A PROPFAN STATUS REPORT

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Abstract

The economic viability of the propfan or Ultra High Bypass (UHB) engine concept is discussed considering such factors as future fuel prices and interest rates. Different design approaches (e.g., the derivative route versus all-new designs) are examined. A brief analysis is made of indicated capacity selection and related potential market. Technical, design, and configuration problems are also examined in regard to airport and en route noise, aerodynamic issues including flying qualities and deep stall, structural dynamics, acoustics, and sonic fatigue. A demonstrator program is finally outlined with projected time schedule leading to technology readiness for production as the unique airframe problems are being solved.

Introduction

The development of the principal aeronautical technologies as applied to subsonic commercial aircraft has, over the last 20-30 years, proceeded in an evolutionary manner. The jet transports of today are significantly more efficient than those first introduced in the late 1950s, but this improvement is the result of many relatively small advances in aerodynamic, structural, and propulsive efficiency.

The fuel crises of the 1970s raised the specter of a future with continually rising fuel prices and escalating operating costs. It was anticipated that fuel costs would become by far the dominating operating cost element. This forced the aeronautical research community to focus its attention on the development of technologies that could achieve drastic improvements in fuel efficiency.

Some of the ideas that surfaced were old ones (laminar flow control, propellers, etc.), which had been examined and discarded in the era of 10¢-per-gallon fuel, while others (such as composite materials) were relatively new.

In this paper, attention is focused primarily on the application of high-speed propellers (i.e., propfans) to subsonic commercial transports.

An Uncertain Future

A new derivative airplane takes about 3 to 4 years to design and develop, and the midpoint of its service life will be about 14 to 16 years after the decision to commit to production.

The airplane designer is faced, during the conceptual and preliminary design phase, with the problem of deciding which new technology developments should be incorporated in his design to enhance the economic viability of the product. In order to make these decisions, he must use forecasts of key economic factors such as the price of fuel, interest rates, and labor costs. Events that have occurred over the last decade illustrate the difficulty in making these forecasts. The fuel crises of the 1970s escalated the price of fuel by at least an order of magnitude by 1980 compared to what forecasters were predicting in the late 1960s, and inflation in the U.S. drove interest rates to unprecedented levels.

In the last year or so, we have seen the collapse of oil prices and a significant abatement of inflation and consequent reduction in interest rates. These events have thrown the forecasters' business into a tailspin with no recovery in sight. Many people feel that it is impossible to forecast the future of fuel prices with any expectation of reasonable accuracy (see Figure 1).

"WE WERE WRONG ABOUT ECONOMIC GROWTH,
WE WERE WRONG ABOUT ELASTICITY OF DEMAND,
WE WERE WRONG ABOUT ESTIMATES OF OPEC PRODUCTION,
WE'VE NEVER BEEN HERE BEFORE,
WHAT WE'RE LIVING WITH NOW DOESN'T HAVE A PROTOTYPE,
WE CAN'T FORECAST THE FUTURE,
IF SOMEONE ASKS ME WHAT'S GOING TO HAPPEN TO OIL PRICES, I TELL THEM TO GO AND TAKE A SHOWER."

FIGURE 1. STATEMENT BY ROBERT McCLEMENTS, JR. PRESIDENT, SUN OIL COMPANY — TENTH LARGEST OIL COMPANY

In doing trade studies to determine whether a technology development makes economic sense or not, the price of fuel is obviously an important factor. If fuel prices are expected to be high, technology developments that save fuel are much more likely to be incorporated than when fuel prices are low, and the impact these developments have on the price of the airplane may be the determining factor.

Figure 2 shows the forecast fuel prices used in Douglas design studies over the past 15 years. Clearly, trade studies using a fuel price of $1.70 per U.S. gallon could produce drastically different answers when recomputed with a fuel price of 61¢ per U.S. gallon.

Interest rates are another important economic parameter that the designer must take into account because of their impact on ownership costs. The variation of interest rates over

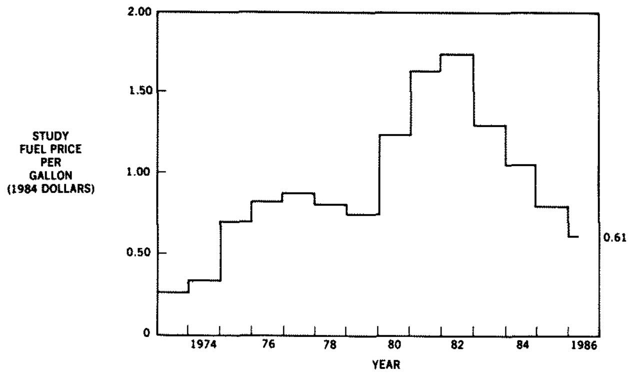

FIGURE 2. FUEL PRICE FORECASTS USED IN DOUGLAS STUDIES

the twelve years between 1972 and 1984 has been significant (Figure 3). In 1982, economists were forecasting interest rates for the 1990s to be around 6 percent, while a year ago they were forecasting 12 percent. Currently a level of 10 percent is favored. These swings are not as extreme as for fuel prices. However, they are substantial and affect the outcome of engineering trade studies.

