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A-7 AIRBORNE LIGHT OPTICAL FIBER TECHNOLOGY (ALOFT) DEMONSTRATION PROJECT

RD Harder, RA Greenwell, GM Holma

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Final Report, March 1974 through January 1977

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The A-7 ALOFT project successfully demonstrated a fiber-optic signal transmission system can accurately transmit data in the demanding environment of a military aircraft. Included is a summary of the most significant test results, the conclusions reached from the economic analysis, and the compilation of reliability and maintainability data.
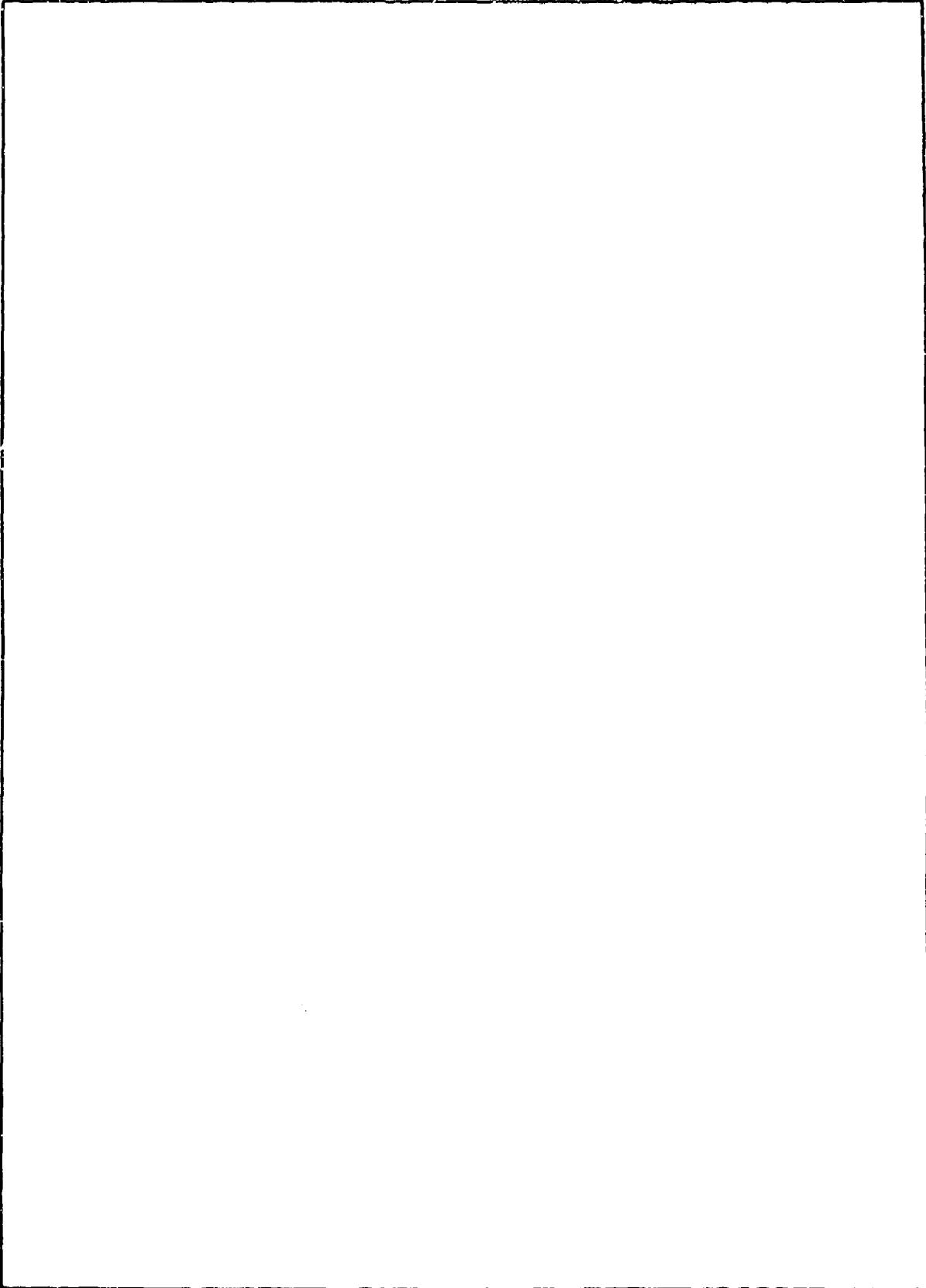
OBJECTIVE

Demonstrate the feasibility of using fiber optics in a military system aboard an airborne platform and determine whether such use of fiber optics could lower the cost and/or increase the performance of military systems.

RESULTS

The Airborne Light Optical Fiber Technology (ALOFT) flight demonstration compared a fiber-optic multiplexed configuration to the existing wire configuration A-7 aircraft navigation weapon-delivery system, and the economic analysis compared fiber-optic and wire versions of A-7 avionic systems. The following results were obtained:

1. Fiber-optic components can operate in the maintenance and mission environments of a military aircraft.

2. In the operating environment of a military aircraft, the multiplex fiber-optic system performed with the same accuracy as the nonmultiplexed existing wire system.

3. In an EMI or lightning environment, the multiplex fiber-optic system was superior to the nonmultiplexed wire system.

4. The results of the economic analysis indicate, in the comparison between conventional wire systems and fiber-optic systems, fiber-optic technology clearly provides substantial future benefits of reduced system weight, improved survivability and reliability, increased data transmission, and ease of maintenance at reduced life-cycle costs while meeting or exceeding the future requirements of EMI and EMP.

5. Reliability data compiled during the first 72 hours of flight testing indicate that the fiber-optic system may be more reliable than the wire-interface system used in the Fleet configuration.

6. The fiber-optic system interface was easier to trouble-shoot and maintain than the wire system.

ADMINISTRATIVE INFORMATION

1

CONTENTS

ILLUSTRATIONS

TABLES

INTRODUCTION

The Airborne Light Optical Fiber Technology (ALOFT) demonstration was sponsored by the Naval Air Systems Command (AIR-360) to show the feasibility of using fiber optics on an airborne military platform and to determine if fiber optics could lower the overall cost or improve the overall performance of military systems.

When signals in an avionics environment are transferred electrically, there is found to be potential operational degradation and damage due to the susceptibility of metallic conductors to electromagnetic interference, radio-frequency interference, lightning strikes, and nuclear-generated electromagnetic pulses. Other sources of electronic interference such as crosstalk, ground-looping, reflection, and short-circuit loading also affect system operation.

When an electro-optical interface is used to transfer signals, information is transmitted through bundles of glass fibers called fiber-optic cables. Because of the dielectric nature of glass, the bundles are immune to electrical interference and are unaffected by electronic conduction problems. Because of these attributes and the high-bandwidth capabilities of fiber-optic cables, multiplexing can be used reliably in a fiber-optic system. Multiplexing reduces the number of the required signal paths and the complexity of cable connectors. The resulting enhancement of system performance and the savings of space and weight may make fiber-optic technology highly cost effective for avionic systems.

PARTICIPANTS

The ALOFT project began in March 1974 when NAVAIR assigned NELC the responsibility for conducting the fiber-optic investigation. The project came to an end in February 1977 after more than 107 flight-test hours of the fiber-optic A-7 system had been conducted by Naval Weapons Center (NWC), China Lake, California.

NELC was tasked by NAVAIR to manage the ALOFT project and to perform evaluation tests on fiber-optic components. IBM, Federal Systems Division, Owego, New York, performed the system design, fabrication, and integration. Ling-Temco-Vought (LTV), Vought Systems Division, Dallas, Texas, developed an installation plan and performed the initial system ground tests. The Naval Weapons Center, China Lake, California, supplied the necessary software for the system, safety-of-flight verification, and the flight test facilities for the ALOFT demonstration. NWC also installed the ALOFT system in the aircraft and performed ground and flight testing. The Naval Air Test Center (NATC), Patuxent River, Maryland, evaluated the reliability and maintainability of the system. Emi and lightning susceptibility tests were performed by LTV, McDonnell Aircraft Company, and personnel of the Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio. McDonnell Aircraft Company, using data and analyses supplied by the Naval Postgraduate School, Monterey, California, executed an economic analysis of the ALOFT system.

PURPOSE OF THIS DOCUMENT

This report contains the results of the tests performed on the ALOFT system, and presents the results of the A-7 ALOFT Economic Analysis. The test plan which was used is contained in reference 1, the basic outline of the economic analysis is presented in

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1. Naval Electronics Laboratory Center Technical Document 438, A-7 ALOFT Demonstration Master Test Plan, by R Harder, July 1975

reference 2, detailed flight test results are contained in reference 3, and details of the system hardware design are discussed in reference 4.

SYSTEM DESIGN

The IBM-designed interface system connected the A-7 avionics as shown in figure 1. Signals which were originally transmitted over a very dense, parallel, point-to-point interface, consisting of 115 channels (302 conductors including twisted shielded pairs and coaxial cables) were multiplexed into 13 simplex information channels. Data in these channels were transmitted over 13 fiber-optic cables. Such extensive point-to-point multiplexing was possible because of the wide bandwidth available with fiber-optic data links. Table 1 shows the different types of signals which were transmitted by fiber-optics in the ALOFT system.

The digital signals were time-division multiplexed and then transmitted using Manchester coding. The maximum multiplexed data rate for the system was 10 megabits per second. The maximum transmission distance was 27 feet and there were five coupling devices, maximum, from the light source to the light detector. The light source was a GaAs light-emitting diode; the light detector was a PIN silicon photodiode. The cable consisted of "high loss," glass core, glass-clad fibers in a 0.045-inch diameter active area bundle with a jacket of outside dimension of 0.120 inch. More detailed system design information can be found in other documents (refs 5 and 6).

2. Naval Electronics Laboratory Center Technical Report 1982, A-7 ALOFT Life-Cycle costs and Measures of Effectiveness Models, by RA Greenwell, March 1976

3. Naval Weapons Center Technical Memorandum 2969, ALOFT Demonstration Flight Test Final Report, by JD Ross (in preparation)

4. Naval Electronics Laboratory Center Technical Report 1968, A-7 ALOFT Demonstration, Interim Progress Summary and Description of the A-7 ALOFT System, by JR Ellis, LCDR, USN, 1 January 1976

5. International Business Machines Instruction IBM-75-ALO-010, A-7 ALOFT Maintenance Instructions, 27 February 1976

6. International Business Machines Report 75-M41-002, Design of ALOFT Fiber-Optic Interface Circuitry, 24 February 1975

PRESSURIZED
BULKHEAD
CONNECTOR

HEADS UP
DISPLAY
(ELECTRONICS)

PROJECTED
MAP DISPLAY
(ELECTRONICS)

INERTIAL
MEASUREMENT
SYSTEM

ARMAMENT
STATION
CONTROL UNIT

MASTER
FUNCTION
SWITCHES

DOPPLER
NAVIGATION

NAVIGATION
WEAPONS
DELIVERY
COMPUTER
CP-952/
ASN-91
TC-2
TACTICAL
COMPUTER

FLIGHT STICK
CONTROL

THROTTLE

INERTIAL
MEASUREMENT
SYSTEM
CONTROLLER

ARMAMENT
SELECT PANEL

ADVISORY
CAUTION PANEL

ATTITUDE
DIRECTION
INDICATOR

ARMAMENT
RELEASE PANEL

BULL PUP
CONTROL

NAVIGATION
WEAPONS
DELIVERY PANEL

PILOT'S
STICK GRIP

COCKPIT AREA

FORWARD-LOOKING
RADAR SIGNAL
GENERATOR

Figure 1. A-7 navigation and weapon-delivery system, electrical interface.

5

TABLE 1. ALOFT SIGNAL TYPES.

- Four 1 MHz
- Nineteen 50 kHz
- Forty-two 5-V discretes
- 27 switch closures

- Twelve 5-V pulse trains
- Eight 28-V discretes
- 2 analog (via A-D conversion)
- 1 analog (direct fiber-optic interface)

Total = 8 signal types and 115 signals

OPERABILITY TESTS

The fiber-optic components underwent extensive environmental testing before they were installed on the aircraft to prove that they would operate in the environment of an A-7 aircraft. The Fleet A-7 navigation and weapons-delivery system was designed to meet the Class 2 environment of MIL-E-5400 (ref 7). The fiber-optic cables, light-emitting diodes, and photodiodes underwent extensive testing at temperatures from $-62^{\circ}C$ to $+95^{\circ}C$ and at simulated altitudes of 70 000 feet (21.336 km). The components were subjected to vibration and shock tests, humidity, salt fog, and temperature-shock tests. These tests are described in NELC documents (refs 1, 8, 9, 10) and proved that the fiber-optic components can survive in the aircraft environment.

