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A Methodology for the Economic Assessment of Nondestructive Evaluation Techniques Used in Aircraft Inspection

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16. Abstract

This report details a methodology for the economic evaluation of emerging nondestructive evaluation (NDE) methods applicable to aircraft inspection. The methodology is based on the economic principle of cost benefit analysis (CBA). CBA measures the future stream of benefits and costs to implement a project (such as investment in a new inspection technique) relative to a scenario in which the project is not implemented. An analysis of the net benefits to both private aircraft operators and society in general is discussed.

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PREFACE

This report is a continuation of the work of Professors John Panzar and Ian Savage in their report to the Federal Aviation Administration entitled *Economics of Non-destructive Evaluation of Airframes*. It is intended as a practical guide to members of the FAA and the airline industry who are interested in employing economic methods in the validation process of new aircraft inspection techniques. Profs. Panzar and Savage, Dr. Aaron Gellman, Mr. Steven Bobo, and members at the FAA Aging Aircraft Nondestructive Inspection Validation Center (AANC) at Sandia National Laboratories have contributed greatly to this report. The author wishes to thank Mr. Steve Erickson of the Air Transport Association, Mr. Pat Walter of the AANC, Mr. Bill Bagot, Mr. Chris Seher, and Dr. Chris Smith of the FAA for their valuable comments.

TABLE OF CONTENTS

EXECUTIVE SUMMARY ..... *ix*

1. INTRODUCTION **1**

1.1 BACKGROUND. 1
1.2 OVERVIEW OF REPORT. 3

2. THE COST-BENEFIT MODEL FOR THE INDIVIDUAL FIRM **5**

2.1 THE MODEL. 5
2.2 MEASUREMENT OF COSTS AND BENEFITS. 6
2.3 USEFUL LIFE. 7
2.4 DISCOUNTING AND THE DISCOUNT RATE. 7

3. A SOCIAL COST-BENEFIT MODEL **10**

3.1 THE SOCIAL CBA MODEL. 10
3.2 SOCIAL BENEFITS. 12
3.3 SOCIAL COSTS. 12
3.4 THE SOCIAL DISCOUNT RATE. 13

4. ESTABLISHING THE BASE CASE **14**

4.1 POLICY OPTIONS. 14
4.1.1 Business as Usual. *15*
4.1.2 Command-and-Control Policy Initiatives. *15*
4.1.3 Market-Based Policy Initiatives. *15*
4.2 PRIVATE INITIATIVES. 16
4.3 CHOICE OF BASE CASE. 17

5. DATA REQUIREMENTS **18**

5.1 MEASUREMENT OF COSTS. 18
5.1.1 Capital Costs. *19*
5.1.2 Operating Costs. *20*
5.1.3 Social Costs. *22*
5.2 MEASUREMENT OF BENEFITS. 23
5.2.1 Cost Decreases to the Individual Firm. *24*
5.2.2 Retirement of Equipment with Scrap Value. *27*
5.2.3 Increase in Consumer Surplus. *27*
5.2.4 Increase in the Probability of Detection (PoD). *31*
5.2.5 External Benefits. *32*
5.2.6 Long-Term Benefits. *33*
5.3 UNCERTAINTY ISSUES. 34
5.3.1 Known Parameter Values. *35*
5.3.2 Risk Analysis. *36*
5.3.3 Uncertainty Analysis. *36*
5.3.4 Risk Premium Approach. *38*
5.4 AGGREGATION ISSUES. 39

6. CONCLUSIONS **41**

7. BIBLIOGRAPHY. **43**

LIST OF FIGURES

FIGURE 5-1: *CONSUMER SURPLUS FROM A TECHNOLOGY RESULTING IN LOWER PRICES* 29
FIGURE 5-2: *CONSUMER SURPLUS FROM A TECHNOLOGY RESULTING IN IMPROVED SERVICE* 30
FIGURE 5-3: *TWO-VARIABLE SENSITIVITY TEST* 37

LIST OF EQUATIONS

EQUATION 2.1: *NET PRESENT VALUE FOR THE INDIVIDUAL FIRM* 5
EQUATION 3.1: *SOCIAL NET PRESENT VALUE* 10
EQUATION 3.2: *SOCIAL BENEFITS* 11
EQUATION 3.3: *SOCIAL COSTS* 11
EQUATION 5.1: *CAPITAL COSTS TO A TYPICAL FIRM* 19
EQUATION 5.2: *OPERATING COSTS FOR A TYPICAL FIRM* 20
EQUATION 5.3: *RELATIONSHIP BETWEEN PROBABILITY OF DETECTION AND THE EXPECTED COST OF ACCIDENTS* 31

EXECUTIVE SUMMARY

A major challenge to the airline industry is that it must maintain a high standard of safety with a fleet of aircraft that is increasing in age in an environment that is economically driven and highly competitive. Cost-effective methods of attaining the required safety standards are critical to operators in today's economic climate. New methods of inspection may prove to be feasible to address the growing concerns of maintaining an aging fleet of aircraft at a cost that is acceptable to the industry. This report addresses the cost implications of one of the most promising developments in evaluating the structural integrity of aircraft: Nondestructive Evaluation (NDE) techniques used for inspecting aircraft.

In this report, a methodology is provided for the economic evaluation of emerging NDE methods. The methodology is based on the economic principle of "cost-benefit analysis" (CBA). CBA measures the future stream of benefits and costs to implementing a project (such as investment in a new inspection technique) relative to a scenario in which the project is not implemented. An analysis of net benefits to both private aircraft operators and society in general is discussed.

First, a model is described for the evaluation of the financial benefits net of costs that an individual aircraft operator may expect to receive if it employs a specific NDE technique. Parameters such as the costs and benefits to the NDE user, the useful like of the NDE technique, and the rate used to discount the future costs and benefits to their present values are required to apply this model. Measurement issues relating to the costs and benefits is discussed. The calculation of the net present value (NPV) of an investment in a new NDE technique to an aircraft carrier or maintenance facility is described.

The second step to the evaluation of an NDE technique is to assess the net benefits to society of the adoption of the new technique. This analysis is particularly appropriate to investment decisions which may be mandated by FAA rule. A social assessment of the costs and benefits of a new NDE technique requires the assessment of **all** costs and benefits to society. The net benefits to all aircraft operators in the industry are included in the social calculation. In addition, costs to the government or any other public institution, as well as any benefits that may accrue to members of society from the airline industry's use of the new technique, are included.

Guidelines for establishing a realistic base case scenario with which to compare the net benefits of a new NDE technique, the data required to perform a cost-benefit analysis, and procedures for an objective sensitivity analysis with uncertain parameters are provided in this report. Issues such as the measurement of benefits, the economic impact of an improvement of the probability to detect flaws, heterogeneity in aircraft maintenance facilities, and estimation in the presence of uncertainty are addressed.

This report outlines areas where NDE advancements could have a large economic impact on both the airline industry and society. It addresses the practical problem of obtaining the data necessary to apply the methodology. It acknowledges that some of the relevant factors are not measurable and that some subjective data may have to be examined regarding the impact of these factors. The methodology presented here is used for the cost-benefit studies that have continued to be conducted by researchers at Northwestern University Transportation Center under grants from the FAA.

1. INTRODUCTION

The commercial airline industry historically has had little need to consider the maintenance and/or retirement of aging aircraft. Rapid postwar technological developments made in the construction of aircraft have generally rendered aircraft economically obsolete long before they have reached the stage of threatening mechanical aging. Current conditions are changing this. Alternative technologies that cause replacement or modification of existing engines are emerging. As a result the physical lifetime for the current commercial airframe is increasing. Stable fuel prices and revisions in pilots' working conditions are also contributing to the increased economic life of commercial aircraft.

The result is that the average age of the commercial fleet of aircraft has risen from 4.6 years in 1970 to 12.7 years in 1989.[1] According to a study performed by Galaxy Scientific Corporation for the Federal Aviation Administration (FAA), "If this trend is maintained, 60 percent of the current fleet will exceed their economic design life by the end of this decade."[2] This shift in the profile of the fleet of commercial aircraft is resulting in an increasing number of maintenance requirements to assure the continued airworthiness of the fleet.

The ensuing challenge to the airline industry is that it must maintain a high standard of safety with a fleet of aircraft that is increasing in age in an environment that is economically driven and highly competitive. Cost-effective methods of attaining the required safety standards are critical to operators in today's economic climate. New methods of inspection may prove to be feasible to address the growing concerns of maintaining an aging fleet of aircraft at a cost that is acceptable to the industry. This report addresses the cost implications of one of the most promising developments in evaluating the structural integrity of aircraft: Nondestructive Evaluation (NDE) techniques used for inspecting aircraft.

1.1 BACKGROUND.

Modern aircraft are constructed with a design philosophy that employs *damage tolerance* criteria (first introduced in 1978). Damage tolerance philosophy recognizes the fact that undetected damage in one area can affect the structure in other areas. The damage tolerance criteria for

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[1] See Galaxy Scientific Corporation (1992).

[2] Ibid, p.1.

assuring the structural integrity of aircraft rely on information that is discovered through inspection of the aircraft structure. Prior to 1978, the industry approached structural integrity in design according to *fail-safe* concepts. Fail-safe concepts required that there be sufficient structural backup in all aircraft so that if an element in the structure of the aircraft were to fail, the surrounding structure would prevent complete, catastrophic mechanical failure. Reinforcement or replacement without inspection was the prevailing method of assuring structural integrity before the damage tolerance criteria were developed. In time, it became apparent that there was no possibility of establishing complete structural redundancy of an aircraft and that the attempt to do so was prohibitively heavy in cost as well as weight.

The damage tolerance philosophy diverges from prior attempts to backup the entire structure with redundant parts. The emphasis is on the detection of flaws prior to structural failure. Critical values for the size of flaws have been established and inspection programs have been developed to evaluate the structural integrity of aircraft. This change in standards signifies a shift towards a more economically efficient means of assuring continuing structural integrity of the fleet of aircraft. The acquisition of more detailed information regarding the specific structural attributes of individual aircraft leads to the more efficient use of resources by reducing or eliminating the need for redundancy, while maintaining and even improving the structural integrity of aircraft.