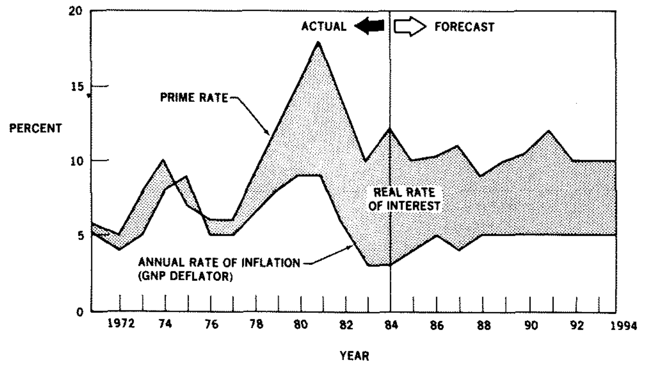

FIGURE 3. UNITED STATES INTEREST RATE — PRIME RATE CHARGED BY BANKS

These uncertainties make life very difficult for the designer of new or derivative airplanes. The impact these swings on forecast fuel prices and interest rates have on the breakdown of operating costs is shown in Figure 4, using the MD-80 as an example.

In 1982, it appeared that fuel costs would be dominant in the future, justifying even a significant airplane price increase to incorporate technologies that saved fuel. In 1986, the situation appears completely different. Fuel, as a percentage of total direct operating costs, has decreased from 40 percent to 20 percent, while the cost of ownership has increased to 34 percent. The forecast ratio of fuel to ownership costs has almost completely reversed between 1982 and 1986. The results clearly suggest that future designs on a relative basis should reflect more emphasis on reducing airplane price than on minimizing fuel consumption. While fuel saving is still important, the related impact on the price of the airplane must be small. One must bear in mind, however, that virtually all fuel forecasts over the last 10 or more years have turned out to be wrong. The present forecast may be no exception. The question is, "In what direction might it change?"

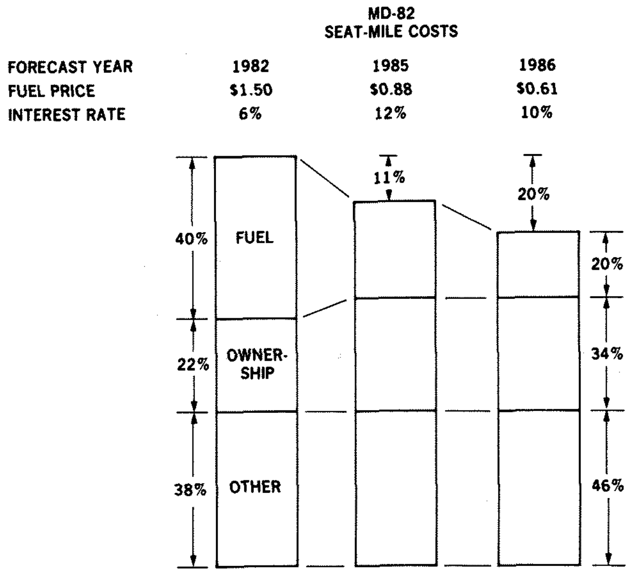

FIGURE 4. OWNERSHIP COSTS HAVE REPLACED FUEL IN IMPORTANCE

Application of the UHB

The new technology development that holds the most promise for the future is the Ultra High Bypass (UHB), or propfan, engine. Studies show fuel savings of 25 to 30 percent compared to similar technology turbofans. Some engine manufacturers have predicted that the price and maintenance costs of the UHB will not be higher than a comparable turbofan. If this is the case, there obviously would be a clear economic advantage for the UHB regardless of future fuel prices.

With the latest forecast of fuel price and interest rates, fuel accounts for 20 percent and ownership for 34 percent of the direct operating costs (DOC) of an MD-80 (Figure 5). If the MD-80 is re-engined with the UHB, fuel costs drop to 10 percent and ownership costs increase to 40 percent.