The components, assembled as a system, were tested on the A-7 ground simulator at Ling-Temco-Vought (LTV). The system performed successfully under temperature and vibration extremes typically used to find problems that appear intermittently in flight. The wire portion of the ALOFT system was also tested to emi conditions found on A-7 aircraft, according to C501, C502, C506, and R502 of MIL-STD-461A. These tests proved that the total ALOFT system would operate in the A-7 environment. (ref 13)

SYSTEM INSTALLATION AND TESTING

The ALOFT system was installed on the A-7 aircraft according to LTV installation plans (refs 11, 12). No special precautions were taken during the installation. Wherever

7. Ling-Temco-Vought Report 2-50360/4R5738, Environmental Definition Analysis Report, 28 June 1974

8. Naval Electronics Laboratory Center Technical Document 460, ALOFT Fiber-Optic Component Tests, By G Holma, January 1976

9. Naval Electronics Laboratory Center Technical Document 418, A-7 ALOFT Hardware Requirements/Environmental Analysis, by G Holma, April 1975

10. Naval Electronics Laboratory Center Technical Document 439, The Effects of Contamination on Fiber-Optic Connector Radiation Patterns, by G Kosmos, July 1974

11. Ling-Temco-Vought Report 2-50360/4R5760, Physical Constraints and Aircraft Installation Requirements Report, December 1974

12. Ling-Temco-Vought Report 2-51734/5R5780, Preliminary Modification Plan for ALOFT Program, March 1975

13. Ling-Temco-Vought Report, Vought ALOFT Test Program Final Report, 29 April 1976

possible the fiber-optic cables were attached to existing wire harnesses with nylon tie straps. No strain relief was used at the cable-connector junctions. During installation, one fiber-optic cable was broken when it was being pulled through the keel of the aircraft from the left to the right avionics bay. The break took place at the connector end where the connector terminal was found to be improperly assembled. The break was repaired and the installation was completed. The break placed emphasis on the importance of providing some form of strain relief for the fiber-optic cable-connector junction in future installations.

SYSTEM ACCURACY TESTS

The Flight tests at the Naval Weapons Center, China Lake, California, consisted of 3 series of flights in which accuracy data were taken. Additional flights were flown to gather information on reliability and maintainability. The first series of accuracy-data flights was with the aircraft in the Fleet configuration, not modified in any manner. This series of flights established a baseline for comparison with later flights in the wire configuration with the modified TC2A computer and in the fiber-optic configuration.

The second series of accuracy flights was in the modified wired configuration. In this configuration, the modified ALOFT computer with its new software and new TC2A converter were installed on the aircraft. Data transmission was still nonmultiplexed over wire as in the Fleet configuration. These tests established a second baseline to determine the level of accuracy of the new modified computer and software compared to the first version.

The final series of accuracy flights used the modified computer in conjunction with the multiplexed, fiber-optic configuration. Comparing the accuracy of these flight data with those of the second series of flights allowed a judgment to be made on the accuracy of the multiplex fiber-optic data transmission. Each series of flights consisted of navigation flights and weapons-delivery flights. The flight-test results are in the NWC Flight Test Report (ref 3) which showed that the fiber-optic configuration was fully as accurate as the Fleet configuration.

The total number of flight hours in the fiber-optic configuration was 107. At the end of the flight tests, 1 percent of fiber degradation (breakage) was noted. The fiber-optic cable breakage data are in appendix A.

During the last half of the flight tests (after 72 hours), the aircraft with its avionic systems, including the fiber-optic interface, was turned over to the NWC Flight Squadron VX5 for use in training missions and other programs not related to ALOFT or fiber optics.

EMI, LIGHTNING, AND EMP IMMUNITY TESTS

A major advantage of fiber optics over wire is its immunity to electromagnetic interference, lightning, and electromagnetic pulse. This is because the fiber-optic cables contain no metallic conductors. They cannot emit nor pick up electromagnetic radiation. Three tests were conducted to demonstrate this advantage of fiber optics at the system level.

The first series of emi tests was performed with the ALOFT hardware operating with the A-7 simulator. These tests measured the bit-error rate of the NWDS double-shielded, wire interface and the NWDS fiber-optic interface when exposed to emi. The bit-error rate for the multiplexed fiber-optic interface was 500 times lower than the bit-error rate for the

nonmultiplexed wire interface when exposed to the same levels of emi. Details of this test can be found in appendix B of this document.

The second series of tests was done at China Lake by McDonnell Aircraft Company. The Heads Up Display (HUD) and Projected Map Display System (PMDS) displays were monitored for picture quality while the systems onboard the aircraft were exposed to emi. No interference was caused the displays when the fiber-optic cables were exposed to emi. The display quality was considerably degraded when single-shielded wire was exposed to emi. Double-shielded wire was not visibly susceptible to the same levels of emi but a massive increase in the bit-error rate is required to produce a noticeable decrease in the quality of the displays. These test results may be found in appendix 1 of the Final Report on the A-7 ALOFT Economic Analysis (ref 14).

The third series of tests consisted of simulated lightning-strike tests performed by the Flight Dynamics Laboratory, Wright-Patterson Air Force Base. These tests were conducted at NATC, Patuxent River. Various test points within the NWDS computer were monitored while the aircraft was exposed to simulated lightning strikes.

A 2000-ampere peak current pulse was applied to the aircraft to simulate the lightning current. The pulse had an approximate 1.6-microsecond rise time and a 50-microsecond delay time to half value. In order to allow a maximum of information to be drawn from the test, the ALOFT computer was tested in a total of 7 different configurations. These included variations in connections of power cabling, signal cabling, fiber-optic cables, and aircraft power.

Induced transient measurements were made on a total of 6 different circuits within the computer in each of the 7 configurations. Multiple observations were made of each transient (3 to 10) in order to establish confidence bounds on the data. In addition to recording the time-domain transient waveforms, most waveforms were also analyzed with the Fast Fourier Transform to yield spectral information.

For the fiber-optic configuration, the induced voltages within the computer, when exposed to a simulated lightning strike, were 85 to 90 percent less than the induced voltages in the wire configuration. This indicates that the fiber-optic configuration would be much less susceptible to damage if the aircraft were to be struck by lightning. This is even more significant considering that the A-7 aircraft signal wiring is all double-shielded wire. Since a lightning strike is similar to electromagnetic pulse (emp) in its induced effects upon avionics, the results could be carried over to emp susceptibility. These results can be found in the Air Force report (ref 15).

These emi and lightning/emp results are significant when future aircraft designs are considered. Future aircraft will emphasize low weight and lost cost. They will be made of composite, non-metallic, structures which will offer very little shielding. The emphasis will

14.   McDonnell Aircraft Company, A-7 ALOFT Economic Analysis Final Report, November 1976

15.   AFFDL Test Report TM-76-100-FES, Simulated Lightning Test on the Navy A-7 ALOFT Aircraft, September 1976

be for non-shielded or single-shielded wires instead of double-shielded wires as is the case with the A-7. The aircraft will also be fly-by-wire with the aircraft survivability directly dependent upon the amount of shielding provided for the avionics. Fiber optics may be the only solution.

RELIABILITY

Data regarding component and system failures were collected over the life of the ALOFT project. The Naval Air Test Center (NATC), Patuxent River, Maryland, supervised the collection of these data and evaluated the data collected during the first 72 hours of flight testing. Although 72 hours is not a sufficient sample to provide an accurate comparison, it is significant that the reliability of the ALOFT system compared favorably to the Fleet reliability figures for the wired system. The Mean Flight Hours Between Maintenance Action (MFHBMA) and the Mean Flight Hours Between Failure (MFHBF) for the fiber-optic configuration were 10.3 and 24.0 hours, respectively. The Fleet figures for the wired configuration are 7.4 and 21.6 hours, respectively. Further details regarding the reliability analysis are contained in the NATC report (ref 16).

MAINTAINABILITY

Maintenance data on the ALOFT system were compiled and evaluated by NATC. The NATC report rates the maintainability of the ALOFT system as good and further details are contained in that report. NATC's rating was based upon the fact that the fiber-optic system eliminated problems such as ground loops, intermittent and bent contacts, broken shields, and electrical shorts which were common to the copper-wire interfaced system. The fiber-optic system connections do not require direct contact between the light emitting diodes, the cable ends, nor the photo detectors for proper operation. The connectors used in the ALOFT system separate the ends of the fiber-optic cables by a small air gap; therefore, problems similar to the intermittent and bent contacts of wire connectors, cannot occur.

ECONOMIC ANALYSIS

The purpose of the A-7 ALOFT Economic Analysis Program was to develop valid cost estimates for performance-equivalent digital-data transfer systems utilizing conventional wire and fiber optics. The analysis developed credible cost projections for three performance-equivalent cable alternatives: coaxial, twisted-shielded pair, and fiber-optic. Cost estimates were generated by an approach which utilized two techniques: one which computes research and development (R&D), investment, and operating and support (O&S) costs for the fiber-optics and wire-interconnect data-transmission subsystems ("Bottoms-Up" model); and another which computes the total weapon system costs as a result of

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16.   Naval Air Test Center Report SA15R-77 ALOFT Reliability and Maintainability

changes in weight of the respective subsystems ("Top-Down" model). The "Bottoms-Up" model outputs became one of the inputs to the "Top-Down" model which yielded the total life-cycle cost (LCC) results. Results from these two models were then consolidated, tested for sensitivity, and evaluated to provide the total LCC for each alternative. Results of the economic analysis are summarized in figure 2 by system configuration, electromagnetic environment, and wire/fiber interconnects. These results must be bounded since they are constrained by the basic assumptions of the program. The major assumptions were:

    1.   All costs were assumed to be applicable to a new program, not a retrofit program since all the alternative configurations were new design subsystems for the A-7;

    2.   Cost elements would only be developed where differences between conventional wire and fiber-optics costs occur for the "Bottoms-Up" approach; and

    3.   Fiber optics presents no serious development, reliability, nor production problems, and the fiber-optic components are environmentally qualified with a life expectancy equal to that of comparable conventional wire components.

For the coaxial, twisted-shielded-pair (TSP), and fiber-optic components, actual costs were used wherever possible. Specifically, the cost of materials was requested from several sources although it was not always received. Where actual data were unavailable, engineering judgment was exercised.
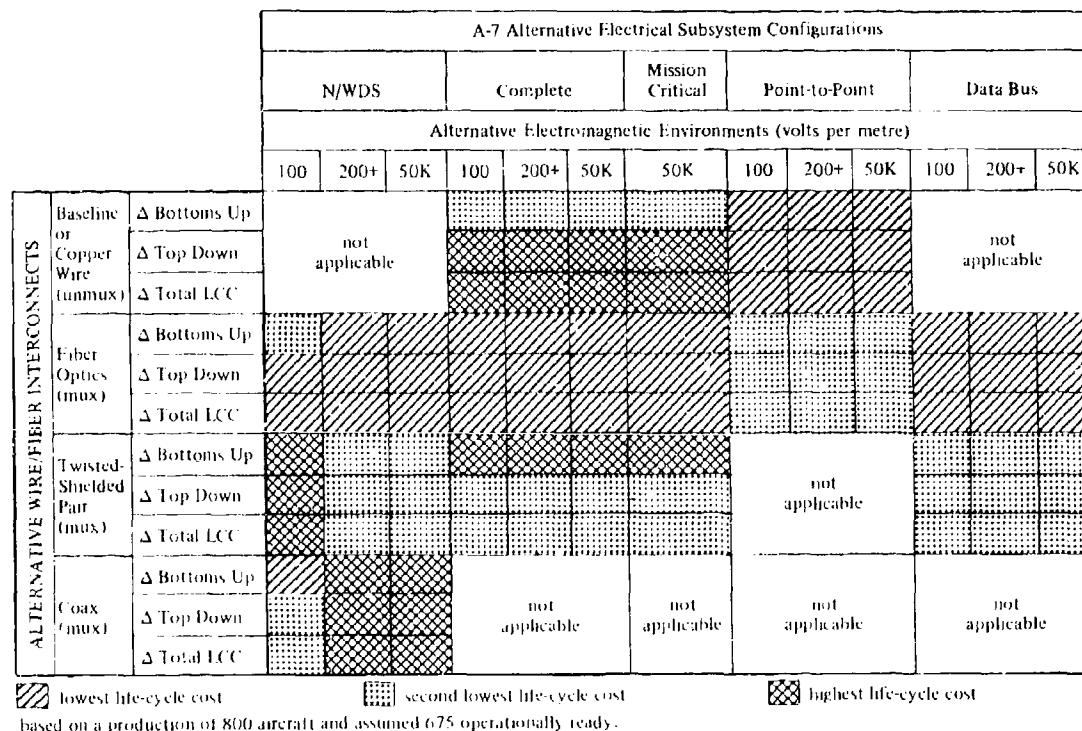
Figure 2. Summary LCC results for A-7 alternative configurations.

based on a production of 800 aircraft and assumed 675 operationally ready.

Legend: lowest life-cycle cost, second lowest life-cycle cost, highest life-cycle cost

Several other basic parameters had to be established before data could be input to the "Bottoms-Up" model. Production schedules and quantities had to be established for each alternative design configuration. Escalation, strategic-commodity rate increases, and experience-curve estimates had to be established for each alternative.

The base year for the economic analysis was established as beginning 1 January 1977 with a 3-year period assigned to perform the research, development, test, and evaluation (RDT&E) of a subsystem design. The next 4 years were assigned to the acquisition of the subsystem, and the final 10 years were assigned as anticipated operational life without a service-life extension program (SLEP). The basic A-7 Navigation/Weapon Delivery Subsystem (N/WDS) was the baseline design in a total production schedule of 812 A-7E aircraft. Of these 812 aircraft, twelve were test vehicles, the costs for which were included in RDT&E fabrication costs. The remaining 800 aircraft would meet the following delivery schedule:

  80 in 1980,
  240 in 1981,
  240 in 1982, and
  240 in 1983.

It was also assumed that, of the 800 aircraft, 675 would be operational vehicles. The utilization rate was assumed to be 35 hours per month for 9 of the 10 years of operation. The remaining year was considered a wartime operational environment and the operation rate was assumed to be 12 hours per day. A-7E aircraft attrition rates in southeast Asia were also assumed for survivability analysis.