Since the time that the damage tolerance criteria were introduced, technological developments in inspection techniques have proliferated. One of the leading developments is the use of NDE with respect to aircraft. NDE techniques can be used to test aircraft for structural flaws (cracks, corrosion, or disbonding) with minimal disassembly of the aircraft. This has the potential to make more accurate and faster inspections possible. Some current NDE techniques used in the industry include high- and low-frequency eddy current, radiographic X-ray, ultrasonic waves and dye penetrants.

The April 1988 Aloha Airlines Boeing 737 accident was pivotal to the development of more sophisticated methods of flaw detection in aging aircraft. The aircraft had been in service for almost twenty years and had accumulated almost 90,000 flight cycles. The FAA found that some fatigue cracking on the 737 could not be reliably detected by the NDE techniques available at that time. The National Transportation Safety Board (NTSB) concluded that "the probable cause was the failure of the airline to detect" flaws.[3] While the investigation result was a critique of the airline's ability to detect visually detectable flaws, it prompted aircraft manufacturers, operators, and the FAA to reinforce efforts related to the evaluation of the structural integrity of aging aircraft.

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[3] See *National Transportation Safety Board Aircraft Accident Report* 89/03, June 1989.

Consequently, the FAA held its first conference on aging aircraft in June 1988. The results of the conference included joint recommendations by operators, manufacturers, and the FAA that NDE techniques and methods be improved. To further support these recommendations, Congress enacted the Aviation Safety Act on November 3, 1988, which mandated specifically the FAA's involvement in developing NDE techniques for aircraft inspection.

As a result, the FAA developed the National Aging Aircraft Research Program (NAARP) to fund and oversee the research and development of new NDE techniques by a variety of public, private, and academic research organizations. Some promising developments include laser-based optical scanning, X-ray diffraction, thermal wave imaging, and applications of acoustic emission techniques. NDE experts believe that these developments can be more effective in detecting flaws than the existing methods if they can be proven to be cost-effective.[4] A validation facility at the Aging Aircraft Nondestructive Inspection Validation Center (AANC), operated under contract to the FAA by Sandia National Laboratories, has been established under the NAARP with the specific purpose of reporting the capabilities and limitations of emerging NDE technologies to the FAA and the airline industry.

A thorough assessment of new techniques must take into account the costs of the techniques to determine whether the methods are economically attractive to either the potential users in the private sector or to society. The developments in aircraft NDE must be economically attractive in order for the technology to become an acceptable inspection method to the aircraft operators. The purpose of the NAARP initiative is not to burden the industry with new techniques that are considered to be of little value, but rather to provide improved flaw detection which is achieved at an equivalent or lower cost. Cost-effectiveness is a prerequisite for new NDE technology to be transferred from the research lab to a practical application on aircraft. Therefore, if the FAA is to accomplish both the recommended actions by the industry and the mandated role established by Congress, an economic analysis of developments in NDE technology is essential.

1.2 OVERVIEW OF REPORT.

This report provides a methodology for the economic evaluation of emerging NDE methods. While most of the NDE literature emphasizes the improved flaw detection of NDE techniques, there is little evidence of the cost of using these techniques on a regular basis. This report serves as a methodological guideline for the measurement of costs and benefits of adopting a given NDE technique for aircraft structural inspection.

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[4] See, for example, Achenbach and Thompson (1992).

The methodology is based on the economic principle of "cost-benefit analysis" (CBA). CBA measures the future stream of benefits and costs to implementing a project (such as investment in a new inspection technique) relative to a scenario in which the project is not implemented. CBA is a well established economic tool that is widely used in the transportation sector, especially in comparing rival schemes for highways and waterways and for evaluating runway and air traffic control systems. An analysis of net benefits to both private aircraft operators and society in general will be discussed.

The organization of this report is as follows: section 2 describes the CBA model from the perspective of the individual NDE user, section 3 broadens the scope of the model to include social costs and benefits, section 4 discusses alternative scenarios to the adoption of the new NDE techniques, section 5 presents the data requirements for an application of the model, and section 6 concludes.

2. THE COST-BENEFIT MODEL FOR THE INDIVIDUAL FIRM

In this section, a model is described for the evaluation of the financial benefits net of costs that an individual aircraft operator may expect to receive if it employs a specific NDE technique. Private firms regularly conduct this type of appraisal of investment opportunities. The key parameters are:

- The costs and benefits to the NDE user (any costs or benefits that are experienced outside of the firm, by government agencies or society for example, are not included in this calculation and will be discussed in the next section)
- The useful life of the NDE technique
- The rate used to discount future costs and benefits to their present values

A discussion of each of these follows the description of the model.

2.1 THE MODEL.

Operators or third party facilities must make an investment decision to employ emerging NDE techniques in aircraft inspection. Inspection facilities have an incentive to invest in a new NDE technique if the future flow of benefits attributable to the new technique are greater than the future flow of the costs, and therefore, the investment is expected to generate a positive return. While there are several methods that may be used to make this calculation, economists agree that the calculation of the *net present value* of an investment is the most useful measurement.[5] Net present value (NPV) measures the expected stream of benefits less the expected stream of costs over the projected useful lifetime of the investment with future figures discounted so that they reflect the present value of the investment. The calculation is as follows:

Equation 2.1: *Net Present Value for the Individual Firm*

$$NPV_i = \sum_{t=0}^{T} \frac{(B_i - C_i)}{(1 + r_i)^t}$$

[5] See Pearce (1983), Schmid (1989), and Sugden and Williams (1978) for derivation of cost-benefit analysis techniques.

where	i		indexes the individual aircraft operator
	t		indexes time
	T	=	useful life of the technique
	B	=	benefits obtained from technique
	C	=	cost of employing technique
	r	=	discount rate

If the NPV is positive, the future stream of benefits outweighs the future stream of costs and the investment in the new technique is expected to yield a positive return, therefore making the investment worthwhile.

2.2 MEASUREMENT OF COSTS AND BENEFITS.

Only avoidable and incremental costs and benefits should be measured. Costs and benefits are avoidable if they are directly attributable to the adoption of the NDE technique. Any costs already incurred prior to the evaluation, regardless of how or why they may effect the cost-effectiveness of the investment currently under question, should not be included in the NPV calculation. Costs incurred prior to the appraisal of an investment are considered "sunk costs" because they have already been incurred and it is not possible to reverse this decision. Similarly, any benefits realized before the evaluation are not measured either.

Additionally, all costs and benefits should be measured as incremental, i.e., in reference to a baseline scenario that is likely to occur if this investment is not pursued. The baseline scenario is referred to as the "base case" in this report and should be the most likely scenario to occur if the NDE technique in question is not employed. The choice of the base case is discussed in section 4. This incremental measurement allows for costs or benefits to be negative. Therefore, a decrease in cost relative to the base case can increase the NPV of the investment and can contribute to the factors that make an investment cost-effective. In this case, the decreased cost resulting from undertaking an investment in a new NDE technique can be viewed as a benefit.

Costs and benefits must be measured by a common unit of value to make them comparable. Constant dollars is a recommended measurement because it nets out the effect of inflation. As prices go up, $1 buys less; therefore it is worth less. In order to make accurate comparisons of dollar values over time, a constant dollar value must be chosen; that is, the value of a dollar in a specific year. Future values are then expressed in terms of the value of money in that specific year. This is referred to as the real value, i.e., the value net of inflation. It is not important what specific year is chosen as the base year to express dollar values, but rather that all dollar values are expressed in terms of this year. This is the constant (or real) dollar measurement.

While most factors can be measured in constant dollar values, it is important to recognize that, for some of the costs and benefits, it may not be appropriate to assign a dollar value. Still, these costs must be identified and described in whatever terms are appropriate so that an assessment can be made of their likely effect.

2.3 USEFUL LIFE.

The time over which the costs and benefits should be evaluated is called the useful life of the investment. The economic useful life of an investment in a new NDE technique is the period in which the technique fulfills the requirement for which it is employed at the lowest achievable cost compared with alternative techniques. This implies a continual (explicit or implicit) re-evaluation of the technique in order to verify that it is achieving the stated requirement at the lowest achievable cost. If there is a lower-cost alternative at any time, the technique has reached the end of its economic life and should be replaced for the sake of economic efficiency.[6]

An accurate estimate of the economic life and life-cycle costs of the NDE technique must be made in order to determine the time period over which the investment should be evaluated in the CBA model. It is for this reason that it is imperative that the NDE techniques be sufficiently developed before they are examined in a CBA framework. If an economically superior alternative replaces the technique before it is expected, the useful life of the original investment diminishes and the CBA model must be adjusted to accurately forecast the future net benefits of the investment.

2.4 DISCOUNTING AND THE DISCOUNT RATE.

The net present value technique requires that the future stream of costs and benefits be discounted in order to take into account the preference of current net benefits over future net benefits. Clearly, $1 today is worth more than $1 next year to most people (and firms). Hence, the net benefits that are realized today are worth more than those that will be accrued from the same investment next year. There are a number of reasons for this. First, there is a pure time preference for consuming something now rather than tomorrow; some economists refer to this as the "rate of impatience." In the financial sector, this concept is explained as the time value of money. Second, there is an element of risk in any investment and some sort of premium is

[6] The cost of using a technique in this discussion refers to the life-cycle cost of an investment, rather than simply the operating cost. Therefore, it takes into account the capital cost of investing in a new technique as well as the cost of employing it.

associated with that risk. Finally, if the overall economy is expected to experience inflation, the net benefits are worth less as time passes.

Economists measure the rate at which the future value of investments are discounted with the opportunity cost of capital. The opportunity cost of capital is the rate of return of an alternative, or more precisely, the "next best" investment. Consider the financing of an investment in a new NDE technique. The investment may be funded either by (1) taking resources away from alternative investments or (2) borrowing money at the market rate of interest. In either case, the opportunity cost to the NDE user of financing the investment is factored into the NPV by discounting the future net benefits with the appropriate rate.

For public sector investments, this is measured by the market rate of interest that is available on an investment covering a similar time period. In the private sector, it is appropriate to discount the value of future net benefits by the rate return on a similar investment to reflect the opportunity cost of the investment. In general, this is considerably higher than the market rate of interest. Clearly, if the discount rate chosen is higher than the opportunity cost rate, then net benefits will be overdiscounted and the investment may be incorrectly rejected by the NPV criteria. If the rate chosen is too low, the investment may be unwisely pursued.