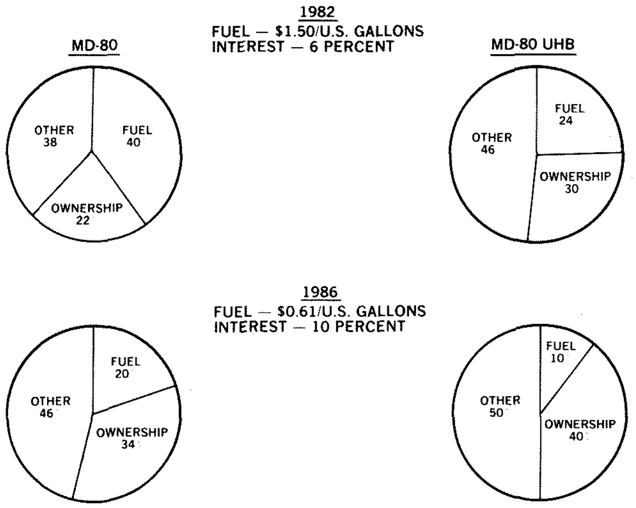

FIGURE 5. EFFECT OF FORECAST ASSUMPTIONS ON DOC DISTRIBUTION

It is interesting to note that, if a technology development that saved an additional 10 percent in fuel (and this would normally be considered a very significant savings) were applied to the MD-80 UHB, the fuel saving itself would reduce DOC by 1 percent. However, if the application of this technology increased the cost to build the aircraft, a price increase of 2½ percent would completely negate the economic benefits of the fuel savings.

The initial applications for the UHB that McDonnell Douglas sees in its product line are shown in Figure 6. The first two would be derivative versions of the DC-9-30 and the MD-80, followed in the mid-1990s by an all-new airplane in about the 180-seat category. The derivative approach offers many advantages, both to the airline operator and the manufacturer. Ownership costs are particularly critical in short-to-medium-range applications, and the derivative airplane, with its much lower nonrecurring and production costs, can be delivered for a lower price than an all-new airplane. There are also many other important advantages for the derivative approach, as described in Figure 7.

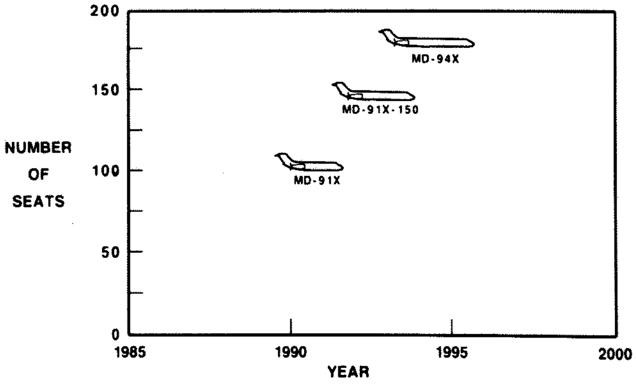

FIGURE 6. PRODUCT DEVELOPMENT PLAN

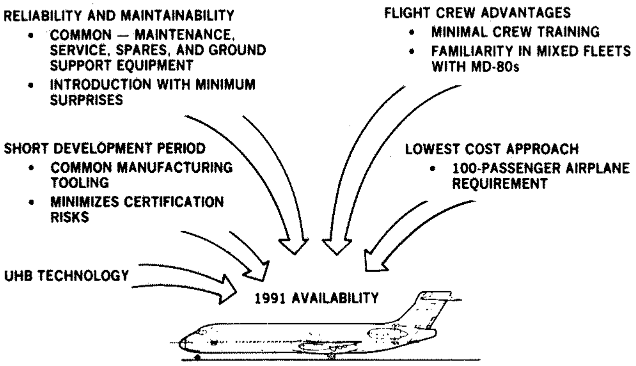

FIGURE 7. MD-91X — THE DERIVATIVE APPROACH

McDonnell Douglas believes there will be a significant market for a fuel-efficient airplane in the 100-seat category. The principal considerations that led to that conclusion are outlined in Figure 8.

100-SEAT AIRCRAFT (DC-9-30 TYPE)
- **OVER 40 PERCENT OF EXISTING FLEET**
- **33 PERCENT OF CURRENT BACKLOG**

OVER HALF THE FLEET IS MORE THAN 15 YEARS OLD

FORECAST DEMAND - 1,000 TO 2,500 UNITS

100-SEAT MARKET
- **SIGNIFICANT NEW PRODUCT OPPORTUNITIES**
- **EARLY AVAILABILITY CRITICAL**

FIGURE 8. FUSELAGE LENGTH SELECTION

The MD-91X-100 sizing criteria have been established to match airline requirements for the 100-passenger market (Figure 9). The design range has been selected to match the range of a DC-9-30 at a cruise Mach number of 0.78. The altitude and rate-of-climb capability have been sized for high-speed operation (M = 0.78). This allows airlines the flexibility of operating the MD-91X-100 at high speeds or, by reducing speeds, they may take advantage of greater range, higher altitude, or higher rate-of-climb performance. The single engine ceiling has been raised to 16,500 feet, which allows for operation throughout the continental United States with no engine failure restrictions in flight planning.