Cost data resulting from exercising the "Top-Down" and "Bottoms-Up" life-cycle cost models applicable to the A-7 aircraft have shown that fiber optics is an attractive alternative to conventional wire data transfer in most cases and especially when the EMI environment places severe demands on the amount of protection required.

For the A-7 ALOFT configuration, the cost results conclude that fiber optics is the best choice followed by TSP and then coaxial in all EMI environments except the one case where the "Top-Down" results indicate the positions of TSP coaxial are reversed for the 100 volt per metre (baseline) environment. The total LCCs of TSP and fiber optics applied to the A-7 ALOFT configuration are similar. Such a result is highly encouraging in that fiber-optic factors also include the added burden of large RDT&E costs plus non-recurring investment, maintenance, and instructor training costs that TSP does not. Assuming reliability objectives for fiber optics can be realized, this investigation concludes that recurring investment and operating and support costs for TSP are greater than those for fiber optics. For the completely multiplexed A-7 aircraft configuration, fiber optics is the only system to show a cost savings over the baseline system in all categories of environment (eg, in the most severe environment (EMP) a TSP system costs more than the baseline system). This weight saving due to multiplexing translates into a significant cost payoff. Savings are realized by both lower total equipment costs and larger weight savings. For the 100 point-to-point (nonmultiplexed, one for one replacement) data-link case, the use of fiber optics does not appear to be justified for any environmental situation, principally due to the large amount of conversion components required. Only if a situation exists where an aircraft system will not function unless a selected number of fiber-optic transmission lines are employed in critical areas can the unmultiplexed point-to-point technique be economically justified.

11

Similarly, the cost data resulting from exercising the "Top-Down" and "Bottoms-Up" life-cycle cost models applicable to the advanced A-7 (data bus) aircraft have shown that fiber optics is an attractive alternative to conventional wire data transfer. For the baseline system in the 100 volt per metre environment, a 25 percent savings in LCC is realized using fiber optics instead of conventional wire for data transfer. Also, the LCC increases as the environment becomes more severe for both the conventional wire and fiber-optics configurations, but the increases are significantly larger for conventional wire. There is no linear relation between weight increases and LCC increases. These results are summarized in figure 2. Table 2 and figure 3 show comparisons of the actual cables used on the ALOFT A-7 and appendix C contains a brief description of the LCC methodology and the cost data.

TABLE 2. SIDE-BY-SIDE COMPARISON, FIBER-OPTIC AND ELECTRICAL CABLES.

|	Wire	Fiber Optics
Number of wires/cables	302	13
Total length	1890 ft (576.07 m)	224 ft (68.27 m)
Total cables & connectors weight	31.9 lb (14 45 kg)	2.7 lb (1.2 kg)
Total cables & connectors cost	$1.63k	$1.03k

Figure 3. Side-by-side comparison of the amount of copper wiring displaced in the A-7 by the 13 fiber-optic cables in the ALOFT system.

CONCLUSIONS

The ALOFT project successfully demonstrated that fiber optics is a feasible technology for signal interfaces on a military platform. In the ALOFT project, the wire interface for the navigation and weapons delivery system on a Navy A-7 aircraft was successfully replaced by a multiplexed fiber-optic interface. This multiplexed fiber-optic interface data-transfer system was shown to offer many advantages over the standard, nonmultiplexed wire interfaces used in current military aircraft. These advantages included reduced weight and space requirements, improved electromagnetic interference (emi), electromagnetic pulse (emp), and lightning immunity, freedom from ground loops, and reduced secondary battle damage.

The ALOFT project proved the following by comparing a fiber-optic and wire version of an A-7 navigation and weapons delivery system:

1. Fiber-optic components can operate in the maintenance and mission environments of a military aircraft;

2. In the operating environment of a military aircraft, the multiplexed fiber-optic system performed with the same accuracy as the nonmultiplexed wire system;

3. In an emi or lightning environment, the multiplexed fiber-optic system was superior to the nonmultiplexed, wire system;

4. The results of economic analysis indicate that, in the comparison between conventional-wire systems and fiber-optic systems, fiber-optic technology clearly provides substantial future benefits of reduced system weight, survivability, improved reliability, increased data transmission, and ease of maintenance at reduced life-cycle costs while meeting or exceeding the future requirements of emi and emp;

5. Reliability data compiled during the first 72 hours of flight testing indicate that the fiber-optic system may be more reliable than the wire-interface system used in the Fleet; and

6. The fiber-optic interface was found to be easier to troubleshoot and maintain than the wire-interface system.

It is important to note that these conclusions pertain only to a system using multi-fiber glass-on-glass cables having an overall diameter of 0.045 inch. At the present time, the components for this type of system are the easiest with which to work, are the least expensive, and the most readily available of any fiber-optic components.

A fiber-optic interconnect system is not susceptible to the battle damage that can be caused by a broken or damaged wire cable. A damaged wire cable can cause secondary damage to an electrical system due to short-circuit overloads. A broken fiber-optic cable cannot cause this type of damage because there are not short circuits, sparks, nor fire if a fiber-optic line is damaged.

The emi immunity of a wire system is dependent upon the integrity of the shielding. The shielding of a wire system deteriorates with time and, as a result, the performance of a wire system may be affected due to shield damage during maintenance. A fiber-optic cable does not require shielding and thus eliminates this type of problem.

The repair of broken or damaged fiber-optic cables is easily accomplished and requires fewer tools and less manual dexterity than does the repair of coaxial cables. Indications are that information on the maintenance of multifiber glass-on-glass fiber-optic cables could be incorporated easily into existing training courses.

13

Trouble shooting of a fiber-optic cable is accomplished easily with a visible light source. Visual inspection quickly determines fiber continuity and transmission quality. Many problems of trouble shooting connected with a wire system are eliminated when fiber optics are used.

DESIGN RECOMMENDATIONS FOR FUTURE SYSTEMS

Although the ALOFT system performed extremely well, there were some difficulties which should be taken into account if any new fiber optic systems are designed. Fiber-optic receiver circuits are susceptible to emi. Relays, which are a source of emi, should not be placed within the same avionics box with the receiver unless proper shielding of the relay and receiver is used. Power-supply lines going to the avionics units and to the receiver circuits should be well filtered at the avionic unit. For the same reason, source-driver circuits should be isolated from the receivers if both receivers and drivers are used in the same avionic box. This includes separate grounds if they are on the same card.

The ALOFT system included three analog signals. Two of the signals were converted to digital signals and transmitted over the fiber-optics cables. This method presented no problems. However, the direct analog link to the attitude direction indicator (ADI) did not work well. With this circuit, the analog signal was converted to an analog light signal and was transmitted over a fiber-optic cable. The required accuracy of the ADI was 5 percent. Over the temperature range from -54°C to 85°C, the accuracy of this analog link was only 50 percent (ref 13). This was because of the large change in light output of the LED with temperature. Also, whenever a fiber-optic cable was disconnected and then reconnected, the zero reading on the ADI converter unit had to be adjusted because of the small change in connector loss which took place during reconnection. An analog signal, in which the absolute signal level is important, is not well suited for transmission over fiber-optic cables unless it is converted first to a digital signal or unless adequate automatic gain control (AGC) is provided. These statements should not be construed to apply to video links using a modulated carrier frequency. These types of signals are well suited for fiber-optic transmission.

APPENDIX A

FIBER-OPTIC CABLE BREAKAGE

TABLE A-1. FIBER-OPTIC CABLE BREAKAGE, 367 FIBERS IN EACH CABLE.

External Cables	Breakage when made 12/19/75	After ground tests 3/24/76	Increase after ground tests
Armament Station Control Unit	40, 16	33, 70	47
Left Hand Bay	① 11, 25	60, 28	52
Right Hand Bay	51, 25	150, 70 ③	144
Forward-Looking Radar	30, 10	34, 43	37
Computer to bulkhead	45, 12, 14, 25, 14	18, 46, 40, 21, 26	41
Bulkhead to cockpit adapter	② 4, 5, 3, 7, 4	8, 8, 3, 9, 7	12

5% increase in breakage

Cables Repaired Before Installation:

External	After A/C Install. 3/24/76	After 72-hours of flight time, 8/12/76	Increase after 72 hours
Armament Station Control Unit	17, 32	17, 32	
Left Hand Bay	28, 23 ④	——, 23	5
Right Hand Bay	24, 25	24, 25	0
Forward-Looking Radar	44, 40	48, —— ⑤	4
Computer to bulkhead	28, 8, 21, 28, 17	28, 11, 21, 33, 20	11
Bulkhead to cockpit adapter	8, 13, 8, 6, 4	8, 19, 8, 6, 4	6

0.4% increase in breakage in 16 cables, 2 broken cables for a total of 18 cables.

① large number of breaks when made because ITT termination procedure.
② NELC made terminations.
③ One broken during tests at connector end.
④ One broken after installation at connector end.
⑤ One broken during flight tests after 72 hours.
⑥ Same as in ⑤, rebroken after 107 hours.

	After 107 hours of flight time 1/14/77	Increase since 3/24/76
Armament Station Control Unit	18, 36	5
Left Hand Bay	29, 33	11
Right Hand Bay	25, 28	4
Forward-Looking Radar	50, —— ⑥	6
Computer to bulkhead	22, 12, 33, 25, 40	30
Bulkhead to cockpit adapter	7, 20, 12, 8, 4	12

1.1% increase for 17 cables, one broken

APPENDIX B

ALOFT EMI TESTS

INTRODUCTION

Emi tests of the ALOFT system were performed to compare the emi susceptibility of the fiber-optic interface system to that of the wire interface system.

Two sets of RS02-type tests were performed in accordance with MIL-STD-461 and MIL-STD-462. The first tests were performed at the Vought Systems Ground Simulator Laboratory by LTV personnel. The bit error rate for each system was monitored during the tests and the results showed that the fiber-optic interface was much less susceptible to emi. The error rate for the fiber-optic system was less than 3.9×10^{-8} errors/bit (no errors detected in 2.6×10^{7} bits of data sent). The double-shielded, twisted-pair, wire interface had an error rate of 2×10^{-5} errors/bit (42 errors detected in 2.1×10^{6} bits of data sent) when exposed to the same emi levels.

The second series of tests were performed by personnel from McDonnell Aircraft Company. These tests were conducted while the system was installed in the A-7 aircraft at the Naval Weapons Center (NWC), China Lake, California.

It was not possible to monitor the bit error rate while the system was installed on the aircraft. As an alternative, the visual quality of the Head Up Display (HUD) and the Projected Map Display (PMD) was monitored. This was a gross method of measuring the system performance, and not a quantitative measure of the system error rate. During these tests, there was no noticeable degradation in the operation of the HUD and PMD displays when the system was in either the double-shielded, twisted-pair, wire interface, or in the fiber-optic interface configurations. However, a large error rate is required to produce a noticeable decrease in the quality of either of these displays. The same tests were then performed with one of the double shields of the wire interface disconnected. With only one of the wire shields connected, there was a significant decrease in the display quality of the wire-interfaced system. No decrease in the quality of the fiber-optic interfaced displays could be observed. These tests are described in detail in Appendix I of the McDonnell Douglas, A-7 ALOFT Economic Analysis, Final Report (ref 11).

TEST DESCRIPTION -- LTV BIT ERROR RATE TESTS

A software program was written at LTV to perform the bit error rate test on the ALOFT system. Figure B-1 shows the hardware set-up for the computer in the glass mode.
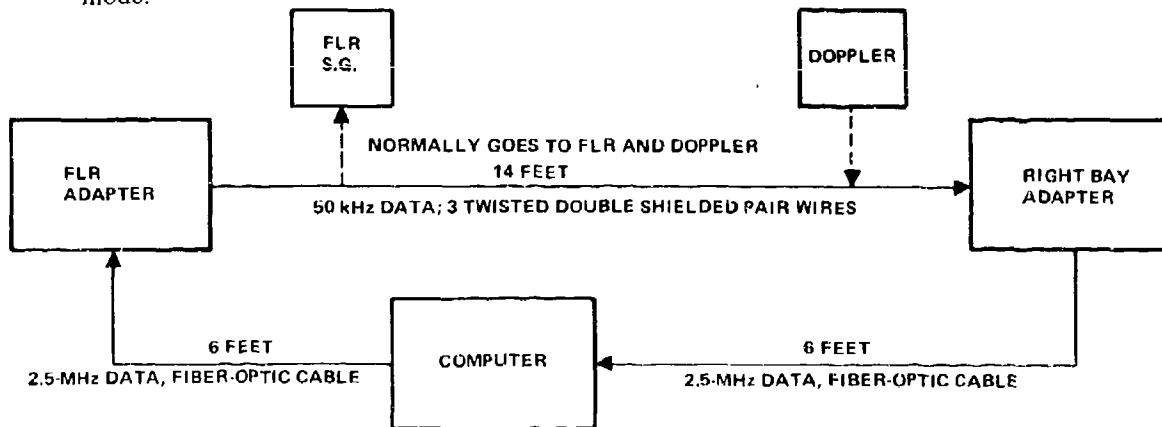

Figure B-1. Computer hardware set-up in glass mode.

In this mode, the computer sends and receives data over fiber-optic cables, using light signals. The TC 2 computer sends 64 different 16-bit words over a fiber-optic cable to the FLR adapter unit. This adapter converts the light signal to an electrical signal. Instead of outputting the data to the FLR sweep generator, as is done in the normal ALOFT configuration, the data are jumpered to the input and sent back to the computer. The computer then compares the received data with the sent data, and counts any error. This cycle is repeated until the desired number of bits are sent.

The system was checked first with no emi present. The program ran for 52 minutes with the computer sending 6.7×10^7 bits of data. No errors were detected by the computer. This represents a bit error rate of less than 1.5×10^{-8} errors/bit.

