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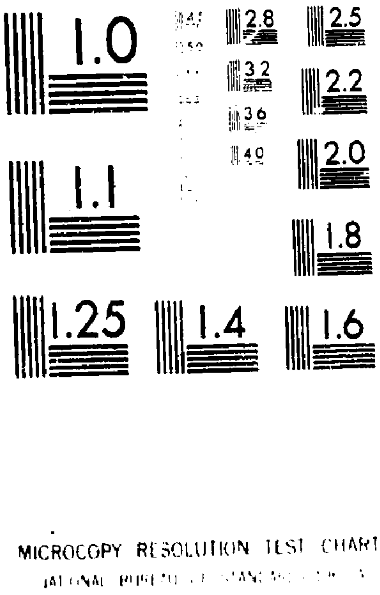

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DESIGN DEFINITION STUDY OF A NASA/NAVY LIFT/CRUISE FAN TECHNOLOGY V/STOL AIRPLANE—RISK ASSESSMENT ADDENDUM TO THE FINAL REPORT

J. M. Zabinsky, R. W. Burnham, C. C. Flora, P. Gotlieb, D. L. Grande,
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16. Abstract

An assessment of risk, in terms of delivery delays, cost overrun, and performance achievement, associated with the V/STOL technology airplane is presented. The risk is discussed in terms of weight, structure, aerodynamics, propulsion, mechanical drive, and flight controls. The analysis ensures that risks associated with the design and development of the airplane will be eliminated in the course of the program and a useful technology airplane that meets the predicted cost, schedule, and performance can be produced.

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SUMMARY AND INTRODUCTION

An assessment of the risk, in terms of delivery delays, cost overrun, and performance achievement, associated with the V/STOL technology airplane is presented. This assessment ensures the risks associated with the design and development of the aircraft will be eliminated in the course of the program and a useful technology airplane that meets the predicted cost, schedule, and performance can be produced.

The technology airplane (model 1041-134) is based on an operational multimission Navy conceptual design (model 1041-133). The airplanes shown in figures 1 and 2 are described in the document to which this is an addendum. The technology airplane will be used to examine handling requirements and operating techniques in the low-speed flight regime. In addition, operation over the full-flight spectrum will be demonstrated.

The areas of interest are those connected with V/STOL operation and the related V/STOL systems. The propulsion system–the core of the V/STOL airplane–is shown schematically in figure 3. The engines, fans, gears, clutches, and interconnecting shafts provide the performance and control in vertical flight. The integration of this system into the airplane is the basis for the V/STOL design.

The assessment discussion is treated in terms of six technology areas: weight, structure, aerodynamics, propulsion, mechanical drive, and flight controls. In each of these areas the problems that need special emphasis are discussed and the action taken to eliminate risk is described.

The tests and associated development required to ensure a low-risk program are reasonable and straightforward. Control of the airplane weight and integration of the propulsion system into the airplane will receive special emphasis. The components comprising these systems are all current state of the art and are mostly operational. Some of the propulsion and flight control components have not been previously operated together; in general, the new arrangements are less demanding than the current operational application.

A discussion of vertical thrust and weight is presented as typical of the performance margins that are available, since vertical flight is most sensitive to these parameters. Weight growth is endemic to the aircraft industry, and for a conventional airplane of this size, a 1900-lb weight growth is considered possible. Increases in weight generally occur in exchange for performance or other improvements and as a result of detailed design definition. For conventional takeoff and landing aircraft, this means a small increase in ground roll. On a V/STOL airplane weight gains are intolerable and will not be lightly traded for performance or other improvements. For this V/STOL aircraft a rigorous weight management program is planned, which will result in keeping the growth within tolerable limits.

An assessment of the V/STOL performance capability may be obtained from the static thrust and weight data shown in figure 4. The static thrust available is plotted as a function of ambient temperature. Both contingency thrust with one engine out, one engine driving three fans, and takeoff thrust with two engines driving three fans, are shown. The contingency thrust at 90° F is the base point at 21 000 lb. Most conservatively, it may be considered constant with temperature with water usage decreasing so that none is required at 60° F. If the water rate is continued (which is the simplest design condition) but no credit is taken for increased compressor performance, the performance shown on the second line is available with 21 700 lb of thrust at 60° F. This performance is slightly more optimistic than the flat rating. The third line with 22 500 lb thrust on a standard day will be achieved if the compressor operation is not limited at the increased corrected speed.

The emergency thrust required is shown as a dashed line. It is the emergency landing weight times 1.03. At this weight, there are 600 lb of fuel and 370 lb of water/alcohol on board, which is enough for about 3 minutes of hovering at 90° F. On a hot day (90° F) there is a 520-lb margin between the thrust available and thrust required. This margin is equal to the fuel required, in addition to the 600 lb already on board for the VTOL research mission. On a standard day with a limited compressor output, this margin is 1220 lb.

1.0 WEIGHT

The operating weight growth of technology demonstrator aircraft is an important consideration because it will reflect the integration of all design and manufacturing risk solutions. It is also critical in providing for proper aircraft performance. This section will address the weight impact of items of concern in the individual design technologies in structure, propulsion, and equipment. The probability of exceeding the preliminary design operating weight estimate and the weight tolerances provided for in the basic design are discussed. Plans for the implementation of a weight control management plan are also described.

1.1 WEIGHT AND BALANCE RISK SUMMARY

Weight concerns on the lift/cruise fan technology V/STOL aircraft are primarily associated with meeting the engine-out emergency landing weight requirement. The operating weight level resulting from an analysis of the preliminary design has been adjusted by past aircraft program weight growth experience to ensure that the technology airplane will meet test objectives.

The design approach in the case of model 1041-134 is based on providing for limited weight growth and understanding the impact of this growth on the design of a V/STOL airplane. Table 1 describes the potential weight risks and solutions in the major airplane systems. As shown in the table, weight growth allowances for 520 lb or 3% of the operating weight can be accommodated and still meet the emergency landing weight requirement. This analysis provides for growth and thrust margins and is based on a payload requirement of 2500 lb, including a fuel weight of 600 lb at the emergency landing condition. It is important to note the basic design at normal operating conditions has excess mission capability, which reflects a potential fuel and associated weight decrease. However, the airplane balance must be reanalyzed to take advantage of the potential weight reduction.

The weight and thrust comparison is summarized in table 2. Weights are shown under two conditions of thrust augmentation for hot day and standard day with a water injection system. The table shows 520- and 1220-lb margins between the estimated weight and the maximum permitted weight. A potential weight growth of 1900 lb is shown based on conventional takeoff and landing aircraft and prototype aircraft experience. The critical design feature of these aircraft is minimum DOC, and weight growth (operating weight and maximum takeoff) is not a limiting case. Whereas on this V/STOL design, emergency landing weight and availability of emergency landing thrust are the critical design features. It is recognized that the increment of potential weight growth on conventional aircraft is greater than may be experienced on a V/STOL program because of the difference in key design objectives. The weight control and weight management plan (described in sec. 1.3.2) will be aimed at minimizing weight growth. The weight management program will properly reflect design decisions to control the weight growth within the allowable 520 lb.

1.2 WEIGHT GROWTH AND ALLOWANCES

Weight growth as a concern and allowance for controlled growth is discussed in section 1.1. The specific weight potential growth is also defined. These data were developed based on previous Boeing experience on the 727, 737, 747, YC-14, and Buffalo programs. While these programs have resulted in an average of 11.5% operating weight increase, there is only a low risk that an intensive weight control program cannot control the weight growth within the allowable 520 lb. The projected weight growth will be minimized by an intensive weight control program that is implemented from design go-ahead. This type of program, although requiring high initial program manning, has proved successful in weight reduction and also ensures a lower total cost.

If the weight control is not entirely successful, a slight limiting of the operational envelope will result. For example, the hovering altitude from which a vertical landing of 12 fps can be made as a function of a possible thrust loss is shown in figure 9. Considering a weight increase as equal to a thrust loss, a safe hovering altitude of 65 ft is possible if the entire 11.5% weight increase occurs.

1.3 WEIGHT CONTROL MANAGEMENT

Especially close control must be exercised in thrust and weight management on a V/STOL airplane to ensure that flight safety and operational criteria for the aircraft in both modes are achieved. On the lift/cruise fan technology aircraft a Weight Control and Management Program will be implemented immediately after design go-ahead to establish stringent controls on early weight changes and to prevent costly weight reduction exercises during later design stages. There are many contractor interface and management requirements associated with such a program. The discussions in this section only highlight the major elements of these requirements in the following areas.

- Weight responsibilities
- Weight and balance control
- Visibility and decision making

1.3.1 WEIGHT RESPONSIBILITIES

Weight control is exercised by involving all levels of contractor and subcontractor management including finance, manufacturing, and engineering activities. Major plans are made and approved to control empty weight, balance, and inertia, with all component weights falling under these controls.

Weight responsibilities are established for the contractor and subcontractor at the design group and individual level with a sharing in the definition of weight at the detail level. Current weight and target weights are defined with emphasis placed on scheduled design, release, manufacturing, and flight test. The Director of Engineering, Chief Engineer–Design, Chief Engineer–Technology, and Weight Staff Chief will support and are involved in establishing target weight levels consistent with the work breakdown structure.

1.3.2 WEIGHT AND BALANCE CONTROL

Aircraft weight and balance will be tracked by the Weight Staff and, with Engineering Management, will increase or decrease target weights wnen effects such as available thrust, loads, allowables, criteria requirements, or configuration change significantly. Weight and balance reserve accounts established at the beginning of the program will be adjusted accordingly. Subcontractor and supplier weight control programs are established to control the weight of selected major manufactured hardware.

1.3.3 VISIBILITY AND DECISION MAKING

Provisions for management weight and balance visibility and decision making is the key to a successful weight and balance control program. Plans for the lift/cruise fan technology aircraft will include the normal periodic status reports to all groups, levels of management, and the NASA contracting office. In addition, a specific Weight Control and Management Workroom display would be established to provide a scheduled time and place to discuss weight status, potential changes, and their effect on weight and thrust management. These meetings would bring all technology and design engineers having weight responsibilities together with program management for discussions and decision making.

2.0 STRUCTURAL DESIGN

The structural analysis and design of the V/STOL technology demonstrator will provide sufficient structural strength and freedom from flutter at a minimum weight, within an allowance that permits successful performance. The loads and stress analyses will be sufficiently accurate and complete to minimize conservative material requirements. While the selection of materials and internal arrangement of the structural members are fundamental to a successful airframe design, the use of conventional proven materials and a simple structural arrangement will virtually eliminate any risk due to these factors. The following paragraphs discuss each of these technologies in greater detail.

2.1 MATERIALS AND ARRANGEMENT

The structure of the technology demonstrator will be built primarily of conventional aluminum alloys, using the 2024 alloy in the wing lower surface and areas critical for fatigue, and the higher strength 7075 alloy in areas such as the wing upper surface. The landing gear will be constructed of 300M steel or other alloy of similar characteristics. To save weight, control surfaces constructed of bonded aluminum will be considered. These material selections provide for assured structural integrity.

Composite structure will be considered for application to the tail surfaces and fan cowlings. This is a particularly effective means of reducing weight for this airplane because it counts double. Both the tails and the fan cowlings are well aft of the airplane center of gravity, and weight reduction there allows weight reduction in the nose area while maintaining proper balance.

The wing consists of a two-spar box with the wheel well located between the spars in the outer wing panel. The leading edges are simple assemblies attached directly to the front face of the spar with no high-lift devices. The trailing-edge flaps consist of single slotted surfaces with external hinges. The ailerons on the outer portion of the trailing edge are conventional in design and installation. The fuselage presents a unique design situation from the standpoint of having a large side-by-side cockpit with upward hinging canopies, a large cutout in the forebody for the forward lift fan, and a cutout in the aft fuselage for the supporting structure for the pivoting engines. Because of the large number of cutouts and the small size, the design of fail-safe load paths will be given careful attention. Special design emphasis will be applied to mounting the engines on a crossbeam across the aft end of the fuselage, providing a pivot, providing for cross-shafting for power transmission, and supplying services for the engines. The empennage consists of a T-tail installation of conventional design. The fin and the all-moving stabilator are of two-spar construction with the rudder hinged on the rear spar of the fin. The structural arrangement is simple with no sophisticated high-lift devices and elaborate mechanisms.

2.2 LOADS AND CRITERIA

The deisgn of the technology demonstrator will be based on criteria for Class VP aircraft as defined in the MIL-A-8860 series specifications, except that the limit load factor will be 2.5g at a flight design gross weight of 20 000 lb. Past practice on technology demonstrators has been to estimate the loads based on theoretical methods and any wind tunnel data that may be available. Such loads for the V/STOL technology demonstrator are considered to be

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accurate within about 10%. The accuracy of the loads predictions will improve to about 5% with the addition of a loads wind tunnel model.

2.3 STRESS ANALYSIS AND DESIGN

Previous technology demonstrator and prototype programs have held costs to a minimum by reducing the level of stress analysis and design support to a minimum. This philosophy carries with it the corollary requirement that fewer details of the airframe will be analyzed and designed to minimize the margins of safety, and similar details that are not analyzed are covered by conservative assumptions resulting in the inclusion of excess material. It is estimated that the YC-14, for example, carries approximately 5000 lb of excess weight in the operating empty weight to cover design compromises for prototype economies. The V/STOL technology demonstrator will avoid this weight growth by providing sufficient stress staff and designer support during the design and release period to analyze all significant details and to design out the excess material.