SIZE (NO. OF SEATS)	110 ALL-ECONOMY
RANGE (N MI) FULL LOAD PASSENGERS AND BAGGAGE	1,500
MINIMUM RATE OF CLIMB (FT/MIN)	
MAXIMUM CLIMB THRUST AT M = 0.78	300
MAXIMUM CRUISE THRUST AT M = 0.78	100
ALTITUDE CAPABILITY (FT)	
AT DESIGN RANGE	31,000
FOR 350 N MI/100% PSGR AND BAGGAGE	35,000
SINGLE-ENGINE CEILING	16,500
TAKEOFF FIELD LENGTH (FT) SEA LEVEL, 84°F AT MTOGW	~6,500
APPROACH SPEED (KEAS) (SEA LEVEL AT MLW)	128
CRUISE MACH NO.	0.78

FIGURE 9. MD-91X-100 SIZING CRITERIA

Compared with the DC-9-30, powered by the Pratt & Whitney JT8D-9A engine, the UHB-powered airplane (MD-91X-100) saves over 40 percent of trip fuel for a 350-nautical-mile mission (Figure 10). This fuel saving can lead to major improvements in direct operating costs. An additional important characteristic of the UHB-powered airplane is the substantial improvement in takeoff performance.

AIRPLANE	DC-9-30	MD-91X-100
ENGINES	JT8D-9A	UHB
ALL-ECONOMY SEATS (NO.)	110	110
OEW (LB)	60,050	65,000
MAX TAKEOFF WEIGHT (LB)	108,000	102,500
RANGE (N MI)	1,450	1,500
TAKEOFF FIELD LENGTH (FT)	7,300	~6,000
CRUISE MACH NUMBER	0.78	0.78
FUEL BURN (350 N MI/100% LF)	BASE	~ -40%

FIGURE 10. COMPARATIVE CHARACTERISTICS

Another relatively straightforward application of the UHB would be to the MD-80. The forward fuselage of the aircraft would have to be stretched to balance the heavier UHB engine, and other changes would have to be incorporated, including a fully powered elevator to accommodate the increased longitudinal control and trim requirements. The trip fuel and takeoff performance improvements would be very similar to the smaller derivative.

The application of the UHB to an all-new aircraft (Figure 11) raises the possibility of incorporating other technology developments that clearly would not be cost effective in a derivative airplane. Some of these technologies are listed in Figure 12, together with the potential improvement in fuel burn.

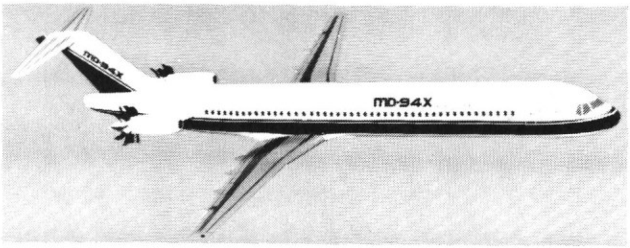

FIGURE 11. ALL-NEW UHB AIRCRAFT — MD-94X

	POTENTIAL FUEL BURN REDUCTION
• ULTRA HIGH BYPASS (UHB) ENGINES	35-40%
• LAMINAR AND TURBULENT BOUNDARY LAYER CONTROL	10-15%
• VERY-HIGH-ASPECT-RATIO SUPERCRITICAL WINGS	8-10%
• AL-LI AND HIGH-PERFORMANCE COMPOSITES	8-10%
• FLIGHT-CRITICAL ACTIVE STABILITY AUGMENTATION	4-5%
• ALL-ELECTRIC SECONDARY POWER SYSTEMS	4-5%
• DIGITAL CONTROL SYSTEMS	1%
• SIDE STICK CONTROLLERS	0-1/2%
• FLY-BY-LIGHT FLY-BY-WIRE	0-1/2%

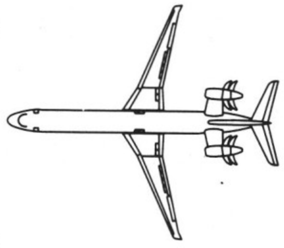

FIGURE 12. EMERGING TECHNOLOGIES FOR MD-94X

Whether this all-new aircraft makes economic sense or not will depend very much on actual fuel prices and interest rates. The price will inevitably be substantially higher than for a mature derivative. Very large savings in fuel costs will be required to overcome the higher ownership costs and, if fuel prices remain low, the entry-into-service date for an all-new airplane may have to be delayed.

UHB Airframe Technology Development

The UHB concept creates a number of unique problems in airframe design that must be solved before introduction into service.

The UHB engines will have much smaller cores than the present turbofan engines. Consequently, they will have less core flow and reduced bleed air capability. The present MD-80 type wing anti-ice system would exceed UHB bleed capability when added to air conditioning and pressurization flow requirements. Several types of alternative ice protection systems are being studied: mechanical de-icing (pneumatic or electro-impulse), which uses no bleed air; thermal de-icing (hot air or electric heaters); and special equipment to boost or supplement flow to an anti-ice system.

McDonnell Douglas has been committed for several years to an aggressive technology development program focused on those airframe technologies most significantly impacted by the UHB, i.e., aerodynamics, acoustics, and structural dynamics. This technology readiness program will be completed before the end of 1987.