Next, a noise source was used to introduce emi onto the double-shielded, twisted-pair, wires. Test levels from RS02, in MIL-STD-461 and MIL-STD-462 were used, as shown in figure B-2.
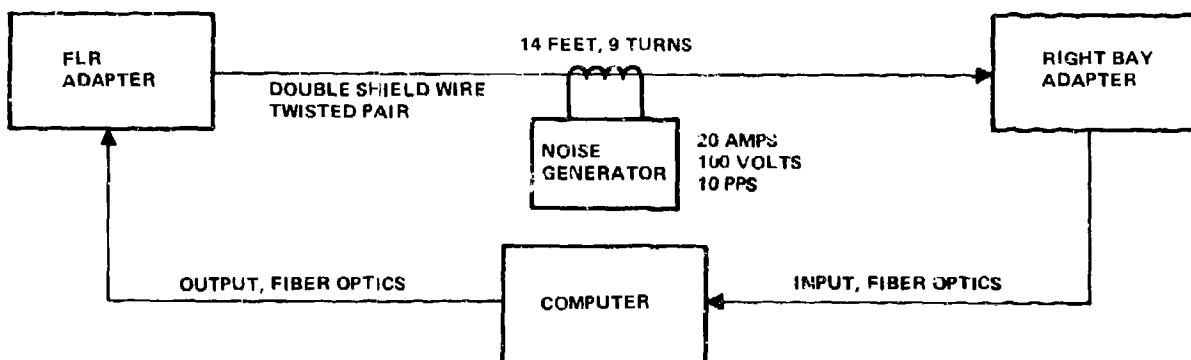
Figure B-2. Introduction of noise into double-shielded twisted-pair wires.

The program ran for 100 seconds with 42 errors in 2.1×10^6 bits. This represents an error rate of 2.0×10^{-5} errors/bit and demonstrates the susceptibility of wire to EMI.

To demonstrate the lack of susceptibility of fiber-optic cables, the test set-up in figure B-3 was used.
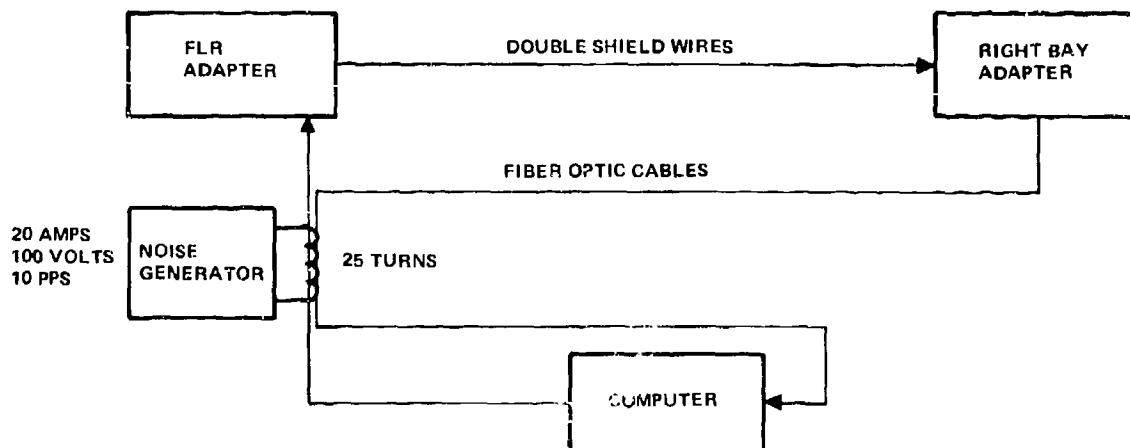
Figure B-3. Susceptibility test of fiber-optic cables.

An attempt was made to couple noise onto the fiber-optic cables. The computer program ran for 20 minutes with the emi source on. The total number of bits sent was 2.6×10^7. No errors were detected. This represents an error rate of less than 3.9×10^{-8} errors/bit. This test also verified that no noise was being conducted through the power lines in the wire test previously run. If there was conducted noise, errors would occur in the second test also. The noise was coupled only on the signal lines.

The final test was performed on the computer in the wired configuration, as shown in figure B-4.
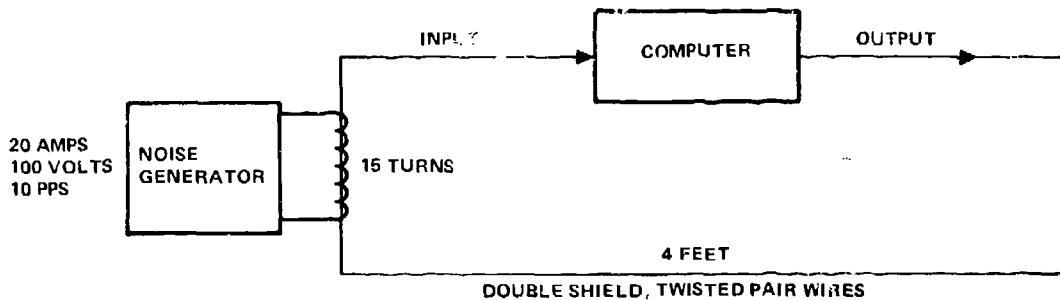
Figure B-4. Emi test of computer in wired configuration.

The computer was converted back to its original wire outputs. The computer output was jumpered to its input with double-shielded, twisted-pair wires. A noise source with the same test levels coupled emi into the wire.

APPENDIX C

THE ALOFT COST MODELS

INTRODUCTION

An economic analysis was conducted in parallel with the A-7 ALOFT test and evaluation effort. NELC coordinated the efforts of Naval Postgraduate School (NPS) personnel and McDonnell Aircraft Company (MCAIR) engineers in the determination of costs and benefits of fiber-optic and wire-interconnect systems. The NPS theses efforts were performed under the cognizance of Dr CR Jones and the MCAIR effort was managed by Mr GL Weinstock. These efforts are summarized in this paper.

The requirement for an economic analysis is defined in most program and planning documents. Economic analysis, as defined by the Defense Economic Analysis Council (DEAC) and as explained in DoD Instruction 7041.3 and DoD Directive 5000.28 as well as many others, is "the process which assists the decision maker in the allocation of resources through the determination of the costs and benefits of each future course of action." During the conceptual phase of a program, the chosen alternatives should be compared with total life-cycle costs and total benefits before a decision is made. All the risks and uncertainties should also be addressed prior to this decision.

The requirement for fiber optics was expressed fairly clearly in the Operational Requirement (OR), "Advanced Aircraft Electrical System (AAES)." Future threats dictate a need for an improvement in the quantity and quality of aircraft and their avionics. The threat to avionics must be met with a reduction in radio-frequency interference (RFI), electromagnetic interference (EMI), and electromagnetic pulse interference (EMP). In addition, there exists a need for a dramatic reduction in weight and volume. Coupled with these items is the desire for improved reliability, maintainability, availability, survivability, and capability. Other ORs and Scientific and Technical Objectives (STOs) have the same requirements. These stated requirements include the proven or expected advantages of fiber optics. The economic-analysis effort compared these desired benefits to other alternative wire-interconnect subsystems and, at the same time, determined the total life-cycle costs for each subsystem. Life-cycle costs are the total costs, directly or indirectly associated with an alternative during its development, acquisition and operational time frame.

COST ANALYSIS DEVELOPMENT

When this study began, it was assumed that a twisted-shielded-pair (TSP) wire-interconnect configuration could not meet the multiplexed data-rate requirements and would, therefore, not be evaluated. The economic analysis was developed to compare only a coaxial wire-interconnect configuration to a fiber-optic subsystem. The primary reason for this was that the engineering design would be the same for both alternatives and each alternative would meet the multiplexed data-rate requirements. However, after several meetings, it was determined that most aircraft companies prefer TSP to coaxial and would rather make extensive design changes to use TSP rather than coaxial. This study, then, became a comparison of three configurations: TSP, coaxial and fiber optics.

The coaxial, twisted-shielded-pair (TSP) and fiber-optic systems have components which are similar to equipment presently in use for multiplexed digital-data transfer systems and which have similar designs and functions. Due to the limited bandwidth capability of TSP, one of the fiber-optics (or coaxial) point-to-point connections in the ALOFT subsystem requires 2 additional TSP lines. Thus, the number of TSP wires is increased to 15 as compared to 13 fiber-optic (or coaxial) cables in the ALOFT configuration. It was assumed that the only changes to the ALOFT adapter boxes would be the addition of 2

line drivers and receivers to accommodate the additional TSP lines and that no internal adapter box design would be required. Figure C-1 is an overall diagram of the A-7 ALOFT interface configuration. Note the 2 additional lines between the modified navigation-weapon delivery computer and the cockpit-area adapter required for the TSP configuration.

The purpose of the A-7 ALOFT Economic Analysis Program was to develop valid cost estimates for performance-equivalent digital-data transfer systems utilizing conventional wire and fiber optics. The cost estimates were generated by an approach which utilizes 2 techniques: one which computes research and development (R&D), investment, and operating and support (O&S) costs for the fiber-optic and wire-interconnect data transmission subsystem ("Bottoms-Up" model); and another which computes total weapon system costs as a result of changes in weight of the respective subsystems ("Top-Down" model). The "Bottoms-Up" model outputs become one of the inputs to the "Top-Down" model which yielded the total life-cycle cost (LCC) results.

The "Bottoms-Up" model was designed to reflect the subsystem cost differences between the fiber-optic and wire-interconnect alternatives. The "Top-Down" model measured changes in weight which affected design options on aircraft LCC. The integration of the 2 models was conducted in the following manner and is illustrated in figure C-2:

1. Detailed subsystem LCC differentials for specifically designed data transmission subsystem were generated from the "Bottoms-Up" model;
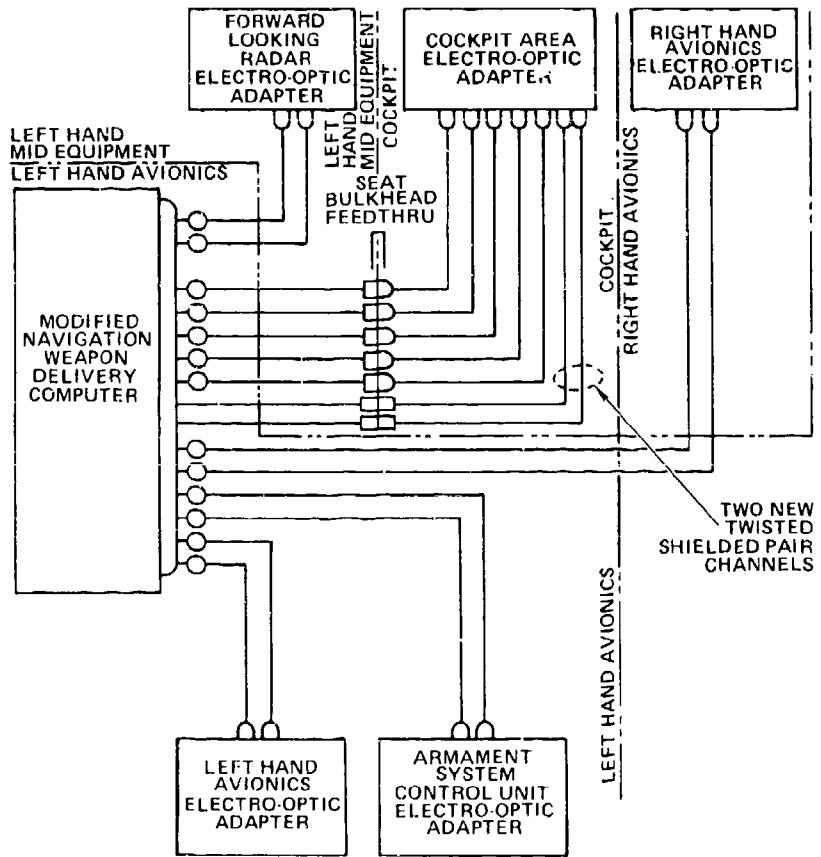
Figure C-1. A-7 ALOFT interface configuration.
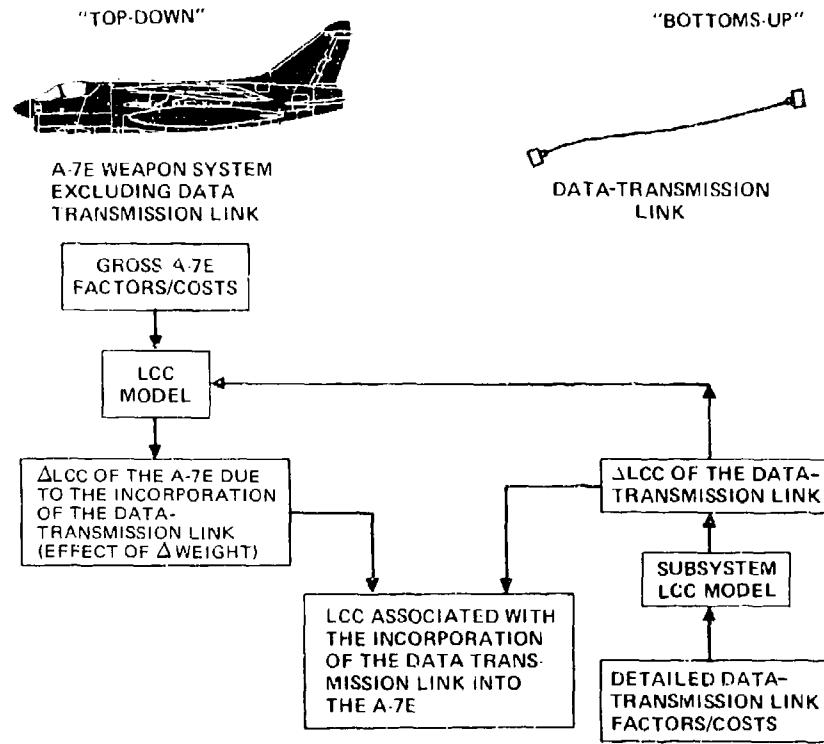
Figure C-2. Two-level LCC approac

2. The delta weight associated with a specific data transmission subsystem (relative to the baseline A-7 aircraft weights) was utilized to determine the change in total weapon system life-cycle costs through changes in the growth or shrinkage of the airframe, engine, etc, to support the respective changes in subsystem weight ("Top-Down" model); and

3. The results from these 2 models were then consolidated, tested for sensitivity, and evaluated to provide the total LCC for each alternative.

