no longer capable of testing most operational aircraft. As shown by Fig. 7, even modern fighter aircraft tax the capability of these facilities. As a result of this, current research and development tests for the F-14 and F-15 fighter aircraft are being performed with 3/4-scale models rather than full-scale test vehicles; and the use of such models will not get at the important interface between structures, propulsion, and aerodynamics.

Rotorcraft

Figure 8 shows the variation of rotor diameter or aircraft span with gross weight and payload for single rotor compound helicopters and tilt rotor aircraft. These variations result from fairly well-defined limits on rotor disk loading and rotor weight. Therefore, the trends shown on Fig. 8 can be expected to be valid into the foreseeable future. The largest diameter rotor which can be tested in the 40- by 80-foot wind tunnel is about 60 ft., and, for this size rotor, the tests are limited by wind tunnel wall constraint of the flow to low wake angle conditions (i.e., high speeds and low lift coefficients). Figure 8 shows that, with this limitation on aircraft span, the 40- by 80-foot wind tunnel is far too small to test full-scale transport rotorcraft, and is capable of testing only the smaller utility and tactical aircraft.

The economics of transport missions dictates higher flight speeds than are available from current helicopters. Even for relatively modest stage lengths, speeds of 250 to 350 knots are required for economic operation. In contrast, the maximum speed capability of the 40- by 80-foot wind tunnel is only 200 knots. As discussed previously the most serious technical risks for high-speed rotorcraft are rotor dynamic stability and vibratory loads in high speed flight. The magnitude of these problems can be expected to increase at least with the flight velocity squared. Therefore, the increase in rotorcraft speeds from the current 200-knot level to the 300-knot level can be expected to more than double the rotor dynamic stability and vibration problem.

In summary, the long-term trends in size and speed requirements for advanced rotorcraft indicate a need for vehicles having rotor diameters or spans of up to 100 ft., and having flight speeds of 300 to 350 knots. A full-scale wind tunnel capable of testing these rotor systems would require a test section size of at least 60- by 120-feet and a speed of at least 300 knots.

High-Disk Loading V/STOL Aircraft

Figure 9 shows the typical variation of aircraft span with gross weight and payload for a variety of high-disk loading V/STOL and STOL transport aircraft concepts. In general, STOL aircraft concepts for which the wing carries a major share of the weight (such as the externally blown flap and the augmentor wing) are near the upper bound of the shaded area on Fig. 9, while concepts for which the propulsion system carries the major share of the weight (such as lift fan aircraft) are near the lower bound of the shaded area. While the size trends shown on Fig. 9 for high disk loading V/STOL aircraft are not

as well defined as those shown on Fig. 8 for rotorcraft, they neverthe-
less indicate that aircraft having wing spans from 60 to 100 ft. will be
required to perform the transport missions envisioned for these aircraft.

The primary technical problems for these aircraft are in the low-
speed flight range (up to about 150 knots) where there is strong inter-
ference between the flow through the propulsion system and that over the
airframe. Under these conditions the aircraft wake is deflected through
a large angle and the flow constraint effects of the wind tunnel walls
become the limiting factor in determining the wind tunnel size require-
ments. On the other hand, in high speed flight these aircraft are more
or less conventional in their operation, and require no special test
requirements other than those used for cruise flight of conventional
aircraft. Therefore, the test requirements for most high-disk loading
V/STOL aircraft can be met in a wind tunnel with a maximum speed
capability of 150 knots. However, the effects of the constraint of the
flow become increasingly serious as the speed is reduced (and the wake
angle is correspondingly increased). Therefore, these aircraft dictate
the size requirements of the proposed facility.

Facility size and speed requirements.- The aircraft size and speed
trends discussed in the preceding paragraphs are summarized on Fig. 10
along with the approximate test section widths required to accommodate
tests of these aircraft. At speeds above 100 knots the test section
width is selected according to conventional wind tunnel practice that
the ratio of aircraft span to test-section width should not exceed 0.8.
At the lower speeds, corresponding to the transition flight regime of
V/STOL aircraft, the size of the test section increases rapidly as the
flight speed decreases. This increase in size is required to alleviate
the growth of wind-tunnel wall constraint effects with increasing wake
angle as the speed is reduced. These test-section width requirements
are shown as approximate areas rather than definitive lines since they
are dependent on a number of factors. However, to conduct tests of
large V/STOL aircraft having wing spans of 100 ft. at speeds of 50 knots
and less, a test section width of 200 feet is indicated. On the other
hand, at the high speeds and low lifts corresponding to the regime of
prime interest for advanced rotorcraft, a test-section width of 120 ft.
would be adequate. The current studies are directed at achieving the
most cost-effective solution to these conflicting requirements.

Figure 11 shows examples of the types of wind tunnels currently
being considered. The first of these is a closed return wind tunnel
similar to the 40- by 80-foot wind tunnel but scaled up to a test-
section size of 75x150 ft. and a speed of 300 knots. (This size and
speed represents a compromise between the high-speed and low-speed test
requirements discussed previously.) The second configuration is a two-
test section facility having a high-speed (350 knots) 60x120 ft. test

section in the closed return circuit, and a low-speed (135 knots) 130x200 ft. test section in an open return circuit. The third configuration is an open return wind tunnel with a test section size of 75x150 ft. and a speed of 300 knots. The open-return design is of interest because it minimizes structural cost, which is the major cost factor in facilities of this size. All of these facilities have power requirements of about 425,000 horsepower.

ECONOMIC CONSIDERATIONS

The overall judgement that must be made in considering the proposed facility is whether the research and development value of the work performed in this facility will justify its cost. Since this facility should have an operational life of at least 25 years, it is obviously impossible to make a detailed and specific cost-benefit analysis. However, it is possible to arrive at a reasonable perspective on the value of the proposed facility by considering three factors: (a) the alternative of flight tests; (b) the estimated cost of future aircraft programs and the possible contributions of the full-scale wind tunnel in reducing these costs; and (c) the experience of the existing full-scale wind tunnels.

Flight Tests as an Alternative to Full-Scale Wind Tunnel Tests

Since many of the requirements for the full-scale wind tunnel presented in previous sections of this report dictate tests of full-scale hardware, the merits of full-scale wind tunnel tests vs. flight tests were examined. There are several reasons why full-scale wind tunnel testing may be necessary or advantageous. For example, rotor dynamic stability or engine stall problems involve safety-of-flight, and the loss of an aircraft due to these causes generally results in the grounding of the flight test aircraft. Under these circumstances further flight tests are not possible. Another example where flight testing may be quite hazardous is during flight operation close to the ground, where the high flow distortions described previously in connection with engine stall may be encountered. An engine stall or loss of control during such conditions might easily lead to loss of the aircraft, since very little altitude is available to recover from a severe upset.