Customary structural criteria require that the airframe be subject to a flight loads survey and a static test before it is permitted to operate at limit load factor. Prior to this, the airplane is restricted to 80% of limit load factor. Since the V/STOL technology demonstrator will fulfill all required performance objectives with an operational load factor of 2.0g, it is considered adequate to provide for a proof load test of the control system and eliminate other structural tests in the interest of minimizing program costs.

2.4 FLUTTER

Flutter prevention on past technology demonstrators has consisted of a flutter analysis supplemented with a ground vibration test to verify the vibration mode shapes and frequencies, and a flight flutter test at the critical flight condition. The V/STOL technology demonstrator, having a relatively small unswept wing and being small and relatively stiff, will tend to have higher modal frequencies and good frequency separation. It is, therefore, considered that the conventional flutter analysis and testing is sufficient, and the risk of encountering a flutter condition within the flight envelope is small.

3.0 AERODYNAMIC CONFIGURATION

3.1 SPECIAL FEATURES

Model 1041-134 does not present any unique aerodynamic problems that cause undue uncertainty about achieving the required performance levels. However, since there are presently no experimental data on this particular configuration, there are several areas that require verification data and some tailoring activity in the wind tunnel. The items requiring attention are ground effects in both the VTO and STO modes; interaction between the airframe and the fan efflux at moderate and high nacelle tilt angles; interference between the body and the nacelles in the cruise configuration; nacelle external flow separation at high nacelle tilt angles; and wing separation at high descent angles in transition flight. These items will be discussed relative to known data and planned test programs in the following paragraphs. They are divided into those that will require verification data only, and those that may result in some configuration tailoring in the wind tunnel.

3.2 VERIFICATION DATA FROM WIND TUNNEL TESTS

The following items require verification data from wind tunnel tests but present no risk to the program.

3.2.1 STO GROUND EFFECTS

The presence of the ground causes changes in the aerodynamic forces that must be taken into account in calculating STO performance. Model and flight test data on ground effects exist for various STOL configurations, but the problem is highly configuration-dependent and the ability to predict these effects for new configurations is limited. At high lift coefficients the effect is usually to reduce the lift; however, at least one powered lift configuration (AMST YC-14) has shown a lift gain. The design goal for STOL performance of model 1041-134 is a 1000-ft takeoff field length with 11 terminal area cycles per mission. If ground effects are not considered, the performance is calculated to be 14 cycles with less than 400 ft of takeoff field length. This allows a considerable margin for adverse ground effects before compromising the design goals.

3.2.2 AIRFRAME-PROPULSION INTERFERENCE

Interaction between the propulsion system flow (nacelle inflow and fan efflux) and the basic flowfield of the unpowered configuration must be considered. Because of the large fan mass flow and the close proximity of the fan efflux to the wing trailing edge at high nacelle tilt angles, interaction effects are expected to be substantial.

For a jet exiting downward at some angle from the trailing edge of a wing, it is well established from theory, wind tunnel testing, and flight testing that a favorable interference occurs (the jet flap effect). Because of difficulties in accounting for entrainment of flow into the jet and predicting the jet path at forward speeds, the magnitude of the favorable effect is not readily predictable for a new configuration.

In order to eliminate any risk to the program from this source, no credit has been taken for favorable interference effects in calculating STO performance.

3.2.3 WING STALL AT HIGH DESCENT ANGLES

During a vertical landing, the flightpath is very steep and extreme wing angles of attack are encountered; however, this generally occurs at very low speeds. If the wing stalls at too low an angle, the resulting buffet could impose a limit on the flight envelope.

The prediction of wing stall angle can be made by using wind tunnel data for the particular configuration together with empirical correlations to correct to full-scale conditions. A large amount of data from past airplanes are available to aid in making this prediction. In the present study, the preliminary estimates have been made based on wind tunnel data from the YC-14, which has the same airfoil as model 1041-134; corrections were made for aspect ratio and sweep. The wind tunnel program will provide a more exact basis for predicting stall of this particular configuration.

Stalling of the wing at steep flightpath angles causes a buffet problem only if it occurs at a condition where the wing load is an appreciable part of the total lift. For an approach with a 1000-fpm descent rate, it is calculated that wing stall onset occurs at a speed of 37 kn if the airplane attitude is level with the ground. Under these conditions, the wing has a total lift of only about 6% of the airplane weight, the rest of the lift being due to direct thrust. Under these conditions, the effects of wing stall buffet on the airplane are expected to be negligible.

3.3 CONFIGURATION TAILORING IN WIND TUNNEL

The following items may require some configuration tailoring in the wind tunnel; however, no large configuration changes are anticipated and risks to the program from these sources are low.

3.3.1 VTO GROUND EFFECTS

For hovering flight near the ground, the jet induces secondary forces on the airplane that may result in either a gain or a loss in net lifting force. If a loss of lift should occur, it would be necessary to offload fuel for the VTO mission. A lift loss of 4% of thrust would result in reducing the number of VTOL terminal area cycles per mission to five compared to the present calculation of eight. This would still meet the design goal for the technology aircraft. A qualitative assessment of the ground effect, based on comparison of model 1041-134 with various configurations for which data are available, indicates that a positive or neutral lift change is likely. However, this effect has proved to be sensitive to the angles of the jets relative to the ground, and it may be necessary to make small changes in the jet toe-in angles to achieve the best result. This change, made early in the program, would have no effect on the cost or schedule and therefore presents no risk to the program.

3.3.2 NACELLE-BODY INTERFERENCE

The fan nacelles are in close proximity to the body and are relatively large compared to conventional configurations. This will require special attention to minimize the nacelle-body interference drag in the cruise configuration. However, the aft fuselage is a very common location for engines and considerable data are available from the 727 airplane program. Design methods are available for finding nacelle and body contours that will avoid excessive interference drag at cruise speeds. Confirmation and final tailoring of the contours will be done in the high-speed wind tunnel tests.

For cruise drag calculations, a conservative approach was taken to estimate the nacelle-body interference by assuming an interference factor of 1.8. If the actual interference factor turns out to be 25% higher (i.e., 2.25%), the ferry range would be reduced by only about 2%. Present ferry range is considered to be adequate at 435 nmi, and small reductions are not considered to be a major factor in the program.

3.3.3 NACELLE EXTERNAL FLOW SEPARATION

For STOL and VTOL transition operation the nacelles will be tilted at high angles relative to the flow. The external nacelle flow will be separated, which requires consideration of the possibility of buffet, especially if periodic vortex shedding occurs.

Two previous airplanes with tilting ducts have successfully flown VTOL transitions, the Doak VZ-4DA and the Bell X-22A. The latter has reportedly flown almost 500 transitions (inbound and outbound). The tilting ducts on these airplanes have length-to-diameter ratios of about 0.5 compared to a value of about 1.25 for model 1041-134. The larger length-to-dimensional ratio may tend to make the wake more closely resemble that of a two-dimensional cylinder. This raises some concern of periodic vortex shedding (which has been shown to exist even at the very high Reynolds numbers of concern here). This problem, which requires full-scale Reynolds number for simulation, will be investigated during the test planned for the Ames 40- by 80-ft wind tunnel.

If a problem of vortex shedding from the nacelles at high angles should develop during the wind tunnel test program, it is anticipated that this can be solved by the addition of aerodynamic devices on the nacelles. One possibility would be the addition of strakes along the nacelle sides. This would result in small weight and cruise drag increases, and a somewhat large increase in drag at high nacelle tilt angles could result. As discussed in section 3.2.1, STO performance is well in excess of design goals, and the impact of this drag increase would be small.

4.0 PROPULSION SYSTEM

The propulsion system includes a number of basic and unique components and features to which special consideration will be given to ensure the design goals are achieved. These include: the lift/cruise inlets; the variable area fan nozzle and yaw vanes; the nose fan inlet, nozzle, and nozzle vectoring vanes; the lift/cruise engines and their integration with the fan; and the transmission and shafting system and its integration with the propulsion system components.

4.1 LIFT/CRUISE FAN INLET

The inlet must provide the required amount of airflow to the fan at high total pressure recovery, and with acceptable distortion to the fan and core engine over a large range of operating conditions. A short, lightweight inlet is an additional design goal. The estimated inlet angle of attack at various conditions is shown in table 4. The most difficult design conditions occur during approach when the inlet angle of attack is 80° to 90° and the speed is 75 to 100 kn.

Lift/cruise tilting propulsion pods have been demonstrated on the Doak VTOL research airplane and the X-22A VTOL research airplane, both which had tilting subsonic pods with ducted propellers geared to engines in the fuselage. The VJ-101C was a V/STOL fighter with tilting afterburning turbojets with supersonic intakes. The ducted propellers operated successfully with fixed geometry subsonic inlets, whereas the VJ-101C, because of the supersonic inlet, used a translating inlet cowl that opened a slot for low-speed operation.

Fixed geometry inlets are currently used on most subsonic airplanes. Fixed geometry inlets have been tested at high angles of attack by Boeing under NASA contract (ref. 1) and by NASA-Lewis (ref. 2). Fixed geometry inlet models were tested up to 80° at 80 kn and up to 60° at 120 kn at certain conditions without internal flow separation, as shown in figure 5 (see ref. 2). This compares with the 1041-134 V/STOL requirement of 90° at 75 kn and 60° at 125 kn. It is considered that an acceptable fixed inlet can be designed by extending the inlet contraction ratio to values above the maximum values of 1.56.

Another method of designing the lift/cruise inlet is by the use of variable geometry. This type of inlet provides a large, distortion-free operating envelope, but is heavier and more complex than the fixed lip inlet. A 1/12th-scale model of a blow-in-door inlet has been tested at angles from 0° to 90° and velocities from 0 to 150 kn with acceptable recovery and distortion (see ref. 3). At cruise Mach numbers of 0.7 and 0.8, acceptable external drag and good inlet recovery were obtained. The fan inlet distortion pattern obtained at $\alpha = 90^\circ$ and $V_0 = 100$ kn is shown in figure 6. An evaluation of this distortion shows it to be within the distortion tolerance of the engine.

The fixed geometry inlet development program provides a high level of confidence that satisfactory inlet performance will be achieved. The blow-in-door inlet is the alternative in the event the fixed geometry inlets appear marginal in performance during the wind tunnel program. The consequence of not achieving the full angle-of-attack capability will be a reduction in the V/STOL takeoff and approach corridor. Experience with inlets at high angles

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of attack show that operation over most of the V/STOL range will be possible and any diminution of the V/STOL corridor will be small.

A three-dimensional potential flow and appropriate boundary layer analysis will be made to determine the inlet lines of three fixed geometry inlets and one blow-in-door inlet model. These inlets will be tested in the Boeing 9- by 9-ft wind tunnel. The best of these inlets will be tested on the Hamilton Standard Q-Fan with the T55 engine in the Ames 40- by 80-ft wind tunnel, where the capability of the inlets at high angle of attack will be demonstrated prior to the program go-ahead.

Subsequent scale-model testing in the 9- by 9-ft tunnel and with the 20-in. turbo simulator at Lewis will test additional operating conditions applicable to the T701 lift/cruise engine that are not demonstrated in the Q-Fan tests. Tests on the airplane with a crosswind simulator and at high taxi speeds will demonstrate full-scale inlet operation prior to flight.

4.2 VARIABLE AREA FAN NOZZLE AND YAW CONTROL VANES

The fan nozzle needs exit variations from full open at low speed (e.g., hover) to about 70% of this at cruise and loiter. Variable area nozzles have been built for many afterburning turbofans and turbojets. Because the fan airflow is cool, a low-drag, leak-free nozzle is planned. Vanes in the fan exhaust are needed to provide yaw control for the low-speed flight control system. The vanes are similar to flight control elevators or flaperons and have been used in previous applications of ducted propellers (e.g., refs. 4 and 5).

The low-speed performance can be attained with no variable nozzle area. The high-speed maximum thrust will be down, and the loiter SFC will be up if a nonvariable nozzle is used.

Although yaw control can be obtained from the nose fan only, the resulting side force coupling can best be eliminated with vanes in the lift/cruise fan.

Yaw vanes will be tested with the Q-Fan in the 40- by 80-ft Ames wind tunnel. The variable area nozzle design will be based on technology used on current nozzle and thrust reverser designs. The primary nozzle will be a conventional fixed area nozzle.

4.3 NOSE LIFT FAN INSTALLATION

The fan installation is similar to fan installations that have been developed in various programs for fan-in-wing and fan-in-fuselage installations (see refs. 6 and 7).

Inlet lines will be analyzed using the three-dimensional potential flow analysis as described in reference 8, and an appropriate boundary layer analysis. Tests in the Boeing 9- by 8-ft tunnel will be made to verify this design. Yaw control vectoring vanes and other installation features will be designed from previous experience and data in the literature. The fan and gearbox will be developed by Hamilton Standard based on their previous experience with variable pitch fans and gearboxes (see ref. 9 for 55-in. Q-Fan test results).

4.4 LIFT/CRUISE ENGINE AND INTEGRATION WITH FAN

Hamilton Standard's fan development will rely heavily upon their past experience with their variable pitch Q-Fan. They have successfully developed and tested a 55-in. 1.18 fan pressure ratio variable pitch fan (ref. 9). The 62-in. fan development will be a direct extension of currently demonstrated hardware. The Hamilton Standard development schedule is shown in figure 7. This development plan includes incorporation of blade design features to withstand bird strikes. Schedule time is allotted to conduct bird-strike tests.