The preceding discussion implies that there exists a single overall market rate of return. In theory, if capital flowed freely between all sectors of society, this would be true. However, individual companies experience a variety of capital constraints and there is not one overall market rate of return, but rather a dispersion of rates. It is, therefore, an important procedure in CBA to choose the discount rate which is relevant to the industry in question. Measured rates of return in the aviation industry need to be explored and a representative figure should be established. This can be accomplished by examining the mean value of industry opportunity cost rates, for example, although the variance will need to be considered as well.

The preceding discussion includes the measure of expected inflation in the discount rate, i.e., the nominal rate of return. There is no need to adjust for inflation in the measurement of costs and benefits over time if all measurements are made in constant dollars, as was recommended in section 2.2. In this case, inflation is not included in the calculations. Hence, expected inflation must be netted out of the discount rate and the real rate of return on alternative investments should be used as a discount rate.

A final consideration when discounting is the decision of timing. Initially, decisions must be made regarding the expected distribution of the costs and benefits of an investment over its useful life on an annual basis.[7] Questions then arise regarding the expected distribution of costs

[7] The discount rate is expressed in annual terms.

and benefits within each year. Are all costs and benefits incurred at the beginning of the year or are they evenly distributed throughout the year? Are the costs necessarily incurred at the same time as the benefits are realized?

In the absence of certainty, some assumptions need to be made. The most conservative assumption is that all costs are incurred at the beginning of each year and all benefits appear at the end of each year. This yields the largest disparity in time between the payment of costs and the receipt of benefits. Alternatively, it could be assumed that all benefits and costs are incurred at the middle of the year or that they are continuously incurred throughout the year.[8] No *a priori* methodology can be established for the decision of when to discount values within the year. The decision must be made on a case-by-case basis.

[8] The difference in outcome between these two methods is negligible.

3. A SOCIAL COST-BENEFIT MODEL

It may be the case that the above calculation yields an NPV that is negative; that is, the new NDE technique is not expected to be economically attractive to the individual aircraft operator. This does not necessarily imply that investment in the inspection technique will result in economic inefficiency. Specifically, if the new NDE technique projects positive net benefits to society, the adoption of the technique will be economically beneficial to society.[9]

A second step to the evaluation of an NDE technique is, therefore, to assess the net benefits to society of the adoption of the new technique. This analysis is particularly appropriate to investment decisions which may be mandated by FAA rule. In this section, the methodology for the measurement of social costs and benefits is described.

A social assessment of the costs and benefits of a new NDE technique requires the assessment of **all** costs and benefits to society. The net benefits to all aircraft operators in the industry are included in the social calculation. In addition, costs to the government or any other public institution, as well as any benefits that may accrue to members of society from the airline industry's use of the new technique, are included. A more specific description of these benefits will follow the discussion of the model.

3.1 THE SOCIAL CBA MODEL.

As stated above, the social NPV, NPV_S, contains the sum of all of the individual firm NPV figures calculated in the previous section. NPV_S also includes all net benefits that the deployment of the NDE technology is expected to provide. Finally, it includes government costs, benefits to consumers in the airline industry, and any external effects that the technique may have on other sectors of the economy. The calculation of NPV_S is described as:

Equation 3.1: *Social Net Present Value*

$$NPV_s = \sum_{t=0}^{T} \frac{(B_s - C_s)}{(1+r_s)^t}$$

where

[9] This may also imply that society should incur some of the costs.

Equation 3.2: *Social Benefits*

$$B_s = \sum_{i=1}^{I} B_i + \sum_{m=1}^{M} B_m + CS_a + EB$$

Equation 3.3: *Social Costs*

$$C_s = \sum_{i=1}^{I} C_i + \sum_{m=1}^{M} B_m + GC_a + EC$$

and

I	=	total number of operators in the industry
m		indexes manufacturers of NDE equipment
M	=	total number of NDE manufacturers
CS_a	=	consumer surplus in the airline industry
GC_a	=	government cost of the implementation of NDE technique
EB	=	external benefits
EC	=	external costs
r_s	=	social discount rate

and all other notation is as previously defined.

The method of calculation and the criteria for evaluating the NPV is identical to that described in section 2. All of the concerns listed in the description of the individual firm are appropriate here. Benefits and costs are discounted over the period of the technique's useful life. There are two key differences in the measurement of a social CBA:

(1) The items included in the flow of costs and benefits include **all** net benefits to society

(2) The rate at which the flow of net benefits is discounted reflects society's discount rate rather than the individual firm's discount rate

3.2 SOCIAL BENEFITS.

Note that the benefits expressed in equation 3.2 include not only the benefits of the technology to the individual operators, B_i, but also the benefits to the manufacturers of NDE equipment that is to be used in the technique, B_m. B_i is most likely realized in terms of decreased costs from performing more efficient inspections, increased reliability of flaw detection procedures, extended useful lives of aircraft, and any increased profits realized from lower inspection costs. B_m is measured in terms of the increased profits due to the sale of the new NDE equipment by the manufacturers.

Other social benefits include those that may accrue to the government or to society in general. The FAA can benefit from inspection techniques which improve the efficiency of its inspectors. Other beneficiaries are consumers in the airline industry. Improved inspection techniques can result in improved levels of safety and/or decreased inspection costs. In a competitive industry, the effects of both of these are passed on to the consumer in the form of increased quality (i.e., safer service) or decreased cost of travel. These social welfare effects can be measured by the term CS_a, the consumer surplus in the airline industry.[10]

Finally, the term EB_s represents any external benefits that may be attributable to the use of the new technique. External benefits are those captured by individuals or institutions that do not participate directly in the market. Examples may include the decrease in the incidence of third-party damage from the reduced incidence of airplane crashes or the spillover applications of NDE technology into other industries. The measurement of social benefits will be discussed more thoroughly in section 5.2.

3.3 SOCIAL COSTS.

The costs that are analogous to the benefits described above are:

- Costs to the operators of using the technique
- Costs to the manufacturers of developing the technique and producing the devices

[10] Consumer surplus is a measurement on the net economic benefit to consumers of either a decrease in the cost of a good or an increase in the level of quality provided. Economists have developed a method for calculating the consumer surplus that a shift in cost or quality may provide by using estimates of demand elasticity for the good in question. In this case, the demand estimates for air travel yield a reliable estimate of consumer surplus. This calculation is described in more detail in section 5.2.

- Costs to the government that are incurred due to the adoption of the new techniques
- External costs

Examples of government costs may include any extra equipment inspection and/or training costs that must be incurred by government agencies if a new technique is adopted by the industry. External costs are directly analogous to external benefits, that is, they reflect the costs of adopting an NDE technique incurred by individuals or institutions that do not participate directly in the airline industry.

3.4 THE SOCIAL DISCOUNT RATE.

The social discount rate used in the calculation of NPV_s reflects society's time preference. There are two reasons to believe that the social discount rate is lower than the real rate of return used by private firms. First, society may place more value on the benefits available in the future than does an individual or the private sector in general. Second, the level of risk of a project may be lower from a social perspective because the social portfolio of projects is more diverse than any private portfolio. The economics literature provides a reasonable range of appropriate values to be used for the social discount rate. The federal government regularly uses social discounting in its project proposals, and the OMB has a recommended figure of 10 percent.[11] This is a high figure relative to other estimations. A high social discount rate will result in conservative NPV_s figures.

[11] See OMB Circular No. A-94 of March 27, 1972. This figure is based on estimates of the rate of return of capital in the private sector of the U.S. economy before federal income taxes and net of inflation. It does not take into account the social rate of time preference or any decrease in risk.

4. ESTABLISHING THE BASE CASE

In section 2.2, it was recommended that all costs and benefits be measured as incremental; that is, they should be measured against the occurrence of an alternative scenario, specifically the scenario that is most likely to occur if the investment in question is not undertaken. The alternative scenario is referred to as the base case. The possible scenarios for future practices in aircraft maintenance are shaped by the actions of both the government and the private sector. Policy initiatives pursued by the Federal Government and facilitated by the FAA can enhance or detract from the private development of new technologies.

In this section, the possible future activities of both the public and the private sectors are discussed and the likelihood of the possible scenarios occurring is assessed. Sections 4.1 and 4.2 address the public and private sectors respectively. In section 4.3, a conclusion is drawn as to which scenario is the most appropriate to use as the base case in the CBA methodology.

4.1 POLICY OPTIONS.

Before attempting to establish a base case, it is necessary to outline the options for governmental policy initiatives in this area. The realistic outcomes for the future of the structural inspection of aircraft can be broadly grouped into three types of public policy initiatives:

(1) Business as usual (BAU): **No action** is taken and industry continues operating under the existing regulations

(2) Command-and-control: Government enacts laws that **require** mandatory repair, modification, or even retirement of aircraft at a specific number of hours or pressurization cycles

(3) Market-based: Government **encourages** the adoption of methods that will provide more reliable detection of structural soundness and which are economically attractive to the airlines

Each of these options is discussed below.

4.1.1 Business as Usual.

The do-nothing approach, often referred to as operating under BAU, presumes that both Congress and the FAA will not adjust their stances regarding the inspection of aging aircraft. It follows that aircraft operators will not adjust their inspection techniques unless private initiatives present a method of inspecting aircraft that is superior from a cost-effectiveness standpoint (see section 4.2). In the wake of the Aloha incident, the FAA initiated research into the aging aircraft problem to find more effective methods for determining and ensuring structural integrity. In 1991, Congress passed the Aging Aircraft Safety Act which mandates that all aircraft must go through a complete FAA inspection after 15 years of service. While this act simply restates the required heavy checks prescribed by aircraft manufacturers, it clearly states the Federal Government's willingness to act on setting guidelines for the airline industry.

4.1.2 Command-and-Control Policy Initiatives.

Command-and-control policy initiatives mandate industry action. While the Aging Aircraft Safety Act was Congress' response to public dismay regarding several incidents in the late 1980s that may have resulted from structural failure, the act set no limits on the physical life of aircraft. It simply required the FAA to assure inspection of aircraft of a certain age. If Congress intended to define the limits of aircraft structural life, it would likely have occurred in this act. Unless subsequent tragedies spur more rigid legislation, it is not anticipated that Congress will reassess this issue. Furthermore, mandatory overall repair of aircraft is contradictory to the damage tolerance philosophy, adopted by the FAA, which adheres to the principal of the detection and repair of flaws. Aircraft engineers generally believe that the design operational lives of aircraft can be safely exceeded with proper maintenance.[12] Research is still ongoing to determine the ultimate life of aircraft structures.