COST MODELS

"BOTTOMS-UP" MODEL

The Naval Postgraduate School began a directed research effort in July 1975 under the management of the Naval Electronics Laboratory Center with a thesis on the history, technology, and costing of fiber optics. This thesis was entitled "An Approach to the Estimation of Life-Cycle Costs of a Fiber-Optic Application in Military Aircraft," and was written by LCDR JM McGrath and LCDR KR Michna. The second effort, a follow-on, emphasized life-cycle cost elements and the development of a differential cost model. This thesis was completed by LCDR EW Knobloch and CDR RJ Johnson in December 1975 and

was entitled "The A-7 ALOFT Cost Model: A Study of High-Technology Cost Estimating." The final effort, completed in December 1976, comprises data collection, data analysis, and calculation of cost elements.

NELC had a requirement to obtain fiber-optic cost information and to develop an A-7 ALOFT Cost Model. Discussions with LCDR J Ellis of NELC, NPS professors and thesis students, identified the Navy problem to be undertaken by the students through a cooperative effort with NELC. The only financial commitment to these students to assist the A-7 ALOFT program was some travel and secretarial expenses. The first effort began with an Operations Research/Systems Analysis (OR/SA) 6-week experience tour at NELC by LCDR R Michna and thesis interaction by LCDR JM McGrath, a financial-management major. LCDR Michna and LCDR McGrath undertook the development of the history of fiber optics, studied the technology to provide a physical understanding of fiber optics for devising an LCC model, and formulated a cost-effectiveness study outline. This led to the challenge of developing a reliable life-cycle costing (LCC) method for a high technology.

Many difficulties arose in the LCC model development. No data base on production-unit costs existed other than those for model-shop work and prototype development. No cost models existed for component-level development such as cables and connectors and particularly the development of virgin-technology fiber optics. Other than in special medical usage and "toy" production, there was no demand for fiber optics and, therefore, no large-scale production. There was also no existing operational fiber-optic system. All these difficulties meant that standard analytical techniques could not be applied to the study and many uncertainties had to be considered.

Highlighting these difficulties in terms of future uncertainties is the showing that current research will lead to a rapid change in the technology base. A decision made at the wrong time would freeze technological design and later production. Such a decision would also create uncertainty in overall demand which, in turn, would impact upon cost. The design-freeze decision always provides a basis for performance uncertainty and directly affects schedule uncertainty. Therefore, the conceptual solution which alleviates some uncertainty is to consider only those costs which are relevant to the problem at hand. The basic decision is to look at nothing except the significant cost differences between coaxial (or wire-interconnect) and fiber-optic systems. These significant cost elements are presented as the NPS LCC "Bottoms-Up" model. The cost elements are separated into four major categories: Research Development Test and Evaluation (RDT&E), Investment (nonrecurring), Investment (recurring), and Operating and support. Each cost element is defined by an estimating equation which may be an existing cost-estimating relationship (CER), an engineering estimate, or a Delphi-structured estimate. This specialized life-cycle cost model was developed by LCDR E Knobloch and CDR R Johnson who are systems acquisition-management majors at NPS. This specialized model was extracted from a larger LCC model which is readily adaptable to other applications of emerging technologies designed to replace an existing technology. Application of this model has been undertaken by NPS students.

Tables C-1 through C-4 present the selected cost categories for the "Bottoms-Up" model with the cost elements underlined. Not all of the elements have costs for coaxial cable. However, a cost for each fiber-optic cost element was supplied by NPS. Initial results of these differential cost elements have been determined.

In fiber optics, data do not exist to establish firm technological, price, or demand trends. In this case, regression, sampling, smoothing, or other mathematical analyses are not applicable as a basis for forecasts. Hence, predictions must rely upon the opinions of experts.

TABLE C-1. RDT&E.

1.0	Research and Development
1.1.1	Contractor
1.1.2	Government
1.2.1.1	Program Management
1.2.1.2	Engineering
1.2.1.3	Fabrication
1.2.1.4	Contractor Development Tests
1.2.1 5	Test Support
1.2.1.6	Producibility Engineering & Planning
1.2.1.7	Data
1.2.1.7.1	Engineering Data
1.2.1.7.2	Support Data
1.2.1.7.3	Management Data
1.2.1.7.4	Technical Orders & Manuals
1.2.1.8	Peculiar Support & Test Equipment
1.2.1.10	General and Administrative
1.2.1.11	Fee
1.2.2.1	Program Management
1.2.2.2	Test Site Activation
1.2.3.3	Government

TABLE C-2. INVESTMENT (NON-RECURRING).

2.1.1	Program Management
2.1.3.1	Production Engineering
2.1.3.4	Manufacturing Support Equipment
2.1.4	Technical Support
2.1.5	Initial Spares and Repair Parts
2.1.6.3.2	Maintenance Training
2.1.6.3.3	Instructor Training
2.1.7.1	Engineering Data
2.1.7.2	Support Data
2.1.7.3	Management Data
2.1.7.4	Technical Orders & Manuals
2.1.10	Peculiar Support & Test Equipment
2.1.12	General & Administrative
2.1.13	Fee or Profit
2.2.1	Program Management
2.2.2.2	Training Devices & Equipment
2.2.2.3.2	Maintenance Training
2.2.2.3.3	Instructor Training
2.2.3	Production Acceptance Test & Evaluation

TABLE C-3. INVESTMENT (RECURRING).

3.1.1	Manufacturing
3.1.2.1	Purchased Equipment and Parts
3.1.2.2	Subcontracted Items
3.1.2.3	Other Material
3.1.3	Sustaining Engineering
3.1.4	Quality Control and Inspection
3.1.5	Packaging and Transportation
3.1.6.2	Site/Ship/Vehicle Conversion
3.1.6.3	Assembly Installation and Checkout
3.1.8	General and Administrative Costs
3.1.9	Fee or Profit

TABLE C-4. OPERATING AND SUPPORT COSTS (O&S).

4.1.6	Other Operations Costs
4.2.1.1.1	Organizational Maintenance Personnel
4.1.1.1.2	Intermediate Maintenance Personnel
4.1.1.1.3	Depot Maintenance Personnel
4.2.1.2	Maintenance Facilities
4.2.1.3	Support Equipment Maintenance
4.2.2.1.1	Organizational Supply Personnel
4.2.2.1.2	Intermediate Supply Personnel
4.2.2.1.3	Depot Supply Personnel
4.2.2.2	Supply Facilities
4.2.2.3	Spare Parts and Repair Material
4.2.2.4.1	Inventory Management
4.2.2.4.2	Inventory Holding
4.2.2.5	Transportation and Packaging

Delphi, as a technological forecasting technique, is generally credited to Olaf Helmer, TJ Gordon, and NC Dalkey of the RAND Corporation. Initial work was done by Helmer as early as 1959. Helmer's publication of a "Report on a Long-Range Forecasting Study" by the RAND Corporation, in 1964, discussed the Delphi technique in detail. In his report, he describes his now well known method of soliciting forecasts from a panel of experts in order to deal with specific questions, such as when a new process will gain widespread acceptance or what new developments will take place in a given field of study. Instead of the participants gathering together to discuss or debate the questions, they are kept apart, usually answering assigned questionnaires through written or other formal means, such as on-line computers.

There are, of course, several advantages and disadvantages to any technique which employs questionnaires for objective evaluation. The Delphi was considered an appropriate technique to estimate the fiber optics costs for the following reasons:

1. Fiber optics is an emerging technology which is fraught not only with technological uncertainties, but also total demand uncertainty. In addition, there are component price uncertainties;

2. The experts in the fiber-optics industry can be easily identified;

3.   Users and producers alike can benefit from the results of a Delphi study. It is to their mutual advantage to cooperate in efforts to realize the potential benefits of this emerging technology; and

4.   Improved forecasts or estimates of future demand quantities, industry growth rates, technological advances and component prices are expected to decrease the range of the estimates for these variables. As a result, the number of scenarios to be developed can be fewer since the range of estimates is smaller.

Initial cost data were gathered with the use of Delphi questionnaires for fiber-optic, life-cycle cost elements. Appropriate Delphi questionnaires were distributed both to aircraft and fiber-optic manufacturers. Telephone and personal interviews were then conducted with manufacturers and other organizations, as appropriate, to finalize the data collection. From the data-collection effort, cost factors were calculated for the fiber-optic cost elements. These cost factors are summarized in table C-5. Except where noted, the cost factor is the ratio of the fiber-optic cost relative to the cost of "equal-functions" performance if coaxial cables are used. The coaxial subsystem costs are based upon the component types and quantities specified in NELC Technical Document 435. An example of the cost factor can be explained by observing the cost element number, 1.2.1.2, Design Engineering. The cost factor value of 0.80 signifies that the estimated aircraft design-engineering cost for electrical subsystems using fiber-optics technology would be only 80 percent of the design-engineering cost using coaxial-cable technology. For some cost elements, where coaxial costs are not applicable, the fiber-optics costs are estimated actual dollar values.

Besides the Delphi Technique as a forecasting tool to predict future costs, experience-curve theory was also used as a forecasting technique to estimate the future cost behavior of fiber-optic components. Experience-curve theory should not be confused with the well-known learning curve theory. Learning curve theory predicts cost reductions for 2 cost factors, labor and production inputs (material) whereas experience-curve theory predicts cost reductions for all cost elements including labor, development, overhead, capital, marketing, and administration. Experience-curve theory is a much broader concept which incorporates learning-curve theory. To facilitate the development of experience-curve theory, the following discussion explains both theories noting their similarities and differences.

Both the experience-curve and learning curve theories are expressed as cost-quantity relationships stating that, each time the total quantity of items produces doubles, the cost per item is reduced to a constant percentage of its previous cost.

The history of learning-curve theory dates back to 1925 when, in the aircraft industry, learning patterns were first observed by the Commander of Wright-Patterson Air Force Base. The phenomenon observed was the constant reduction in direct labor hours required to build airplanes as the number of aircrafts being built doubled. Subsequently, learning-curve theory has been documented and used in many industries to predict cost reductions for direct labor and raw material or production inputs. Typical learning-curve slopes have ranged from 75 to 90 percent. Some of the factors commonly mentioned that account for direct labor and material cost reductions are summarized as follows:

1.   Job familiarization by workmen. This results from the repetition of manufacturing operations;

2.   General improvement in tool coordination, shop organization, and engineering liaison,

3.   Development of more efficiently produced subassemblies; and

4.   Development of more efficient tools.

TABLE C-5. TABULATION OF DIFFERENTIAL COST ELEMENTS.

COST CATEGORY	COST ELEMENT NO.	COST ELEMENT DESCRIPTION	COST FACTOR
RDT&E	1.2.1.2	Design Engineering Cost	0.80
	1.2.1.3	Fabrication Cost (Test Aircraft)	0.95 (Labor) 1.05 (Material)
	1.2.1.4	Development Test Costs	$100,000
	1.2.1.5	Test Support Costs	$100,000
.	1.2.1.8	Test Equipment Costs	$100,000
Non-Recurring Investment	2.1.5	Initial Spares and Repair Costs	0.83
	2.1.6.3.2	Maintenance Training (Contractor)	$4,000
	2.1.10	Peculiar Support Test Equipment	1.30
	2.2.2.2	Training Devices Costs	2.00
	2.2.2.3.2	Maintenance Training (Government)	$8,000
	2.2.2.3.3	Instructor Training (Government)	$8,000
Recurring Investment	3.1.1	Manufacturing Costs	0.80
	3.1.2.1	Purchased Equipment & Parts	0.83
	3.1.3	Sustaining Engineering	0.80
Operating & Support	4.2.1.1.1	Organizational Maintenance	0.80
	4.2.1.3	Support Equipment Maintenance	0.80
	4.2.2.3	Spare Parts & Repair Material	0.50
	4.2.2.4.1	Inventory Management Costs	1.60

Experience-curve theory dates back to 1965*. Experience-curve theory is much broader in scope than learning-curve theory. It considers the full range of costs which include development, capital, administration, marketing, and overhead, as well as labor costs. Raw-material cost is not included in this list. The cost of raw materials usually depends upon factors such as the availability of supply. For example, the price of unprocessed lumber fluctuates from year to year partly as a result of Federal policy concerning the nation's timber reserves. Strictly speaking, correct measurement of the experience effect, therefore, requires that expenditures be calculated net of the cost of raw materials, ie, on value added to the product. In general, experience curves do not apply if major elements of cost, or price, are determined by patent monopolies, natural material supply, or government regulation. The experience curves apply to products in industries with multiple producers who interact as rivals as well as to other products in purely and perfectly competitive industries.