Aerodynamics

For a variety of reasons, the initial Douglas UHB configuration studies concluded that the aft-mounted configuration was optimum. However, this configuration does introduce some new technical problems (Figure 13).

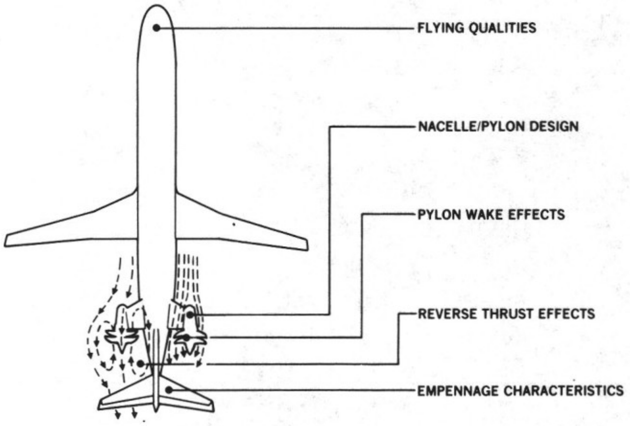

FIGURE 13. AERODYNAMIC ISSUES

The power loading on the propeller is about three times that of the Lockheed Electra. This means that the flow acceleration through the propellers is higher and the stream tube contraction is greater. It was felt that these differences, together with scrambling of the flow during reverse thrust, might create unique aerodynamic problems, particularly at low speeds.

For these reasons, a significant part of the Douglas technology readiness effort has been devoted to the exploration of UHB airframe aerodynamics.

The first low-speed tests were completed in April 1985 (Figure 14) in the MCAIR wind tunnel, and deep stall tests were completed in the United Technology Research Center wind tunnel in the third quarter of 1985 (Figure 15).

The low-speed tests were conducted on a 9-percent scale model of the MD-80 featuring fully powered propeller systems. These tests served to confirm the acceptability of the aerodynamic configuration of the MD-UHB. A minor reduction in rudder effectiveness was observed, which might require an increase in the maximum rudder deflection. There was some indication that the fuselage boundary layer was being entrained into the tips of the propellers at high thrust coefficients, which

FIGURE 14. UHB LOW-SPEED WIND TUNNEL MODEL

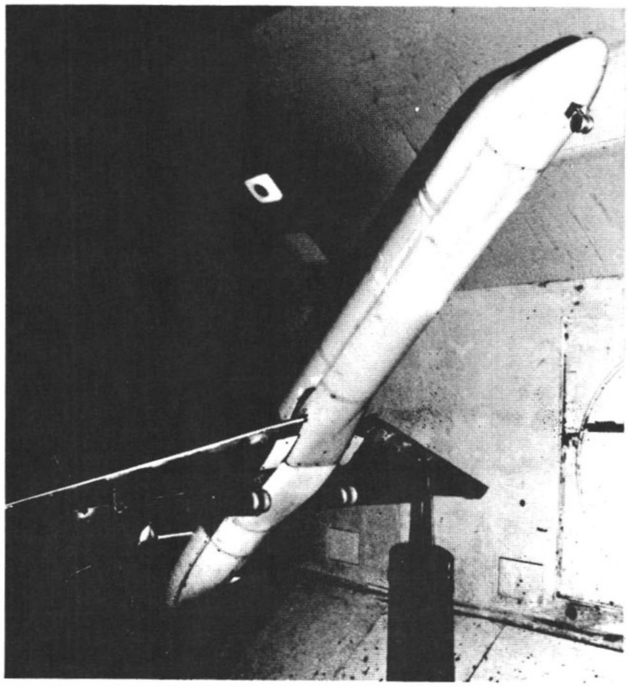

FIGURE 15. UHB DEEP STALL WIND TUNNEL MODEL

could be corrected by increasing propeller tip-to-fuselage clearance. Near the stall, as the propellers passed through the wing wake, propeller vibrations were observed, which could affect structural design for the propeller blades (Figure 16).

RESULT	IMPACT
THRUST MOMENT EFFECT AS EXPECTED	REQUIREMENT FOR POWERED ELEVATOR CONFIRMED, POTENTIAL AUTOMATIC TRIM SYSTEM FOR THRUST EFFECTS WILL REQUIRE INCREASED RUDDER THROW
RUDDER EFFECTIVENESS LOSS FOR DERIVATIVE AIRCRAFT	
STALL CHARACTERISTICS SIMILAR TO MD-80	NONE
WING WAKE INGESTED BY PROPELLERS NEAR $C_{L_{MAX}}$	DESIGN CONSIDERATION FOR PROPELLER STRUCTURAL INTEGRITY
COUPLING OF FUSELAGE BOUNDARY LAYER AND PROPELLER POWER INDICATED	MAY REQUIRE MORE PROPELLER TIP TO FUSELAGE CLEARANCE

FIGURE 16. UHB LOW-SPEED WIND TUNNEL TEST — SIGNIFICANT CONCLUSIONS

Deep stall is also a concern with aft-mounted engine installations and, although we had no reason for anticipating a problem in this area, we did include deep stall tests in our wind tunnel program. The tests were completed in December 1985, and it was found that the UHB aircraft deep stall characteristics were at least as good as those of the basic MD-80.

