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Validation of the Magneto-Optic/Eddy-Current Imager

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Final Report

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16. Abstract

This report details the validation analysis of PRI's Magneto-Optic/Eddy-Current Imager (MOI). The analysis includes both a reliability analysis of the system and an economic analysis of the potential benefits and costs related to its use.

The reliability analysis consisted of blind inspections of well characterized panels simulating a fuselage lap splice. The panels contained cracks of known sizes emanating from under rivet heads on the upper row of rivets. The MOI inspection times were less, on average, than were inspection times using a sliding probe. Twenty percent reduction in inspection times is consistent with the data obtained and is used as a baseline for the economic analysis.

The economic analysis considers the effects of individual factors that contribute to the cost effectiveness of the MOI. The possible returns on the investment for a representative maintenance facility are calculated using the net present value methodology. Specific characteristics are defined for the representative facility, and then they are varied to account for the differences in the maintenance community.

For a facility which can take full advantage of the potential time and labor savings associated with implementation of the MOI, the investment in MOI would generate a positive return in less than one year. In this fully competitive scenario the cumulative net present value at the end of the tenth year would be over $160,000. Under a semi-competitive scenario, the net present value is negative throughout the life cycle of the investment.

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PREFACE

In August 1991, a major center with emphasis on validation of nondestructive inspection (NDI) techniques for aging aircraft was established at Sandia National Laboratories (SNL) by the Federal Aviation Administration (FAA). This center is the Aging Aircraft Nondestructive Inspection Validation Center (AANC). It resides at the Albuquerque International Airport in a hangar leased from the City of Albuquerque, New Mexico. The FAA Interagency Agreement, which established this center, provided the following summary tasking statement: "The task assignments will call for Sandia to support technology transfer, technology assessment, technology validation, data correlation, and automation adaptation as on-going processes."

An initial activity of the AANC was to establish a framework for the validation of NDI processes. The approach was keyed to various development phases of an NDI system. The validation process explicitly recognizes that reliability assessments are not the only issue in implementing any new NDI technique or process and that associated implementation costs are also of importance.

The AANC is working with the Transportation Center at Northwestern University to develop a generic cost-benefit model that can readily incorporate new NDI processes. That document will be published as a Department of Transportation document entitled "A Practical Guide to Measuring Costs and Benefits of NDE Techniques Used in Aircraft Inspection."

The Magneto-Optic/Eddy-Current Imager (MOI) is an NDI technique first introduced in 1990. The intent of this document is not to market the MOI, but to provide decision making criteria for the OEMs (transport, commuter, general aviation), airlines, and maintenance facilities as to whether this NDI technique will provide benefit to them

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EXECUTIVE SUMMARY

The validation work on the Magneto-Optic/Eddy-Current Imager (MOI) presented here includes a reliability assessment as well as an economic analysis of benefits and costs related to its use. The following highlights the findings of both portions of the validation.

The MOI was used for inspections as part of an experiment designed to assess the reliability of detecting a crack originating within fastener holes in thin aluminum structures. The inspections were performed in aircraft maintenance facilities by nondestructive test (NDT) personnel. The resultant probabilities of detection as a function of crack length for the MOI were comparable to the values obtained for sliding probe eddy current inspections.

The angle that a crack emanates from the rivet hole influences detection rates. A 90 percent detection rate was achieved for 0.079 inch cracks that were horizontal (in the direction of scan). The same detection rate was achieved for 0.095 inch cracks, when the cracks were as much as 22° off-horizontal. The stated crack lengths are as measured from the rivet shank. There is no indication that the noted effect of the angle direction on detection rates is a limitation of the MOI technology as opposed to an inspector "bias" that could be addressed in procedures and training.

The MOI inspection times were less, on average, than were inspection times using the sliding probe. Twenty percent reduction in inspection times is consistent with the data obtained and is used as a baseline for the economic analysis. Inspection time savings of the MOI compared to eddy current template procedures would be even greater. The possibility of a greater time savings is addressed in the sensitivity analysis of the economic analysis assumptions.

The economic analysis considers the effects of individual factors that contribute to the cost-effectiveness of the MOI. The possible returns to the investment for a representative maintenance facility are calculated using the net present value methodology. Specific characteristics are defined for the representative facility, and then they are varied to account for the differences in the maintenance community.

Different scenarios are analyzed in the economic analysis. Included are a *competitive scenario* and a *semi-competitive scenario*, with a concentration on the *competitive scenario.* This scenario is defined as a facility where productivity improvements and decreased aircraft downtime derived from faster inspection techniques are realized and a lower training requirement is observed by cross-training of inspectors. The analysis focuses on inspection procedures that are currently approved and practiced by the industry where the MOI has been identified as a viable inspection method.

The assumption of the competitive scenario has a strong impact. Not only does the investment in the MOI generate a positive return in less than a year under the competitive scenario, savings are also generated over the life cycle of the investment. The result is a cumulative net present value at the end of the tenth year of $160,787. Without the assumption of a competitive scenario, the net present value is negative throughout the life cycle of the investment.

In the sensitivity analysis, it is discovered that the most influential factor on the economics of the MOI is the proportion of the inspection time savings that can be transferred to decreasing aircraft downtime. If the time savings achieved with the MOI can be implemented in the inspection schedule to achieve at least a 10 percent decrease in aircraft downtime, then the investment in the MOI is cost-effective for the representative facility. This assumes that there is no need to strip paint on the aircraft.

Even if inspection time savings are not transformed to decreased aircraft downtime, if the MOI allows for the elimination of the requirement to strip paint on one or more aircraft then it would be a cost-effective investment. Other factors that impact the decision to invest in the MOI are the degree to which the MOI can enable faster inspections and the number of inspections for which the MOI is applicable.

Potential purchasers of the MOI should compare their circumstances to the assumptions used in the economic analysis and reported in detail in section 3.

1. INTRODUCTION.

A brief description of the Magneto-Optic/Eddy-Current Imager (MOI) instrument is given in section 1.1. This is followed by a discussion of aircraft applications that are covered by procedures from transport aircraft manufacturers. Section 2 presents reliability assessments of inspections performed with the MOI, both in the laboratory and at airline maintenance facilities. To complete the validation exercise a cost-benefit analysis of employing the MOI is presented in section 3. A summary of the reliability findings is given in section 2.3 and a summary of the economic analysis is given in section 3.6.

1.1 DESCRIPTION OF MOI.

The MOI instrument consists of a hand-held imaging scanner head, a power unit, a video monitor, and 30 feet of interconnecting flexible cables. The imaging head weighs approximately 3 pounds and contains the eddy-current inducing system, a magneto-optic sensor, and a camera.

The MOI images result from a Faraday magneto-optic sensor response to weak magnetic fields that are generated when MOI induced eddy-currents interact with defects in the inspected material. Images appear on the sensor and can be viewed directly. However, the usual operation mode is to use a small charge-coupled device (CCD) camera located inside the imaging unit for remote viewing. In this mode, the operator views the image on the video monitor while moving the imaging head continuously along the area to be inspected.

The MOI produces video images in real time that show flaw-induced irregularities and inconsistencies in the inspected material. In contrast to conventional eddy-current methods, the images loosely resemble the defects that produce them. This makes the interpretation of the results more intuitive than the interpretation of traces on a cathode ray tube (CRT) screen. Since the image is in a video format, it can be recorded for inspection documentation.
The present implementation of the magneto-optic/eddy-current imaging technology uses a 3-inch diameter sensor and is designed to provide an image of a relatively large area (approximately 7 square inches) compared to that covered by an eddy-current probe. This capability makes the technology appropriate for large, flat or slightly convex, unobstructed areas such as an airplane fuselage, wings, and control surfaces.

Images are formed when defects or other obstructions such as rivets or holes divert the otherwise uniform flow of induced electric currents near the surface of the test piece. This diversion of eddy-currents creates weak magnetic fields perpendicular to the surface of the test piece. These weak magnetic fields are imaged in real time by the magneto-optic eddy-current imager. Since alternating current is used to excite the inspection area, only half of the image is generated during each half of the cycle of applied current. The current-switching process occurs so rapidly that the image appears complete to the inspector. The images of rivets and holes appear as the head of a slotted screw. The "slot" results from a null region of the overlay of the two half images.