Aside from the risks involved in flight tests, the quality, quantity, and type of test data that can be obtained in flight is limited by lack of control over the test environment, cost, and the constraints due to the fact that controlled flight must be maintained. For example, tests to identify the specific contributions of various aircraft components by progressive tests with various components removed are not possible in flight tests, but are a valuable standard technique in the wind tunnel. Again, the ability to vary one significant parameter while holding all other parameters constant is a valuable wind tunnel test technique which cannot be done in flight. In Ref. 11 several comparisons are made between flight tests and tests in ground-based facilities. Among the conclusions are:

(a) The number of measurement channels available is generally less in flight testing.

(b) The accuracy of flight test data is usually about 5% compared to accuracies of 1-2% in ground-based facilities.

(c) The cost of flight tests are an order of magnitude more expensive than those for tests in ground-based facilities.

Costs of Typical Aircraft Programs

The prime justification for the proposed facility is that the cost of the facility is reasonable in terms of the cost of the aircraft programs which it would support, and in terms of the savings that can be realized for these programs over the costs that would be incurred in the absence of the facility. This assessment is difficult to make in specific cases, since the operational life of the proposed facility would be at least 25 years (i.e. from about 1977 to 2002). However, some perspective on this can be realized by considering the costs of typical aircraft programs such as are described in Ref. 12.

Figure 12 compares the funding schedule for a typical aircraft program (from Ref. 12) with the cost of the proposed facility. Figure 12 shows that the first major input from tests in the facility occurs prior to flight test when both the level of funding and the rate of increase of funding are low. These tests typically would involve full-scale demonstrator hardware of the high-risk items (e.g. rotors, fans, engines) installed in inexpensive "boiler plate" airframe mockups. Data obtained at this early stage of the program has extremely high leverage on program costs, since the funds committed are still low. The second period of major influence of the facility shown on Fig. 12 corresponds to the early flight test stage. If unanticipated problems are encountered in flight,

the aircraft can be returned to the full-scale wind tunnel for rapid and safe exploration of these problems. The alternative to this is continued flight tests with the accompanying risks to the aircraft and pilot. By the time flight tests can resolve major discrepancies the cost of the program exceeds that of the facility. In addition, by that time commitments have been made such that the cost incurred by changing the design may be as much as the funds expended. Thus, the cost of the proposed facility should be viewed as an insurance premium which reduces the risk of potential losses in advanced technology programs to acceptable levels. It is quite likely that, without the assurance provided by early tests of critical components in the proposed facility, many advanced aircraft programs (e.g., high-speed rotorcraft and V/STOL aircraft) will not be initiated due to excessive financial risk.

Experience with Existing Full-Scale Wind Tunnels

NASA has operated full-scale wind tunnels since the late 1920's, and there is considerable historical evidence of the value of this type of facility. The first NASA full-scale wind tunnel (the 20-ft. Propeller Research Wind Tunnel) showed the absolute necessity of using cowls for radial engines and variable pitch propellers for high performance aircraft. The incorporation of these features provided the first high performance transports which launched the era of practical commercial air transportation. Similarly, the application of this research to fighter aircraft culminated in the high-performance radial engine fighters of World War II fame.

The prime justification for construction of both the 30 by 60 and the 40- by 80-foot wind tunnels was for the performance of drag reduction studies. Drag reduction work in the 30- by 60-foot wind tunnel just prior to, and during the early part of World War II, added an average of 30 MPH to our World War II fighters. The sources of drag reduction were each small in themselves, but the total effect was large. They included such items as unnecessary air leakage, unfaired scoops, improper cooling air discharge, necessity of using cowl flaps to control cooling airflow, etc. This drag reduction and cooling work had to be done with the full-scale hardware since it involved details of the interface between construction practices and details with aerodynamics.

While the prime justification for both the 30- by 60 and the 40- by 80-foot wind tunnels was for drag reduction studies of military aircraft, the major contributions of these facilities have been in technological areas which were not anticipated at the time the facilities were planned. The contributions of these facilities to the research and development of V/STOL aircraft is an example of this. The 40- by 80-foot

wind tunnel has more than paid for itself by preventing catastrophic
failures of experimental V/STOL aircraft in flight. These aircraft
encountered failures during tests in the 40- by 80-foot wind tunnel
which could have been catastrophic in flight. All of these failures
involved the complicated interface between aerodynamics, dynamics, and
structures. Therefore, tests of the full-scale hardware were the only
way that these problems could have been discovered. For example, the
XV-1 compound helicopter encountered a rotor speed instability during
the wind tunnel tests which required changes to the rotor control
system. Tests of the XV-3 in the 40- by 80-foot wind tunnel were
requested after a catastrophic rotor-pylon whirl instability was
encountered in flight, resulting in loss of the aircraft and serious
injury to the pilot. After two tests in the 40- by 80-foot wind tunnel,
separated by a one-year analysis effort, this stability problem was
alleviated so that a highly successful flight research program could be
completed. As a result, the tilt rotor aircraft is considered today to
be one of the more promising high performance rotary wing aircraft
concepts. The first wind tunnel test of the XH-51 rigid-rotor helicopter
ended in a catastrophic break-up of the rotor due to a bonding failure.
The rotor blade was redesigned, a successful wind tunnel test was
completed, and the XH-51 went on to a highly successful flight research
program which culminated in a rotorcraft speed record. During wind
tunnel tests of the XV5A lift-fan airplane, structural failure of the
fan inlet guide vanes was encountered. If these had failed in flight
and entered the fan rotor the aircraft would have been lost. Also,
excessive deflection of the fan exit louver control mechanism was
encountered during these wind tunnel tests. This would have severely
limited the fan-supported flight envelope of the XV-5A. Both of these
problems were remedied following the wind tunnel tests, and the XV-5A
airplane has completed a series of successful flight research programs.
The lift-fan propulsion system is currently considered to be one of
the most promising concepts for a high performance V/STOL airplane.

The total cost of the aircraft programs which have been saved by
tests of the full-scale aircraft in the 40- by 80-foot wind tunnel has
more than offset the total cost of construction and operation of this
facility for 25 years. To these savings could be added the savings
due to the cancellation of flight test programs of aircraft which had
been shown by full-scale wind tunnel tests to have fundamental deficien-
cies. A partial list of such aircraft is the Kaman K-16 tilt wing, the
Avrocar, and the Vanguard low-disk loading fan-in-wing airplane.

Actually, the most important contributions of the full-scale wind
tunnels have been in research areas where it is nearly impossible to
put a firm dollar magnitude on the value of the contribution. The
contributions of the full-scale wind tunnels to the development of the
externally-blown flap and the augmentor wing turbofan STOL aircraft are

almost solely responsible for the fact that these concepts are today considered to be the most promising types for application to large commercial and military STOL transport aircraft. The use of the full-scale wind tunnels was also instrumental in establishing the feasibility of conventional landings of lifting body spacecraft. This included tests of all of the full-scale flight vehicles in the 40- by 80-foot wind tunnel plus studies of free-flight models in the 30- by 60-foot wind tunnel. These studies added immeasurably to the confidence level required before flight tests could be initiated with these radically new and different aircraft. This is perhaps the best example of an application of the full-scale wind tunnels to fill a need which could not have been anticipated when the facilities were justified.