The Allison T701 as currently used in the Vertol heavy lift helicopter is below the horsepower required to meet the contingency (engine-out) requirement for model 1041-134. To increase the power output of the T701, the power turbine will be modified and a water/alcohol injection system will be used for the emergency condition. The water/alcohol system is currently operational on the Allison T56 turboshaft engine and will be modified to meet the requirements of the T701. An assessment of the V/STOL performance capability may be obtained from the static thrust and weight data. The static thrust available is a function of ambient temperature, as shown in figure 4. Both contingency thrust with one engine out, one engine driving three fans, and takeoff thrust, two engines driving three fans, are shown. The contingency thrust at 90° F is the base point at 21 000 lb. Most conservatively, it may be considered constant with temperature with water usage decreasing so that none is required at 60° F. If the water rate is continued (which is the simplest design condition), but no credit is taken for increased compressor performance, the performance shown on the second line is available with 21 700 lb of thrust at 60° F. The T701 compressor operation may be limited at the high $N/\sqrt{\theta}$ associated with water injection on a standard day. For this reason only the added thrust resulting from the increased mass flow of the water itself is considered. The third line with 22 500 lb of thrust on a standard day will be achieved if the compressor operation is not limited at the increased corrected speed. Allison's development and test program (fig. 8) will include a contingency test of the modified T701 with water/alcohol injection to determine if the required horsepower is attainable. If, however, the required power level is not achieved, the program will continue with the fan integration; modifications will be made to the system and another contingency test will be run on the second engine. The fan-plus-engine testing will also determine if the normal vertical thrust requirements will be met. This will be a low-risk item due to the thrust margins available at these conditions, as shown in table 3.

If the contingency thrust of 21 000 lb on a 90° F day is not achieved, a slight limiting of the operational envelope will result. For example, the hovering altitude from which a vertical landing at 12 ft/sec can be made as a function of a possible thrust loss is shown in figure 9. A thrust loss of 1200 lb will reduce the thrust to the emergency weight. After a loss of 1500 lb the safe hovering attitude is reduced to 35 ft on a hot day.

Engine backpressuring effects at low altitudes will not be a problem due to adequate primary nozzle ground clearance. Reference 10 suggests that for a ground clearance of one nozzle diameter or more, the backpressuring effects are minimal. Tests will determine the effects of ground clearance on the lift/cruise-fan-plus-engine nacelle. A moderate thrust loss is tolerable due to the thrust margins indicated in the table.

5.0 MECHANICAL SYSTEM

The mechanical fan drive system interconnects the fans for both driving and flight control load transfer power. The system includes the shafting, gearboxes, and front fan clutch. Each element in the drive train is critical to the design of the total airplane system.

The mechanical transmission, with the exception of the front fan clutch, is essentially state of the art and does not require development testing. The clutch will be developed to ensure availability for the technology demonstrator. Features will be incorporated in the basic system design to ensure low cockpit noise, and sufficient testing and analysis will be done to ensure that the engines, shafts, fans, gearboxes, and fuselage do not have adverse dynamic coupling. Each of the areas are discussed in detail in the following paragraphs.

5.1 TRANSMISSION DRIVE SHAFT AND GEARS

The mechanical transmission shaft operating speeds and loads are within those currently used on production helicopters. The spiral bevel gearing loads and stress levels will be less than the demonstrated capability of the UTTAS helicopters and expected of the HLH. The engine reduction gearing is typical of that used in the T56 engine. Although the reduction gears will be turning at a higher rotational speed, the lubrication environment is less severe because the unit is operated with a fixed (instead of rotating) planet carrier.

The shaft and gear key design areas and related experience are shown in table 5 and figure 10. Shaft design experience on the Boeing helicopters is compared to the 1041-133 airplane in figure 11.

Vertol, in conjunction with Allison, has developed analysis techniques to calculate rim stress and resonant stress levels that exist in the gearing but were not predicted by conventional AGMA techniques. Therefore, the ability to design the spiral bevel gears required by the V/STOL airplane is within the demonstrated state of the art, and the spiral bevel gear stresses are to be maintained at levels below those experienced in the HLH and UTTAS helicopter designs. The drive system design bevel gear stress comparison to state of the art is shown in figure 12.

In the event that the gearing or shaft elements would prove marginal, the effect on airplane performance requirements would be minimal. Limited performance ground tests, and possible flight tests, could be conducted under partial power until appropriate fixes could be determined. (A typical example would be the HLH spiral bevel gear sets where the DSTR tests have continued at partial load until the improved gear sets could be incorporated.) Then the full spectrum of operating conditions could be run. Excessive gear-train power losses would be minimal and have a relatively minor effect on the total airplane operating envelope because of associated loss of thrust. The loss prediction methods are based on empirical methods established by previous experience with numerous gearboxes; thus, losses can be calculated with considerable confidence.

Shop requirements and test facilities are typical of those needed for the HLH. For the technology demonstrator, only one major test rig appears to be required. This would test the combiner box, clutch, and shafts.

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The transmission program schedule will allow for minor fixes. Major problems that could result in a program extension are not anticipated because of the development work and production techniques already available for the airplane.

5.2 FRONT FAN CLUTCH

The front fan clutch must be capable of accelerating the front fan to full rpm under drag load conditions, synchronize the shaft speeds, and provide positive engagement. Clutches capable of accomplishing these requirements are based on Vertol past experience with friction clutches designed to engage reciprocating engines to helicopter rotor drives and rotor brake technology. The ability to handle high-torque clutching requirements and high energy absorption by clutch material is not the basic problem; the task is to develop a controlled actuation clutch that will meet the airplane requirements at an acceptable weight. Vertol has experience with graphite brake disks capable of absorbing high heat loads per unit weight and sustaining high centrifugal speeds that will be applicable to the clutch design.

The program costs include development work on a suitable clutch. However, a minimum of two clutch designs are to be pursued after initial analytical screening and possibly some preliminary development testing. The second clutch design will probably be more conservative and heavier; this would provide backup capability in the event that the prime clutch candidate should prove inadequate.

5.3 COCKPIT NOISE–GEAR TRAINS

The noise level in the cockpit will be a composite of gear-train noise and engine noise. The noise levels of gear trains vary widely between gear trains and manufacturers. The transmission of noise is dependent on the gearbox, mounting, structure, and spectral frequency range at which the noise is generated.

For this airplane the dominant noise occurs during takeoff with the front fan engaged. The fan turns at 3500 rpm and the shaft at 11 500 rpm. If unsuppressed, the gear train would produce overall sound pressure level (OASPL) = 98 dB and speech interference level (PSIL) = 78 dB noise, dominated by noise at 4000 Hz, at the crew compartment. The peak noise occurs at frequencies corresponding to the tooth-meshing frequency of reduction bevel gears. Through proper gearbox design, construction, mounting, and cockpit insulation treatment, the resulting noise level is reduced to OASPL = 74 dB and PSIL = 68 dB. The treatment is primarily for reducing the high-frequency (4000-Hz) noise component. Materials and procedures for reducing this frequency are well established.

In normal flight, with the front fan shut down, the gear noise in the cockpit reduces to approximately OASPL = 64 dB. These cruise noise levels should not affect crew comfort and efficiency.

The program will include gearing noise considerations to ensure proper design for required cockpit noise levels.

5.4 ENGINE/TRANSMISSION/AIRPLANE DYNAMIC COMPATIBILITY

Tests will be made to ensure that the dynamic characteristics of the transmission, engine, and airplane are compatible so as to prevent dynamic coupling, which could cause instability and/or component failure.

The dynamics of each element–engine, shafts, gearboxes, and support structure–are well understood. The dynamic effects on the airplane and propulsion system when the airplane is operated as a system will be evaluated by analysis ground rig and airplane tests. This procedure is the same as that normally followed in helicopter development testing and includes analytically modeling the propulsion system to provide total torsional dynamic simulation.

If propulsion system dynamic instability is found during development testing, fixes required to provide adequate damping can be readily determined and instability eliminated by simple shaft redesign. Instability discovered during airplane tests would probably result in a limited airplane performance profile until appropriate design solutions are made.

To ensure adequate propulsion/airplane system dynamic compatibility, the required ground test rig will be used. An iron ground rig using engines, fans, and transmission is considered basic to the program and would provide propulsion system dynamic response. Total evaluation could be obtained from a ground test vehicle (GTV), which utilizes the airplane fuselage buildup, engines, and transmission. The GTV rig would require a second fuselage section and probably add cost to the program, but might eliminate some airplane ground testing.

The cost of the test schemes must be evaluated to determine effects on program cost and schedule. The basic test fits within the program schedule; the GTV might not. Failure to accomplish adequate testing could require a program schedule extension to evaluate any problems encountered.

6.0 FLIGHT CONTROL SYSTEM

The technical areas that are treated in this section are as follows:

- Development of the aerodynamic configuration
- Analytical definition of the flight stabilizing and control system
- Implementation and integration of the flight stabilization and control system

The Boeing model 1041 airplane has all the VTOL features for safe operation in the powered flight regime. The mechanical interconnect transmission gives excellent engine-out flying qualities. The fan blade angle control gives the airplane excellent VTOL handling qualities.

The major design emphasis will be on hover, transition, and conversion operating modes. Conventional flight poses no special problems. Standard, reliable design procedures and well-known design criteria will be used to achieve the desired results with good success. A typical list of the areas that will receive the most emphasis are:

- Definition of hover and transition aerodynamics
- Integration of the basic VTOL flight control elements (blade angle and thrust vector vane angle) with the conventional controls during transition
- Definition of flight control laws for hover transition and conversion
- Implementation for a digital "fly-by-wire" flight control system

The design goals for these areas can be reached within time and cost guidelines by applying state-of-the-art technology and off-the-shelf hardware. An important ingredient is the Boeing experience gained in directly applicable programs (heavy lift helicopter and YC-14) that allows goals to be defined with confidence. VTOL flight control power and response times are not problem areas. The secret to success is system integration using a state-of-the-art fly-by-wire C/SAS digital system combined with timely wind-tunnel-validated airplane dynamics, "pilot in the loop" flight simulation testing, timely delivery of hardware, and a well-planned system ground test and qualification program.

6.1 AERODYNAMIC CONFIGURATION DEVELOPMENT

Model 1041 is a reasonably conventional aerodynamic configuration characterized by a large lift/cruise fan nacelle, a small wing, and a large tail. Control system augmentation for the rudder, stabilizer, or aileron will not be a safety of flight item in conventional flight. Consequently, the design emphasis can be placed on the powered lift flight regime with low risk as long as the airplane can make an emergency conventional takeoff and/or landing.

In summary, the risk is that inadequate definition of the transition aerodynamic characteristics will result in restrictions to the airplane flight envelope due to inadequate trim capability. This risk can be reduced to acceptable values by a well-planned and timely wind tunnel test program.

The important features of the powered flight regime that will be emphasized in the early wind tunnel test are:

- Longitudinal trim and control requirements, including induced and inlet momentum effects
- Flow field at the empennage
- Moment comparisons in and out of ground effects including the effect of airplane attitude.
- High angle-of-attack and sideslip data for steep descent, crosswind, and gust sensitivity evaluations
- Thrust vectoring performance of the control vanes in the fan slipstream

The stability of the unaugmented airframe in conventional flight will be reasonable. The design goal is to develop the configuration in the first series of wind tunnel tests so that an emergency conventional takeoff or landing is possible without stability or control augmentation. The high angle of attack and sideslip boundary will be defined such that high AOA flight safety can be achieved by suitable pilot warning techniques (stick shaker, lights, or horn). When these design goals are achieved the design attention can be focused on the VTOL flight envelope. Early definition of the VTOL transition and conversion trim requirements and the flow field at the empennage are important. The flow field at the horizontal tail is largely affected by the lift/cruise fan nacelle incidence and thrust. Downwash angles in the order of 45° are expected (but at very low airspeeds). The first series of wind tunnel tests will be used to define a schedule between horizontal tail incidence and nacelle incidence that will keep the nominal tail angle of attack in a reasonable range such that deflections from the nominal can be used for trim and control in the airspeed range from 50 kn to conversion. Below about 50 kn the horizontal tail is not important.

The horizontal tail incidence envelope will be large but the T-tail configuration is arranged to allow for this feature. The horizontal tail panel for model 1041 is the same size as the panel of the 1985 airplane, while the wing area has been reduced by one-third. The result is a large tail volume coefficient of 0.9. The design philosophy is that tail span to match the nacelle span is more important than matching wing-area-based coefficients. This is a conservative approach. As a result, the airplane should have an extremely wide range of allowable center of weights and still meet guideline requirements for a stability margin of 5% wing mean aerodynamic chord with low risk.

The flow field at the vertical fin is complicated by propulsive interference effects. Examination of the data for configurations that feature aft fuselage nacelles indicates a trend toward static directional instability. Instability will not compromise model 1041 because rudder control power is not affected. Rudder control effectiveness combined with the VTOL yaw control and

VTOL C/SAS will easily mask the directional instability without using the undersirable option of enlarging the vertical fin. The vertical fin has a fair-sized ventral panel (tail bumper to protect the lift/cruise nacelle). On model 1041-134, this panel should have a stabilizing effect that is better than on the 1985 airplane.

The wing trailing edge allows the integration of a flap and aileron lateral control that can be powerful enough to provide all the lateral control at airspeeds above 100 to 125 kn. The high lift system will be tailored so that the conversion corridor is at least 20% of stall speed for normal operation and 10% with one engine out. These features will be validated in the first series of wind tunnel tests. Any modifications will be made in ample time so that the final tailoring can be validated as necessary to be evaluated in the flight control system studies of flightpath control. The key to success and low risk is timely wind tunnel testing well before scheduled engineering releases.