The instrument is capable of inducing currents in a frequency range of 1.6 to 102.4 kHz. For typical aircraft aluminum, the depth of penetration for these frequencies is 0.12 to 0.015 inch, respectively. At the higher frequencies, the MOI can be used to image and detect fatigue cracks near rivets in the field of view in the outer surface of aluminum aircraft skins. Although images more diffuse and less sharply defined than surface cracks result, at lower frequencies the instrument can image some subsurface cracking and corrosion in aluminum.

The MOI technique is relatively insensitive to the effects of lift-off. However, maintaining contact with the test surface helps achieve the highest quality images. Thus, decal and paint removal are not necessary unless the thickness is excessive.

Figure 1.1 shows the MOI being used in a simulated lap splice inspection. Additional information on the MOI can be found in references [1- 5]. A more technical presentation is given in [3] and the references contained therein.

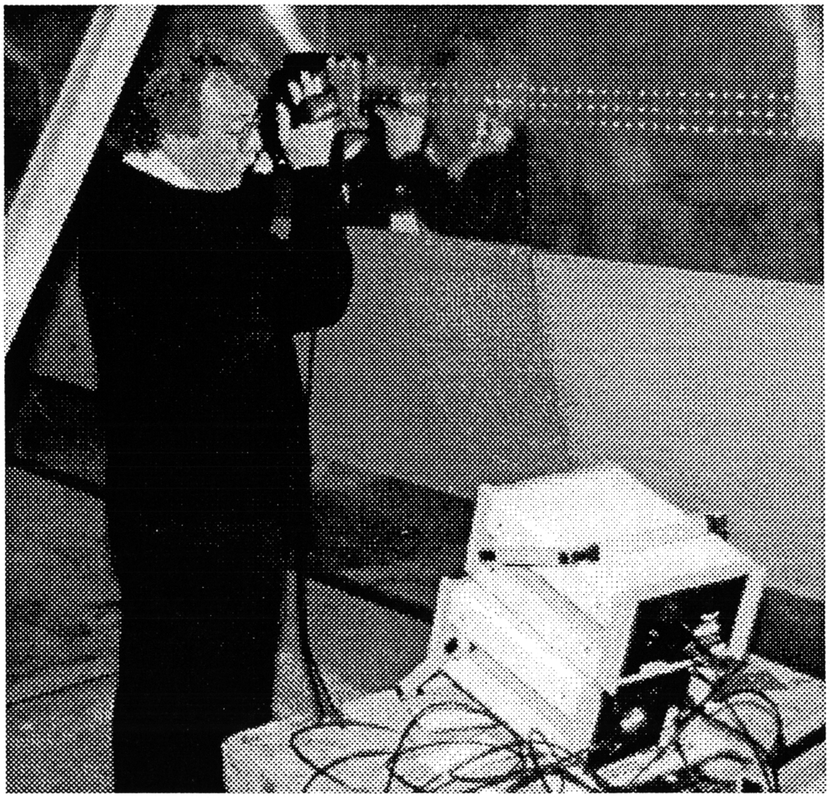

FIGURE 1.1 THE MOI BEING USED IN A SIMULATED LAP SPLICE INSPECTION

1.2 MOI APPLICATIONS.

In April 1992 Boeing published the procedure "General Surface Inspection of Aluminum with the Magneto-Optic Imager (MOI)" with effectivity covering all models [6]. The stated purpose of the procedure is "to find surface cracks on flat or convex aluminum structure with the use of the Magneto-Optic Imager (MOI). Cracks to be found are those that extend more than 0.060 inch (1.5 mm) farther than the heads of countersunk fasteners." (Note: Crack lengths used in characterizing reliability in this report are measured from the rivet shank -- not from the edge of the rivet head.)

The McDonnell Douglas Corporation has included an MOI inspection procedure in their Standard Practices Manual. The stated purpose is for surface crack detection on aluminum structures with flat and slightly convex surfaces only. The procedure states: "This eddy-current imaging procedure is used to detect surface cracks that extend 0.125 inch or more from under the heads of flush head aluminum fasteners where the inspection area is large, involving many fasteners"[7].

Lockheed has included the MOI as an inspection technique suitable for inspecting the upper surface wing vent stringers 9/10 on the L-1011[8].

The surface crack inspections for which the MOI has been approved in Boeing and McDonnell Douglas general procedures have traditionally been done using eddy-current methods with either a sliding probe or with template and pencil probe. Both McDonnell Douglas and Boeing procedures for surface crack detection using the MOI call for the removal of paint (or other nonconductive material) if the thickness exceeds 0.015 inch. Paint removal is not required for the sliding probe and template procedures as long as the rivet heads are visible.

Because of the MOI's ability to inspect for cracks without actually viewing the rivet head and its easy-to-read image, there is a potential for faster inspections and less aircraft preparation before an inspection. These issues will be addressed in section 3 where the results of a cost-benefit analysis are given.

Along with the general procedures discussed above, McDonnell Douglas has approved the MOI as an alternate means of compliance for DC-10 Supplemental Inspection Document (SID) inspections in several areas; 57-20-01, 57-20-04 (wing), and 53-30-02 (fuselage). These (and other) mandated inspections will be considered as ingredients to the cost-benefit analysis of section 3.

There are no currently approved applications of the MOI for corrosion or subsurface crack detection. A feasibility demonstration for using the MOI for corrosion detection has been reported [9]. The MOI developers are currently working with the FAA and aircraft manufacturers to extend procedures into these areas.

2. MOI INSPECTION RESULTS.

In this section, inspection results from three laboratory and fourteen field inspections are presented. The background for the experiment and a discussion of the test specimens used to gather inspection data are described in section 2.1. An analysis of the data and the resultant probability of detection (PoD) curves are given in section 2.2.

All the inspection data were gathered as blind experiments. The intent of the laboratory inspections was to gather data with qualified inspectors while minimizing the effects of possible performance influencing factors, such as light, noise, and time pressures. On the other hand, the field data were gathered with the inspections being located in the hangar environment while simulating routine inspections. The comparison of field data to laboratory data is reflective of the influence of a multitude of factors, such as training, experience, and environmental influences.

2.1 EXPERIMENT BACKGROUND.

The field data are from inspections performed at the American Airlines maintenance facility in Tulsa, Oklahoma; Dalfort Aviation in Dallas, Texas; and the United Airlines maintenance facility in San Francisco, California. The field data for the MOI was taken in conjunction with the eddy-current inspection reliability experiment (ECIRE) described in reference [10]. Two consecutive weeks was spent at each of these three facilities gathering inspection data.

2.1.1 Flaw Statistics.

Two types of test samples were used in the experiment. One type was 20- by 20-inch panels that could be moved and presented differently for each inspection. The second type of specimen was large panels that were produced with all the structural components found on an aircraft fuselage. Each type is explained more fully in reference [10], where the nature of the flaws in each type of specimen is also discussed. A brief summary of the specimen flaw statistics is given here for each type of specimen.

Forty-three specimens of the first type were fabricated. Thirty-six of them were used in the field portion of the experiment. The remaining seven were built as backups in case of field damage. However, it was not necessary to employ them during the field experiment. They are, however, included in the laboratory inspection data discussed in section 2.2.1. The cracks in these panels were propagated through cyclical loading on the upper skin, before assembling the lap splice.

Some of the cracks emanated from the left side of the rivets, some from the right side, and some from both sides. The cracks were horizontal, 11 degrees off-horizontal, or 22 degrees off-horizontal. The cracks that were off-horizontal could be either above or below horizontal. Table 2.1 summarizes the attained crack characteristics for the 20-inch lap splice skin specimens. For the off-horizontal cracks, the left (L) -- right (R) pairing in the table reflects the pairing that would occur within any given specimen. That is, if the left cracks were down from horizontal, then the right cracks would be up and vice versa.