Since the cost of the proposed full-scale wind tunnel has already been compared with the typical cost of current aircraft programs, it is of interest to compare the cost of the existing full-scale wind tunnels with representative aircraft current at the time these facilities were justified. This comparison is presented in the following table.

TABLE I

Cost of Full-Scale Wind Tunnels Relative to Aircraft

Year	Cost of A/C	Cost of F.S.W.T.	W.T. Cost A/C Cost
1930	$25,000	$1,000,000 (30x60)	40
1940	130,000	7,000,000 (40x80)	53
1975	7,000,000	200,000,000	28

This comparison shows that the cost of the proposed full-scale wind tunnel relative to the cost of current aircraft is of the same order as the comparable relative costs for the 30- by 60- and 40- by 80-foot wind tunnels. In addition, the need and the potential for both military and civil air transportation is much more apparent now than it was at the time the existing full-scale wind tunnels were justified. In retrospect our predecessors showed a high degree of foresight and courage in building the 30- by 60-foot wind tunnel and 40- by 80-foot wind tunnel during the great depression and at the outset of World War II, respectively. It is now our turn to make a similar investment in facilities to ensure our future in the aeronautical world.

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MAJOR PROBLEM AREAS AND ASSOCIATED TECHNOLOGY
FOR CIVIL AIR TRANSPORTATION