The VTOL flight control system dominates the aircraft at speeds below 90 kn. The quick response of the fan-thrust-to-blade-angle change produces powerful roll and pitch control moments. They can trim the airplane with engine out and produce attitude maneuver accelerations more than twice the guideline requirements. This conclusion is based on a conservative analysis of the airplane. Trim requirements are based on conservative margins for momentum moments, induced moments, ground effects moments, engine-out moments, and gyroscopic effects.

The VTOL yaw control vanes in the slipstream of the fans need special consideration. Several tradeoffs in vane orientation have been made before arriving at the test configuration. The selected system features design simplicity while achieving the design goal that allows development of pure control moments throughout transition (no cross-axis control coupling) with a simple interconnect between nacelle angle and vane angle.

6.2 ANALYTICAL DEVELOPMENT OF THE FLIGHT CONTROL SYSTEM

The analytical development phase includes these major items:

- Definition of the airplane mathematical model
- Definition of the flight control laws
- Simulation of the flight control system
- Definition of the specifications of flight control system hardware for procurement
- Implementation of software for the digital flight control computer

A flight simulator will be used in all phases of the flight control system, beginning with definition of control laws and remaining dominant throughout the flight test phase in terms of pilot checkout. Boeing has demonstrated capability in a number of simulator-based studies. A typical simulator description is shown in figure 13. A discussion of flight simulation and how it impacts flight control system design is discussed in the following paragraphs.

The flight simulation program is planned to ensure an acceptable level of safety and reduce technical and design risks. Initially, the flight simulator will be used to provide design requirements and design confirmation. Later the simulator will be used to predict airplane flight characteristics with particular emphasis on flying qualities, transition to and from the powered lift regime, control system failure states, and engine-out control. Prior to first flight, the simulator will be used to familiarize project pilots with the airplane's operating characteristics and to develop flight test procedures.

The initial simulations will use estimated aerodynamic characteristics and will evaluate the baseline control augmentation and stability augmentation systems. This test period is structured to evaluate flying qualities for takeoff and landing flight conditions–all-engine and engine-out. Results will support planning for the final wind tunnel test and provide a data base for control system design requirements including control law specification, feel system requirements, C/SAS authority limits, and actuator rate requirements.

The next test period will take place after data from wind tunnel tests are available. The control system will be updated to represent the current design. The test goal is to verify the airframe/propulsion system integration and control system design and to demonstrate the airplane's safety and evaluate its flight research potential. Control system validation is a key element since a flight control system specification for system components will be released following this test.

6.3 HARDWARE DEVELOPMENT AND SYSTEM INTEGRATION

The secret to success in the hardware phase is the timely availability of hardware so that adequate bench testing and system integration can be made without holding up other airplane system development. The risk is low because the flight control systems will be composed of components that are clearly state of the art, and have been flight proven in other programs. Hardware will be selected based on Boeing experience with the component and its manufacurer's capability.

Several control system implementations are under consideration. Tradeoffs will be made to ensure that NASA gets the most research capability value per dollar. The systems under consideration are:

- Full-time, full-authority automatic system with a triplex or quadruplex digital logic and fly-by-wire links
- Simplex digital automatic system with backup triplex direct analog fly-by-wire- links
- Simplex direct analog links for the rudders, ailerons and stabilizer combined with either an analog or digital fly-by-wire automatic system

Both digital computers and fly-by-wire links are desirable to technology. There is no doubt that fly-by-wire has all the features that make for a good flight control system. Figure 14 is a good definition of fly-by-wire benefits. Digital flight computers are state of the art and Boeing has the experience to take advantage of the technology. Figure 15 is a flight control technology map for V/STOL airplanes. Clearly digital fly-by-wire is within the state of the art. Several digital computers are available on an on-the-shelf basis. Cost comparisons made on other programs indicate the digital implementations are cost effective.

The major elements of the nominal flight control system are:

Logic and Switching

- Air data computer
- Digital-to-analog/analog-to-digital converter
- Digital flight control computer
- Engine fuel control and power management system

Sensors

- Air data sensors (airspeed, altitude, etc.)
- Inertia gyro package
- Rate gyro package
- Engine torque
- Fan speed
- Acceleration sensors
- Radar altitude

Actuators and Servo Mechanisms

- Fan blade angle actuator and position feedback
- Aerodynamic panel actuator and position feedback
- Vectoring vanes actuator and position feedback
- Nacelle incidence actuator and position feedback

Each flight control element will be selected based on flight-proven capability. As an example, the engine fuel control (Allison T701) and associated power management control have been developed for the HLH and can be used directly on model 1041 with minimal change. This system, described in the next paragraph, was expensive to develop but cheap to modify for the Boeing model 1041 program with low technical risk.

The Allison T701 engine control system design for the HLH propulsion system couples three Allison XT701-AD-700 engines to a common shaft, which in turn drives two rotors. Three types of controllers are employed in this system: one power management control; and an engine electronic control and a hydromechanical fuel control for each engine.

The power management control governs engine speed based on the pilot's selected speed, provides automatic load sharing between the engines, and transmits torque and rpm signals to the cockpit for display. For the VTOL airplane, the engines are essentially constant speed, being operated at maximum continuous rpm during hover and transition flight and at a lower rpm during cruise for improved performance. The automatic load-sharing circuit will compare the torque at the output shaft of each engine and transmit signals to the engine electronic control of the engine operating at the lower torque output, with the outer loop speed control governing rpm of the overall system. Torque increasing signals are used in the inner loop control to ensure that loss of an engine will have a minimal transient effect on flight operation. By controlling engine speed and torque, thrust command changes (in terms of fan blade pitch angle commands) from the primary flight control system are not required in the engine control circuit. The pilot would have a manual command capability relative to the torque control loop in addition to the engine speed control.

The engine electronic control and hydromechanical fuel control govern each engine's internal operation. The engine electronic controller manages power turbine speed governing, power turbine inlet temperature limiting, overspeed protection, automatic start sequencing, and gas generator and power turbine signal conditioning. The hydromechanical fuel control schedules gas generator speed, compressor variable geometry, acceleration/deceleration transients, and limits fuel flow, gas generator speed, and compressor discharge pressure.

This is just one example of taking advantage of existing technology while at the same time incurring minimal technical risk.

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Table 1.—Weight and Balance Risk

Item	Problem statement	Program impact	Solution
Structure	Airframe weights are the result of preliminary analyses in conventional aluminum structure. Detailed design could reflect weight increases.	See table 2 for summation of structure, propulsion and equipment systems, weight impact.	The design will tolerate a weight increase of 520 lb (see table 2). A weight reduction program instituted at the beginning of the design will be directed at precluding weight increases.
Propulsion including —Fans —Engines —Drive system	Primarily vendor data developed from existing hardware. Significant deviations from these weight levels are not anticipated; however, a propulsion weight increase will increase the balancing payload requirement.		
Airframe systems	The research airplane systems are minimal except for flight control systems.		
Operation weight	Of the operating weight items, the propulsion system and flight control systems are considered a moderate risk.	Potential operating weight impact = 1900 lb.	Same as above.
Payload	The payload design requirement = 2500 lb. This also satisfies the balance requirement of 2250 lb.	Flight test equipment cannot exceed 2500 lb.	
Fuel	Normal V/STOL takeoff weight provides for mission fuel in excess of the guideline flight test program.	The fuel will provide for eight V/STOL research missions. The number of required research missions is five.	The design incorporates excess research mission capability (fuel) and excess payload capability.
	The emergency landing fuel allowance of 600 lb is provided for an emergency landing.	Emergency landing procedure is easily accomplished within 1 to 2 min; 2 min are available.	
Takeoff weight	The probability of a weight increase and thrust degradation to the point that the thrust/weight margin is less than 1.05 is low.		Takeoff thrust levels provide a T/W margin sufficiently greater than 1.0 including the impact of weight risk to make a good VTOL demonstrator.
Emergency landing weight	The probability of weight increase and emergency thrust degradation to the point that thrust-to-weight margin is less than 1.03 may be significant.	In event the weight control program cannot be met, only 250 lb of payload can be offloaded due to aircraft balance.	Emergency thrust levels requested from the propulsion manufacturers include the impact of weight reduction and weight growth to extent described above.

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Table 2.—Operating Margin

Item	Emergency thrust (lb)	
	Hot day, water injection	Standard day
Emergency thrust available	21 000	21 700
1.03g margin requirement	-610	-610
Minimum flying weight	20 390	21 090
Emergency fuel and water/alcohol	-970	-970
Operating weight plus payload permissible	19 420	20 120
Payload required	-2 500	-2 500
Maximum permitted operating weight	16 920	17 620
Operating weight estimated	16 400	16 400
Weight growth tolerance	520	1 220
Possible weight growth estimate	1 900	1 900

Table 3.—Comparison of Thrust Available With Required Thrust

Condition	Thrust required, lb	Thrust available, SL 90° F, lb
Normal vertical landing	23 600	27 680
Vertical takeoff	23 600	27 680
Emergency landing	20 480	21 000

Table 4.—Lift/Cruise Fan Inlet Design Conditions

Flight operation	Airspeed, KTAS (Mach)	Airplane gross thrust level, % max	Inlet angle of attack, deg	Remarks
Vertical landing flare	40	100	120	A flare from a steep descent approach. $\alpha_{NAC} = \lambda + \theta - \gamma = 90^0 + 15^0 - (-15^0) = 120^0$. Thrust includes 2000 lb for trim and control.
STO	75		70	A deck end condition that includes AOA excursions for "round out" to the climb/accelerate profile as well as trim and control. Nose fan is lightly loaded.
Approach	75	50	90	A steep approach; c.g. trim and control is included. Several conditions must be used to cover approach flight. The selection criteria is a given speed and incidence combination with excursions in thrust to cover variation in control, trim, flightpath angle, and gross weight.
	100	70	80	
	100	30	80	
	125 (0.2)	50	60	
	125	15	60	
	125	15	60	
Conventional flight—loiter	270 (0.42)	0.09 *	25	Represents flight maneuvers consistent with ASW loiter operations at an altitude of 10 000 ft.

* Net thrust

Table 5.--Key Design Areas–Related Experience

Area	Experience
Large bevel gear design	Strain measurement, finite element analysis, damping techniques, and excitation testing applied to HLH and UTTAS
Bevel gear bearings	High-speed taper roller bearings tested 3000 hr (rig, HLH bench, and DSTR) and Air Force tests
Overrun clutch	CH46, 47, UTTAS, and HLH field experience and testing (HLH application closest to -133 requirement)
High-speed drive shafting	1 500 000 A/C hr (CH47A, B, C) and HLH application
Integration of fan and gearbox	Q-Fan and propeller gearing development
Planetary gear reduction	60 000 000 hr of T-56 and related field experience and testing