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* Experience curve theory is primarily credited to Mr Bruce Henderson, founder and president of Boston Consulting Group, Inc, a management consulting firm specializing in developing corporate strategy.

The factors, identified by the Boston Consulting Group, that cause the experience curve effect include:

1. The "learning curve effects"

2. Competition (rivalry) among producers in a given product market;

3. Economies of scale and specialization, the "scale effect;" and

4. Investment in capital to reduce cost and increase productivity.

The learning effect, people learning by doing, has already been discussed in learning-curve theory and is the major factor which causes reduction in labor costs. The second factor, competition (rivalry) among producers, forces each producer to find means of lowering his total average costs in relations to his competitors. The successful low-cost producer will then be able to lower his prices and induce a situation which causes a "shakeout" of those producers who have been unsuccessful in reducing costs. This will give the low-cost producer an increased market share. With increased market share, the third factor, economies of scale, can be realized. With scaled-up volume due to increased market share, it is possible to use more efficient tools and spread their cost over enough units so that both labor and overhead costs are reduced. Increased volume may also make it possible to consider alternative materials and alternative methods of manufacture and distribution which are uneconomic on a small scale. The final factor, investment in capit.l, is a further attempt to reduce cost by displacement of less efficient factors of production. This can be accomplished by automating various stages of production, thus reducing labor costs.

Thus, experience-curve theory predicts cost reductions based on all cost inputs. Experience-curve theory means that present costs from industry of components in full-scale production can be expected to reduce by a fixed percentage of previous cost with each doubling of industry's production volume. Past costs of fiber-optic cable, which constitutes only one of the required building blocks to build interface systems, indicate that the experience curve slope will be between 70 and 80 percent (see figure C-3).
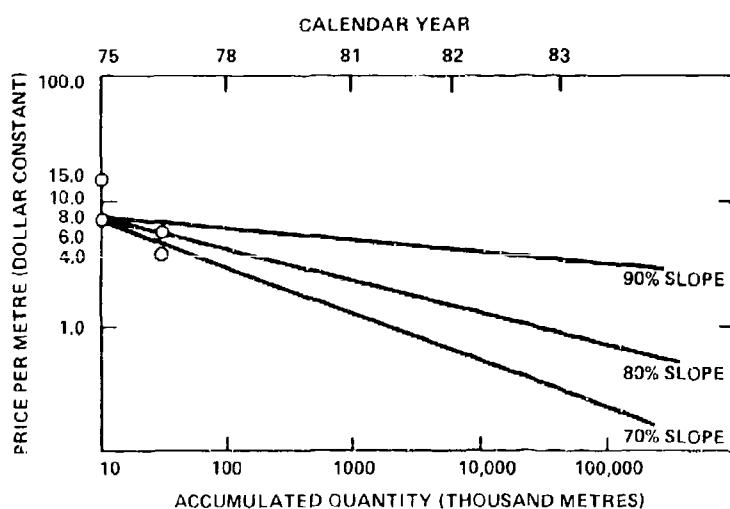

Figure C-3. Fiber-optic cable experience curves.

This means that future cost of the required fiber-optic components, which will be determined by the demand placed on industry, should be reduced to 80 percent of the previous cost as industry's production volume doubles. Figures C-4 and C-5 are current cost-prediction curves of two fiber-optic components compared to coaxial-component counterparts. The fiber-optic component costs are actual dollars, including inflation.

The costs of the hardware, such as the fiber-optic cables and connectors, are only the acquisition costs. Having only future acquisition costs of the fiber-optic components does not provide an adequate cost evaluation. It has been determined, through previous studies, that between 70 and 80 percent of total costs incurred on a program are those for operating support. Figure C-6 gives an estimated life-cycle cost breakdown based on DoD
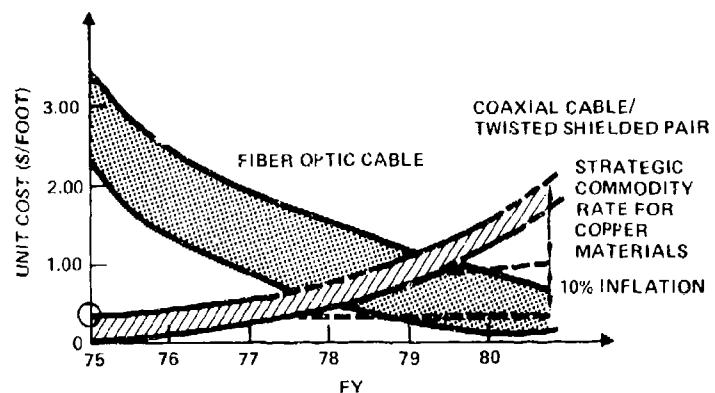

Figure C-4. Cost prediction curve: cables.
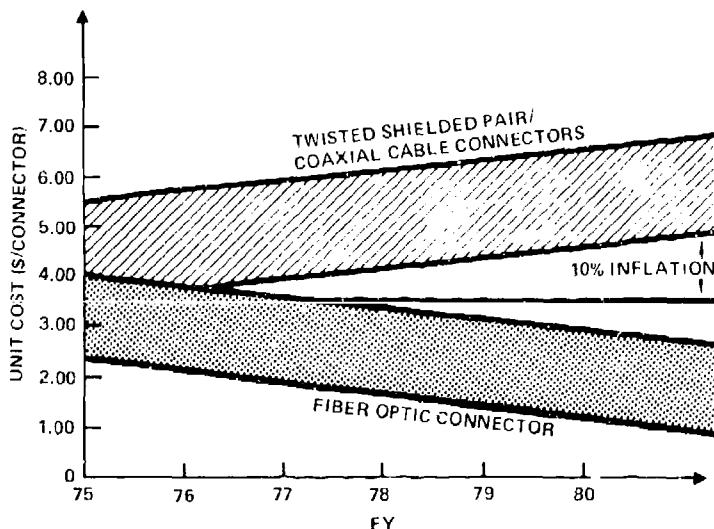
Figure C-5. Cost prediction curve: single-channel bulkhead connectors.

31
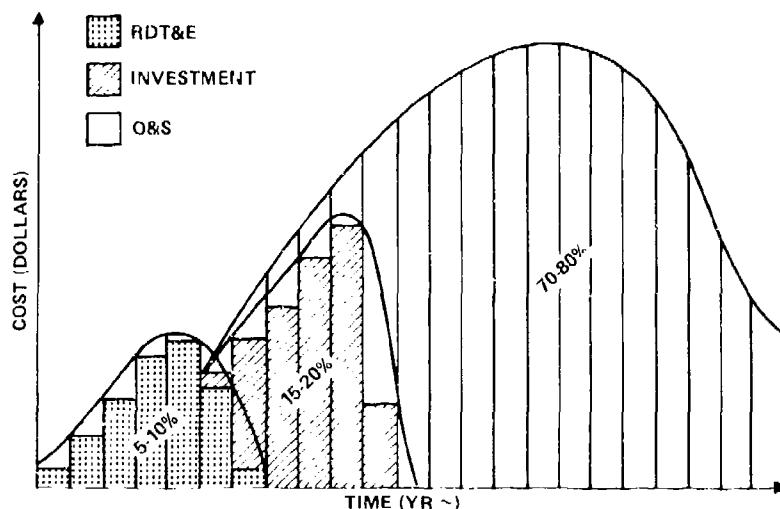
Figure C-6. Total life-cycle costs.

expenditures. It is, therefore, important that all life-cycle costs be estimated from research and development through acquisition to operation and maintenance for the life of the system in order to more accurately represent actual costs. The 3 principal factors of life-cycle costing are estimated unit-production costs, estimated reliability, and assumed manpower costs. There must be a conscious recognition of the need and prediction of these factors in production, reliability, and logistic-support analysis if life-cycle cost credibility is to improve.

"TOP-DOWN" MODEL

The second major effort undertaken was the definition, quantification, and evaluation of system effectiveness. In other words, the determination of what benefits are received for the dollars expended. The comparison of total costs of each alternative subsystem meets only half the requirements for an economic analysis. Benefits such as improved mean-time-between-failure (MTBF) and mean-time-to-repair (MTTR) may result from one alternative or the other. Immunity to EMP, EMI, or RFI may also be achieved by one alternative. Signal-bandwidth capacity may be increased, cable redundancy may be improved, weight and volume may be reduced, and many more benefits may be achieved. Each of these effectiveness parameters must be quantified, ranked, verified, and revised in terms of cost offsets and levels of attainment. An advanced-concept cost model estimates costs and benefits as functions of design and weight requirements while air-superiority mission analysis determines the availability, reliability, survivability, maintainability, and capability which relate to system effectiveness, which again relate to cost.

An individual mission analysis accounts for state variability transitions resulting from changes in dependability and survivability with time (mission phase) from takeoff and climb-out through penetration of hostile territory. Aircraft single-mission capability is assessed based upon the values of the state variables at the start of combat. The aircraft-state vector, upon return to base, determines the maintenance, servicing, and battle-damage repair required to put the aircraft in a ready state. This is the "Top-Down" approach of an effectiveness model which quantifies the effectiveness parameters and relates them to total cost.

32

Figure C-7 illustrates the analysis methodology used on a typical air-superiority mission. Certain combinations of equipment failure permit degraded modes of operation (not requiring an abort but also not operating in an "all-up" condition). The mission is divided into phases, and state transitions take place from phase to phase based upon dependability (equipment failure) or survivability (combat damage). Dependability and survivability transition matrices are generated from detailed considerations of failure rates and combat battle-damage rates for aircraft equipment, subsystems, and components. Failure rates and degraded modes of operation are derived from reliability analyses. Combat battle-damage rates account for aircraft component vulnerabilities to specific threats, both nuclear and nonnuclear, and the specific threats to be encountered during each mission phase. System capability, during the combat phases, determines the result in terms of enemy kills and friendly damage or loss. In addition to the various degraded modes which can result from failures and battle damage, combat capability also reflects differences in aircraft weights. Thus, the anticipated increased weight to achieve a specified level of shielding for a coaxial avionics system as opposed to a fiber-optic configuration would result in decreased combat capability. When the aircraft returns to base, its availability for the next mission is determined by the expected ground-time portion of the dependability-transition matrix, which depends upon the component failures and damage experienced during the mission and the required times for combat-damage repair, unscheduled-maintenance repair, and turnaround and scheduled maintenance times. Thus, these effectiveness factors are assumed to be equal and only the changes in aircraft weight due to a proportional change in electrical subsystem weight effect changes in life-cycle costs.

In order to relate the effectiveness factors into some quantifiable measures, a direct cost relationship approach is applied. Figure C-8 presents the relationship of the "ilities" to sortie rate. To calculate these values, a scenario must be developed to establish equal level-of-effectiveness ground rules. The basic aircraft strike missions are defined to determine a required sortie rate, aircraft attrition rate, probability of mission success, and EMI, EMP, and RFI conditions. The aircraft availability must equal the required sortie rate which, in turn, affects ground-support costs per sortie. The system's reliability affects inflight failures which in turn affect mission success and thus increases or decreases the total sorties. How susceptible the aircraft is to enemy action determines the probability of mission completion and probability of mission survival which again increases or decreases sortie rates. These factors determine the capability of mission effectiveness under equal effectiveness conditions. These summarize into a specified sortie rate which relates to operation and support costs which are measurable benefits.

This "Top-Down" model involved changes in aircraft size which resulted from possible weight savings that occurred when fiber optics was used or the possible weight increases caused by increased wire and airframe shielding required to meet performance requirements. The "Top-Down" model included cost categories normally used with the Advanced Design Level (ADL) studies at McAir for making projected weapon-system cost estimates.

The electrical subsystem weight-analysis phase of the cost-benefit evaluation was executed by parametrically increasing and decreasing the electrical subsystem weight of the basic A-7 aircraft to illustrate the effect upon weapon system costs.