PROBLEM AREAS

- NOISE
- CONGESTION
- SHORT HAUL SYSTEMS

ASSOCIATED TECHNOLOGY

- HIGH-LIFT AND V/STOL AERODYNAMICS
- PROPULSION
- ACOUSTICS
- AVIONICS

Figure 1

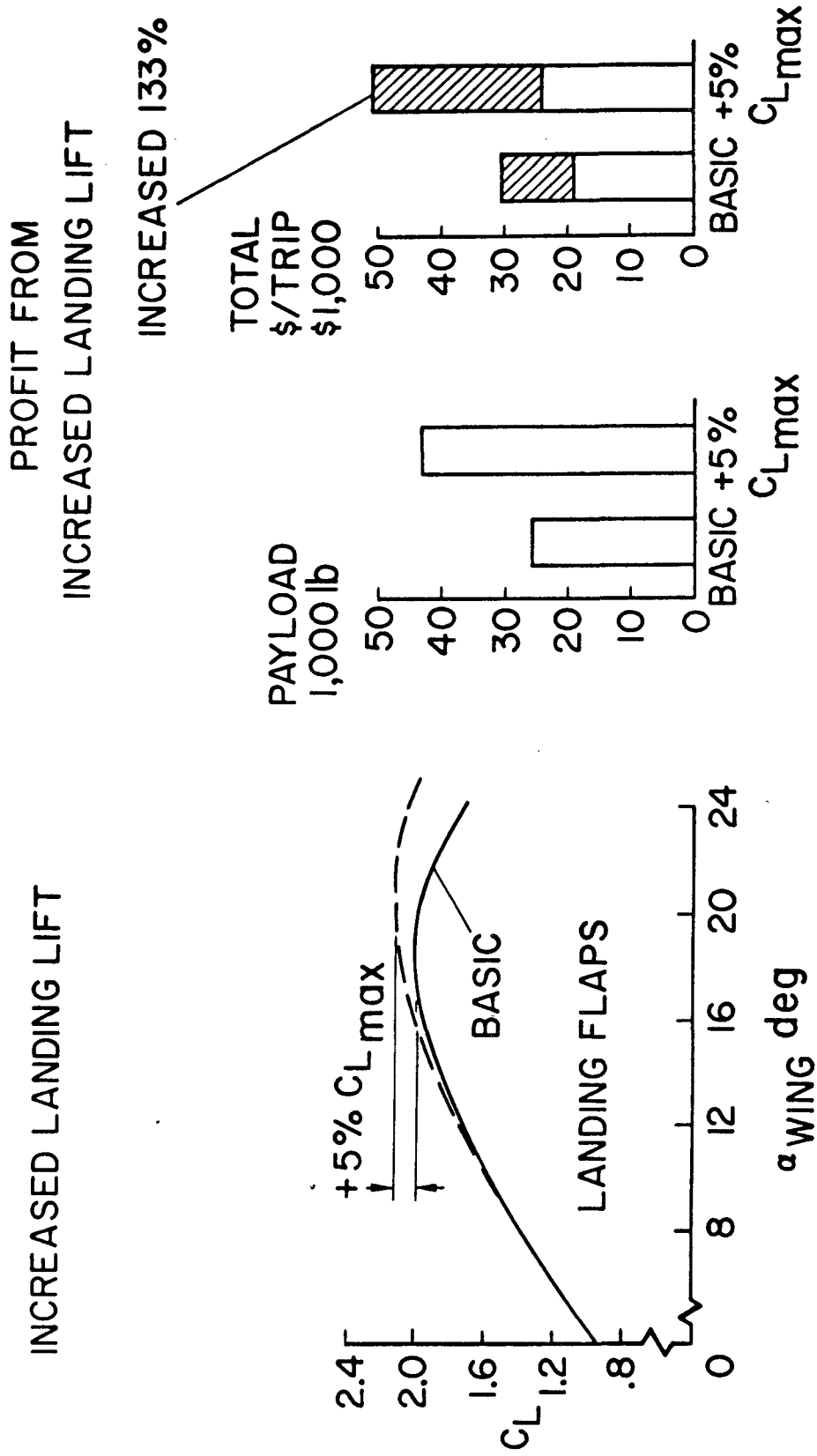# EFFECT OF MAXIMUM LIFT ON COMMERCIAL TRANSPORT ECONOMICS

Figure 2

21

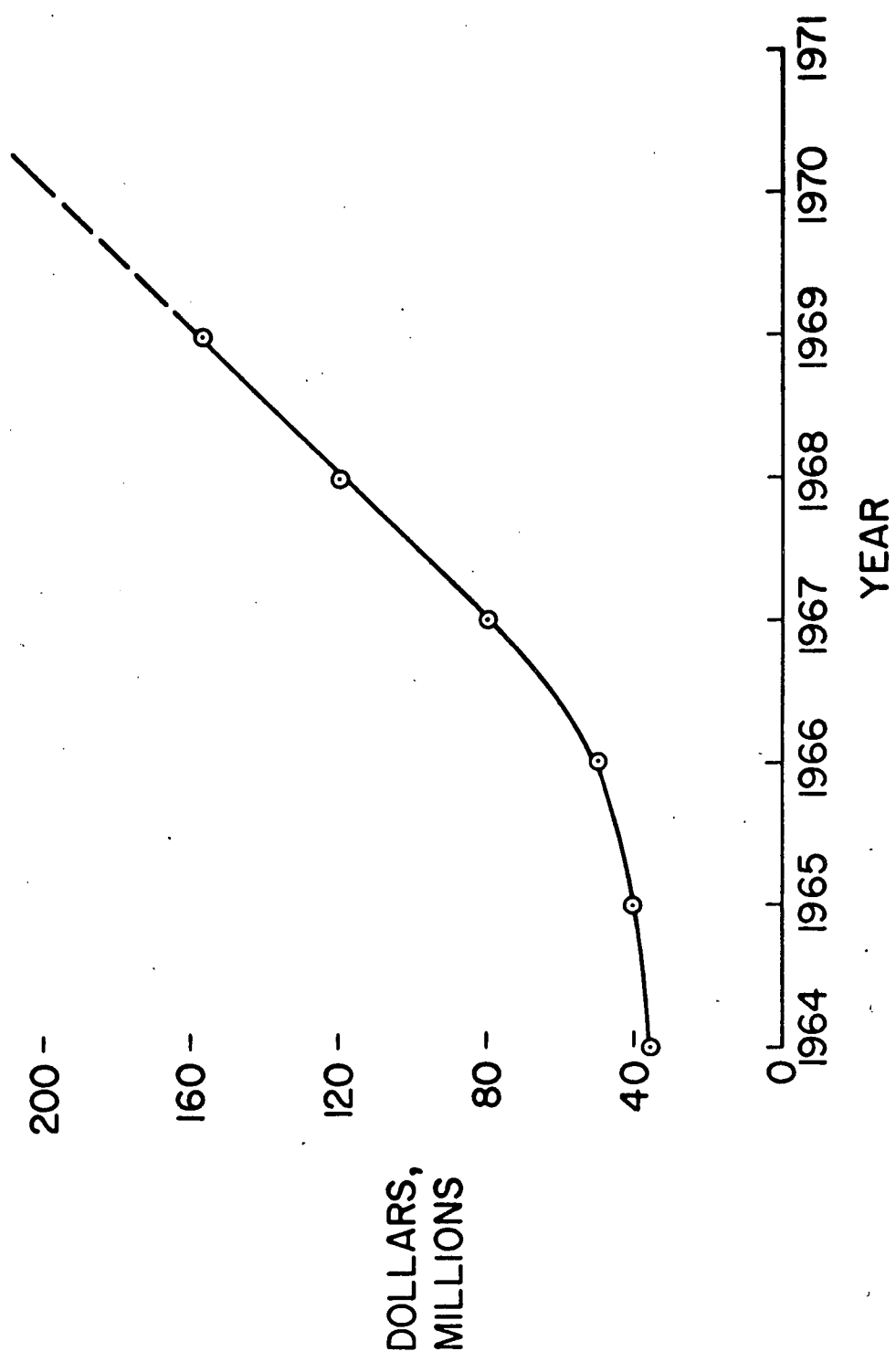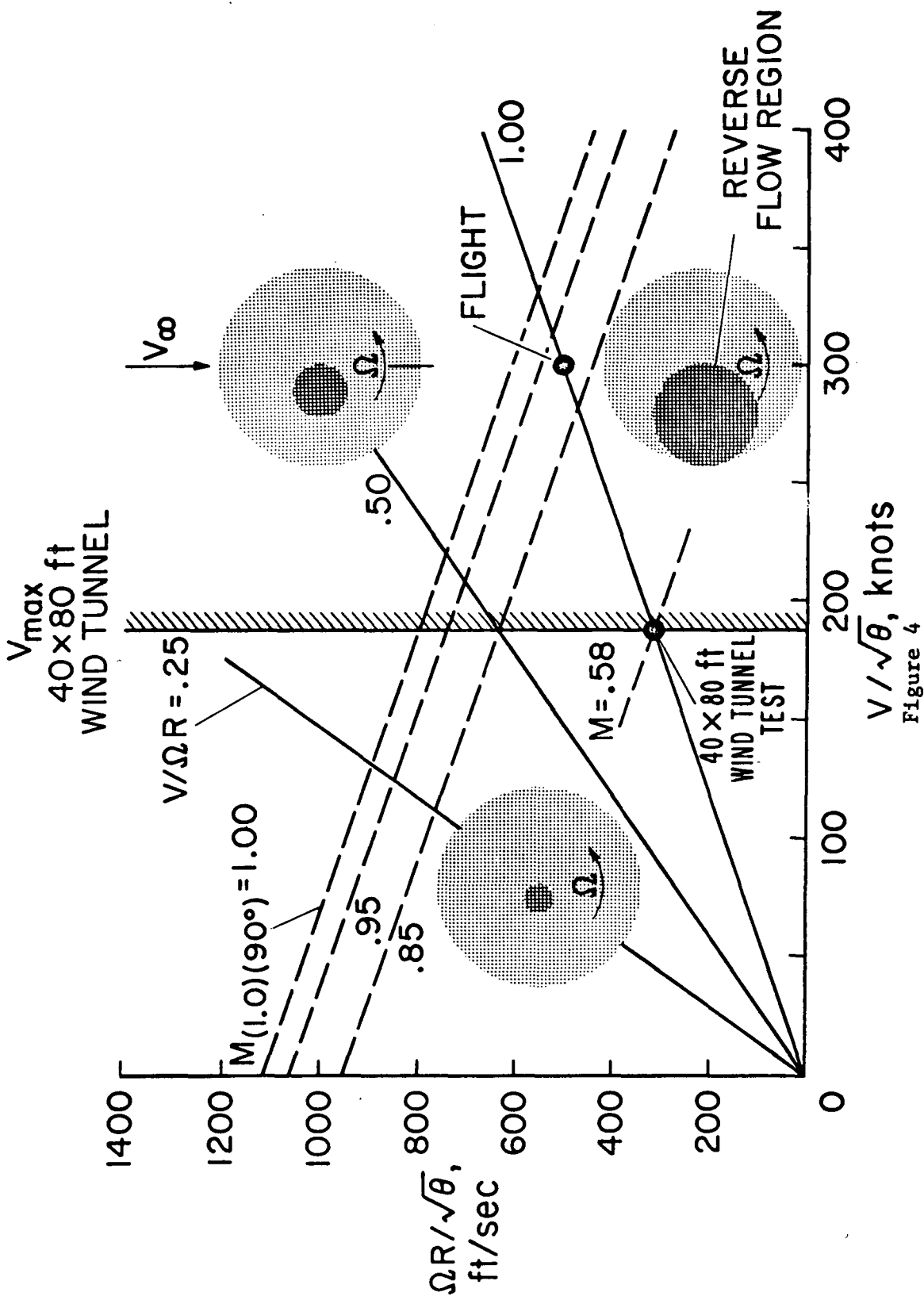# U.S. AIRLINE COST FOR TERMINAL AREA DELAYS