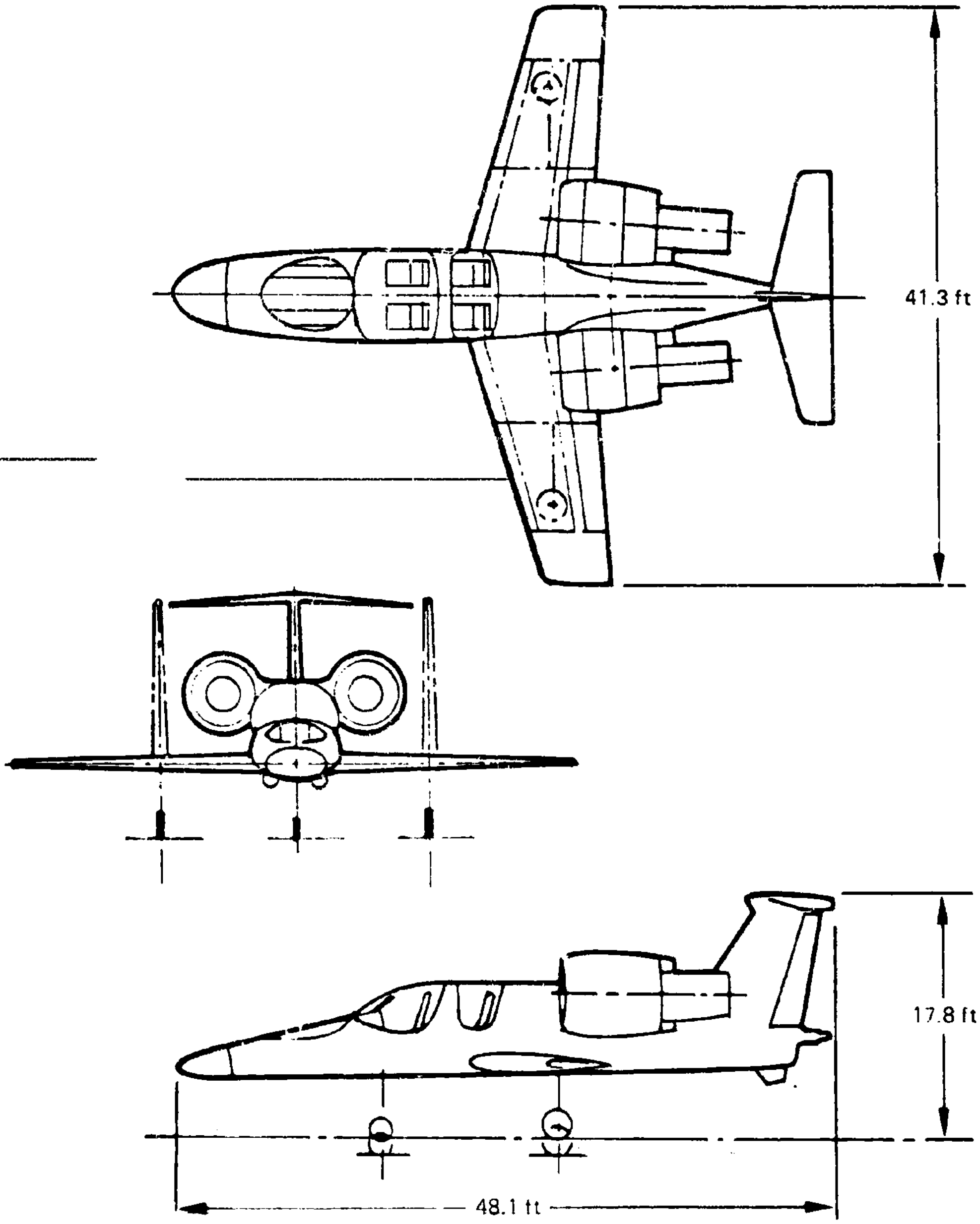


Figure 1.—Multimission Airplane, Model 1041-133

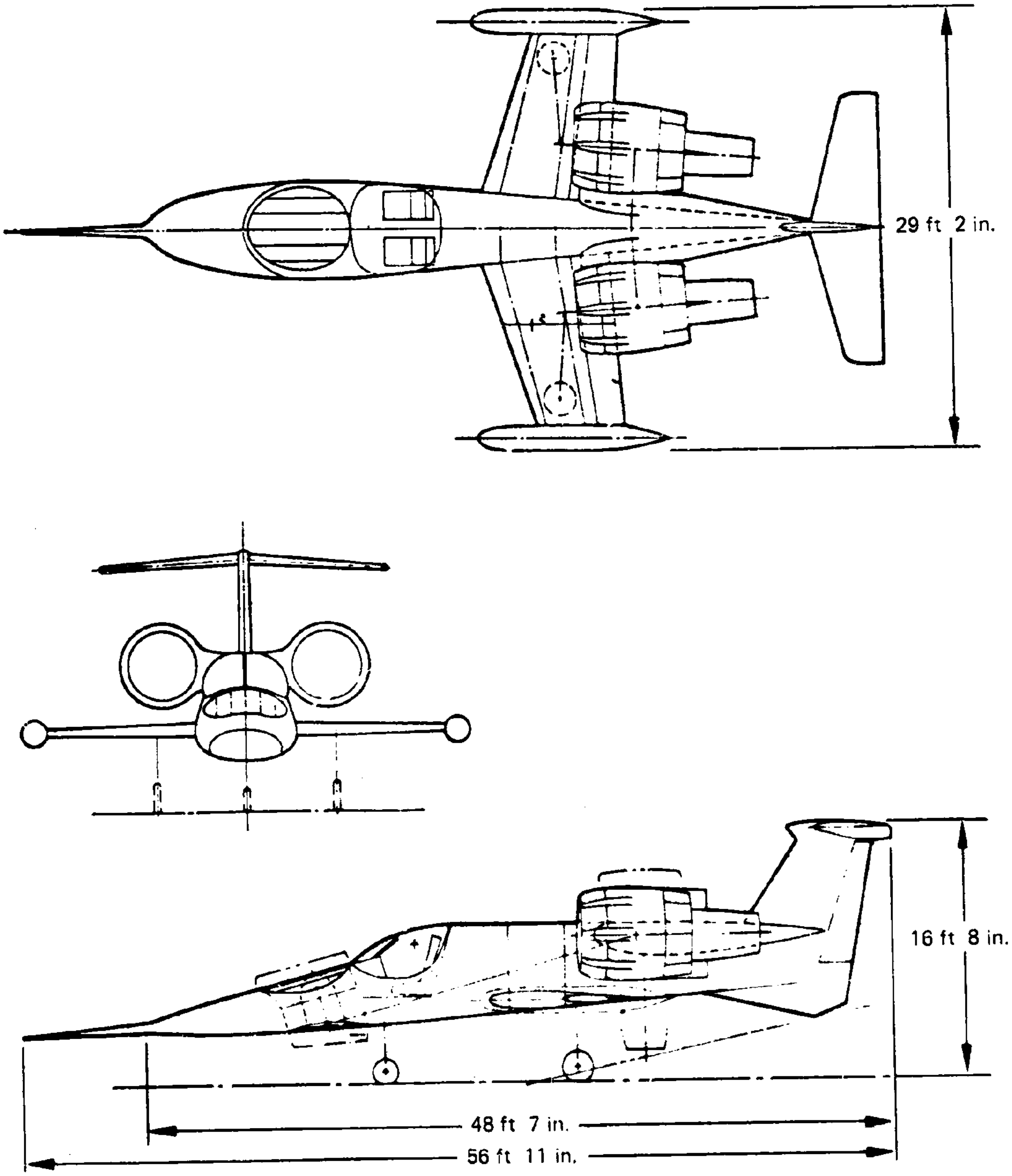


Figure 2.—Technology Airplane, Model 1041-134

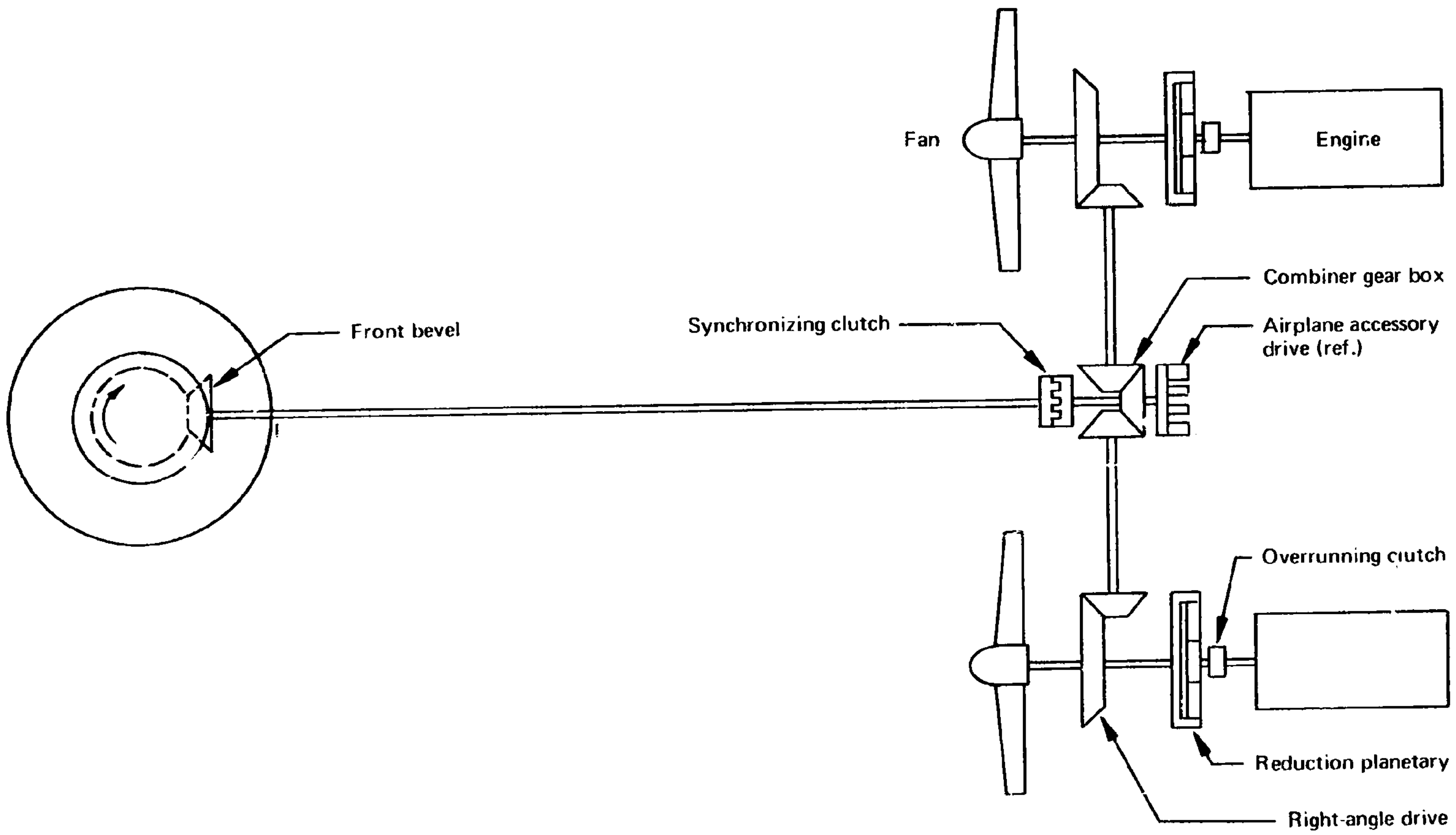


Figure 3.—ASW Airplane Transmission Schematic

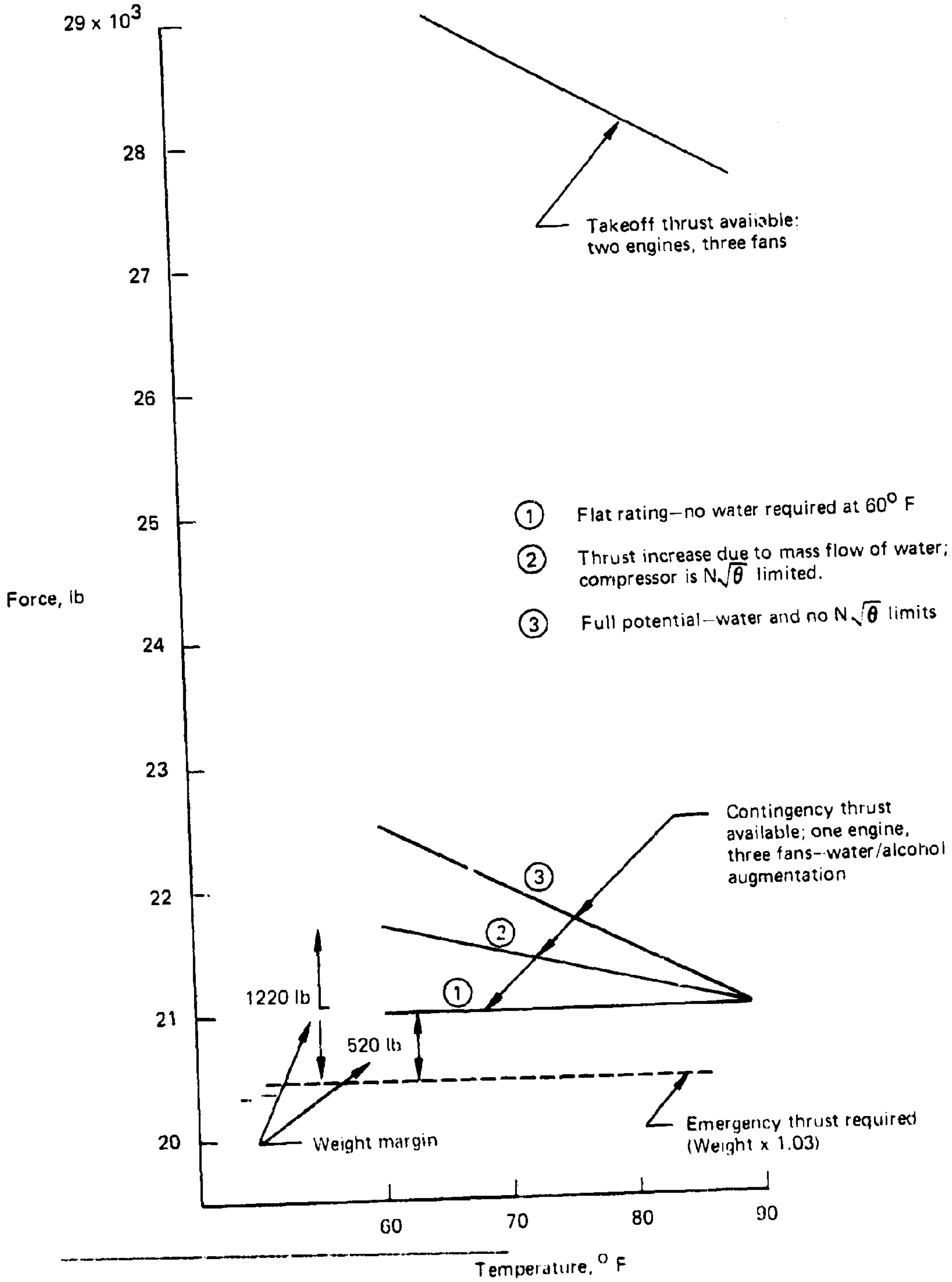
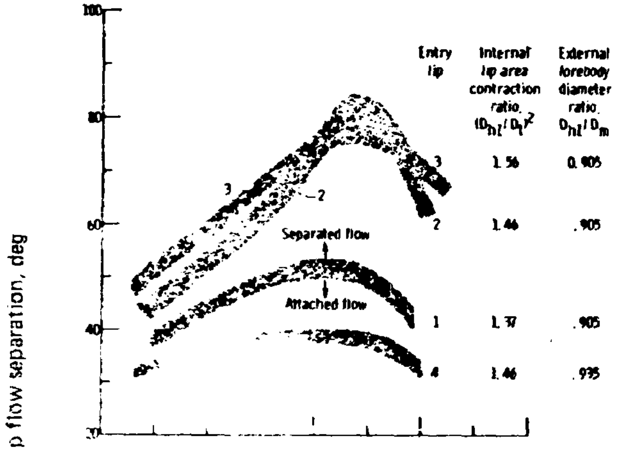
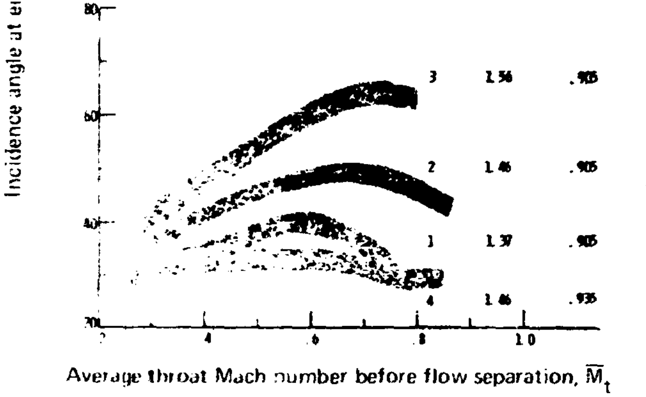