TABLE 2.1 *CRACK DISTRIBUTION BY LENGTH AND DIRECTION IN SKIN SPECIMENS.*

	Crack direction										
	horizontal		11 degrees				22 degrees				
			up	down	down	up	up	down	down	up	
Crack Length* (inch)	L	R	L	R	L	R	L	R	L	R	Totals
0 to 0.02	2	1				1	(1)		(1)	1 (1)	5 (3)
0.02^+ to 0.04	4 (2)	5 (1)	1	1 (2)	1 (2)	(1)		1 (1)	3	2 (1)	18 (10)
0.04^+ to 0.06	7 (2)	7 (3)	1	3	(2)	1 (1)	1 (1)	1 (2)	2	4	27 (11)
0.06^+ to 0.08	5	4		1	(1)		(1)	2 (1)			12 (3)
0.08^+ to 0.10	9	8 (1)	3		2 (1)		1	1		1	25 (2)
0.10^+ to 0.12	8 (1)	6 (1)	1		1		1 (1)	1 (1)	1	1 (1)	20 (5)
0.12^+ to 0.14	3	5	1				(1)		1		10 (1)
0.14^+ to 0.16	3	2					1	2		1	9
0.16^+ to 0.18	3	3	(1)	1		1	1 (1)	(1)		1	10 (3)
0.18^+ to 0.20	1 (1)	2	1	1					1		6 (1)
>0.20	11 (1)	9 (1)	1	1	2	1 (1)	2		2 (1)	1	30 (4)
Totals	56 (7)	52 (7)	9 (1)	8 (2)	6 (6)	4 (3)	7 (6)	8 (6)	10 (2)	12 (3)	172 (43)
second crack	33 (4)	33 (4)	4 (1)	4 (1)	2 (2)	2 (2)	6 (4)	6 (4)	5 (2)	5 (2)	100 (26)

*Crack lengths are measured from the shank of the rivet. ( ) denotes distribution on spare panels.

Along with the lap splice skin specimens, larger test structures that simulated complete aircraft structure were used. These large panels (8 foot by 4 foot) were produced with all the structural components found in an aircraft fuselage. See figure 2.1. Cracks were generated in the panels using a custom designed load machine developed for this purpose by Foster-Miller. The structural test frame provided a bi-axial load (hoop stress and axial stress) that simulated the fuselage loads incurred during aircraft pressurization. The loads were applied in a cyclic manner and the cracks were allowed to initiate as they would in a high cycle aircraft. The distribution of the observed cracks in the full-size panels is given in table 2.2.

TABLE 2.2 *CRACK DISTRIBUTION IN FULL-SIZE AIRCRAFT PANELS.*

	Painted Panel		Bare Panel		
Crack Length* (inch)	L	R	L	R	Totals
0.06^+ to 0.08		3	2	2	7
0.08^+ to 0.10		11	5	1	17
0.10^+ to 0.12		11	2	2	15
0.12^+ to 0.14		8	1		9
0.14^+ to 0.16		7	2	3	12
0.16^+ to 0.18	1	4	2		7
0.18^+ to 0.20		1	1		2
Totals	1	45	15	8	69
Doubles	1	1	6	6	14

*Crack lengths are measured from the shank of the rivet.

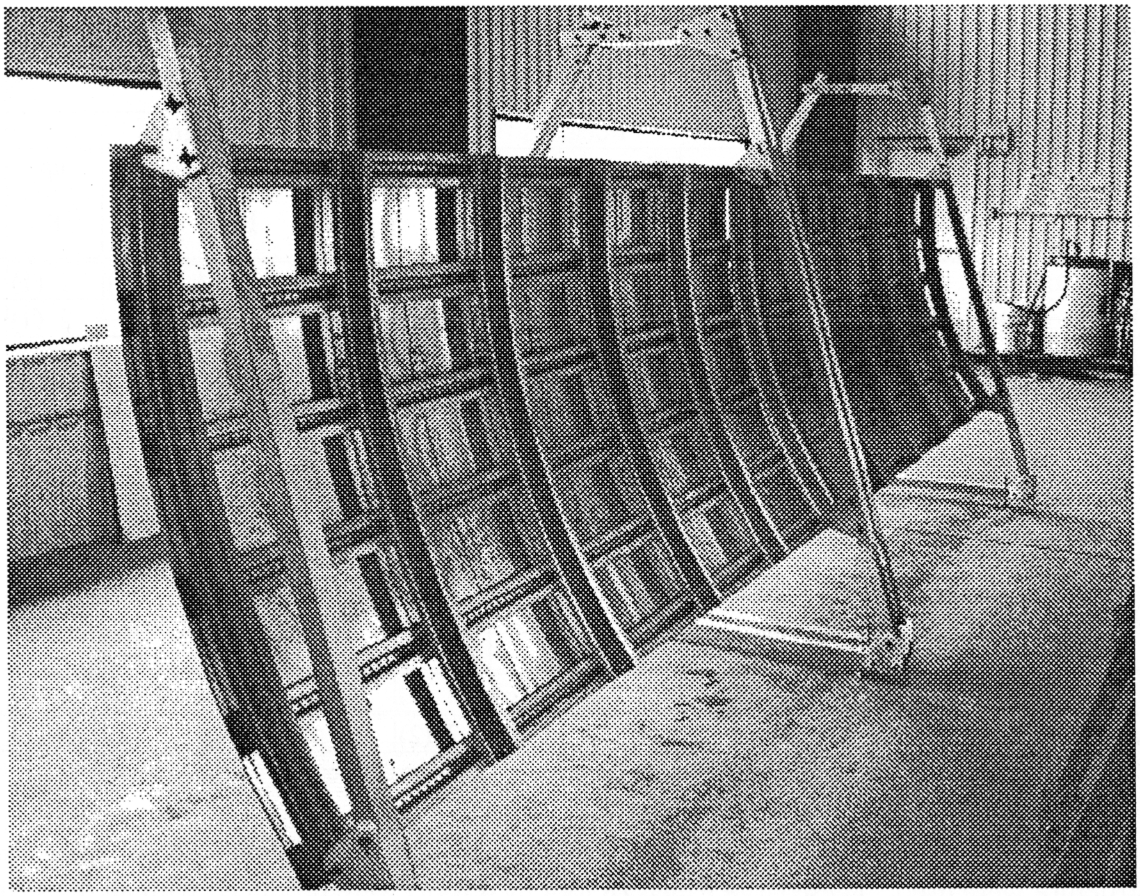

FIGURE 2.1 BACKSIDE OF AIRCRAFT PANELS SHOWING STRUCTURE.

2.1.2 Inspection Protocols.

Both laboratory and field inspections were performed as part of this program. The protocols for performing each of these inspections are discussed below.

Three laboratory inspections were carried out at the FAA's Aging Aircraft NDI Validation Center in Albuquerque, New Mexico. Two of the inspections were performed by trainers from PRI Instrumentation, the MOI manufacturer. The third inspection was performed by an NDI technician from Sandia National Laboratories. These inspections provide a benchmark for capabilities devoid of the facility specific factors that could influence inspectors' performance. Using the PRI trainers to establish a benchmark also removed training on the use of the MOI as an issue.

The forty-three small lap splice test panels and the two large aircraft panels discussed in section 2.1.1 were used for the inspections. The two PRI inspectors were given each of the small lap splice panels in a random order. They scanned each small panel with the panel placed on a bench top. The inspectors verbally made their calls, and a monitor recorded those calls on a check sheet. The same recording process was followed on the full-size aircraft panels. However, these large panels were hung from frames thereby simulating 17 feet of an aircraft fuselage. See figure

2.1. This arrangement required the inspectors to move the MOI equipment and otherwise interact with the inspection in the same way that would have been required on an aircraft. Both PRI inspectors completed the total inspection task within 2 ½ hours.

The third laboratory inspection differed from the first two. The technician performing the inspection worked the inspections into his daily schedule over several days. He recorded his calls directly onto check sheets, without the aid of a monitor.