4.1.3 Market-Based Policy Initiatives.

Market-based policy initiatives encourage the industry to invest in equipment or ideas that are economically attractive to the industry *per se* and that have not been initiated by the private

[12] At the first International Aging Aircraft Conference in June, 1988, a general consensus was reached that, with proper maintenance and structural modifications and with attention to service-related damage such as fatigue and corrosion, the original design objective of aircraft could be safely exceeded.

sector due to the existence of market failures. Economists have long recognized underinvestment in R&D as a result of market failures in several industries.[13] Underinvestment in technology can occur for a number of reasons: the pertinent investment information is not widely available in the industry, the uncertainty and risk associated with the investment is too high, or the scale of the investment is too large for an individual operator to incur. Market-based policies attempt to transfer information to the private sector, reduce the level of risk and uncertainty by "pooling" it throughout the industry (and in some cases throughout society), and share the financial burden of large investments.

The FAA initiative towards the National Aging Aircraft Research Program (NAARP) is a clearly a market-based measure. NAARP funds research projects that may not otherwise be undertaken in the private sector for any of the reasons listed above. It provides a regularized method for introducing new technologies to the airline industry. It also correlates and coordinates information between different agents in the industry, disseminates information throughout the industry, and facilitates the technology transfer process. The adoption of new NDE techniques that are developed by agencies under the direction of NAARP are the result of a market-based policy initiative by the federal government and probably would not have occurred without FAA support.

4.2 PRIVATE INITIATIVES.

It was suggested above that the airline industry lacks a cohesive technological base due to the existence of market failures. However, the industry does have an economic incentive to evaluate new techniques for aircraft maintenance and improve safety. Therefore, private sector initiatives will continue regardless of the policy actions taken by the Federal Government. For example, several new technologies or techniques that address a particularly pressing inspection procedure may be developed by private companies because of the urgent need for a solution. In this case, a realistic base case would compare two emerging techniques. Another possibility is that new NDE methods are developed to replace particularly arduous visual inspections. This is often the case, as over 80% of current inspections are performed visually.

The public policy actions may act as obstacles to the functioning of the market or they may stimulate the private development of cost-effective techniques. The combined effect of the continued private initiatives of the aircraft maintenance community with the policy actions taken

[13] Underinvestment is defined as a level of investment that, when increased, results in a superior economic position for either a firm, industry, or society.

by the Government need to be analyzed in order to establish a realistic base case scenario with which an investment in new NDE technology can be compared.

4.3 CHOICE OF BASE CASE.

The possible courses of action for both the public and the private sectors have been described above. The purpose of determining the base case is to examine an investment relative to an alternative scenario that is most likely to occur if the investment is not undertaken. Given the current economic climate and without Government support, it is likely that the industry will continue to develop new methods for inspecting aircraft at a decreasing rate. It is unlikely that Federal Government will set a mandatory retirement age for aircraft, for the reasons mentioned in section 4.1.2. Market-based research initiatives, i.e., the activities of NAARP, are likely to continue and future research may determine ultimate life limits for aircraft. This climate may change and it will be necessary to continually assess the selection of the base case scenario.

Therefore, the recommended base case is the scenario where the industry and government agencies continue to operate as they currently are, although many factors need to be determined on a case by case basis. In general, the analysis of a specific NDE investment compares the costs and benefits of using the new technology or technique with the costs and benefits of the currently employed method. Often this will be a comparison of a new NDE technique with an already established NDE technique or with a visual style of inspection. Hence, the calculation made may be an expression of the marginal benefit of one technique over another.

5. DATA REQUIREMENTS

This section describes in more detail the data required to perform the calculations described in sections 2 and 3. The measurement of costs is discussed in section 5.1, first with respect to the individual NDE users and then from the perspective of society as a whole. In section 5.2, the measurement of both private and public benefits is described.

5.1 MEASUREMENT OF COSTS.

Accurate measurement of costs must take into account the life-cycle costs of any NDE technique. These include:

- Capital costs: Investment costs in both physical capital and human capital and any relevant R&D
- Operating costs: Continuing costs of employing the inspection technique
- Termination costs: Any costs associated with the retirement of the new equipment at the end of its useful life

Capital costs are incurred at the beginning of a project and relate to the capital investment in the technique. Operating costs will continue over the lifetime of the technique and may vary with the number of inspections that will be provided. Each of these is discussed below. Termination costs are incurred at the end of the useful life of the technique. They include dismantling costs and the cost of restoring the site to its original form. A "negative cost" associated with termination is the scrap value of retired capital, which is discussed in the section on benefits. For most techniques the termination costs will be negligible, but it may be important in some cases (such as where hazardous waste is an issue).

The implication in this section is that the NDE user purchases the NDE equipment. This may not always be the case. Some techniques involve such a large capital investment with a relatively low utilization rate (e.g., X-ray sources) that an optimal market solution is for the equipment to be leased or for inspections to be contracted out. The industry can take advantage of the economies of scale of equipment with a high capital cost by hiring third party companies to either perform the maintenance or to lease the equipment. If this is the case, the aircraft maintenance facility is making a decision about lease costs, rather than investment costs, and the cost-benefit methodology is not an appropriate model for this type of decision. However, the investment

decision to purchase NDE equipment for lease or to provide contracted maintenance can be evaluated by the third party facilities with this model.

5.1.1 Capital Costs.

Capital costs are the investments in durable facilities and equipment, site preparation, services and training made at the beginning of the project that are generally not assumed to continue for the life-cycle of the project. Hence, capital costs are fixed to the extent that they will not vary directly with the number of inspections occurring. Capital costs to the typical firm, K_i, are described in equation 5.1:

Equation 5.1: *Capital Costs to a Typical Firm*

$$K_i = K_i(RD) + K_i(IC) + K_i(TC)$$

where	K_i	references capital costs
	RD =	capital costs associated with research and development
	IC =	capital costs associated with investment in durable equipment
	TC =	capital costs associated with the initial training of personnel

It was stated in section 2.2 that the measurement of costs associated with an NDE technique should include only avoidable costs. Any costs that have already been incurred are "sunk costs" and should not affect the decision to invest in a project. In this case, only the costs of R&D necessarily incurred after the analysis is made should be included in the calculation. Further product development may be required to make NDE equipment more "user-friendly;" this is an example of an R&D cost that may be necessarily incurred after the evaluation.

Investment costs [K_i(IC)] include investment in durable tools and equipment required to perform inspections; these are "physical capital costs." These costs include any transportation costs required to get equipment to the sites and the cost of any additional space or alteration in the physical structure of the inspection site. For example, the use of X-ray or gamma-ray inspection techniques may require a lead-encased inspection area that conforms to safety standards.

K_i(TC) represents the cost of investment in human capital; that is the initial training of personnel to use the NDE equipment. Initial training costs include such factors as instruction costs, travel, subsistence, and lodging for the recipients of training, and the wage compensation for employees during training.

5.1.2 Operating Costs.

After the equipment is purchased and the personnel are trained, the operating costs, or variable costs, will be sensitive to the number of inspections performed. Operating costs for the typical firm, V_i, are defined as:

Equation 5.2: *Operating Costs for a Typical Firm*

$$V_i = V_i(RD) + V_i(EC) + V_i(LC)$$

where V_i references operating costs
EC = costs associated with the use of disposable equipment/materials
LC = continuing costs associated with personnel

All other terms have already been defined.

Disposable equipment and materials are continuing costs (expenses) which are incurred throughout the lifetime of the technique. Different NDE methods will vary in the cost of materials needed to perform each individual inspection. For example, the cost of crack inspections with penetrant is highly sensitive to the number of inspections performed because the main inspection "tool" is disposable. On the other hand, crack inspections using eddy current techniques utilize a durable piece of equipment, which involves a relatively small marginal cost.

The cost of preparing the aircraft for inspection is another case of a continuing cost. For example, stripping and reapplying paint or decals, erecting sophisticated docking stations, isolating the aircraft for hazardous procedures, additional aircraft out-of-service time, or disassembling part of the aircraft all require that labor and material costs be incurred in order to perform the inspections accurately.

A large component of the continuing costs are personnel costs [V_i(LC)]. These are measured as the annual costs of the personnel required to perform the inspections. An accurate measurement of annual personnel costs includes such factors as vacation time, overtime premiums and shift differentials (X-ray is performed on midnight shifts), sick leave, life insurance, health and retirement benefits provided by the airline or third-party maintenance facility. Descriptions of the working practices of airline employees can be obtained from manufacturers' information and FAA publications such as the Air Traffic Staffing Standards System. Other government

publications, such as the general schedule of pay scales and statistical abstracts, provide wage and benefit estimates.

Personnel need retraining to maintain and advance their skills, and new employees have to be trained periodically. There is some reason to believe that these retraining costs will be significantly different from the current costs because more sophisticated equipment may entail more and increasingly costly training. Alternatively, new equipment that is easier to use may involve less training requirements. These costs need to be examined on a case-by-case basis. Employee turnover should not change, unless there is a considerable negative change in work conditions. The volume of training may not be substantially different between methods.

The degree to which inspector productivity can be improved depends on the flexibility in the allocation of job duties within the facility. In some inspection facilities, work rules are rigidly established such that NDE inspectors are assigned to perform NDE inspections only. So that even if inspection procedures can be executed more rapidly, there is little for the inspectors to do with the time saved. Therefore, in this work situation, there is little scope for the productivity of NDE inspectors to increase. In a facility with more flexible work rules, where NDE inspectors are expected to perform other tasks and visual inspectors and maintenance technicians can be cross-trained to do some NDE tasks, the improved efficiency of quicker inspections can be more fully realized. Once again, the assessment varies on a case-by-case basis.

The economic case for NDE technology will be greatly advanced by two situations:

(1) More flexible working assignments, which allow inspectors to perform a wider variety of tasks
(2) The simplification of operating the equipment and interpreting the results so that flexibility of work assignments within the inspection facility can be enhanced

It should be noted that either of these situations are not exclusive to new techniques and can also apply to the base case scenario.

Other examples of cost decreases can be found in section 5.2.1. They are included in the benefits section because a cost decrease to the firm is properly viewed as a benefit of the technique by the industry.