The relationship of RDT&E costs to electrical subsystem weight is shown in figure C-9. Because the baseline cost was so large (1 016 988 millions in constant 1977 dollars), the cost deltas for ±50 kg were proportional to the weight. The RDT&E cost delta was linear over this range of weights. The slope of the cost delta is 1.716×10^5 per kilogram.
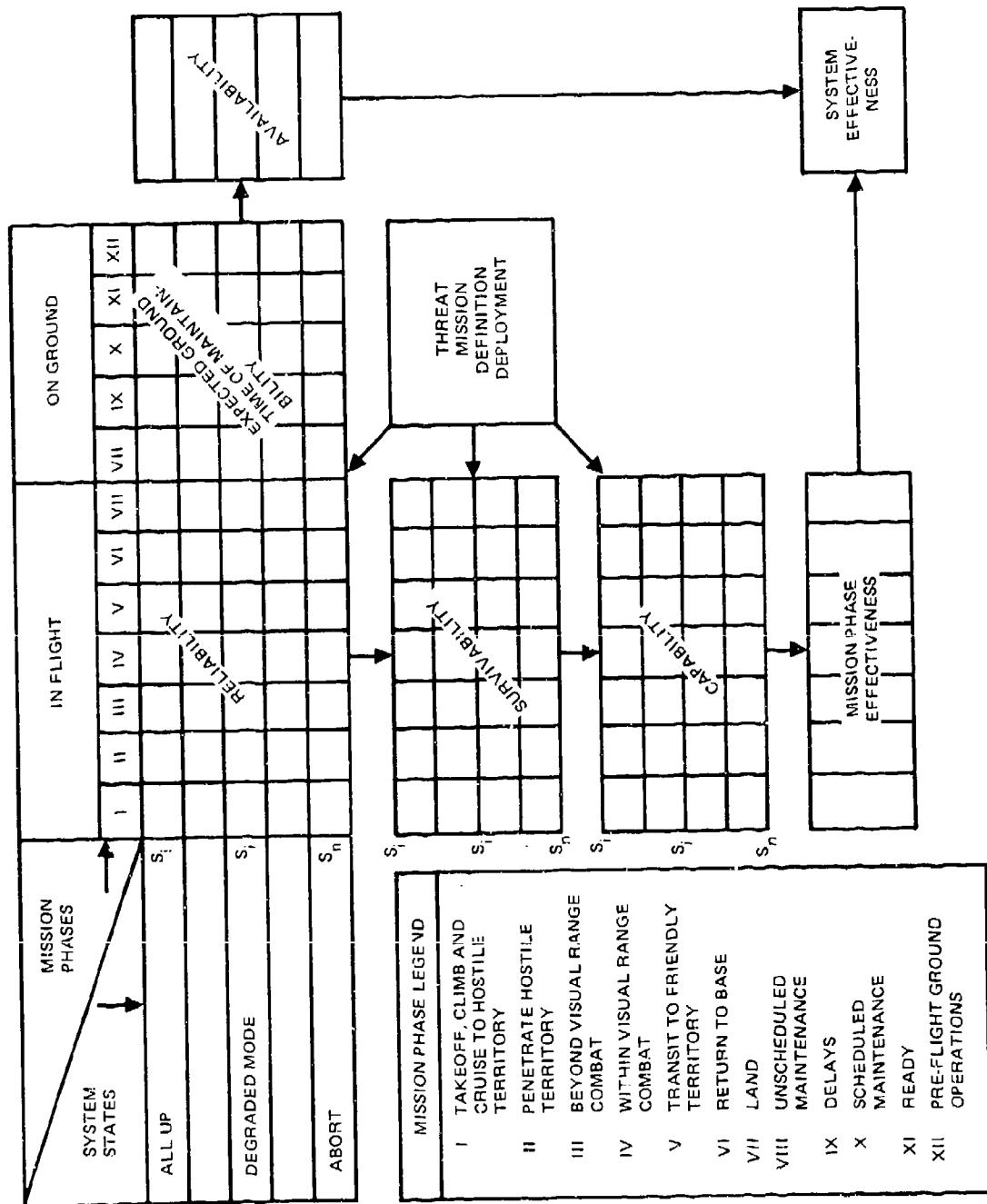
Figure C-7. Air-superiority mission analysis.

34
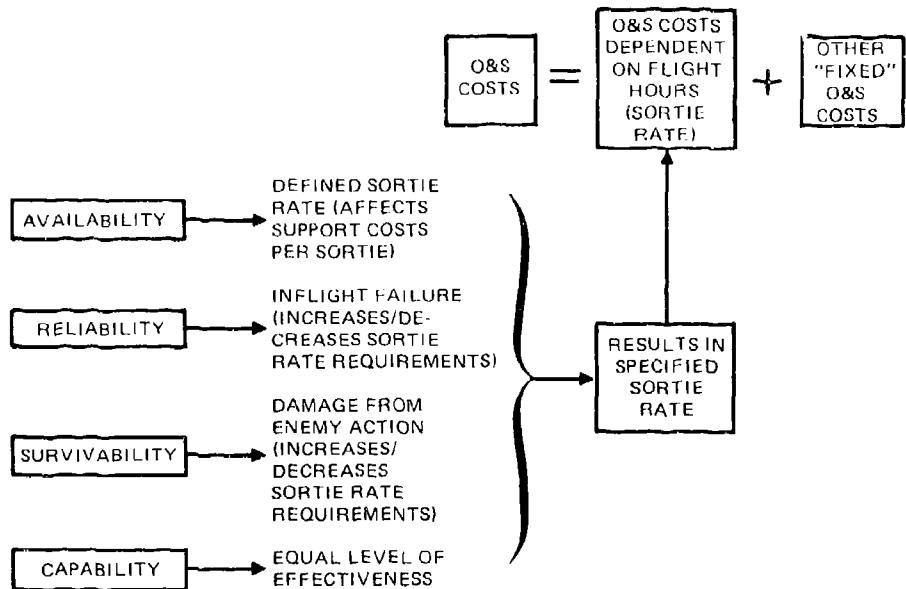
Figure C-8. Consideration of effectiveness factors.

The procurement cost delta was computed from the baseline cost for 800 aircraft of 4 260 198 millions in 1977 dollars. Performing the same type of calculations as previously discussed, yields the results shown in figure C-10. The cost delta was again linear. The maximum positive delta was 47 millions for the addition of 50 kilograms, while the reduction of 50 kilograms results in a negative delta of 47 millions.

It should be noted that the cost delta shown for procurement included the cost delta shown for Flyaway and that all the spares were included in procurement costs. The slope of the procurement cost delta is 9.6×10^5 per kilogram.

The cost delta associated with the effect of electrical subsystem weight upon operating cost is shown in figure C-11. The baseline operating cost for 675 aircraft for 10 years is 6 182 194 millions in 1977 dollars. The cost delta was piecewise linear and has a slope of 6.05×10^5 per kilogram. The step in the cost delta between –20 and –30 kg was a consequence of the structure of the "Top-Down" model. Integer squadron maintenance staffing was assumed, and realistically so. Thus, at a given input level, staffing must increase or decrease by one unit which was reflected as a substantial increase or decrease of cost delta over the life-cycle of the aircraft.

Figure C-12 is a summation of cost deltas which results in the total life-cycle cost delta for the aircraft due to electrical subsystem weight variations. The plot was piecewise linear with a slope of 17.22×10^5 per kilogram.

An initial utilization of these weight sensitivities was applied to the three alternative subsystem component weights. The fiber-optic subsystems weights were based upon projected weight estimates of future components. The total weights included the cable, connectors, and signal drivers and receivers for the complete NWDS subsystem. The estimated total weight for the fiber-optic subsystem was approximately 0.87 kilogram. The coaxial subsystem weight, as defined in NELC TD 435, was 1.3 kilogram which is a delta weight increase of approximately 0.43 kilogram over the fiber-optic subsystem. The weight

35

(1977 $100 000)

($1.716 · 10⁵/KG)
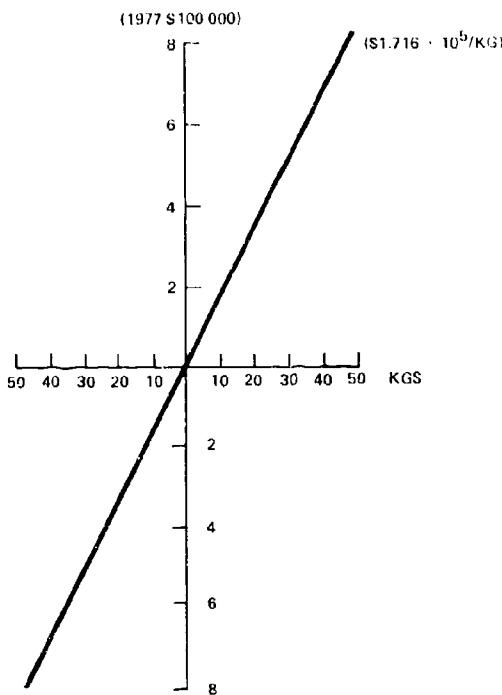
Figure C-9. RDT&E cost deltas for electrical
subsystem weight sensitivity.

(1977 $ 1 000 000)

($9.46 · 10⁵/KG)
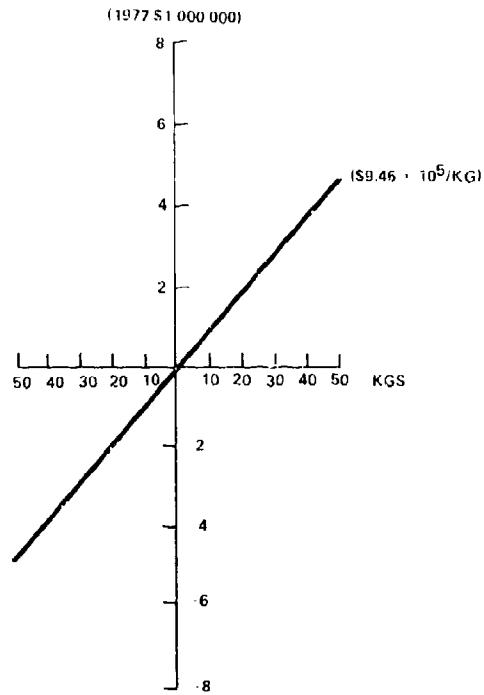
Figure C-10 Procurement cost deltas for electrical
subsystem weight sensitivity.

(1977 $; 1 000 000)

NOTE: SPARES ARE INCLUDED
IN PROCUREMENT
COSTS

($6.05 > 10⁵/KG)
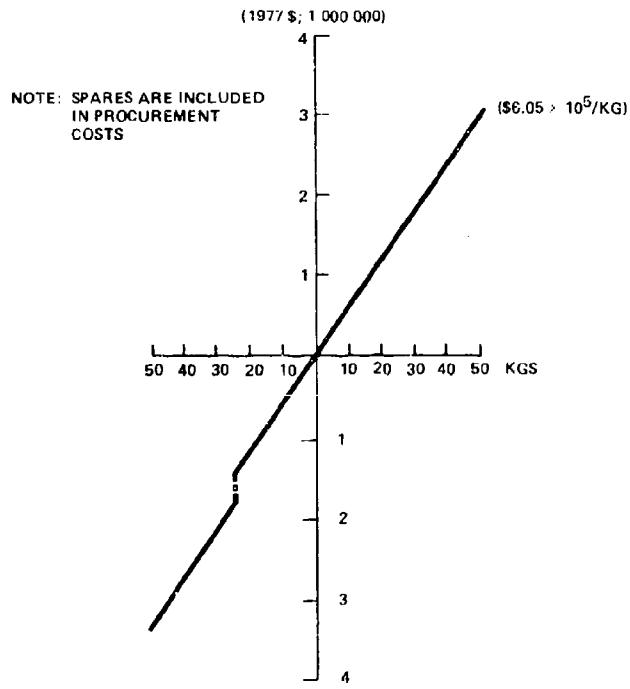
Figure C-11. Operating cost deltas for electrical
subsystem weight sensitivity.

(1977 $; 1 000 000)

($17.22 × 10⁵/KG)
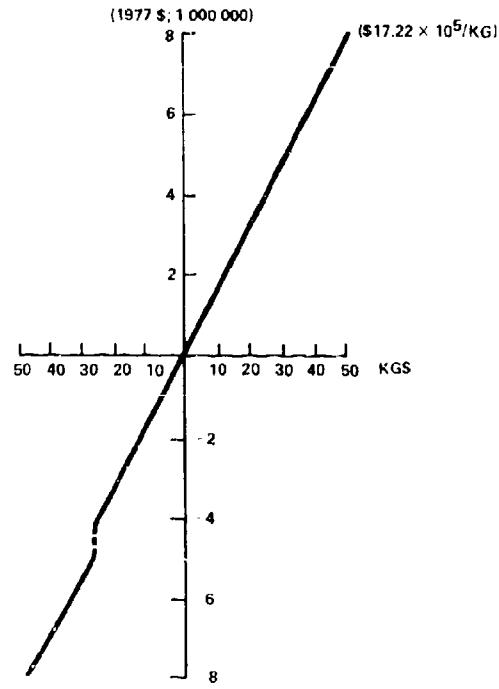
Figure C-12. Total life-cycle cost deltas for electrical
subsystem weight sensitivity.

of the twisted shielded-pair subsystem as designed by the McDonnell Aircraft Company, was 1.91 kilogram which is a delta weight increase of approximately 1.04 kilogram over the fiber-optic system.

COST RESULTS

Few books have been written on the subject of cost estimating in new technologies, but each warns of the potential problems and hazards faced by anyone venturing into a new field looking for nonexistent data. Cost data in the field of fiber optics are no exception; they exist today only in limited amounts and many times are considered as proprietary.

The field of fiber optics today is infantile and the future is speculative at best. There is no high demand for quality fiber-optic cable nor associated fiber-optic components. Fiber-optic cable and component manufacturers have been unable to establish a production base upon which to project (predict) future prices. Users and potential users of fiber-optic technology have only a minimal data base upon which to build and expand their fiber-optic applications.

Extensive research and development were required to establish both a high demand for quality fiber-optic cable/components and the production base necessary to reduce the cost of such items. As additional uses for fiber-optic technology are discovered and fiber-optic cable/component manufacturers strive to reduce manufacturing costs, available cost data will become more accurate.

Table C-6 provides a breakdown of total costs nondiscounted for the major LCC categories. Only RDT&E costs are greatest for fiber optics over the 2 alternative wire configurations. Also shown in table C-6 are the optimistic and pessimistic costs of the fiber-optic subsystem. The sensitivity analysis utilized to determine these cost variations was devised by estimating errors in market forecast demands, uncertainties in RDT&E costs, and reliability and maintainability risks. The pessimistic fiber-optic costs are based on worst-case estimates from the Delphi study of RDT&E costs increasing by an additional 3/4 million, fiber-optic components costing twice that of most likely estimates, and labor costs being increased 1.5 times that of the most likely estimates. The optimistic fiber-optic cost estimates are based upon the assumptions that very little additional R&D is required, large production demands reduce component procurement costs, and improved support and fabrication equipment reduce labor costs.