For all three inspections, the information recorded for a call at a given rivet site consisted of the side of the rivet a crack was observed (R-right, L-left, or B-both) and a confidence rating for the call. The confidence ratings were based on a three-point scale. A rating of 3 was used when the inspector was certain of the crack call. A rating of 2 was used when the inspector was reasonably sure but had some doubt of the crack call. A rating of 1 was used when the inspector had doubts that the call was reportable, but felt that an indication was present. The rating system was to provide data that could be used in comparing false call rates to detection rates through Relative Operating Characteristic (ROC) curves. There was, however, little use of the rating system (see section 2.2.2) and few false calls overall. Therefore, the ROC type of analysis is not presented here.

All three inspectors set up the inspection equipment using the standard provided with the MOI. This standard is fabricated from two 0.040 inch thick 2024-T3 aluminum sheets, and is 6 inches on a side. The two plates are riveted with 0.156 inch diameter rivets. It contains electro-discharge machined (EDM) notches in the top plate of 0.080 and 0.125 inch in length. There is also an EDM notch 0.188 inch long in the bottom plate. All EDM notch lengths are measured from the rivet shank and are 0.010 inch wide.

For the field inspections a one day training course on the use of the MOI was provided for the inspectors at each of the two facilities that had no prior experience with the MOI. The training was provided by a two man team from PRI Instrumentation approximately two weeks before the inspections. The training course work was at a level that the PRI Instrumentation staff felt was adequate to prepare inspectors for field use of the MOI.

Training was not provided at American Airlines. Because the MOI was part of their available equipment, those inspectors were assumed to be qualified in its use. Some of the inspectors at American Airlines had received training through PRI. Others had received on-the-job training.

For the field inspection thirty-six small lap splice test panels and the two large aircraft panels were presented to the inspectors with the test panels mounted on frames. The presentation on the frame was designed to model a total of forty-seven feet of an aircraft fuselage. Thirty feet of this "fuselage" consisted of the small lap splice test panels mounted end-to-end in an upper and lower row (figure 2.2). The remaining seventeen feet of the "fuselage" was comprised of the two large panels (figure 2.1).

The presentation of the small lap splice test panels can be seen in figure 2.2. The test lap splice in the upper row of simulated fuselage was at approximately eye level. The lap splice in the lower row of the simulated fuselage was at knee-level (approximately 2 feet from the floor). The two rows were part of the overall experimental design to characterize the differences between levels of accessibility of the inspection area.

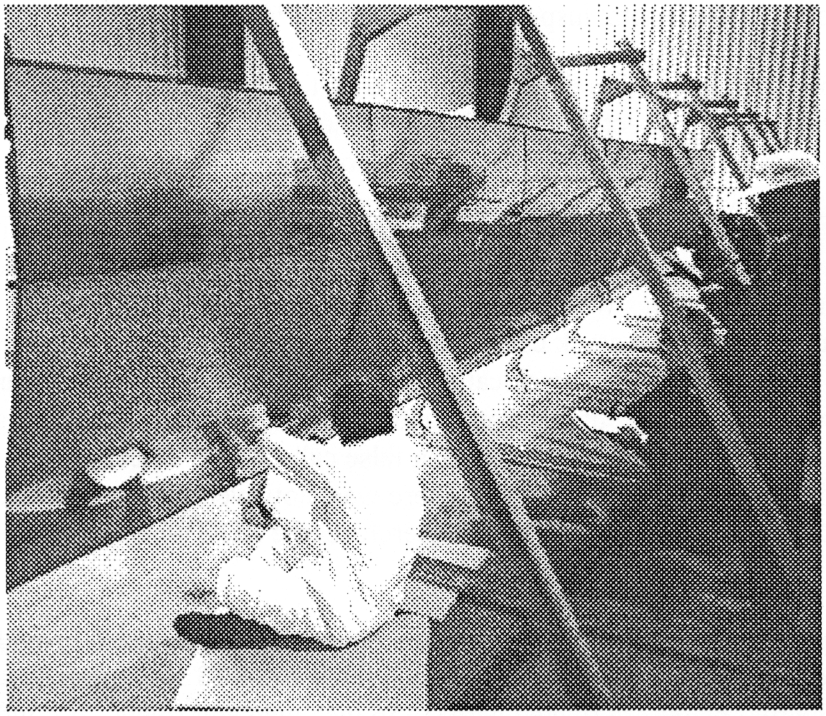

FIGURE 2.2 PRESENTATION OF LAP SPLICE SKIN SPECIMENS.
(Inspector is shown inspecting bottom row with eddy-current equipment.)

All inspectors were briefed on marking a crack detection directly on a protective tape that the monitors put into place before each inspection. The inspector was asked to circle the rivets where cracks were detected and to indicate from which side of the rivet the crack emanated. The inspectors were also asked to give a subjective rating (1, 2, or 3) reflecting their confidence that a flaw signal was present. The inspections were performed according to Boeing procedures for lap splice inspections.

If the facility routinely assigned two inspectors to work as a team then the MOI inspections were also done as a team. This was the case at two of the facilities. The usual procedure was for one member of the team to operate the imaging head while the other member watched the monitor. In most of the cases the inspector operating the imaging head also viewed the video monitor at least part of the time.

2.2 ANALYSIS OF DATA.

Probability of detection (PoD) curves have been used extensively to assess the accuracy or reliability of NDI systems and procedures. All probability of detection curves presented here were fit using a probit analysis for binary data with the logarithm of crack length as the explanatory variable. Discussion of fitting PoD curves can be found in Berens [11] and Annis, et al [12].

The usual probability model assumes that the probability of detection approaches 1 as the crack length gets larger. A generalization of this model allows for the probability of detection never to exceed some threshold strictly less than one. The inclusion of a threshold models a miss rate attributable to lack of attention, distractions, or other causes that are independent of crack size. This model was considered in Spencer and Schurman [10] and is given by $\mathrm{PoD}(a) = (1-C) \bullet \Phi(\alpha + \beta \bullet log(a))$, where Φ is the standard normal distribution and α, β, and C are parameters fit to the data. The variable a is crack length.

2.2.1 Laboratory Inspections.

The MOI equipment settings used by the individual laboratory inspectors are given in table 2.3. All of the laboratory inspectors used the calibration standard provided by the MOI manufacturer for inspection setup.

TABLE 2.3 *EQUIPMENT SETTINGS FOR LABORATORY INSPECTIONS*

Inspector	Frequency (kHz)	Power Level
1	102.4	Low
2 & 3	51.2	High

The probability of detection curves fit to the three laboratory inspections are given in figure 2.3. Every crack was considered as a detection opportunity in fitting the curves. Thus, a rivet having cracks from both sides would yield two detection opportunities. Each crack is represented by its length from the rivet shank on the x-axis and by the proportion of the three laboratory inspections in which it was detected (i.e., 0, 1/3, 2/3, 1). For example, there were four cracks with lengths between 0.073 and 0.084 inch that were each missed by one of the three inspectors. (The same inspector did not miss all four.)

The data and curves of figure 2.3 consider all calls (inspector ratings of 1,2, and 3) as detections. Table 2.4 shows the distribution of detections and false calls for each inspector among the subjective ratings of 1, 2, and 3. For example, Inspector 1 rated 224 of the cracks as a 3, that is, he was sure that a flaw indication was present. He also called four rivet sites as having a crack when, in fact, cracks were not present (false calls). One false call was given a 3 rating (inspector certain) and three false calls were rated as 1's (inspector doubtful). There were 708 opportunities (unflawed rivets) for false calls among the rivet sites inspected.