5.1.3 Social Costs.

Social costs include:

- Private costs of all of the individual airlines who use the NDE technique
- Private costs of the manufacturers associated with the production of the NDE technique
- Costs of the government
- Any negative external effects the technique may have on society
- Loss of opportunity to seek economically beneficial alternatives from mandated use of specific techniques

The costs to individual airlines were discussed in the previous section and all that was stated there is relevant here. The costs to the manufacturers are associated with the production of the equipment and software and can be estimated by developers projections of what the production will entail. These costs can be refined during validation and field testing.

The costs to the government include costs due to any increase in regulatory functions or factory inspections that a regulatory authority may be required to undertake if new techniques are employed. For example, in the case of new x-ray techniques, it may be necessary to send inspectors on site to ensure that the maintenance facilities are meeting the required safety standards. It is also possible that a new technique will decrease or eliminate the need for regulatory inspections. These costs will vary with the type of NDE technique under consideration and judgments regarding the impact on government costs need to be considered on a case-by-case basis.

Finally, the external costs include any negative impacts that the technology may have on society. Examples of these include any increase in the emission of pollutants or hazardous materials, increased risk of exposure to unsafe materials, decreased levels of safety, or any increase in noise level for those residing near the inspection area. External costs must be assessed and measured on a case-by-case basis.

5.2 MEASUREMENT OF BENEFITS.

There are a wide range of potential benefits that both aircraft inspection facilities and members of society in general may derive from the adoption of a new NDE technique. Some of the benefits can be quantified in monetary terms. Others may not be so easily translated into dollar figures. Some of the benefits may be more effectively measured and characterized in non-monetary terms, such as the increased probability of detecting flaws. There may also be some long-term benefits that shift the way in which the industry approaches the assurance of structural integrity. One of the long-term objectives of the NAARP is to develop a philosophy of structural life enhancement for new aircraft designs. Current developments in NDE technology aid the long-term goals of retaining structural integrity in future aircraft. Some of these benefits cannot be quantified without strong assumptions about the future implications of NDE technology. Benefits of this nature are nonetheless important factors to decision making and should not be omitted from the analysis. In cases where it is difficult or even ineffectual to attach monetary values to such benefits, other methods can be employed to include these factors. If a factor is omitted entirely, it is implicitly assigned a value of zero, which may not be appropriate.

Turning now to the measurement of potential benefits while keeping the preceding discussion in mind, the areas in which potential benefits may be found are listed below in decreasing order of quantifiability.

- The individual maintenance facility can benefit from a technique that lowers or avoids inspection costs

- The technique may allow the facility to retire equipment with a substantial scrap value

- The technique may result in a decrease in cost to the consumer or an increase in the level of service provided by the airline, therefore increasing the consumer surplus for consumers in the airline industry

- The technique may increase the probability of detecting flaws, which can lead to a benefit to both the airline and society in the form of increasing safety and a benefit of increased time intervals between inspections

- External benefits to society may be accrued from the use of a new technique

- Other benefits include any long-term benefits to the industry from attaining a more aircraft-specific view of inspection and maintenance

Each of these alternatives is discussed in more detail below.

5.2.1 Cost Decreases to the Individual Firm.

One example of decreased personnel costs was already cited in the discussion of operating costs (section 5.1.2). Opportunities for cost decreases from the use of a new technique are not limited to that case. Costs to the individual firm may decrease with any of the following factors:

- Decreased labor hours required for inspection
    - Shorter inspection times
    - less preparation required to perform inspection
    - Decrease in the number of personnel required to perform inspection
- Less frequent inspections required
- More economic labor costs
- Decrease in the number of false positive detections
- Increased inspector confidence

Each of these is discussed in detail below.

5.2.1.1 Decrease in Labor Hours Required for Inspection.

The development of a new NDE technique that decreases the time it takes to perform inspections will also decrease the inspection cost to airlines in both labor cost and aircraft downtime. There are a number of ways in which inspection times are lessened with new techniques.

First, it may be that a new technique will enable inspectors to examine areas that otherwise required dismantling or visual inspection before mechanical inspection could be applied. This would eliminate the need for much of the preparation work required by current inspection techniques. This may also decrease waste disposal costs and avoid the need for reapplication of decals or protective coatings.

Second, the new technique may enable inspectors to perform more rapidly accurate inspections over a much larger portion of the aircraft. This would improve the economies of scale in the cost of inspections, causing a lower unit cost per inspection.

Finally, several techniques may be integrated into a system so that one technique may enhance the detection performance of another technique and decrease the need for more labor-intensive activities. With the development of complementary techniques (and the identification of substitutes), it may be found that there exists an optimal set of NDE techniques for a specific task, given a fixed technology base.

Clearly, estimates of inspection times must to be gathered in order to measure these benefits. This entails an examination of the types of inspections that the new NDE technique is capable of performing and comparisons with the time it takes to perform a comparable inspection with existing or alternative techniques. Hence, a standardized definition of the various types of inspections performed and a comparison of laborhours between the techniques will be required.

Of course, the savings may not only be in inspection time; for example, there may also be a decrease in the number of personnel required to perform the inspection. It will be necessary to obtain data on the total labor hours required to perform a standardized level of inspection in order to account for both shorter inspection times and decreased personnel requirements. These data must be identified in the collection of information on operating costs.

It may be found that a certain technique is cost-effective for some types of inspection but not for others. For example, techniques that are bulky and cumbersome to employ may reduce the labor cost of performing large-scale inspections where they are able to achieve substantial economies of scale. These same techniques may not be cost-effective to use in performing spot inspections on the line where the cost of mobilizing the equipment is high. The analysis of the cost of using NDE equipment must be sufficiently detailed in order to determine the optimal strategies for the use of the new techniques.

5.2.1.2 Less Frequent Inspections Required.

Another potential benefit of NDE techniques that improve the probability of detecting a flaw is the possibility of increasing the time interval between inspections. Aircraft manufacturers stipulate in aircraft repair manuals the maximum time intervals between inspections that are required to detect a flaw before it reaches a critical size (as determined by damage tolerance criteria). Techniques which can detect flaws that are smaller and/or with a higher probability of detection (PoD) are permitted longer time intervals between inspections. Inspection intervals are determined such that the cumulative PoDs over time of the a new technique and other less reliable techniques meet the same minimum requirements. Therefore, if the PoD of the new NDE technique is significantly higher than that of the existing methods of detection, the

manufacturer can require less frequent inspections without effecting overall reliability. Consequently, the cost of performing inspections over time decreases.

The preceding discussion presumes that PoD data is available for new and existing NDE techniques. This is not necessarily the case and, even if the data has been collected, it may not always be available. It is in the interest of the aircraft manufacturers to find less expensive ways for operators to maintain their aircraft, so the manufacturers have an incentive to collect such information in order to determine frequency intervals. Manufacturers have traditionally either collected data in an experimental setting or extrapolated the necessary information in order to establish frequency intervals for inspections. The AANC has obtained a specimen aircraft and structural samples available for comparison of techniques against well-characterized flaws. For example, the AANC has collected PoD data for two eddy current techniques: the sliding probe and the magneto optic imager (MOI). Data collection of this nature is necessary for a comprehensive analysis of the economic effect of new NDE techniques.

5.2.1.3 More Economic Labor Costs.

A new NDE technique may also reduce the per unit labor cost of performing inspections. As already mentioned in section 5.1.2, a new NDE technique can generate labor cost-savings if the technique can be employed by lower-skilled personnel. Current work on emerging NDE techniques will help make NDE investments more "user-friendly" and financially attractive to inspection facilities.

5.2.1.4 Decrease in the Number of False Positive Detections.

A new NDE technique that renders more accurate detection may also reduce the probability of a false alarm (POFA), which would decrease the cost of investigating false calls. In the event of the detection of a flaw, the aircraft may have to be disassembled, at least at the point of detection to determine the nature of the flaw. In some cases, the flaw is misdiagnosed; that is, disassembly determined that the flaw was nonexistent or insignificant. Improved detection methods may result in a decrease in the cost of inspection by yielding more dependable results and reducing the need for unnecessary disassembly or retest. For this cost decrease to be measured accurately, it is necessary that the assessment of the improved detection methods measure any change in the number of false positive detections that a new technique may yield.

5.2.1.5 Increased Inspector Confidence.

A related, but less tangible, benefit of an inspection method that produces more reliable results is increased confidence in the inspection results. A belief in the integrity of the equipment tends to generate more effective use by those who operate it. For example, a technique that produces many false positive detections will undermine confidence in the technology and may lead to apathy on the part of the inspectors. Improved detection methods may generate a considerable increase in the efficiency level of the inspectors by increasing their confidence in the technique. This effect is difficult to measure, but it is an important qualitative factor of more reliable inspection methods. Once again, this potential benefit can only be realized if the work force can be redeployed to other productive tasks or reassigned.

5.2.2 Retirement of Equipment with Scrap Value.

Any equipment that is to be replaced may carry a substantial scrap value. In many cases this value is small, but in others it is substantial. An assessment of the relevance of the scrap value of retired capital must be performed on a case-by-case basis. This also includes the scrap value of the equipment associated with a new technique when it is terminated. This is a "negative cost" associated with termination costs. Estimates of the surplus value of equipment must be derived from accounting records and observable market values.

5.2.3 Increase in Consumer Surplus.

As explained earlier in section 3.2, consumers in the aviation industry may benefit from improved inspection techniques. Consumers in the commercial aviation industry are the people who purchase air travel or who use air travel services, such as air cargo, or airmail delivery. Consumer surplus represents the difference between consumers' demand price--the highest price they are willing and able to pay for a service--and the actual market price. Consumer surplus is a measure of the "profit" that consumers realize as a result of their consumption of a service.

There are two ways in which a new NDE technology can increase consumer surplus. First, the technology could result in lower consumer prices. Any decrease in the unit cost of inspection could be passed on by the industry to decrease the cost of air travel services to consumers in a competitive industry. Second, a new technology could result in improved safety levels, thereby improving the quality of the air travel service and increasing the quality of the goods that the aviation consumers receive for the same price.

The first case is illustrated in figure 5.1. The curve labeled "D" in the diagram represents consumer demand for air travel services. Initially, the price in the market is established at P_1 while Q_1 of the service is purchased. Next, suppose that a new cost-saving NDE technology results in the market price of the service falling to P_2 resulting in an increase in quantity demanded to Q_2. This results in an increase in consumer surplus given by the shaded area in figure 5.1 (i.e., the area P_1ABP_2). The initial customers in the market (i.e., those consuming quantity Q_1) were willing to pay P_1 for the service, but now pay only P_2. Clearly, they receive a benefit given by the difference between P_1 and P_2. In addition, new customers in the market (i.e., those consuming the difference between Q_2 and Q_1) also receive additional surplus since these buyers were willing to pay a price higher than P_2 but below P_1.