DOLLARS, MILLIONS

Figure 3

22

ROTOR VELOCITY DIAGRAM

Figure 4
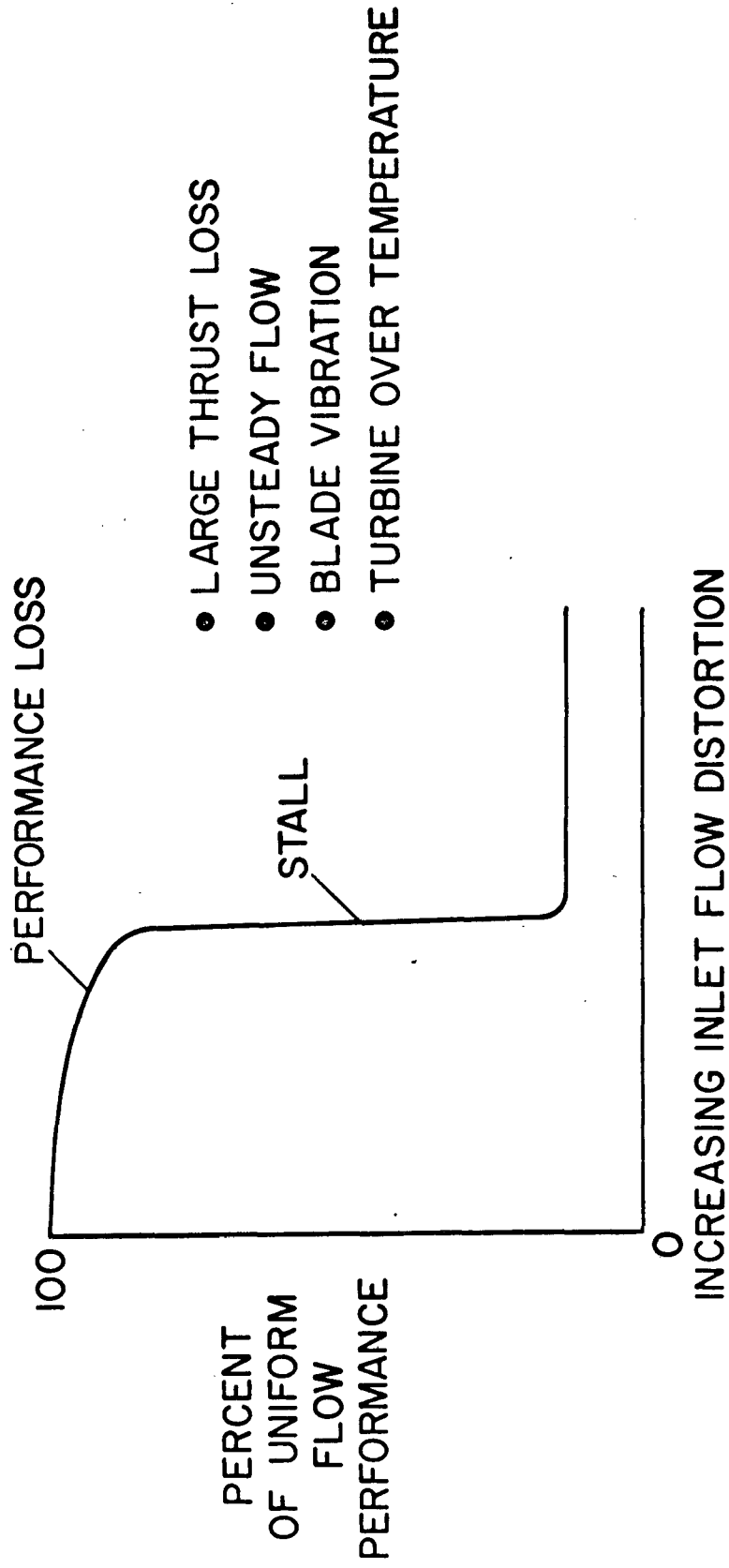
EFFECT OF FLOW DISTORTION ON ENGINE PERFORMANCE