Figure 4.—Available Thrust

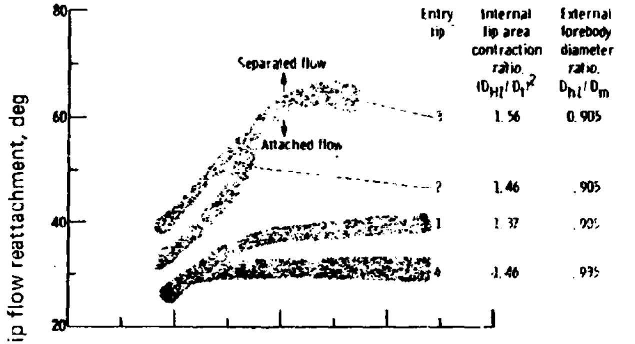


(a) Free-stream velocity, 41 meters per second (80 knots).

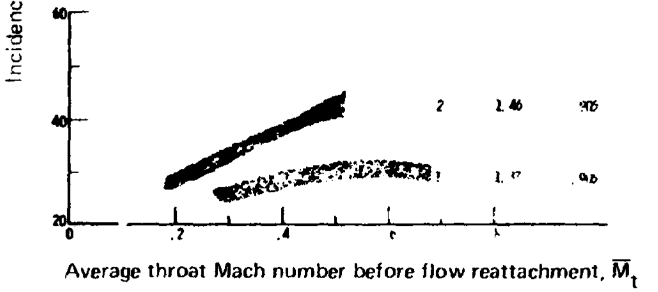


(b) Free-stream velocity, 61 meters per second (120 knots).

(A) Effect of entry-lip design and average throat Mach number on incidence angle at entry-lip flow separation. Data obtained by increasing incidence angle to point of flow separation.



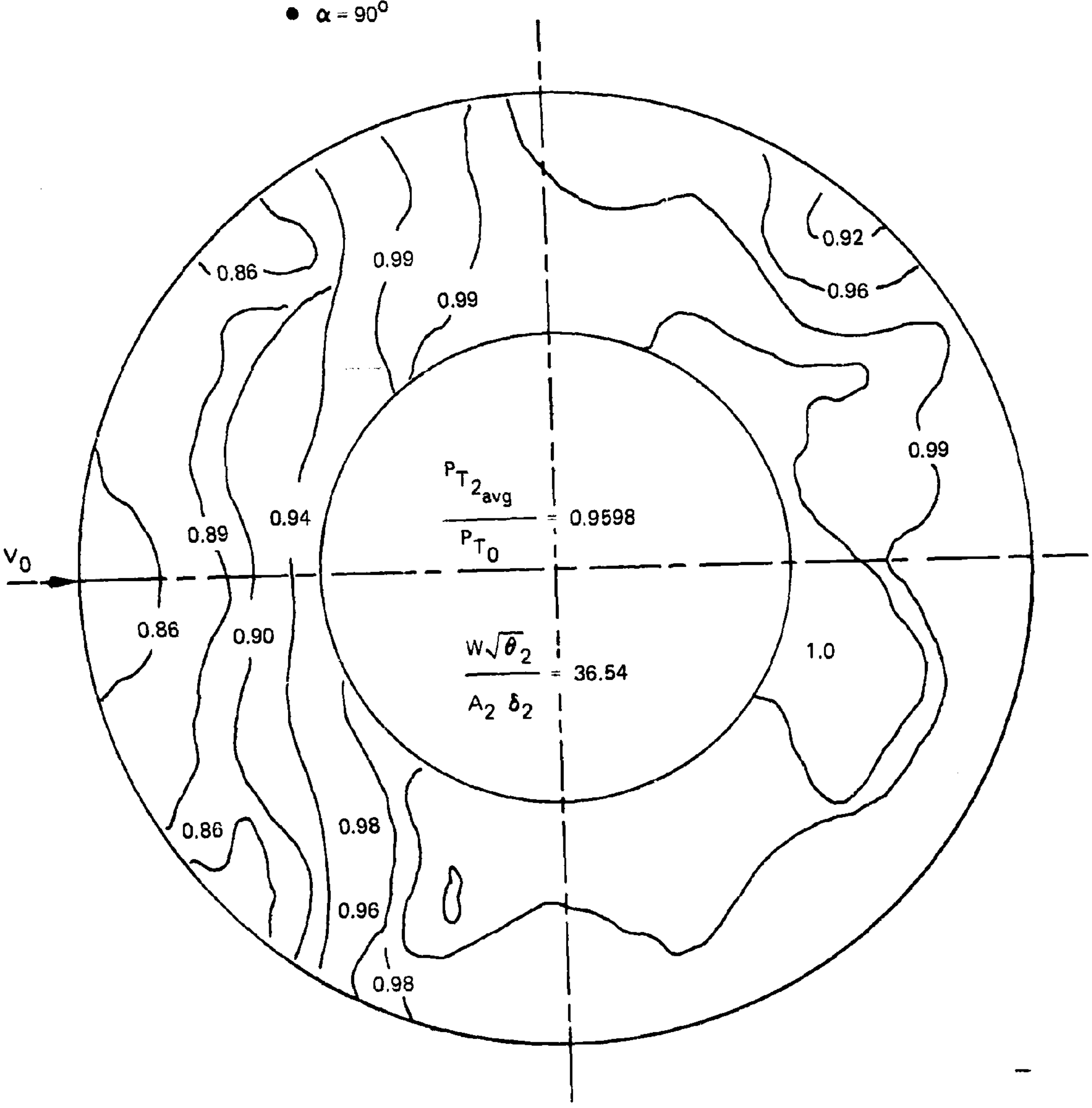
(a) Free-stream velocity, 41 meters per second (80 knots).



(b) Free-stream velocity, 61 meters per second (120 knots).

(B) Effect of entry-lip design and average throat Mach number on incidence angle at which entry-lip flow reattachment occurs. Data obtained by decreasing incidence angle to point of flow reattachment.

Figure 5.—Separation-Free Regions for Fixed Geometry NASA Inlets (Ref. 2)



- Inlet: blow-in door
- Condition 3.6340
- Reference 3
- $V_0 = 100$ kn
- $\alpha = 90^\circ$