The second case is illustrated in figure 5.2. Initially, consumer demand in the market is given by D_1. As a result of an improvement in the quality of air travel flowing from a new NDE technology (i.e., an improvement in safety), consumer demand in a market increases to D_2. In this case, consumer surplus is generated because consumers in the market are now willing to pay the higher price for the product, but they are still paying the market price. In this case, consumer surplus increases by the shaded area in figure 5.2 (i.e., the area ABDC).[14]

Estimating consumer surplus in the first case (figure 5.1) requires information on the slope of the consumer demand curve,[15] including an estimate of the price elasticity for air travel services. Price elasticity of demand estimates are available and well-accepted by the airline industry. In the second case (figure 5.2), estimates of the value to consumers of increased safety resulting from the NDE technology are required. Specific examples of how consumer surplus is actually estimated using these data will be provided in future case studies.[16]

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[14] For ease of presentation, it is assumed in this example that the increase in consumer demand does not result in a change in price. In general, this will not be the case, but even if the prices in the market increase, some consumers will receive additional surplus.

[15] This need only be a local estimate for relatively small price changes.

[16] For a confirmation of the empirical process of assigning values to increased utility levels, see Robert D. Willig (1976), "Consumer's Surplus Without Apology," *American Economic Review*, Sept. 1976.

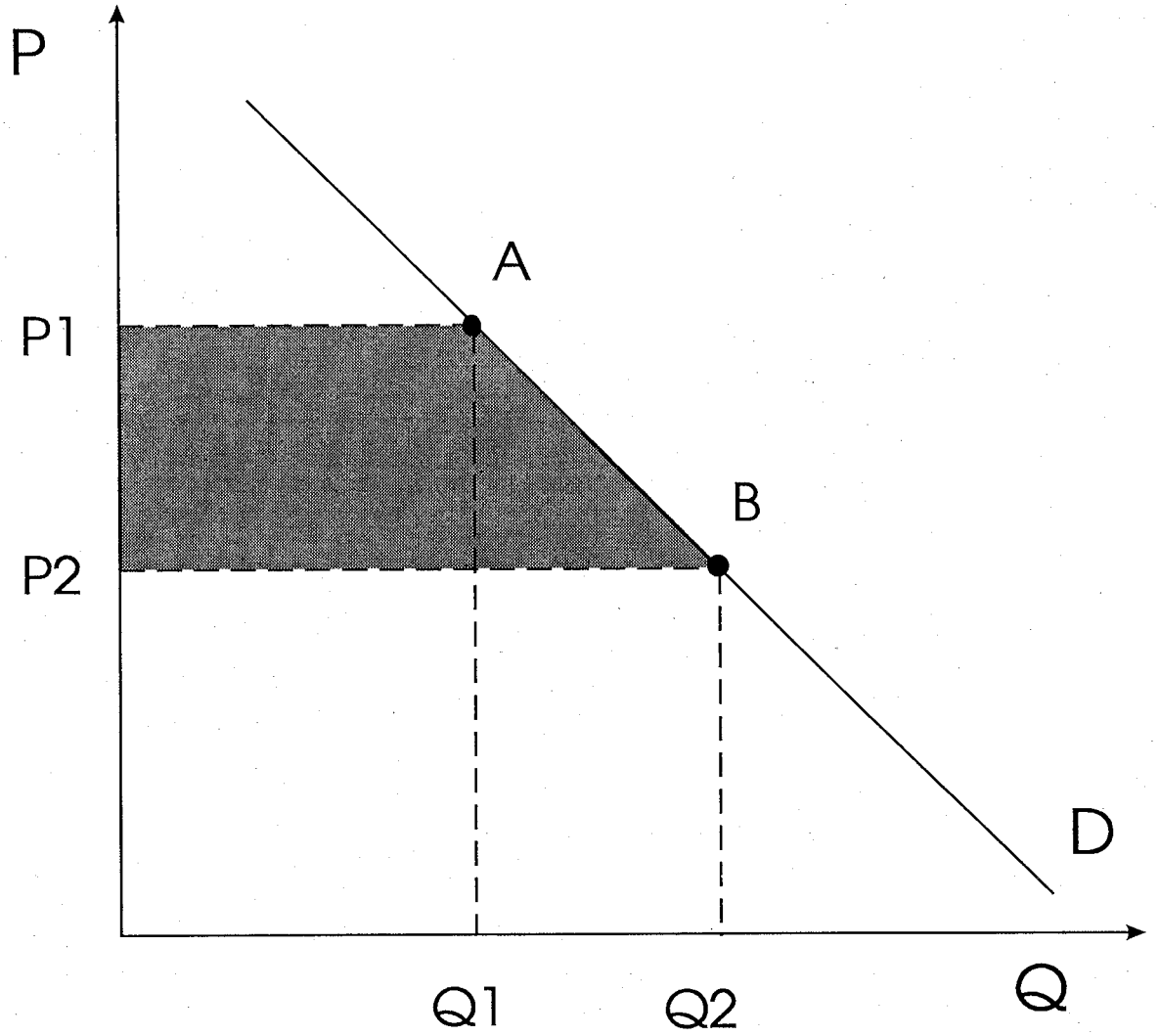

FIGURE 5-1: CONSUMER SURPLUS FROM A TECHNOLOGY RESULTING IN LOWER PRICES

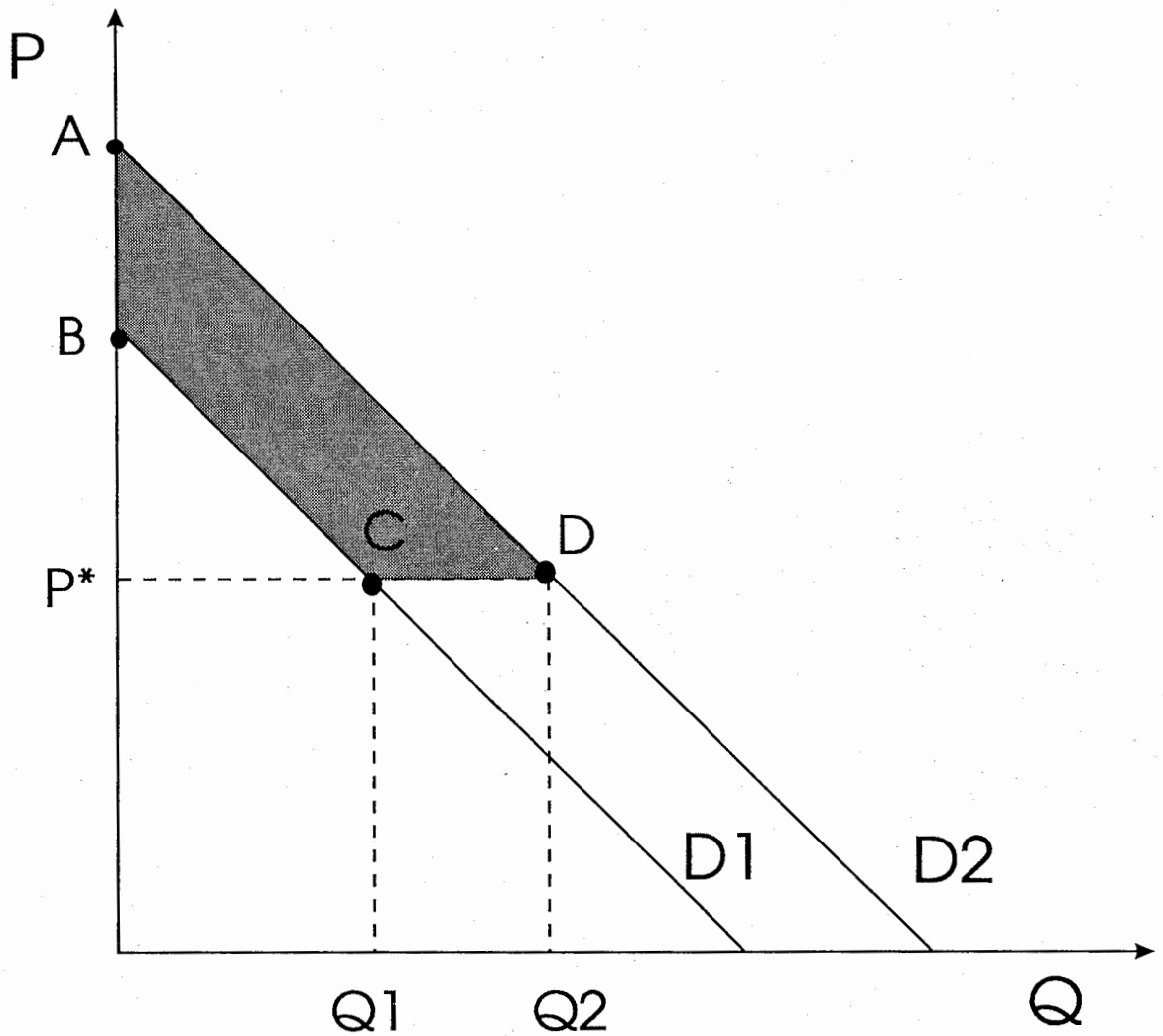

FIGURE 5-2: CONSUMER SURPLUS FROM A TECHNOLOGY RESULTING IN IMPROVED SERVICE

Note: Demand curves, D, D1 and D2 in figures 5-1 and 5-2, are not necessarily linear.

5.2.4 Increase in the Probability of Detection (PoD).

Both airlines and society may benefit from a technique that increases the probability of detecting a flaw in the aircraft structure because of its contribution to improving safety. As was previously mentioned, empirical studies are currently underway that calculate the probability that a flaw will be detected by specific NDE techniques. The results of these studies are used to construct PoD curves which indicate the probability of detecting flaws of varying sizes with a specific technique. The PoD curves convey that a method will detect a certain proportion of the total flaws in the inspection area dependent on the size of the flaw.