TABLE 2.4 *DISTRIBUTION OF (DETECTS, FALSE CALLS) AMONG LABORATORY SUBJECTIVE RATINGS*

Inspector	Rated 3	Rated 2	Rated 1	Total
1	(224,1)	(9,0)	(1,3)	(234,4)
2	(204,0)	(15,1)	(5,3)	(224,4)
3	(210,0)	(4,0)	(2,0)	(216,0)

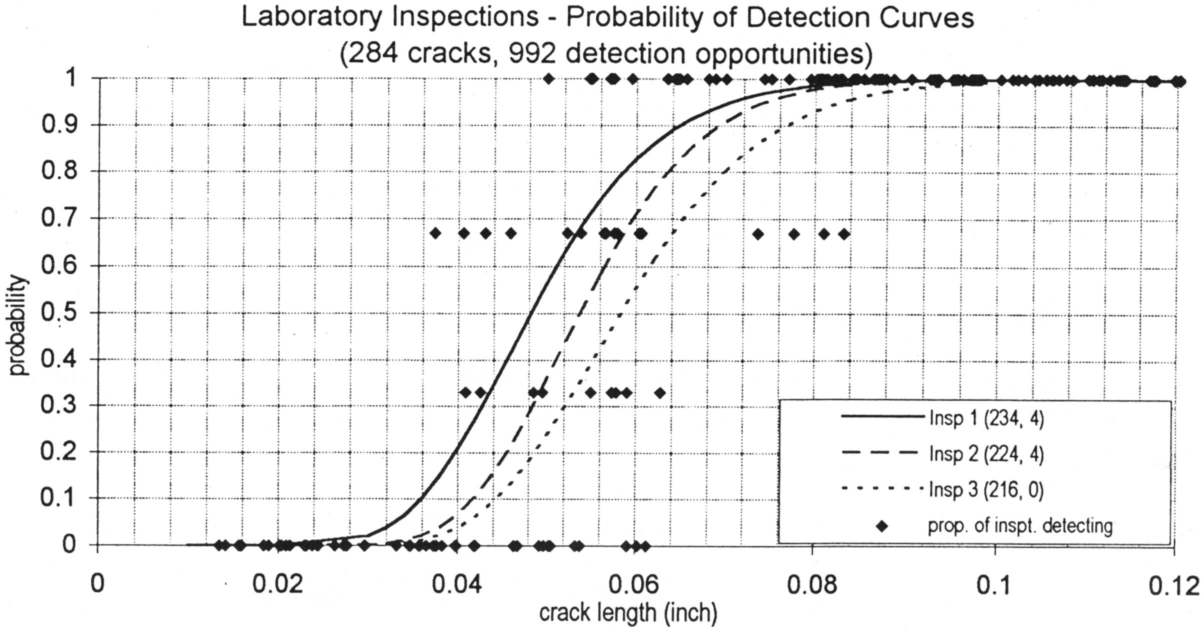

FIGURE 2.3 PoD FITS TO LABORATORY INSPECTIONS.
Legend shows (total number of detects, total number of false calls).

Each of inspectors 1 and 2 had three false calls for which they were doubtful (rated "1"). Because Inspector 1 was not identifying many additional cracks with the "1" calls, the leftmost curve of figure 2.3 represents attainable detection characteristics with relatively few false calls (0.6 percent or 4 calls out of 708 opportunities). From table 2.4 it is also apparent that inspector 3 was employing more stringent criteria to make calls than were the other two inspectors. The result was no false calls but also fewer detections. In no cases were cracks larger than 0.08 missed.

The curves of figure 2.3 allowed for an asymptote other than one, as discussed earlier. However, this additional parameter, C, was estimated to be zero in all three cases. Thus, there was no indication of a background miss rate in the laboratory inspections.

2.2.2 Field Inspections.

The equipment settings and the inspection times for the field inspections are given in table 2.5. The inspection times do not include break times. Also shown in table 2.5 is whether the inspector verified calls with a pencil probe and template eddy-current procedures. Boeing procedures for the MOI call for this verification. All the inspectors did not, however, perform the verification step. The four inspectors that did not verify the MOI calls averaged 112 minutes of inspection time. The seven inspections where MOI calls were verified averaged 200 minutes of inspection time. Recall that most of the inspectors were inexperienced in using the MOI. We expect the times to be longer as compared to experienced users. This is borne out in comparing the inspection times to those obtained in the laboratory.

Also given in table 2.5 are the calibration standards used by the inspectors during setup. The inspectors used either the standard provided with the MOI or they used an in-house Boeing standard. In either case, the inspector set frequency and power levels of the equipment and adjusted contrast of the image from a standard where they knew of the presence of a crack.

Two of the 14 inspections were repeat inspections where an inspector (or inspection team) repeated the full inspection. At least four days intervened between the repeat and the initial inspections. Different configurations of the test specimens were used with each inspection to keep inspectors from recognizing flaw patterns.

TABLE 2.5 *EQUIPMENT SETTINGS AND INSPECTION TIMES FOR FIELD INSPECTIONS*

Inspection	Frequency (kHz)	Power Level	[1]Calibration Standard	Inspection Times (min.)	Verification
A1	25.6	H	Manuf.	126	partial
A2	25.6	H	Manuf.	255	yes
A3	51.2	H	Manuf.	107	no
A4	25.6-51.2	M-H	Manuf.	100	no
B1	25.6	H	#290	180	yes
B2	25.6	H	#290	160	yes
B3	25.6	H	#290	218	yes
B3R	25.6*	H	#290	211	yes
B4	25.6	H	Manuf.	185	yes
C1	51.2	H	none	127	partial
C2	51.2	H	Manuf.	102	no
C3	51.2	H	Manuf.	138	no
C4	25.6	H	Manuf.	219	yes
C4R	51.2	H	Manuf.	174	yes

[1] Manuf. - setup specimen provided with the MOI, #209 Boeing ID for two sheets of 0.04 inch 2024-T3 or T4 Al Clad material, riveted and containing 0.10 inch cracks referenced to rivet shanks, including 60 degree off-horizontal flaws.

*Changed frequencies often during inspection

Probability of detection curves fit to the individual inspection data for each of the three facilities are given in figures 2.4 through 2.6. In fitting the curves each rivet site that had either one or two cracks was considered as a detection opportunity. Each site is represented on the x-axis by the length of the largest crack as measured from the rivet shank. Also shown in each figure is the proportion of the inspections at each facility for which each flawed site was detected.

The probability of detection curves presented in figures 2.4 - 2.6 are based on all positive calls from the inspectors regardless of their subjective ratings. Most of the inspectors made little use of the subjective ratings as is shown in table 2.6, where the ratings breakdown is given for detections as well as for false calls.

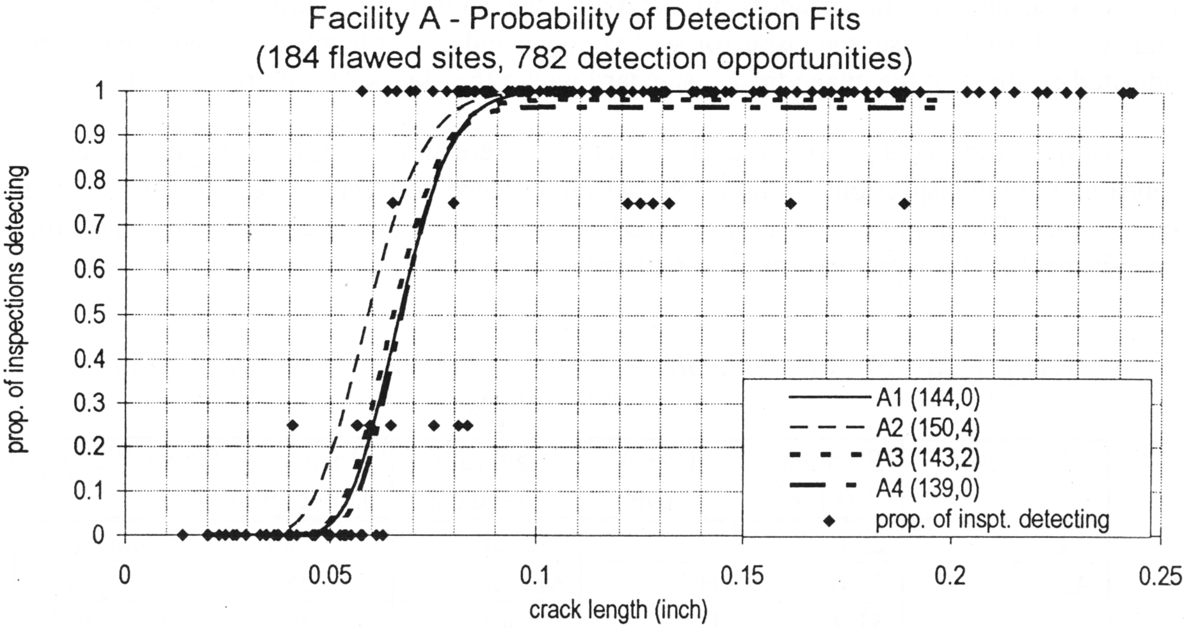

FIGURE 2.4 PoD FITS TO FACILITY A INSPECTIONS.
Legend shows (total number of detects, total number of false calls).