The high-speed wind tunnel tests will be completed this summer.

The results from these wind tunnel tests will be incorporated in the Douglas UHB moving base simulator tests starting late this year. Douglas pilots will be able to get hands-on experience with UHB airplane flight characteristics in both the product and demonstrator configuration prior to actual flight.

The results of the Douglas wind tunnel tests up to this time suggest that it is highly unlikely that there will be any aerodynamic "show stoppers" that will inhibit the development of a UHB-powered airplane.

Acoustics

The UHB noise certification estimates indicate that UHB aircraft will be as quiet as modern turbofans when, after development beyond the level of technology implemented in the demonstrator, they enter service in 1991 (Figure 17). The range of sound levels implied by the hatched lines indicates the considerable potential for noise control identified in ongoing research. This potential does not, however, extend to the approach condition where airframe noise sets the lowest levels that may be achieved.

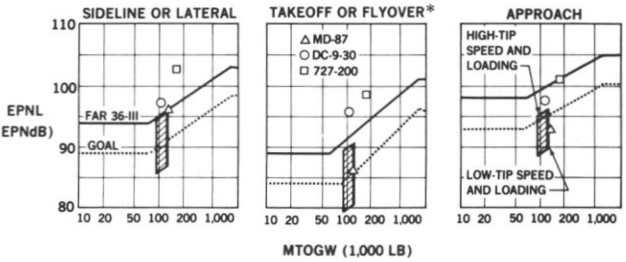

FIGURE 17. NOISE ESTIMATES

At cruise speeds, the tips of the propeller blades of the UHB will be operating at transonic speeds. The shock waves emanating from the propeller result in very high noise levels on adjacent structure and create for the designers unprecedented problems associated with the design of fatigue-resistant structures, as well as the challenge of controlling the noise transmission through the structure into the passenger cabin.

For several years now, McDonnell Douglas has been developing analytical methods and conducting experimental research required to provide the designer with the tools necessary to deal efficiently with the acoustic problem.

There are several key acoustic technical issues that need to be better understood. These include the magnitude and characteristics of the sound coming from the propellers, how it propagates through the air and boundary layer to the aircraft surfaces, how it is transmitted through the aircraft structure into the passenger cabin, and finally how it can be controlled to reduce the noise in the passenger cabin to acceptable levels.

The magnitude of the UHB acoustic problem is illustrated in Figure 18. At cruise conditions, structure immediately adjacent to the power plant will be subjected to noise levels up to 155 decibels, and most of the empennage will experience noise between 125-150 decibels. These noise levels are much higher than any experienced on turbofan-powered subsonic transports.

The noise spectrum of the UHB engine is very different from that of a turbofan. The turbofan gives off a continuous broadband noise, while the UHB noise is characterized by spikes at multiples of the propeller rotation speed. This different noise characteristic of the UHB creates possibilities for dealing with the acoustic and fatigue impact of these high noise levels that would not be applicable when dealing with continuous broadband noise.

The resistance of aircraft structures to sonic fatigue induced by high-intensity acoustical environments is being evaluated in the progressive wave tube test facility at Douglas (Figure 19). In these tests, a noise generator with an exponential horn is attached to a rectangular progressive wave tube (PWT) containing a test section and an absorptive termination section. As the acoustic waves travel the length of the tube, they graze the test panel, which is mounted to one side of the PWT, (or impinge on an internally mounted specimen), exciting it with the specified noise spectrum and pressure level. Accelerated testing at a sound pressure level (SPL) substantially greater than those encountered in service can uncover structural deficiencies in a relatively short period of time.