PERCENT
OF UNIFORM
FLOW
PERFORMANCE

PERFORMANCE LOSS

STALL

100

0

INCREASING INLET FLOW DISTORTION

- LARGE THRUST LOSS
- UNSTEADY FLOW
- BLADE VIBRATION
- TURBINE OVER TEMPERATURE

Figure 5

24

SOURCES OF FAN DISTORTION
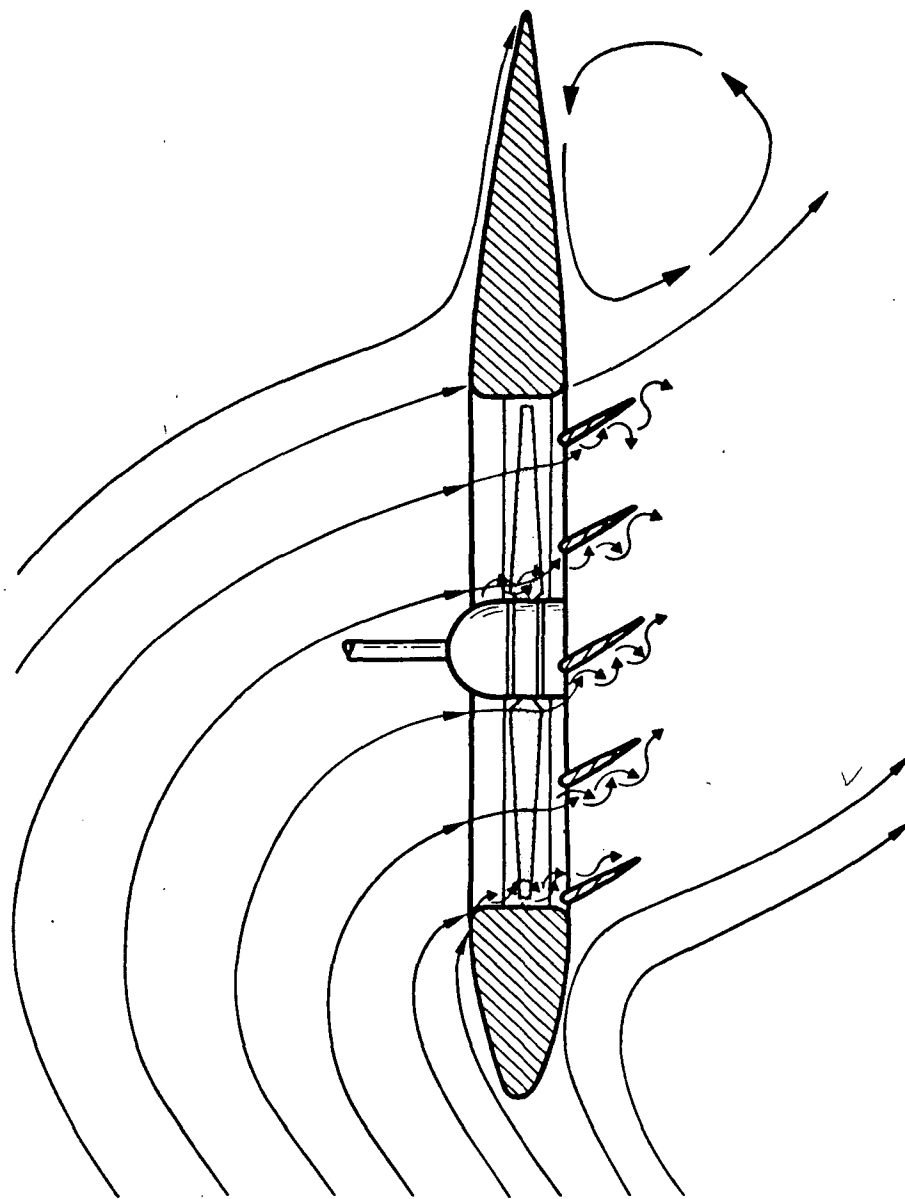DURING TRANSITION TO FORWARD FLIGHT
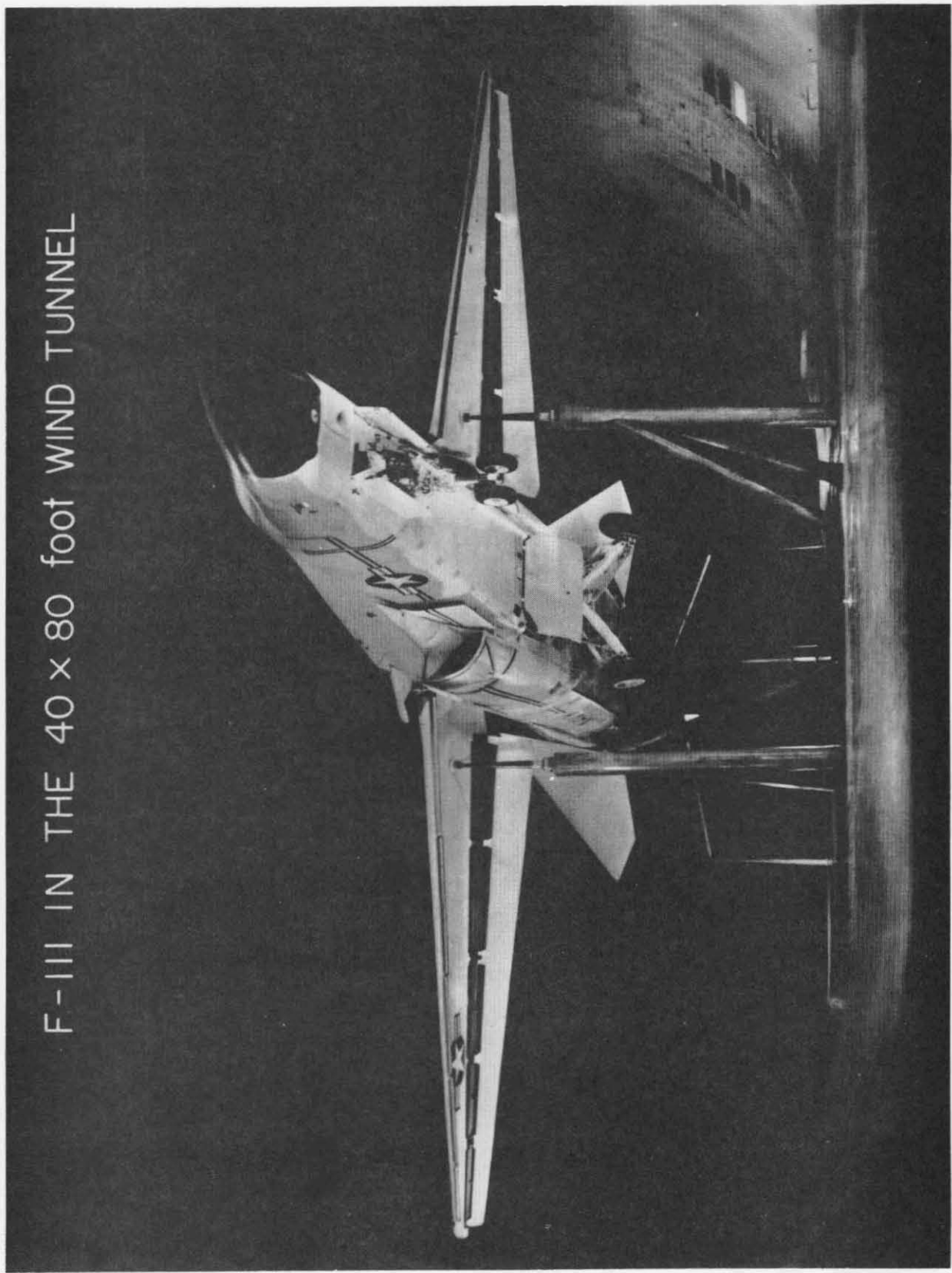