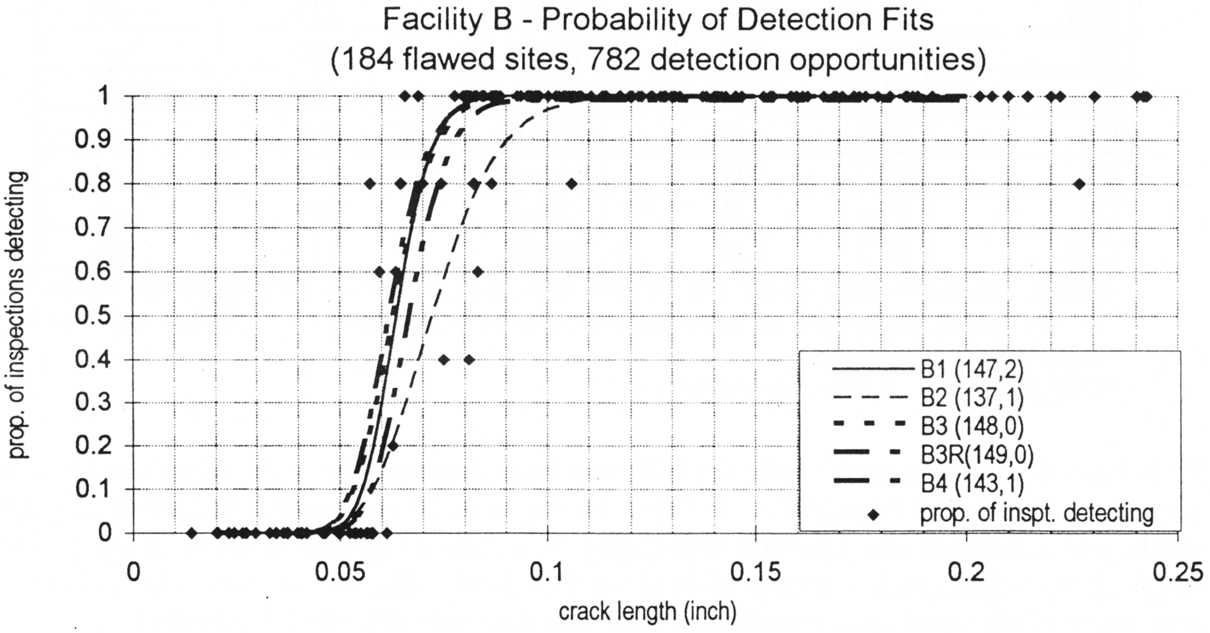

FIGURE 2.5 PoD FITS TO FACILITY B INSPECTIONS.
Legend shows (total number of detects, total number of false calls).

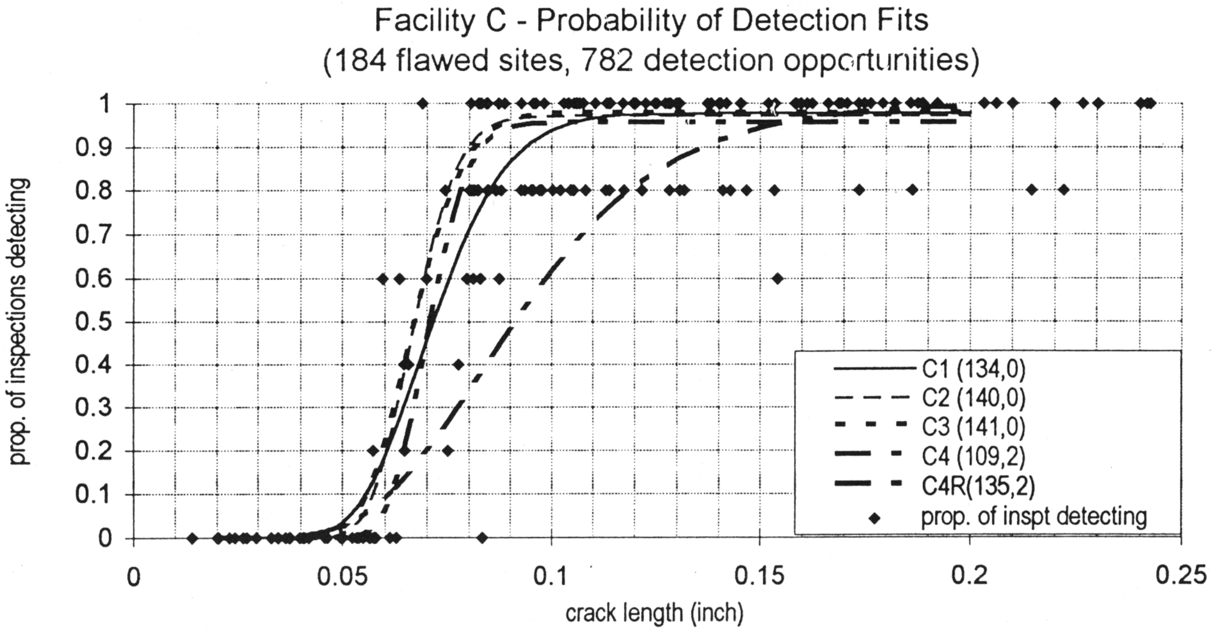

FIGURE 2.6 PoD FITS TO FACILITY C INSPECTIONS.
Legend shows (total number of detects, total number of false calls).

TABLE 2.6 *DISTRIBUTION OF (DETECTS, FALSE CALLS) AMONG FIELD SUBJECTIVE RATINGS*

Inspector	Rated 3	Rated 2	Rated 1	Totals
A1	144,0	0,0	0,0	144,0
A2	146,0	0,1	4,3	150,4
A3	140,2	2,0	1,0	143,2
A4	139,0	0,0	0,0	139,0
B1	145,0	1,1	1,1	147,2
B2	129,0	8,1	0,0	137,1
B3	148,0	0,0	0,0	148,0
B3R	149,0	0,0	0,0	149,0
B4	142,1	1,0	0,0	143,1
C1	65,0	36,0	33,0	134,0
C2	136,0	3,0	1,0	140,0
C3	139,0	2,0	0,0	141,0
C4	109,2	0,0	0,0	109,2
C4R	115,0	20,2	0,0	135,2

The detection opportunities for the field inspections differ from the laboratory inspections for two reasons. First, all the panels produced for the ECIRE program [10], including seven panels that were fabricated as backups for the field experiment, were inspected in the laboratory. These seven panels were not included in the field inspections. Second, detections were considered on a rivet site basis for the field inspections. Thus, if a rivet contained a crack from both sides and was marked as flawed, credit for detection was given regardless of whether both cracks were explicitly marked. This was done because in following normal procedures an inspector would mark flawed rivet sites, but not explicitly mark crack locations.

2.2.2.1 Thresholds (Background Miss Rates).

Of the 14 field inspections, the PoD curve fits on 7 of the inspections were significantly better with the incorporation of the threshold parameter C, as discussed earlier. Table 2.7 gives the threshold parameter, C, for those inspections. All inspections were performed in specific orders with respect to the test specimens and were monitored, with notes taken concerning inspectors' behavior. A review of the inspection records indicates that some of the inspectors had difficulty in marking the exact location of observed flaws. That is, in the process of removing the imaging head from the inspected area they would displace the location by one rivet. The review of the records associated with the larger missed cracks identified five (5) of the inspections where flaw locations were likely mismarked. These are also shown in table 2.7, with the mismarked crack lengths given. When the mismarked cracks were considered as being detected, the threshold, C, was eliminated as a significant factor in three of the inspections and reduced in the other two. It is worth noting that the aspect of correct location of the flawed site was not mentioned in any of the training sessions.