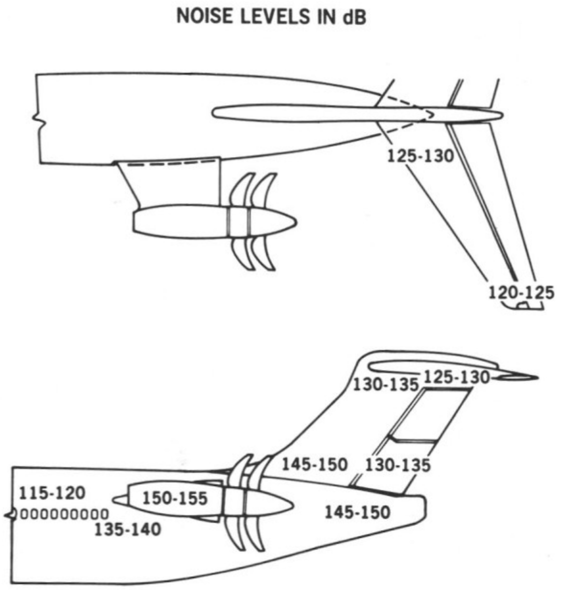

FIGURE 18. ACOUSTIC ENVIRONMENT AT CRUISE

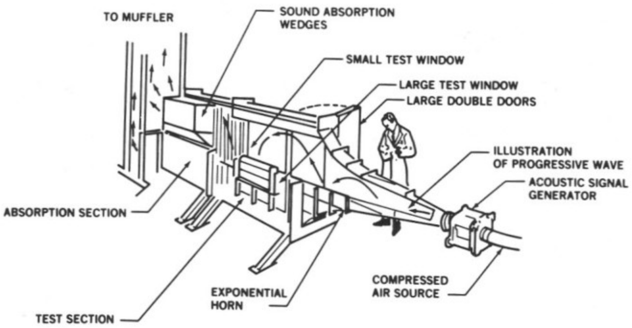

FIGURE 19. PROGRESSIVE WAVE TUBE FACILITY

Sonic fatigue tests of multipanel structural specimens simulating the aft fuselage structure have been conducted to validate analytical methods (Figure 20). Various types of adhesively bonded damping materials were applied to the test specimens, which were subjected to pressure wave excitation forces and combinations of discrete frequencies to simulate the pressure pulses of the UHB counterrotating propulsors. The tests were conducted at various temperatures to satisfy the damping requirements at takeoff and at cruise environments. The materials with optimum damping have been selected, and the panels will be subjected to accelerated testing to failure for evaluation of sonic fatigue life.

FIGURE 20. TEST PANEL

The results of this program have been very encouraging (Figure 21). The aircraft weight penalty associated with the structural fatigue considerations applied in our initial design studies has been drastically reduced as a result of this work.

The considerable challenge of providing interior noise levels equivalent to those on turbofan aircraft is being addressed by an extensive research program to develop and integrate noise control treatments in the designs. The high exterior noise levels and lower (mainly discrete) frequencies of the UHB call for a range of tuned and untuned treatments to limit both airborne and structure-borne noise. Figure 22 lists a number of noise-control features that are actively being studied.

Figure 23 illustrates features of the Douglas acoustic panel test program. Good progress is being made in developing lightweight acoustical absorbent sidewalls, and this work is continuing.

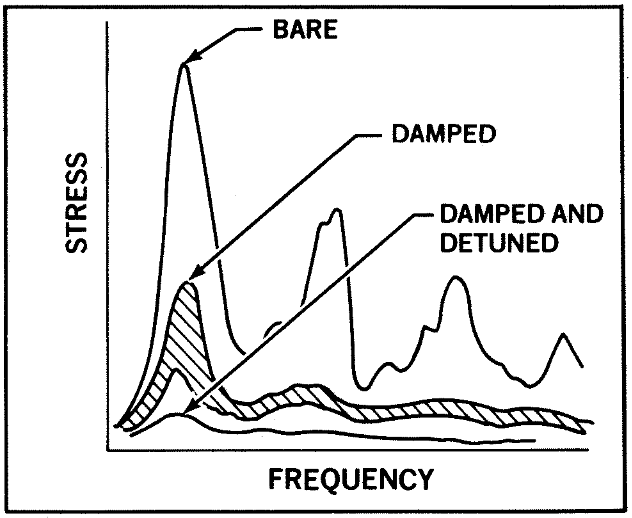

FIGURE 21. PANEL (ACOUSTIC FATIGUE) TESTS

DESIGN BASED ON PANEL TESTS, COMPONENT TESTS, AND FUSELAGE TESTS

- ENGINE ISOLATORS
- ENGINE TUNED ABSORBERS
- FUSELAGE STIFFNESS CONTROL
- DOUBLE-WALL SIDEWALL AND BULKHEAD WITH RESONATORS
- DAMPED, HEAVYWEIGHT TRIM PANELS
- BAGRACK ISOLATORS
- FRAME TUNED ABSORBERS

FIGURE 22. INTERIOR NOISE CONTROL

NOISE CONTROL DEVICE	PROOF OF CONCEPT DAC/NASA 1984	PARAMETRIC DAC 1985/86	PRODUCTION DAC 1985/86
RESONATORS VARYING CAVITY DIMENSIONS AND INSULATION LOCATION IN SINGLE AND DOUBLE PANELS	6*	13	4
VENTED PANELS TUNED VENTS AT PANEL EDGE	10	7	2
STIFF/LIMP PANELS VARYING MASS STIFFNESS RATIO OF LIMP PANEL IN STIFF/LIMP SIDEWALL	2	12	2
COMPONENTS	0	0	2
WINDOW AND TUNED ABSORBER TESTS	0	3	1