Figure 6

25

F-III IN THE 40 × 80 foot WIND TUNNEL

Figure 7

ROTORCRAFT SIZE TRENDS
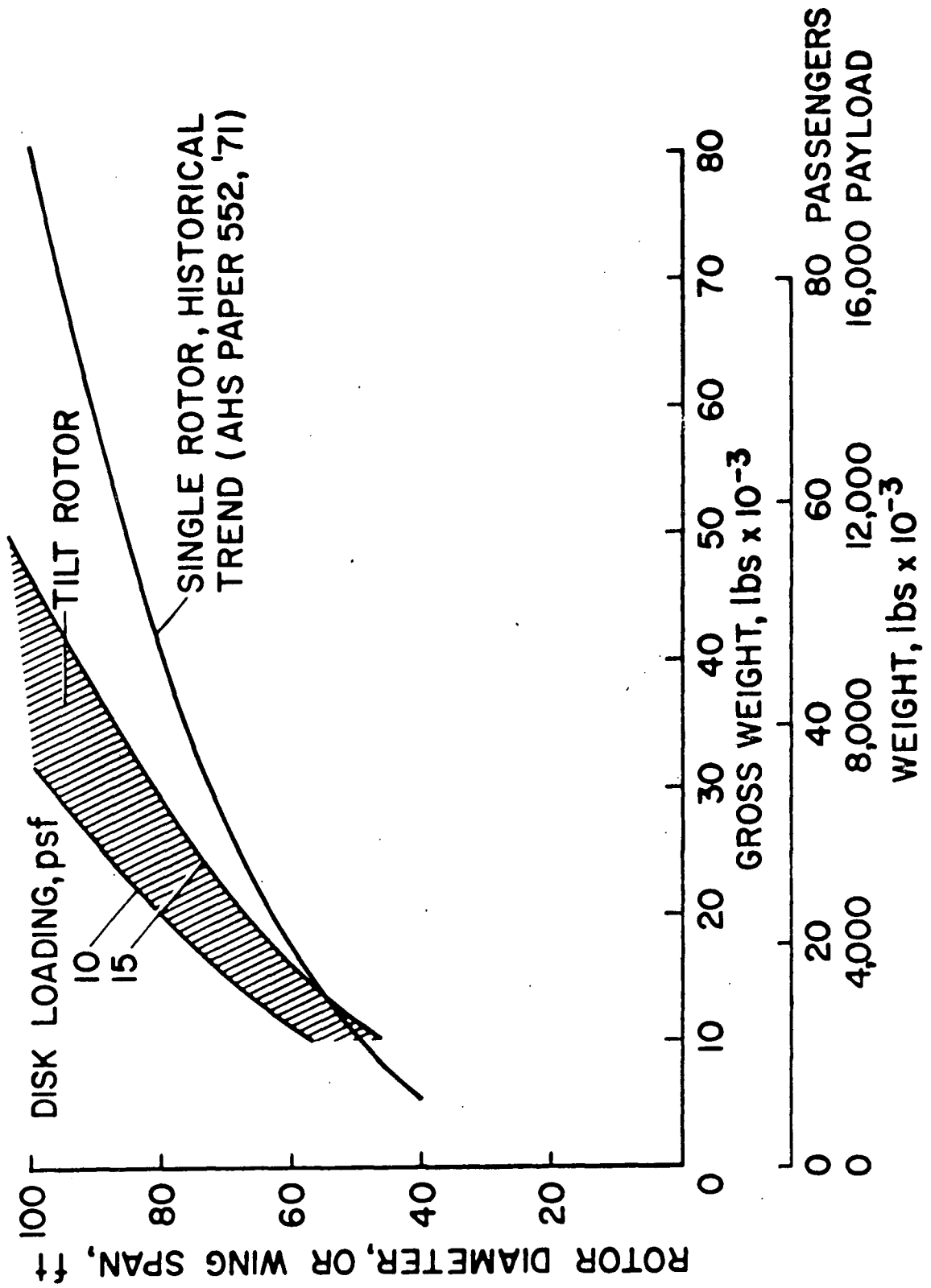
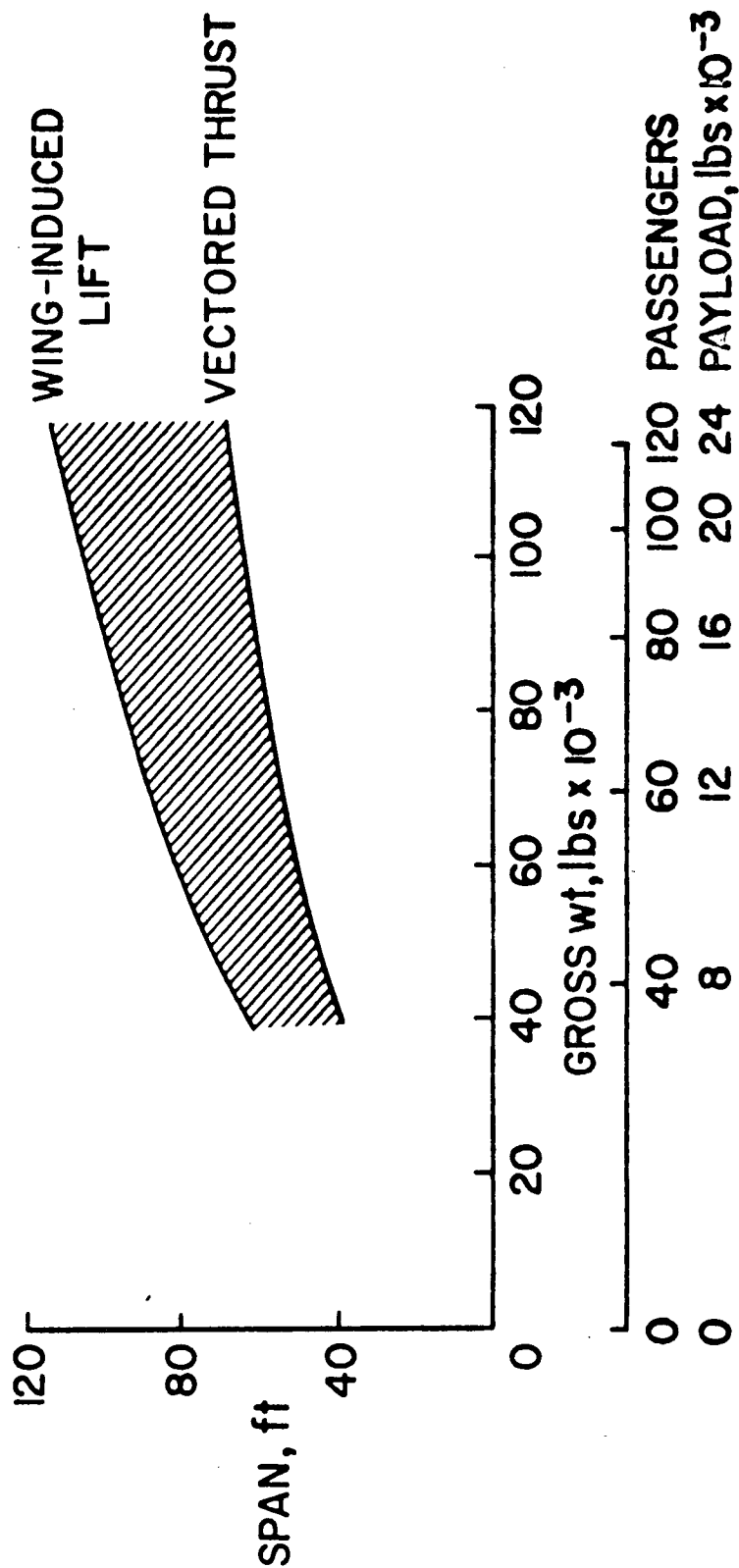