Even though changes occur in the estimate of C, the estimated crack lengths for 50 percent (a_{50}) and 90 percent (a_{90}) detection rates change very little (less than 0.001 inch in all cases). On the other hand if the threshold is left out of the PoD model then the estimated crack length for a 90 percent detection is greatly influenced (0.015 to 0.030 inch in the cases considered). For comparison purposes the estimates for a_{50} and a_{90} in the threshold and no threshold models are shown in table 2.7. Apparently the two parameter (no threshold) model PoD curves are impacted by phenomenon unrelated to equipment capabilities (such as mismarking).

Additional inspection behaviors were observed that led to failures in identifying cracks. One inspector missed two large cracks while discussing the use of the equipment with a colleague. Nonuniform alignment in the lap splice test panels when mounted on the frames could lead to a lip next to a cracked rivet site. This would result in a liftoff of the imaging head from the rivet site. Some inspectors followed procedures and checked such sites with an eddy-current pencil probe. Others manipulated the test panels and the imaging head to assure good contact. However, a few inspectors did not compensate for the liftoff. This could have been due largely to a lack of experience.

TABLE 2.7 EFFECT OF THRESHOLD FITS ON PROBABILITY OF DETECTION CURVES

				PoD Curve Crack Size (inch)			
				Threshold Model		No Threshold Model- Original data	
Insp	Miss Rate (C)	Mismarked crack lengths (inch)	Adjusted Miss Rate (C)	a_{50}	a_{90}	a_{50}	a_{90}
A3	0.019	0.128, 0.189	0	0.065	0.079	0.064	0.095
A4	0.036	0.122, 0.125, 0.132, 0.161	0	0.067	0.080	0.067	0.101
B4	0.009	0.227	0	0.067	0.078	0.064	0.093
C1	0.022	none	0.022	0.072	0.094	0.071	0.107
C2	0.028	0.131	0.019	0.067	0.080	0.067	0.097
C3	0.020	none	0.020	0.067	0.081	0.065	0.098
C4R	0.043	0.097, 0.122, 0.132	0.027	0.071	0.083	0.069	0.113

2.2.2.2 Verification of Findings.

The Boeing procedures for MOI inspections call for the verification of crack detections with a high frequency eddy-current inspection using a template and pencil probe. As shown in table 2.5, four of the inspectors did not follow the procedures of verifying the MOI findings with eddy-current inspections. Additionally, in two of the inspections the verification step was followed for only part of the total inspection.

The procedures call for verification of finds with eddy-current. If an inspector strictly followed the procedures and only checked the rivets where original calls were made, there would be no increase in detection rates. The net result could, however, be a decrease in false calls. For most of the inspectors that followed the verification procedures, there were very few changes made as a result of the eddy-current verification.

Inspector C4 provides one example of a possible consequence of the verification process. Inspector C4 did not feel comfortable with the subjective ratings. He used a rating of 3, only if the eddy-current verification also indicated a crack. As a result, Inspector C4 changed 10 initial MOI detections in the 0.057 inch to 0.108 inch range to no calls because of the inability to verify the call with eddy-current. He also converted 5 calls that would have been false calls. In the repeat inspection, C4R, instead of changing the MOI calls that were not verified with an eddy-current inspection to no-crack calls, the inspector gave them a rating of 2. The difference in probability of detection curves is apparent in figure 2.6. For this particular inspector, the implementation of the eddy-current procedure was less capable than the MOI procedure. As a consequence, if the eddy-current inspection was used as the final determination then detection capability was diminished. It should be noted that other inspectors at the same facility, using the same equipment for verification, did not exhibit the same outcomes. In the other cases, the verification step was consistent with the original call.

2.2.2.3 Inspection Times.

Inspection times can be important to an economic analysis of one method compared to another. Here, inspection times gathered on the MOI are compared with inspection times gathered for eddy-current inspections at the same facilities. Table 2.8 shows the inspection time statistics at each of the three facilities for both eddy-current sliding probe inspections and MOI inspections. All inspections were performed on both types of panels in the frame arrangements shown in figures 2.1 and 2.2. The inspectors performing the MOI inspections were not the same inspectors as those performing the eddy-current inspections. Comparisons of the two methods are made by facility to minimize the effect of the different environments (break schedules, team versus single inspectors, work conditions, and likelihood of distractions).

TABLE 2.8 *INSPECTION TIME STATISTICS BY FACILITY*

Facility	MOI Inspection - minutes mean (std. dev.)	EC Inspection - minutes mean (std. dev.)	Percent difference from EC to MOI
A	147 (73) [111 (13)]*	157 (27)	-6 percent [-29 percent]*
B	191 (24)	214 (34)	-11 percent
C	152 (46)	193 (68)	-21 percent

* 1 extreme MOI value removed. Five inspections/site and technique except 4 for MOI-Facility A.

Inspection times were less, on average, for the MOI than for the eddy-current inspections at all three facilities. At each facility the average inspection times for the MOI were from 6 percent to 21 percent less than the eddy-current inspections. There was substantial inspection-to-inspection variability as is evidenced by the standard deviations in table 2.8. In facility A the relatively high standard deviation of 73 minutes resulted from a single inspection taking more than twice as long as the others. The other MOI inspections averaged 111 minutes, which is a 29 percent savings in time as compared to the eddy-current inspections. A 20 percent reduction in inspection times for the MOI compared to sliding probe eddy-current was chosen as the starting point for the economic analysis of section 3.

2.2.2.4 Factor Effects.

The MOI field inspections were carried out using the same protocols as were employed in the ECIRE experiment. The design of that experiment in discussed in reference [10]. The accessibility factor, as reflected by the two different rows of lap splices, had no significant impact on the probability of detection curves for the MOI inspections. Off-angle cracks had a significant impact on the probability of detection curves for the field MOI inspections, as well as for the laboratory inspections. Probability of detection curves fit to the horizontal cracks are compared to those fit to the off-horizontal (11 and 22 degrees) in figure 2.7. The crack sizes for 50 percent and 90 percent detection are also summarized in table 2.9.

The 11 degree and 22 degree off-horizontal cracks were considered as a single population for estimating the curves of figure 2.7. There were no significant differences in the curves fit individually to the 11 degree and 22 degree off-horizontal cracks in the laboratory data.

However, for the field data, the PoD curves for the 22 degree cracks and those for the 11 degree cracks differ. If one considered only the population of 22 degree off-horizontal cracks to estimate the off-horizontal field curve of figure 2.7, the curve would be shifted 0.016 inch from the field horizontal crack curve.

TABLE 2.9 *EFFECT OF ORIENTATION ON ESTIMATED 50 AND 90 PERCENT PoD CRACK LENGTHS*

	Field Horizontal	Field Off-horizontal	Lab Horizontal	Lab Off-horizontal
50 percent crack length (inch)	0.066	0.074	0.050	0.059
90 percent crack length (inch)	0.079	0.095	0.069	0.077