*NUMBER OF PANEL CONFIGURATIONS NOT INCLUDING BASELINE AND COMBINATIONS

FIGURE 23. ACOUSTIC PANEL TESTS

UHB-generated noise differs from turbofan-generated noise because the sound pressure levels generated by the UHB occur at lower frequencies. In addition, UHB noise reaching the cabin includes more pure tone content than the noise on present turbofan aircraft. The difference in character of the UHB noise was evaluated in late 1985 during psychoacoustic tests conducted in an MD-80 interior mockup (Figure 24). Volunteers were seated in the mockup interior and exposed to various simulations of UHB and turbofan noise and asked to measure subjectively the annoyance of each. From these psychoacoustic tests, Douglas will be able to gage whether sound level goals currently established for the UHB need adjustment to ensure an overall interior comfort level equivalent to that of modern turbofans.

OBJECTIVE

- SET CABIN NOISE GOAL IN TERMS OF APPROPRIATE NOISE DESCRIPTOR

SOUNDS

- UHB: 6 x 6, 8 x 8, 10 x 8, 10 x 10, AND 11 x 9
- REGULAR TURBOPROP AND TURBOFAN ENGINE NOISE
- BACKGROUND NOISE OF BOUNDARY LAYER AND ECS NOISE

EXPERIMENTAL PLAN

- 80 RANDOMLY SEQUENCED SOUNDS
- 100 SUBJECTS

STATUS

- TEST COMPLETED LATE 1985
- ANALYSIS UNDERWAY

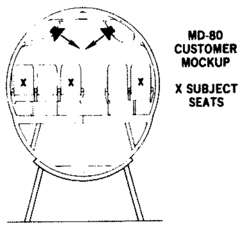

FIGURE 24. PSYCHOACOUSTIC TESTS

A facility is currently being prepared to evaluate sound transmission in a fuselage structure in 1986. Tests will be conducted on a full-scale DC-9 aft fuselage section inside an anechoic chamber at the Douglas Long Beach facility (Figure 25). The fuselage test section will be pressurized to depict sound transmission with structure under pressure loads as in cruise. The fuselage test section will be exposed to acoustical fields representing the frequency, phase, and directivity of the UHB engine. In addition, shakers will be mechanically fastened to the pylon structure and vibrations introduced into the fuselage for evaluation of vibration transmission.

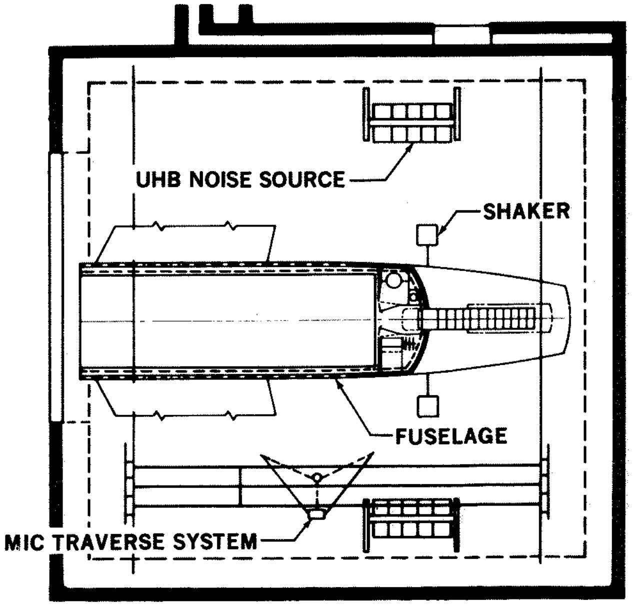

FIGURE 25. FUSELAGE ACOUSTIC TEST SYSTEM

The Technology Readiness Program will culminate in 1987 with flight test demonstrations of the General Electric unducted fan (UDF) gearless engine and the Pratt & Whitney/Allison geared engine on an MD-80 (Figure 26). The demonstrator program will provide Douglas the opportunity to validate design tools and analytical models developed during the Technology Readiness Program. Furthermore, it will pro-

FIGURE 26. UHB DEMONSTRATOR

vide an opportunity to measure, at full scale, the acoustic and structural dynamic characteristics of both the geared and gearless propfan systems. The design modifications required by these configurations are currently being defined and will include the use of pylon and fuselage modifications common to both the geared and gearless systems. The demonstrator program and the Technology Readiness Program both utilize participants from other aerospace companies.

Conclusions

A UHB-powered subsonic transport will be more economical than one powered by an equivalent-technology turbofan.

The critical airframe technology issues are being resolved. Low-speed wind tunnel tests have revealed only minor aerodynamic problems, and design solutions have been developed that reduce the weight penalty initially assessed to deal with sonic fatigue by almost an order of magnitude.

The McDonnell Douglas UHB Technology Readiness Program is expected to be completed on schedule.