If the PoD of the a technique is greater than that of the existing technique, then it seems likely that both the airlines and society will benefit from improved safety. This benefit can be measured by the variables in the following relationship:

Equation 5.3: *Relationship Between Probability of Detection and the Expected Cost of Accidents*

$$PoD \xrightarrow{-} PoA \xrightarrow{+} E(CA)$$

where	PoD	=	probability of detection
	PoA	=	probability of an accident occurring
	CA	=	cost of accident
	E( )		signifies expected value
	→		signifies causality
	+		signifies a positive relationship
	-		signifies a negative relationship

If the probability of detection increases, it follows that the probability of an accident occurring should decrease. This will in turn lower the expected cost incurred from future accidents.

In order to estimate the cost of accidents averted by using inspection techniques with better detection capability, the following three parameters must be known:

(1) the cost of future accidents
(2) the relationship between the PoD and PoA
(3) the relationship between the probability and the cost of an accident occurring

The cost of future accidents depends on the value of the loss of aircraft equipment, the value of injuries and the loss of human lives, the cost of third-party damage, and the cost of the accident investigation. The loss of equipment, the extent of third-party damage, and the investigation costs can be estimated with the use of historical data on accidents from the NTSB or National Safety Council. The FAA has constructed estimates of the value of human life and injuries that can be used to determine the value of injuries and fatalities. The cost of future accidents is adjusted by the probability that they will occur in order to provide the expected cost of future accidents.

The third parameter is the relationship between the probability of detection and the probability that an accident will occur. In equation 5.3, it is assumed that an increase in the PoD will decrease the PoA. While there is widespread agreement that this is a plausible assumption to make, there is no existing model in the literature that precisely defines this relationship. Without a model, it is impossible to quantify the relationship.

In conclusion, it is impossible to precisely determine the monetary impact of improved safety in this analysis because there is a missing link in the relationship between PoD and PoA in equation 5.3. Although the value of improving safety by increasing the PoD in an inspection procedure cannot be measured directly, an indirect method of calculating the value of improved detection to the airlines does exist and has already been suggested in this report (see section 5.2.1). The establishment of frequency intervals for inspection is determined by the PoD of the inspection technique employed. Therefore, the cost saved by conducting less frequent inspections when using a technique with a higher PoD can serve as an alternative method of measuring the value of improved PoDs.

5.2.5 External Benefits.

External benefits reflect any downstream benefits from the new technique received by individuals or institutions that do not participate directly in the market. These may include the net spillover benefits to other industries from broad-based NDE technology advancements. NDE is already considered an important technological advancement in the nuclear power and defense industries. It may also prove to be particularly useful to use in infrastructure maintenance, e.g., bridge inspections, and in other transportation areas.

The ability to measure such benefits will depend greatly on the availability of data. It is difficult to be specific about how to estimate the value of spillovers to other industries of advancements

made in NDE technology for aircraft inspection. Data availability on the impacts of technology spillover has to be assessed on a case-by-case basis.

5.2.6 Long-Term Benefits.

A final consideration in the discussion of benefits is the impact of increased use of NDE technology in the long run and its contribution to improving aircraft maintenance practices. The increased acceptance and further development of NDE technology within the airline industry may well alter the way aircraft maintenance is performed. In section 1.1, it was suggested that the shift to the damage tolerance philosophy as a basis for aircraft maintenance can be seen as a shift towards a more efficient allocation of resources. The emphasis is transferred from redundancy to inspection in order to gain more information regarding the integrity of specific aircraft. The immediate result is aircraft that are lighter weight with lower fuel burn, emitting less pollution, with an assured life. NDE technology is an application of the damage tolerance philosophy that can cause the efficiency implications to be even more far-reaching.

A fully developed NDE system could provide a better indication of the "true" state of the structural integrity of a specific aircraft. This can in turn affect the maintenance procedures by creating more specialized maintenance plans for each individual aircraft type. The result may be lower long run maintenance costs by causing detection of flaws at an earlier stage when they are less damaging, less costly, and easier to fix. Near-term finds of smaller flaws can also be more expensive economically because they occur earlier and therefore more frequently over the fixed life of an aircraft.

With more reliable inspection techniques, the frequency intervals between mandatory inspections could be relaxed and determined by the condition of the aircraft rather than by the fleetwide criteria currently established by the manufacturers and the FAA. This could result in a decrease in the number of inspections necessary overall or at least lead to a method of scheduling inspections that reflects the specific needs of the individual aircraft. These effects on maintenance practices and inspection intervals can eliminate some of the inefficiencies that are caused by redundancy and lack of foresight regarding maintenance.

In some cases, a more thorough maintenance and inspection plan can actually extend an aircraft's life by attracting attention to flaws before they can have a destructive effect on other parts of the aircraft. In fact, it is the opinion of many aircraft engineers that the lifetime of a given aircraft is indefinite if it is properly maintained.

A more complete profile of the structural integrity of the fleet of aircraft through the use of NDE technology may also help airlines in planning future repairs and retirement of aircraft. Advanced scheduling decisions could be made with regard to future maintenance needs, and a more accurate prediction of the lifetime of the aircraft could be made. This type of foresight would aid greatly in the development of a more efficient system for allocating aircraft and scheduling aircraft downtime.

Also, NDE could aid in the future development of models of fracture mechanics for aircraft structures. The data that are collected by improved inspection techniques may generate a more accurate depiction of, for example, the growth path of corrosion or the relationships between different types of flaws. New models may become available for approaching the problem of multiple-site damage. More accurate monitoring of flaws can advance the stock of technological knowledge greatly.

There is much uncertainty regarding the realization of the benefits listed in this section. Therefore, it is not advised that estimation of their monetary value be pursued. They are presented here as possibilities, and their feasibility must be examined in the context of the specific technology under investigation.

5.3 UNCERTAINTY ISSUES.

It is evident that many of the costs and benefits discussed in this section are based on estimates and assumptions. Since, in many cases, there is currently no market operating for the new NDE equipment or for the personnel required to operate the new NDE techniques, it is difficult to be certain about the figures necessary for estimation. A working prototype of a new NDE technique will enable many of these parameters to be addressed with more certainty. As markets develop for the equipment, price will be driven downwards. As the techniques begin to be used on the line and in the hangar, personnel allocations will be tested and refined.

At this stage of the analysis, there is a necessity for many assumptions to be made regarding costs. This is often the case in cost-benefit analysis, and it should not deter an analysis of this nature. Uncertainty can be addressed and educated estimations can be made regarding the costs associated with NDE technology.

In any analysis that includes uncertain factors it is, therefore, necessary to address the sensitivity of the NPV results to uncertainty. It is convenient to divide the parameters of the model into three categories:

- Category 1: Parameter values are considered to be accurate and future uncertainty is considered very unlikely to alter these values

- Category 2: Exact parameter values are difficult to pinpoint, but the probability that the parameter may take on certain values is known

- Category 3: Exact parameter values are difficult to pinpoint, and the only indication that can be deduced is a range of possible answers, but with no known probabilities

In these three categories, the level of uncertainty increases with the category number. Different levels of uncertainty must be addressed in a different fashion. A description of the type of sensitivity analysis that is required for each of the above categories follows.

5.3.1 Known Parameter Values.

Clearly, the parameters that fall into category 1 will be represented strictly by values considered to be accurate. Factors that fall into this category are those that are currently observable and can be measured with a high degree of certainty. No adjustments need be made for uncertainty in this case. Full forecasting for expected future events should accompany the projection of future costs and benefits. (Recall that all measures are made in constant dollars, so inflation is not a concern here.)

Examples of parameters that fall into this category may be found in some of the costs or benefits to the techniques that are currently in use, i.e., the "base case" figures. The data for these techniques can be observed with a minimal level of uncertainty by examining the current work practices in the aviation industry.[17] For example, the wage rates received by NDE inspectors and visual inspectors are well defined and are clearly observable. These parameters can be measured with a high degree of certainty.

[17] There may be some deviation in these parameters based on varying work practices or accounting methods. See section 5.4 for a discussion of diversity in observable parameters.

5.3.2 Risk Analysis.

Category 2 includes parameters that may vary, but with a known probability distribution. The analysis of these variables is called *risk analysis*. The probability distributions can be either objective, i.e., based on data from past sources (the labor time it currently takes for inspections, for example), or subjective, i.e., judgments made based on expert opinions (the labor time it will take to perform inspections with the new techniques, for example). Both of these types of distributions are treated in a similar fashion. The mean values and statistically relevant ranges can be measured by the probability distribution for each of the risk parameters. Reutlinger (1970) recommends that these individual probability distributions be aggregated to yield one probability distribution for the NPV. Therefore, a mean value with confidence intervals can be calculated for the overall NPV. The robustness of the results can be evaluated by examining the probability that the NPV will be positive or negative.

5.3.3 Uncertainty Analysis.

In the most uncertain case, category 3, some plausible values or ranges for the parameters may be known, but no probability distribution can be assigned. Therefore, an analysis of the sensitivity of the NPV to these variables cannot include confidence intervals. This is referred to as *uncertainty analysis*. This situation may occur when there are a variety of possible outcomes that are uncontrollable, such as changes in federal legislation or changes in work practices as negotiated with labor unions. Parameter values can be chosen under a variety of scenarios, but the prevailing scenario cannot be predicted with any certainty or known probability.

With plausible values and/or ranges being the only source of information, there are a number of directions that the analysis can take. First, a one-variable test examines the effect on the NPV of changing the value of one uncertain variable while holding all other variables constant. This will show how sensitive the model result is to the uncertainty of one variable. If the NPV is positive regardless of the value of the uncertain variable, the result is not sensitive to the value of that specific parameter. In this case, the results can be considered robust only with respect to the one uncertain parameter.

A variation of the one-variable test is to calculate a "switching value" for each uncertain variable. This is the value that the variable must take in order for the NPV to be equal to zero. If the "switching value" is considered to be within the feasible range of values for the uncertain variable, then the results are not particularly robust with respect to the uncertain parameter. While one-variable tests are not all encompassing in that they hold all other uncertain variables fixed, they give an indication as to how sensitive the NPV figure is to each uncertain variable.

The infinite number of combinations of values generated from varying all uncertain variables causes this procedure to be valid only when performing a one-variable test.

It may be appropriate to shift certain combinations of variables to examine the effects they jointly have on the NPV. For example, as a result of performing a one-variable test as described above, it may be concluded that there is a continuous relationship between the value of an uncertain variable and the NPV (holding all other variables constant). This relationship can be represented by either of the curves in figure 5.3.