Figure 6.—Fan Face Total Pressure Distribution

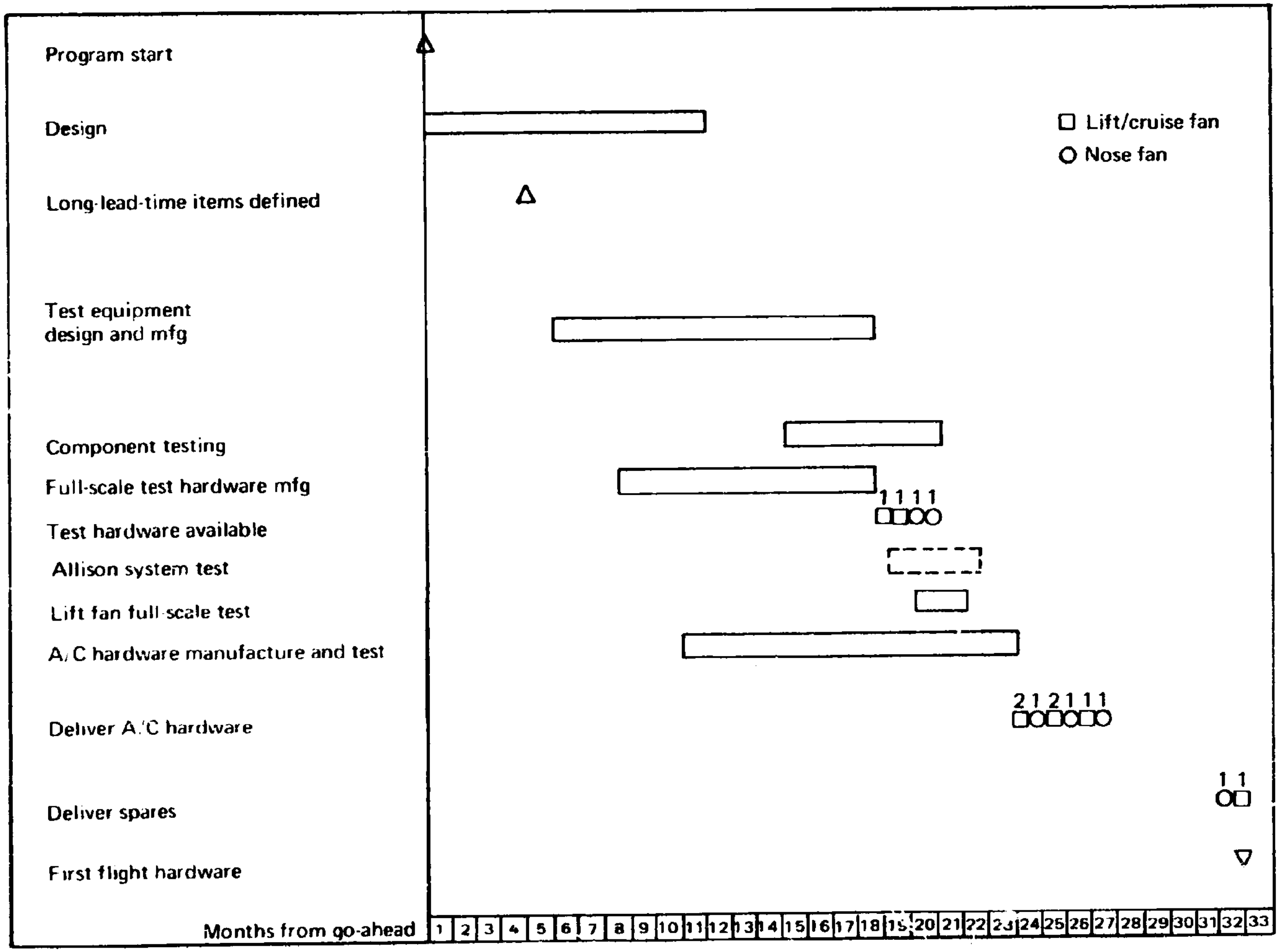


Figure 7.—Hamilton Standard Fan Development Program

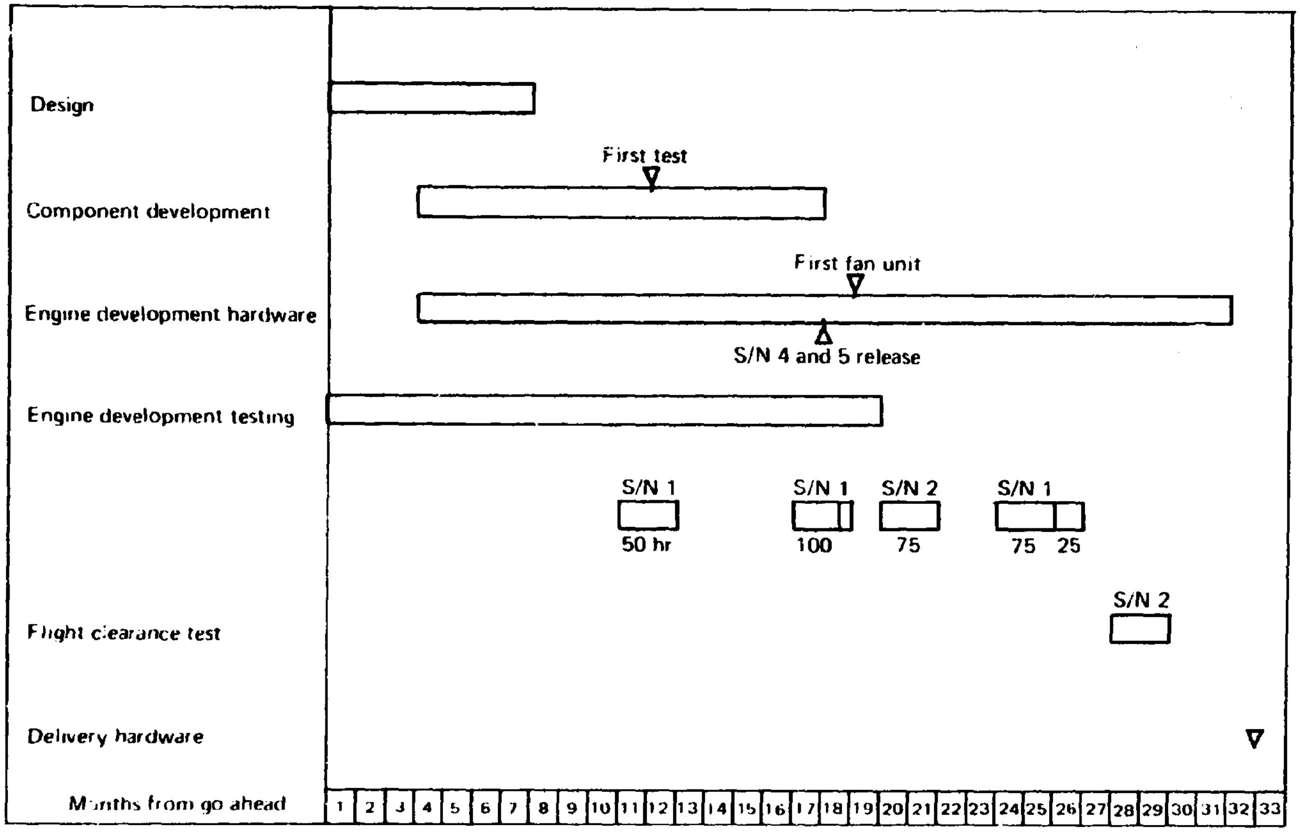
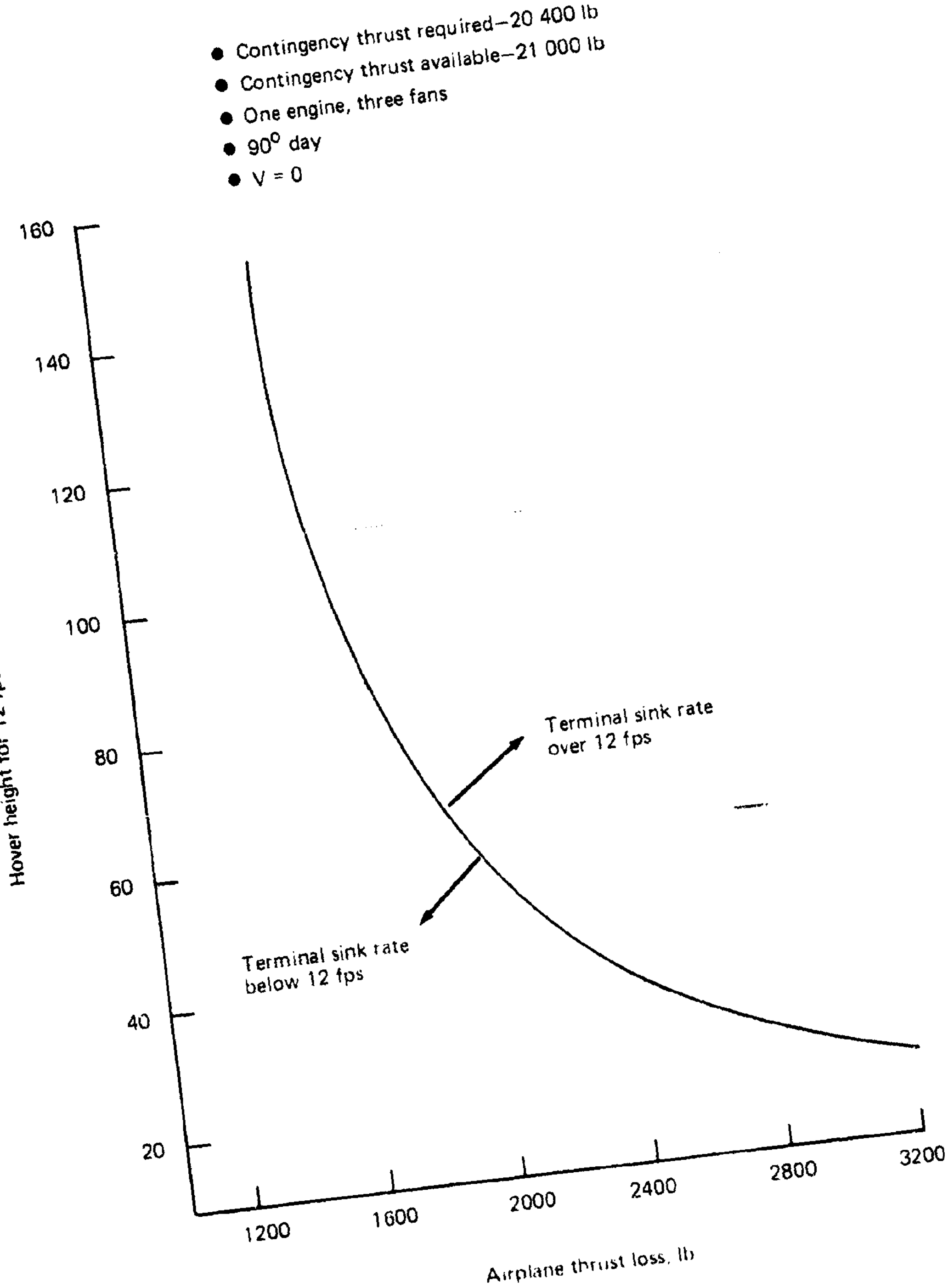


Figure 8. Detroit Diesel Allison Engine Development Program



- Contingency thrust required—20 400 lb
- Contingency thrust available—21 000 lb
- One engine, three fans
- 90° day
- V = 0