TABLE C-6. "BOTTOMS-UP" MODEL LIFE-CYCLE COSTS.
(Constant 1977 dollars, millions)

	Pessimistic	Fiber Optics Most Likely	Optimistic	Coaxial	ı ı
RDT&E	$ 1.07	$ 0.32	$ 0.17	$ 0.02	$ 0.02
Investment (Nonrecurring)	0.52	0.46	0.40	0.46	0.60
Investment (Recurring)	0.52	0.46	0.40	0.57	0.78
Operation & Support	0.14	0.13	0.12	0.19	0.24
Total Life Cycle Cost (Current 1977 dollars)	$ 2.25	$ 1.37	$ 1.09	$ 1.24	$ 1.64

The "Top-Down" model results for the A-7 ALOFT configurations are summarized in table C-7. The weight deltas are derived from the original baseline system. The cost offsets shown result principally from the ability to "shrink" the size of the aircraft. For example, 1-kilogram weight reduction in the electrical subsystem yields a 3-kilogram weight reduction in the aircraft. Thus, less labor and material are required to build the aircraft, simpler design parameters are required to develop the aircraft, and the aircraft is easier to maintain, uses less fuel and provides a smaller target signature while maintaining the same performance characteristics. The delta life-cycle costs for coaxial and TSP over fiber optics amount to $730 thousand and $1.79 million, respectively.

In order to evaluate these benefit deficiencies or cost offsets with the differential costs developed in the "Bottoms-Up" model, the costs must be allocated by year for discounting to present worth. The "Top-Down" model has provided this percentage breakdown, as shown in figure C-13 by year from 1977 to 1993 for RDT&E, procurement, and operating costs. However, discounting and escalating the life-cycle cost have no impact upon the ranking of the alternatives.

Adding these cost deficiencies ("Top-Down" and "Bottoms-Up" results) the initial cost/benefit evaluation of the A-7 ALOFT fiber-optic subsystem and the 2 alternative wire-interconnect subsystems was determined. Figure C-14 shows the cumulative cost/benefit evaluation of the A-7 ALOFT N/WDS configurations. Also shown in the figure are the minimum and maximum sensitivity parameters for the fiber-optic subsystem. These results clearly indicate that the fiber-optic subsystem is superior to the TSP subsystem no matter what the future conditions may be. It is also evident that, at a 90-percent confidence level, the fiber-optic system is more beneficial than the coaxial. This graphical representation is divided into the three major cost categories: RTD&E, Investment, and Operation and Support.

The primary benefit from the use of fiber optics in military aircraft was the inherent noise immunity and the resulting reduction in EMI preventative measures which accompany conventional wired systems. These EMI sources were categorized into man-made, nuclear electromagnetic-pulse, and atmospheric environments. Man-made electromagnetic sources

TABLE C-7. "TOP-DOWN" MODEL LIFE-CYCLE COSTS.

|		Baseline	Coax	TSP	Fiber-Optics
	Weight (kg)	14.5	1.298	1.910	0.868
	Δ Weight	0	-13.202	-12.590	-13.632
Life-cycle Costs (1977 $, millions)	RDT&E	0	- 2.270	- 2.160	- 2.340
	Proc	0	-12.490	-11.910	-12.890
	D&S	0	- 7.990	- 7.620	- 8.250
	LCC baseline	0	-22.750	-21.690	-23.480
	LCC fiber-optic	+23.480	+ 0.730	+ 1.790	0
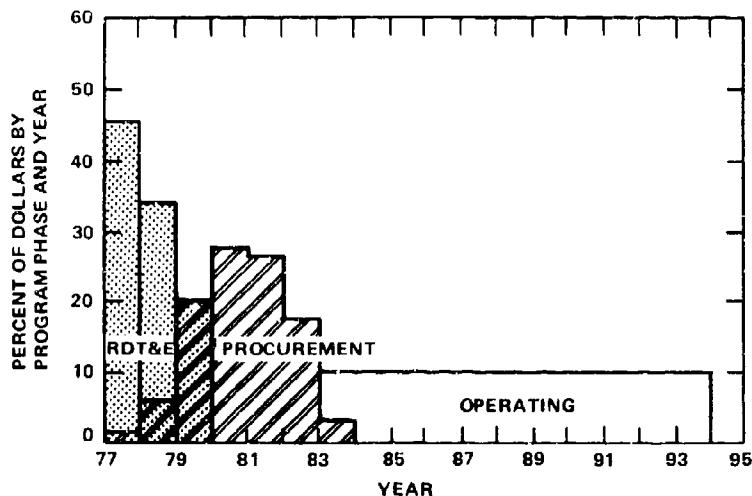
Figure C-13. Relative cost allocation versus time, constant-year dollars.
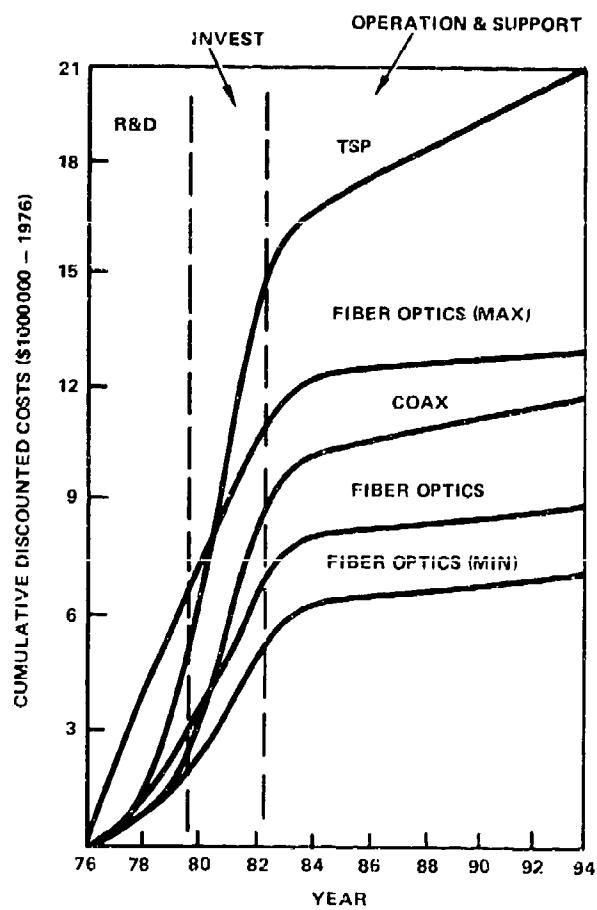
Figure C-14. Cost/benefit, evaluation of A-7 Aloft N/WDS configurations.

39

include ground-based emitters which are generally remote from aircraft operations such that induced power levels are near or below 100 volts per metre, and shipboard emitters which induce power levels on the aircraft surface from 200 volts per metre to above 10 000 volts per metre depending upon the transmitter involved and the proximity of the aircraft to the transmitter of interest. Typical EMI-reduction techniques involving interconnect wiring are interface design, filtering, transient suppression, shielding, bonding, and grounding. The use of fiber optics instead of wire reduces or eliminates the need for some or all of these EMI techniques.

The cost/benefit evaluation results (tables C-8 and C-9) indicate cost offsets for TSP versus fiber optics at approximately 4.75 million dollars in total life-cycle costs when aircraft carrier EMI criteria were met. For coaxial versus fiber optics, a 10 million dollar total cost offset could be achieved with fiber optics under the same EMI conditions. The cost offsets were even greater in a tactical EMP environment. The TSP subsystem would yield a 6 million dollar life-cycle cost increase over the fiber-optics subsystem due primarily to the filtering, double shielding, and interface. Coaxial could be as high as 11.5 million dollars over fiber optics under the same EMP conditions. Therefore, fiber optics has not only proven itself as a feasible technology but also appears to be very economical as well in terms of total life-cycle costs and future benefits.

TABLE C-8. A-7* NWDS COST/BENEFIT EVALUATION FOR
AIRCRAFT CARRIER EMI REQUIREMENTS (IN MILLIONS).

	Fiber Optics	COAX/TRIAX	TSP/TDS
RDT&E	$ 0.32	$ 0.93	$ 0.47
Investment	0.92	6.90	3.79
O&S	0.73	3.58	1.85
Total (1977 dollars)	1.37	11.41	6.11

* based on a production of 800 aircraft and assumed 675 operationally ready.

TABLE C-9. A-7* NWDS COST/BENEFIT EVALUATION FOR
A TACTICAL EMP ENVIRONMENT (IN MILLIONS)

	Fiber-Optics	COAX/TRIAX	TSP/ Double Shield
RDT&E	$ 0.32	$ 1.05	$ 0.61
Investment	0.92	7.82	4.56
O&S	0.13	4.02	2.29
Total (1977 Dollars)	1.37	12.89	7.46

* based on a production of 800 aircraft and assumed 675 operationally ready.

The following tables provide the total cost/benefit evaluation results for the different alternative configurations of the A-7 aircraft. Tables C-10 through C-12 provide cost/benefit results for a full-multiplexed A-7 aircraft, and table C-13 considers only those circuits critical to the completion of the mission of the aircraft. Tables C-14 through C-16 compare total costs for 100 point-to-point lines in the A-7 aircraft. Tables C-17 through C-19 present the results of the data-bus configuration. More detailed data may be found in reference 12.

TABLE C-10. A-7 FULL MULTIPLEXED COST/BENEFIT EVALUATION FOR 100 J/M EMI REQUIREMENTS.

Cost Elements (1977 dollars, millions)	Fiber-Optics (mux)	Twisted-Shielded Pair (mux)	Copper Wire Baseline (no mux)
RDT&E	$ 5.6	$ 7.9	$ 32.6
Investment	185.9	289.7	347.2
O&S	33.7	58.8	141.0
Total	$ 225.2	$ 356.4	$ 520.8

TABLE C-11. A-7 FULL MULTIPLEXED COST/BENEFIT EVALUATION FOR AIRCRAFT CARRIER EMI REQUIREMENTS.

Cost Element (1977 dollars, millions)	Fiber-Optics (mux)	Twisted-Shielded Pair (mux)	Copper Wire (no mux)
RDT&E	$ 6.3	$ 16.1	$ 35.5
Investment	185.9	421.5	361.8
O&S	33.7	108.5	149.2
Total	$ 225.9	$ 546.1	$ 546.5

TABLE C-12. A-7 FULL MULTIPLEXED COST/BENEFIT EVALUATION FOR A TACTICAL EMP ENVIRONMENT.

Cost Element (1977 dollars, millions)	Fiber-Optics (mux)	Twisted-Shielded Pair (mux)	Copper Wire (mux)
RDT&E	$ 6.9	$ 20.3	$ 49.4
Investment	189.5	447.8	445.4
O&S	34.4	123.6	209.0
Total	$ 230.8	$ 591.7	$ 703.8

41

TABLE C-13. A-7 MISSION CRITICAL CIRCUITS COST/BENEFIT EVALUATION FOR A TACTICAL EMP ENVIRONMENT.

Cost Elements (1977 dollars, millions)	Fiber-Optics (mux)	Twisted-Shielded Pair (mux)	Copper Wire (no mux)
RDT&E	$ 6.8	$ 23.6	$ 48.7
Investment	186.4	463.2	433.7
O&S	33.8	133.1	201.8
Total	$ 227.0	$ 619.9	$ 684.2

TABLE C-14. A-7 POINT-TO-POINT COST/BENEFIT EVALUATION FOR 100 V/M EMI REQUIREMENTS

Cost Elements (1977 dollars, millions)	Fiber-Optics	Copper Wire
RDT&E	$ 9.8	$ 6.6
Investment	241.6	205.2
O&S	48.7	35.6
Total	$ 300.1	$ 247.4

TABLE C-15. A-7 POINT-TO-POINT COST/BENEFIT EVALUATION FOR AIRCRAFT CARRIER EMI REQUIREMENTS.

Cost Elements (1977 dollars, millions)	Fiber-Optics	Copper Wire
RDT&E	$ 10.3	$ 7.3
Investment	243.6	207.9
O&S	48.6	36.2
Total	$ 302.5	$ 251.4

TABLE C-16. A-7 POINT-TO-POINT COST/BENEFIT EVALUATION FOR A TACTICAL EMP ENVIRONMENT.

Cost Elements (1977 dollars, millions)	Fiber-Optics	Copper Wire
RDT&E	$ 9.2	$ 7.9
Investment	249.0	215.8
O&S	36.6	37.6
Total	$ 294.8	$ 261.3

TABLE C-17. A-7 DATA BUS COST/BENEFIT EVALUATION
FOR 100 V/M EMI REQUIREMENTS.

Cost Elements (1977 dollars, millions)	Fiber-Optics	Twisted-Shielded Pair
RDT&E	$ 4.7	$ 5.4
Investment	115.0	170.4
O&S	21.0	32.7
Total	$ 140.7	$ 208.5

TABLE C-18. A-7 DATA BUS COST/BENEFIT EVALUATION
FOR AIRCRAFT CARRIER EMI REQUIREMENTS.

Cost Elements (1977 dollars, millions)	Fiber-Optics	Twisted-Shielded Pair
RDT&E	$ 6.0	$ 12.8
Investment	114.9	243.4
O&S	21.0	57.9
Total	$ 141.9	$ 314.1

TABLE C-19. A-7 DATA BUS COST/BENEFIT EVALUATION
FOR A TACTICAL EMP ENVIRONMENT.

Cost Elements (1977 dollars, millions)	Fiber-Optics	Twisted-Shielded Pair
RDT&E	$ 6.0	$ 18.6
Investment	120.4	178.2
O&S	21.7	72.8
Total	$ 148.1	$ 269.6

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