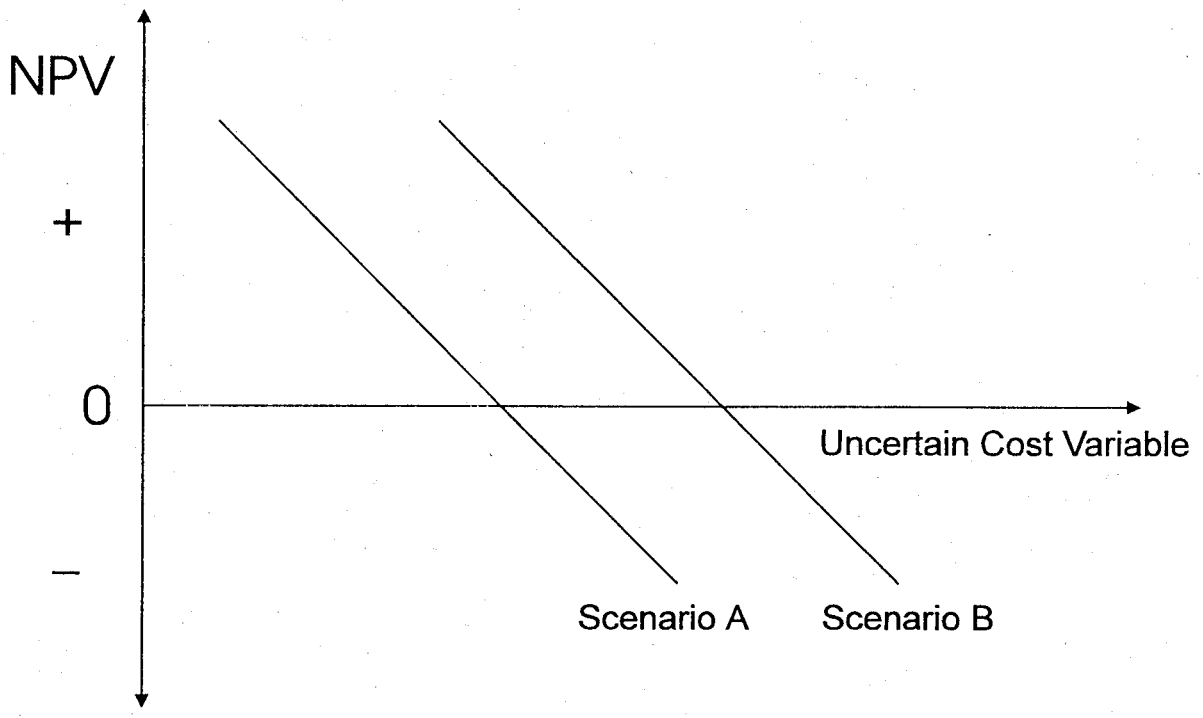

FIGURE 5-3: *TWO-VARIABLE SENSITIVITY TEST*

- Scenario A - Current personnel allocations are retained and NDE technicians perform all inspections.

- Scenario B - New personnel allocations are applied utilizing cross-trained general inspectors and mechanics for some NDE functions.

If another uncertain parameter is allowed to vary discretely, a set of curves will develop--one curve per discrete value that is chosen for the second variable. This two-variable test allows a family of curves to be developed, as depicted in figure 5.3. Each curve gives the possible combinations of NPV and an uncertain parameter. The different curves represent different values of a second uncertain parameter. This type of analysis is particularly suitable for the sensitivity analysis of a combination of variables where one can only take on certain values, while the other can vary continuously. For example, figure 5.3 examines an hypothetical relationship between the NPV and a continuous, uncertain variable under two different work-practice scenarios.

This test can be expanded to a three--or more--variable test, although this becomes more difficult to present graphically. Nevertheless, rapid advancements in micro-computer technology allow economists to vary a large number of variables at a time in many different combinations. Random sensitivity testing is not advised, though, as it is not thought to yield fruitful data and may result in the "discovery" of some spurious relationships. Relationships between variables should be recognized and based on some type of sound economic reasoning before their combined effect is included in a sensitivity analysis.

The final approach to uncertainty analysis is to allow all parameters to vary in a predetermined fashion, i.e., to develop a number of scenarios that may be of interest and assign values to all uncertain parameters. The best-case scenario examines all uncertain variables at the most optimistic level. The worst-case scenario examines all uncertain variables at the most pessimistic level. The most-likely scenario chooses the values that are most likely to occur. These three scenarios can be combined to yield a "pseudo" mean and a "pseudo" range of possible values. The robustness of the results can then be judged by examining the range of possible NPVs when uncertainty of all parameters is taken into account.

Clearly, the methods used for uncertainty analysis rely heavily on subjective opinions. These are important not only in the selection of the criteria used in the analysis, but also in the evaluation of the analysis. It will be necessary for as many knowledgeable individuals as possible to reach a consensus on the selection of sensitivity tests and whether the empirical evidence is sufficiently robust.

5.3.4 Risk Premium Approach.

Recall that one of the functions of the discount rate is to account for the risk involved in making an investment (see section 2.4). It is rational to require higher rates of return for riskier investments. Hence, it may be appropriate to include the discount rate in the analysis of risk. Specifically, a higher discount rate will reflect a higher level of risk. The addition of a "risk-

premium" onto the discount rate will decrease the future net benefits in order to take account of the level of risk.

The use of the *risk premium approach* as a means of accounting for risk entails an estimation of the expected value of the risk premium, which is a difficult factor to measure in practice. However, this is not necessarily the most problematic element of the risk premium approach; there are two others. First, a time frame is imposed on the risk, which may not be entirely compatible with the profile of the risk. For example, the risk involved with an investment in a new technique generally tends to decrease and may disappear as time passes and more is known about the capability of the technique. Second, if the risk premium is related only to the costs of applying the technique, it discounts future costs, which has the opposite effect of increasing the cost of the investment. It decreases the value over time. Therefore, while the risk premium approach is appealing, it does not produce consistent results and its use is not recommended.

5.4 AGGREGATION ISSUES.

It is evident from the above discussion that the analysis for measuring costs and benefits described in sections 2 and 3 may not yield a specific value but rather a range of possible values. The diversity in NPV figures may not only be attributable to uncertainty, but also to heterogeneity. For example, the collection of "base case" data which are observable and considered to be measured with a high degree of certainty may yield a variety of parameter values.

The large number of aircraft operators in the industry and varying work practices suggest that the collection of observable data may yield diverse figures. Airlines have different fleet profiles and have developed routines of maintenance and inspection to serve the specific needs of their fleets. Also, some airlines may perform limited inspection and maintenance in house, opting to send it to third-party maintenance facilities. Some of the preliminary evidence suggests that the cost of inspection varies widely between airlines and third-party maintenance facilities as well as within these two groups.[18] Collecting a full set of data for all operators would be an arduous and expensive task. Therefore, some form of aggregate analysis will be necessary.

A total aggregation of data from all airlines, i.e., using industry average values, would not yield particularly helpful results. All airlines in the industry can be viewed as falling either above or below the industry average. Each individual airline will need to perform its own analysis in order to determine where they are in relation to the industry average. An analysis which

[18] See the *World Aviation Directory* (1991) for the maintenance costs of individual airlines.

aggregates values yields little explanatory power unless the aggregation is based on specific characteristics of the airlines.

It is therefore advisable to develop some representative groups of airline characteristics which can serve as a benchmark for comparison. Operators may differ in the frequency of the inspections they perform and in some cases, the types of inspections they perform. For example, some operators may find it more economical to simply perform the "termination order" (i.e., do the required maintenance regardless of the detection of flaws) on a required inspection rather than continuing the inspections. It was already suggested in section 5.2.1 that the costs of inspection should be examined on a "per inspection" basis. This is necessary to compare the costs of a standard level of inspection. It will also be necessary to disaggregate further to examine other factors that affect cost.

The representative groups may be characterized by the type of inspection performed, the type of aircraft on which the inspection is to be performed (age, size, model, manufacturer), the weather conditions to which the aircraft are exposed, and the working practices of the airline. A collection of the representative groups can be established and NPVs can be calculated for a variety of different cases. This will result in a matrix of NPVs which makes the analysis useful to a number of different airlines with varying characteristics.

6. CONCLUSIONS

This report has presented a methodology for the economic assessment of NDE advancements in aircraft inspection. The methodology is based on the principle of cost-benefit analysis, a well-established economic tool for making investment decisions. This report has outlined areas where NDE advancements could have a significant economic impact on both the airline industry and society. It has also addressed the practical problem of obtaining the data that is necessary to apply the methodology. It acknowledges that some of the relevant factors are not measurable and some subjective data will have to be examined regarding the impact of these factors. Finally, this report has addressed the issue of heterogeneity in aircraft maintenance practices.

The analysis presented in this report can have three possible outcomes:

Outcome 1: The net present value to an individual firm of an investment in a new technique is calculated to be positive

Outcome 2: The net present value to an individual firm is calculated to be negative, but the social assessment yields a positive net present value

Outcome 3: Neither the private nor the social assessment generate a positive net present value

If outcome 1 occurs, it would clearly be rational for the aircraft operators to invest in new equipment that is projected to generate net benefits over its useful life. Therefore it is expected that the operators would make the appropriate investments. In the event that this does not occur, there should be some investigation into the potential for market failures in this area. If the second outcome occurs, the operators may not find it economically beneficial to invest in the equipment, but the societal benefits outweigh the costs. In this case, it may be warranted for the public sector to be involved by encouraging the development and use of NDE equipment by the aircraft operators.

The third outcome is not as clear cut and requires some judgment. If neither the private nor social net benefits are sufficient, it may be concluded that the technique is not a good investment, but there are some reasons to further investigate the technique. First, it may be that the technique needs further development to enhance its cost-effectiveness or that its proper application has not yet been found. Assessment of the individual technology's future capability and the industry's future needs are required to make this judgment. Second, it is possible that the positive factors that can not be quantified outweigh the negative returns. In this case, the degree of the negative

NPV should be compared with the qualitative benefits and an assessment of the technique should be made on this basis. Finally, it may be the case that regulations are expected to change in the near future and this change may cause a future reevaluation of the potential costs and benefits.

This report addresses the question of whether the benefits outweigh the costs of using a new NDE method. Several of the benefits listed in this report cannot be currently measured with a high degree of certainty, and some are not even approachable by uncertainty analysis. Benefits with such far-reaching and long-term implications can rarely be quantified before their occurrence. Therefore, this report has concentrated on the short-run cost implications of NDE technology.

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