Figure 9.—Effect of Airplane Thrust Loss on a Safe Emergency Landing

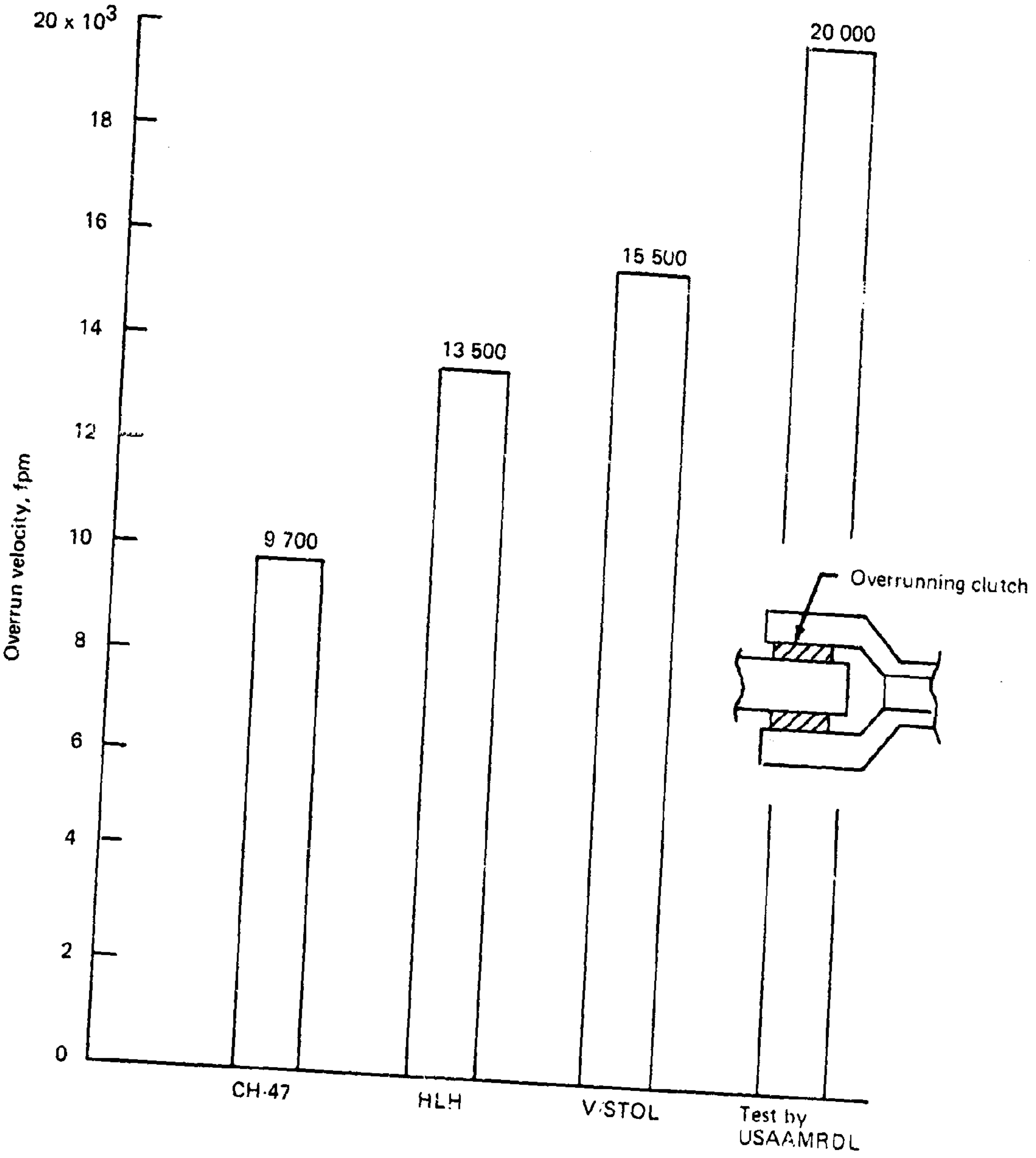


Figure 10.--Overrunning Clutch Experience

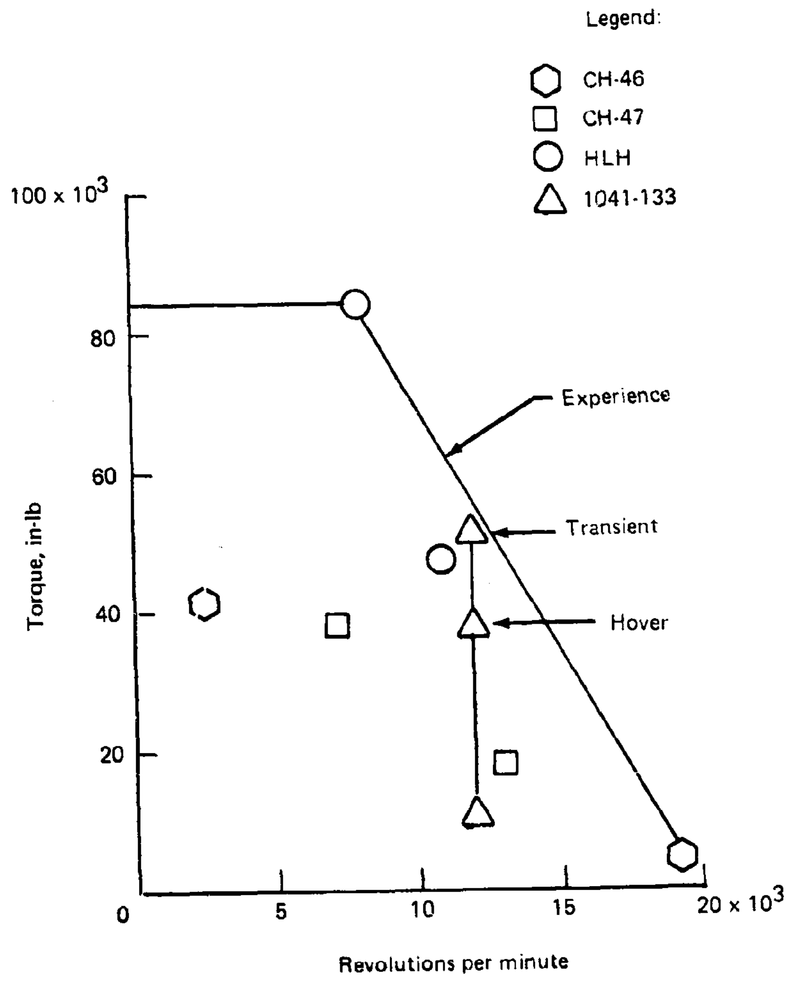


Figure 11.—Boeing-Vertol Helicopter Drive Shaft Experience

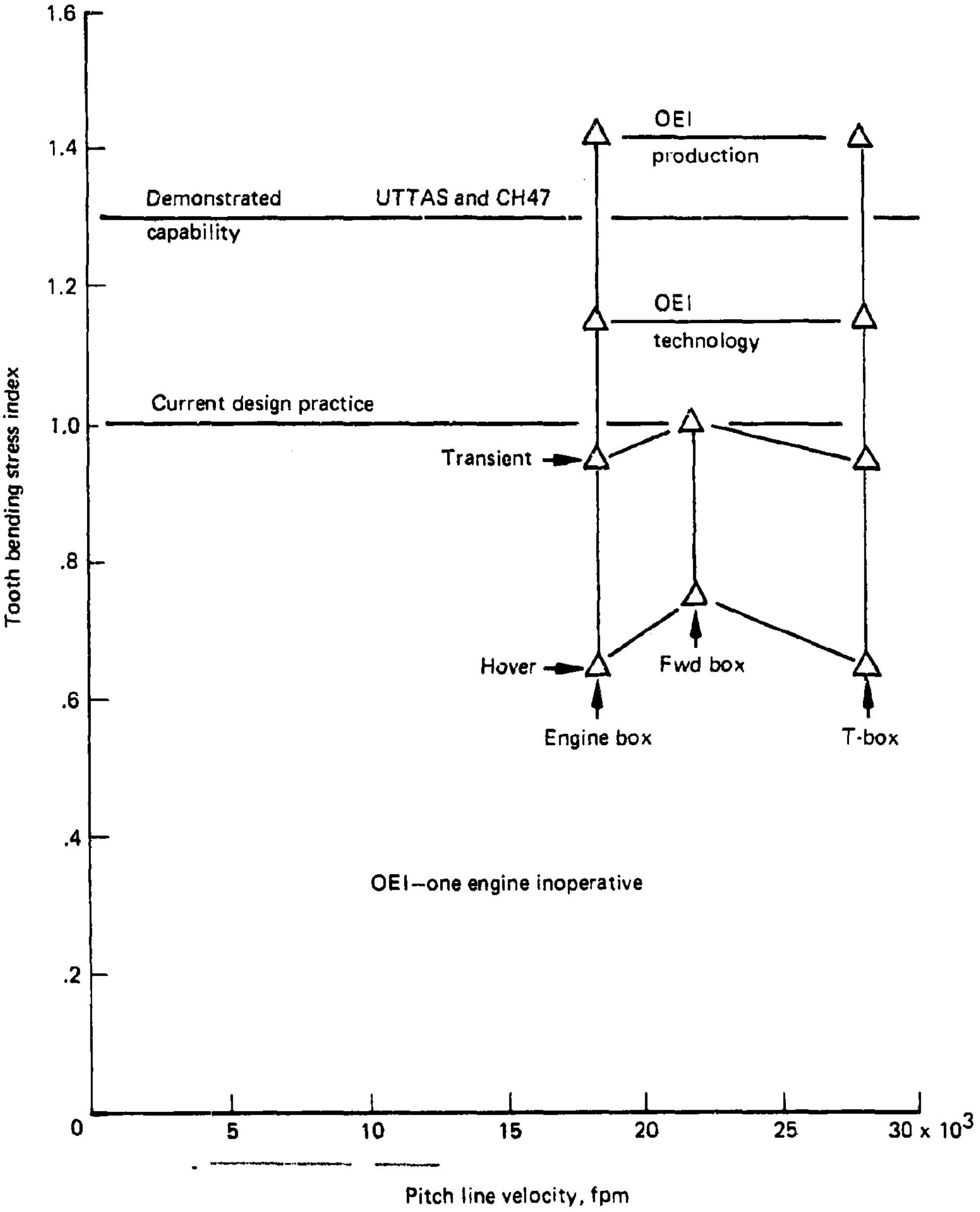


Figure 12.–Model 1041-133 Drive System Design Bevel Gear Tooth Stress Comparison

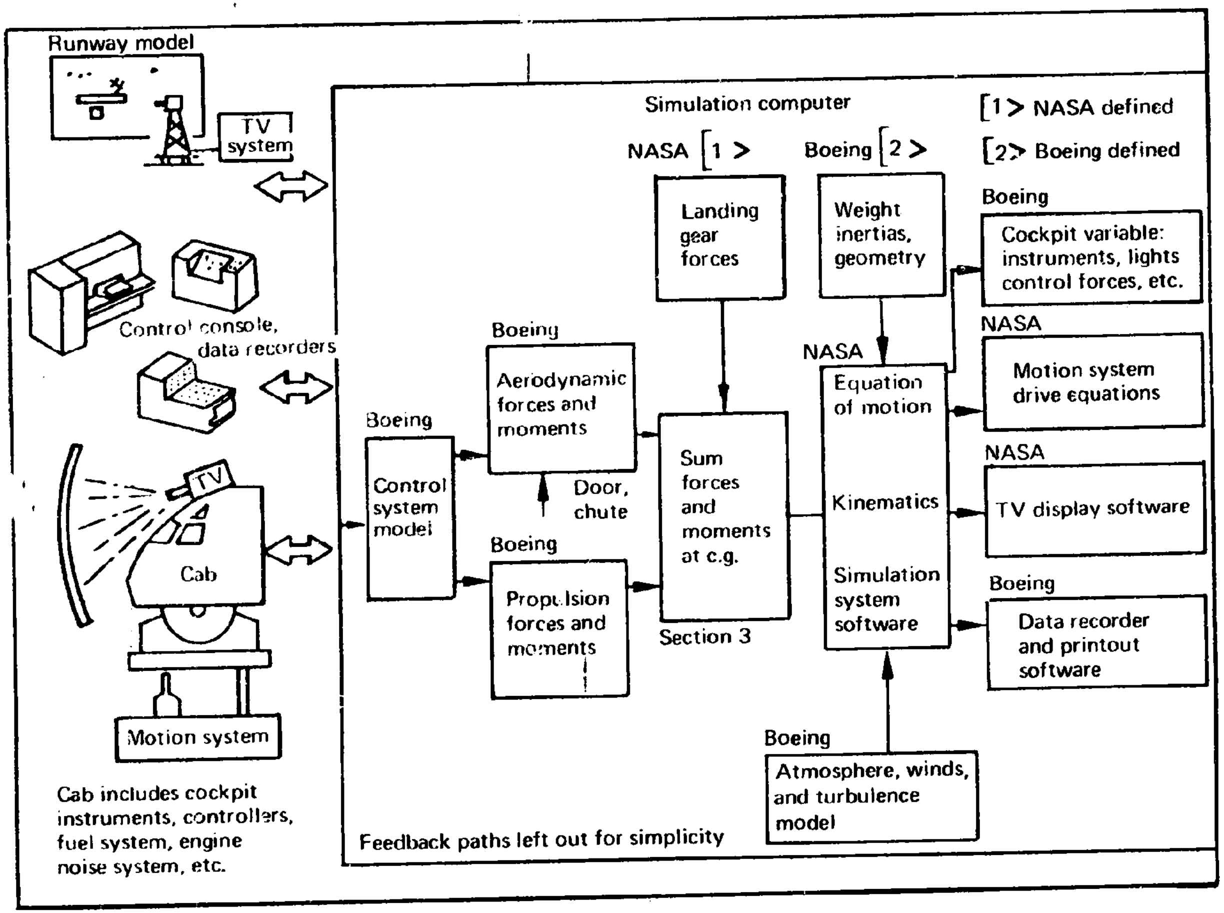


Figure 13.—Simulation Description

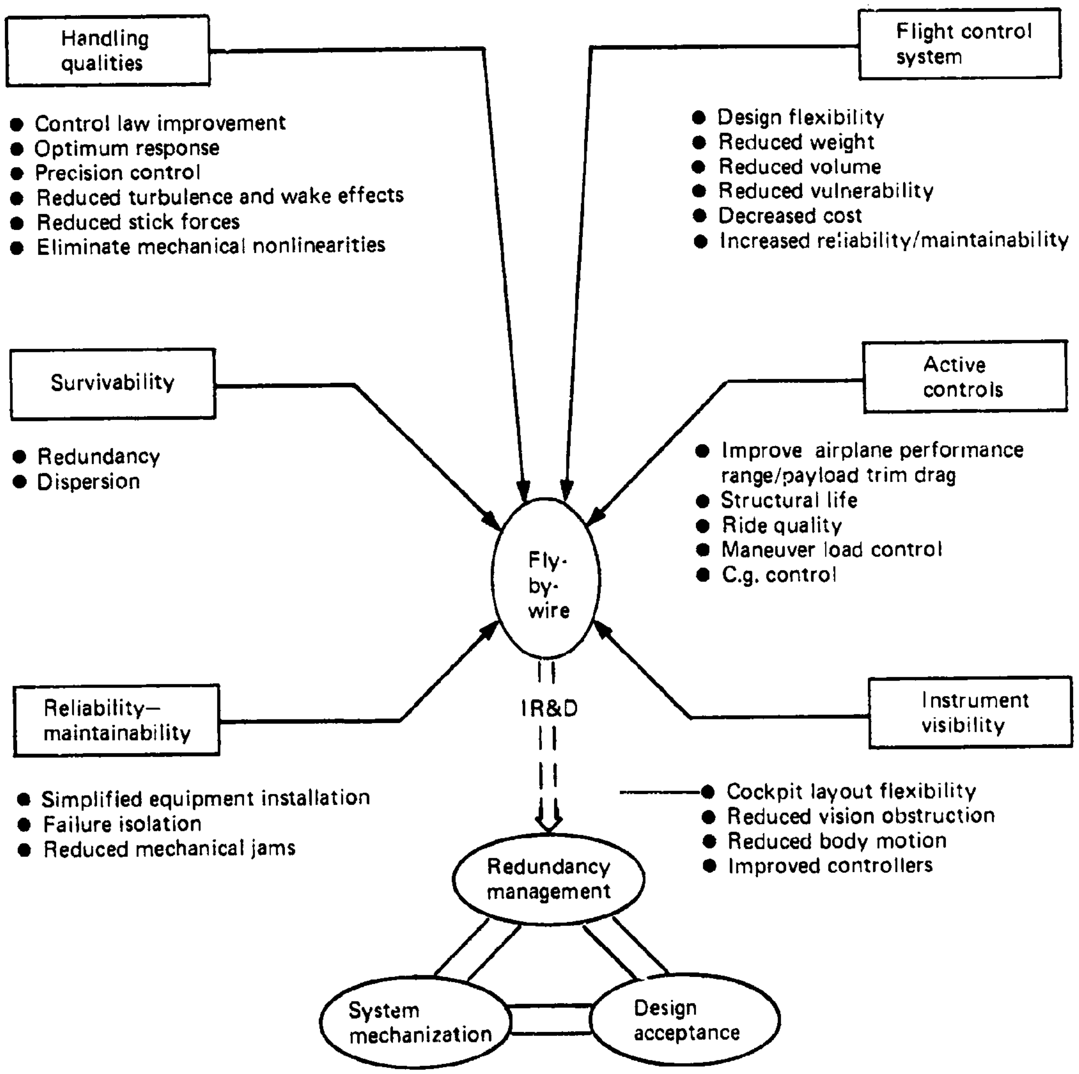


Figure 14.—Why Fly-by-Wire?

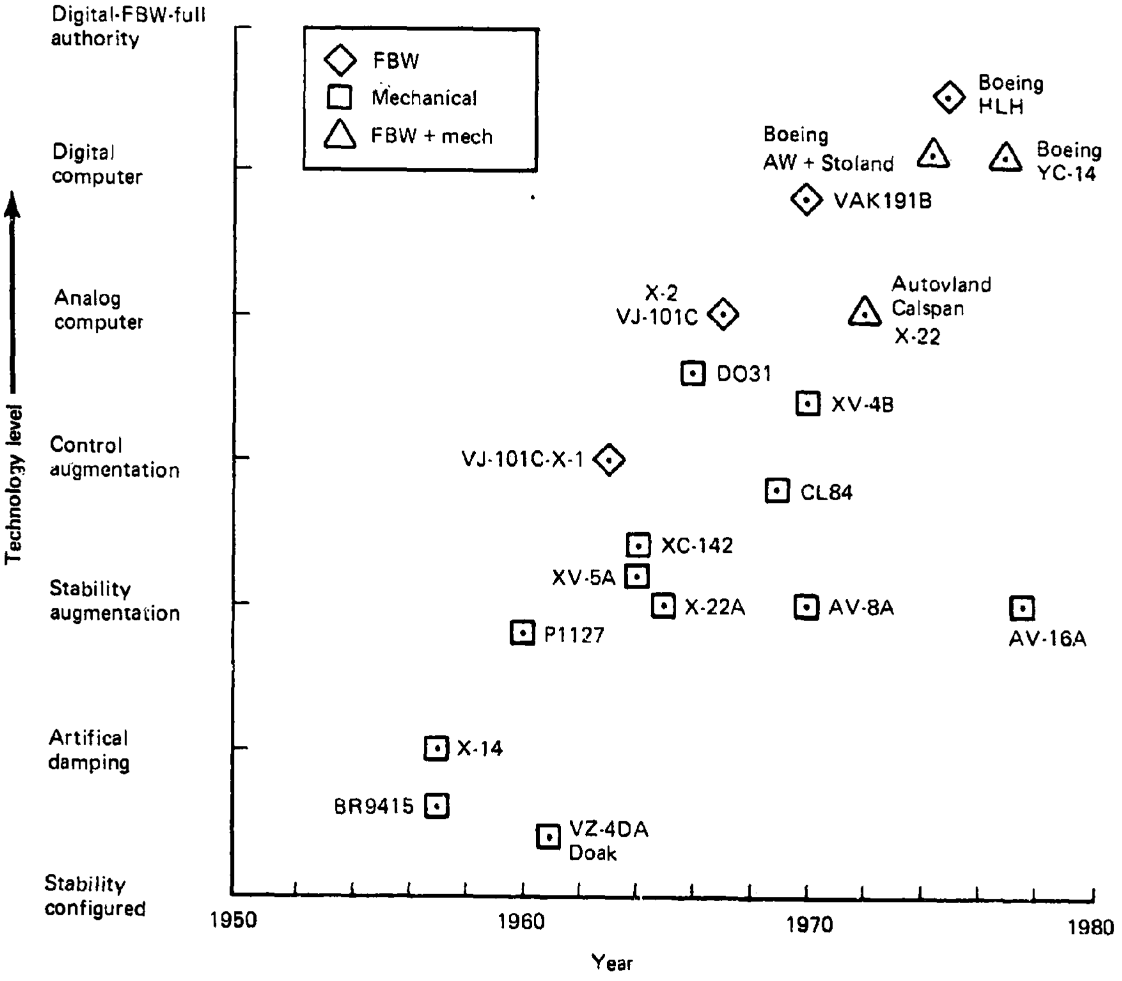


Figure 15.—V/STOL Flight Control System Technology