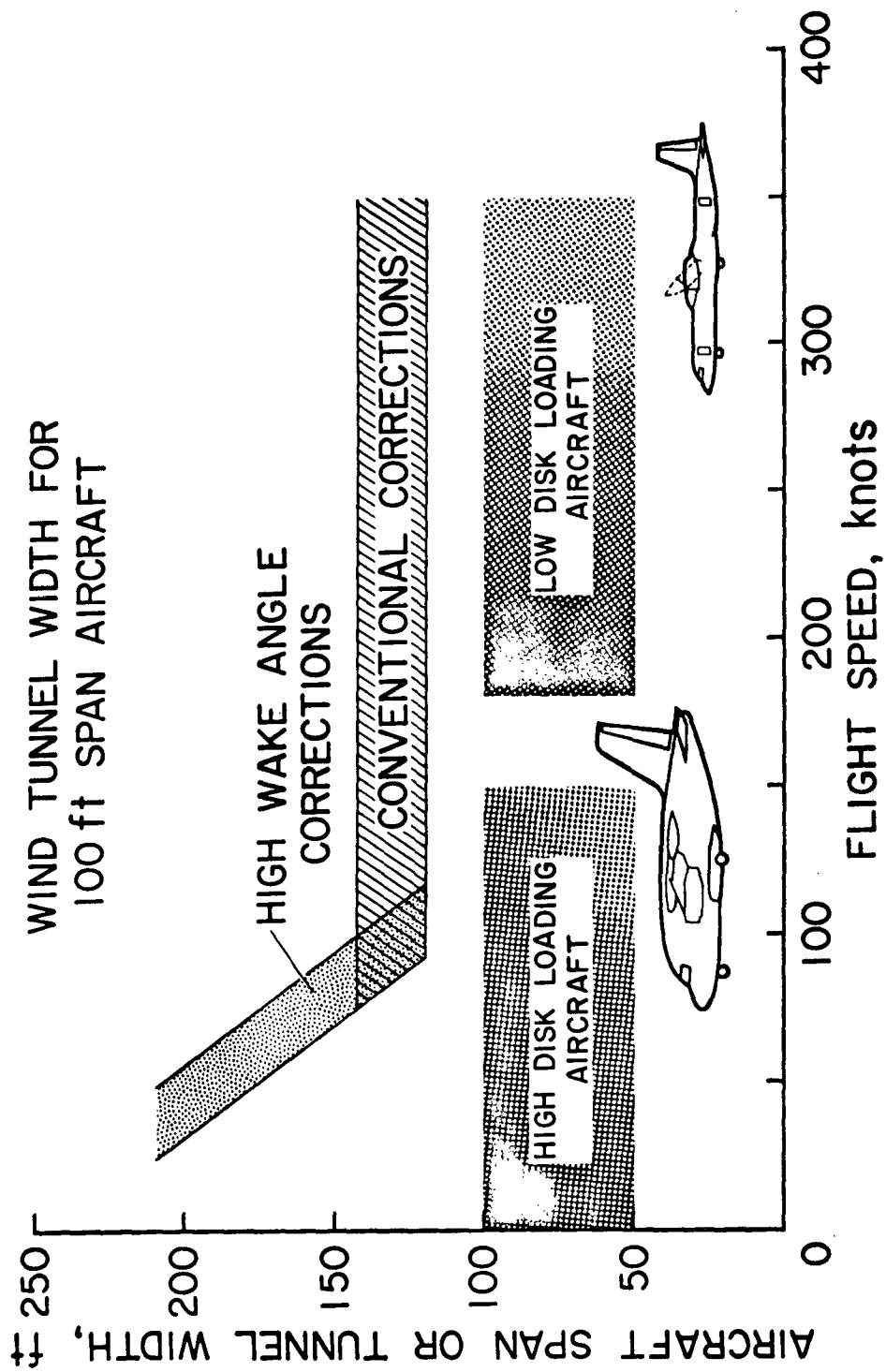Figure 8

HIGH DISK LOADING V/STOL AIRCRAFT SIZE TRENDS

WING-INDUCED LIFT

VECTORED THRUST

SPAN, ft

120						
80						
40						
0	20	40	60	80	100	120

GROSS wt, lbs x10^{-3}

| 0 | 40 | 60 | 80 | 100 | 120 | PASSENGERS |
| 0 | 8 | 12 | 16 | 20 | 24 | PAYLOAD, lbs x10^{-3} |

Figure 9

WIND TUNNEL WIDTH FOR
100 ft SPAN AIRCRAFT

HIGH WAKE ANGLE
CORRECTIONS

CONVENTIONAL CORRECTIONS

LOW DISK LOADING
AIRCRAFT

HIGH DISK LOADING
AIRCRAFT

AIRCRAFT SPAN OR TUNNEL WIDTH, ft

ft 250

200

150

100

50

0

0   100   200   300   400

FLIGHT SPEED, knots

Figure 10

29

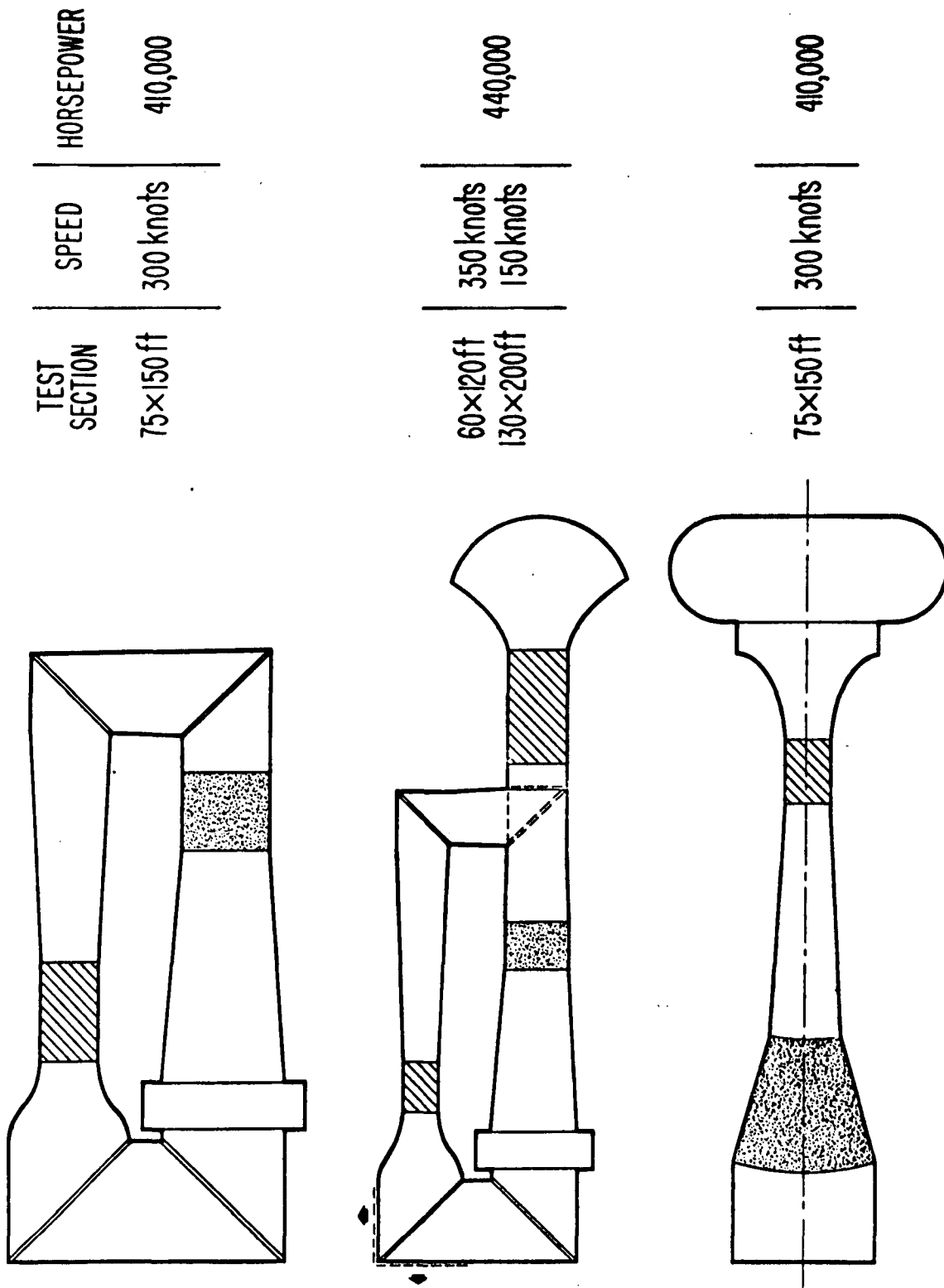| TEST SECTION	SPEED	HORSEPOWER
75×150ft	300 knots	410,000
60×120ft	350 knots	440,000
130×200ft	150 knots	
75×150ft	300 knots	410,000

Figure 11

30

TYPICAL AIRCRAFT FUNDING SCHEDULE AND DECISION POINTS SHOWING TEST LEVERAGE (CUMULATIVE)

Figure 12