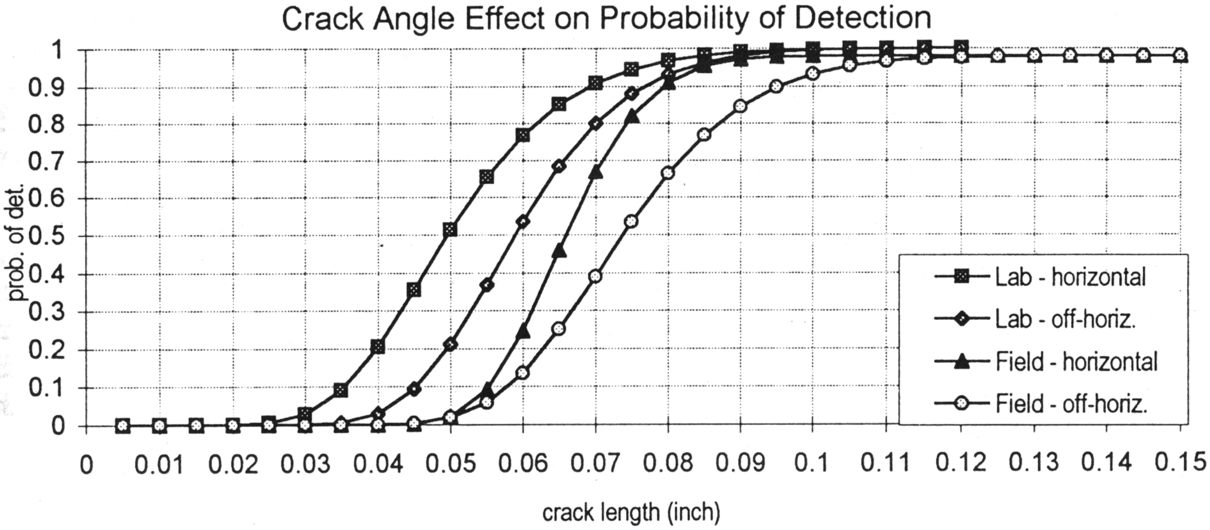

FIGURE 2.7 EFFECT OF CRACK ORIENTATION

There is no indication that the observed differences in the probability of detection fits for the different crack angles represent an inherent limitation of the MOI technology. It is possible that the inspectors are biased towards looking for indications in the direction perpendicular to the "null" slot in the MOI rivet indication. This is only a conjecture. It would take further study to establish actual causes. It is noted, however, that when causes are properly understood, that it may be inspection procedure changes and inspector training issues that are capable of eliminating the crack direction effect.

2.2.2.5 Comparisons to Eddy-Current Inspection Reliability Experiment.

In figure 2.8 the MOI reliability data are compared with the data obtained in the ECIRE. The curve for the eddy-current field data is estimated using only the inspection data gathered at the three facilities where both the MOI and eddy-current data were gathered. All of the inspectors at these facilities used the sliding probe procedure when performing the eddy-current inspections.

The MOI laboratory curves are similar to the sliding probe eddy-current laboratory inspection obtained in the ECIRE. The field results are also similar between the two methods. The MOI field inspections detected those cracks in the 0.08 to 0.10 inch range slightly more often than the sliding probe eddy-current field inspections. Ninety percent detection rates were achieved at 0.084 inch for the MOI and at 0.094 inch for the eddy-current sliding probe. However, the MOI inspections were not detecting the cracks in the 0.040 to 0.070 inch range as often as were the eddy-current inspections. The result is the steeper curve for the MOI as is seen in figure 2.8. Both sets of curves reflect the mix of horizontal and off-angle cracks present in the test specimens. The angle of the crack to horizontal was shown to affect the detectability for both techniques. The relative proportions of cracks in the experiment were approximately 10:3:4 for horizontal, 11°, and 22° respectively.

Considering the inspector-to-inspector variations observed for both inspection techniques (see figures 2.4 - 2.6 for MOI variations) and the "overlap" of the probability of detection curves noted above, no net reliability gain is assumed for the economic analysis of section 3 for employing the MOI instead of sliding probe eddy-current procedures.

Although the detection rates are comparable, the false call rates that go with these detection rates were different between the two methods. The average number of false calls per inspection was 2.7 for the eddy-current inspections and 1.0 for the MOI inspections. The higher rate for the eddy-current inspections is influenced greatly by three inspections. When the proportion of inspectors making 0, 1, 2, and >2 false calls are compared across the MOI and eddy-current inspections the differences in relative proportions are not significant. This implies that the higher overall average false call rate for the eddy-current inspections is unduly influenced by the magnitude of false calls from relatively few of the eddy-current inspections.

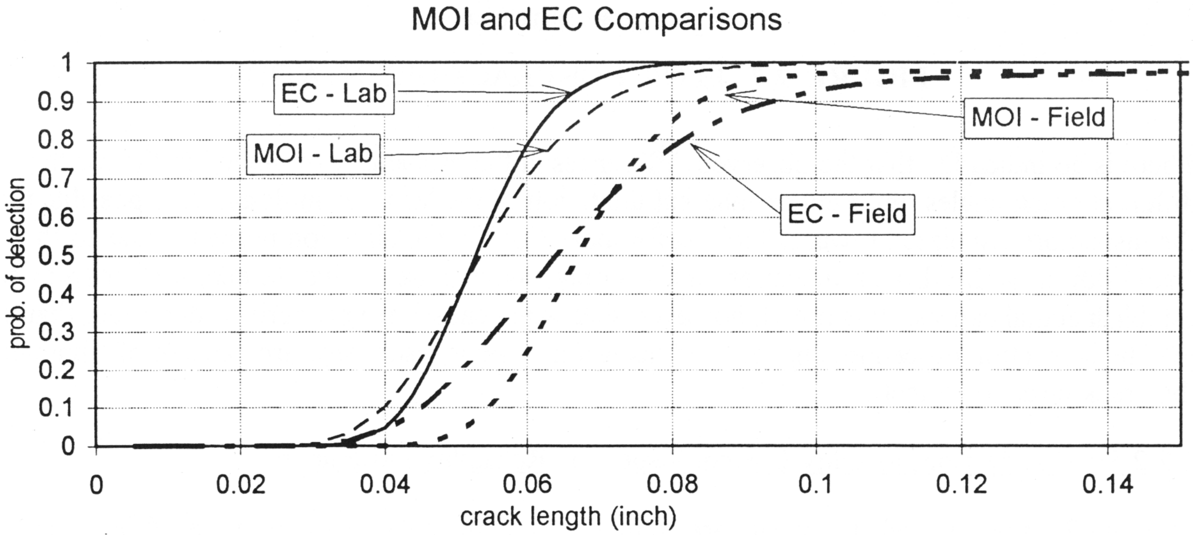

FIGURE 2.8 COMPARISON OF PROBABILITY OF DETECTION CURVES

2.2.2.6 Comparison to Other Studies.

PRI Instrumentation has reported on PoD curves fit to data obtained from the Boeing QA-R&D Group [13]. Although the data reported on was gathered in a laboratory environment, the inspectors were not all experienced with the use of the MOI. PRI Instrumentation reports a 90 percent detection rate being achieved at 0.090 inch. This value is between the estimates obtained in this study for horizontal (0.079 inch) and the up-to-22° off-horizontal cracks (0.095 inch).

2.3 SUMMARY OF RELIABILITY FINDINGS.

The MOI inspection data were gathered in airline facilities using inspectors with typical NDI backgrounds. A one day training class was provided to those inspectors unfamiliar with the MOI. These conditions are representative of any facility deciding to include the MOI amongst their NDI capabilities. Thus, the gathered reliability and inspection time information are appropriate for the basis of an economic analysis as is carried out in section 3. It is not unlikely that the inspection times with the MOI would decrease with inspector experience. A decrease in the inspection times is addressed in a sensitivity study included in the economic analysis.

The detection rates as related to crack lengths for the MOI were comparable to those achieved by the sliding probe eddy-current inspections. The average MOI detection rate for cracks with lengths in the 0.080 to 0.100 inch range was slightly higher than that for sliding probe eddy-current methods used at the same facilities. The average detection rate for cracks with lengths in the 0.040 to 0.070 inch range was lower than that for the sliding probe eddy-current methods.

The angle that a crack emanates from the rivet hole influences detection rates. Having cracks as much as 11° to 22° off-horizontal shifted the upper end of the field derived PoD curves by approximately 0.016 inch. The corresponding shift in the laboratory derived curves was 0.009 inch.

The average level of false calls for the MOI inspections was lower than that for the eddy-current inspections. However, the majority of the inspections from both techniques (24 of 29) were completed with 0, 1, or 2 false calls. The relative number of inspections in these categories was consistent across the two inspection methods.

MOI inspection times were less on average than were inspection times using the sliding probe. Discounting one extreme MOI inspection time, the reductions in inspection times were 11 percent, 21 percent, and 29 percent at each of the facilities. Twenty percent reduction time was chosen for a baseline for the economic analysis of section 3.

In inspections where relatively few calls would be expected to be made, the procedure of using an eddy-current template to verify the MOI calls could help alleviate a problem of mismarking the site of an observed call. To do so, however, the inspector would have to be sure to check sites next to a site marked from the MOI inspection. The procedures used in verification should be at least as sensitive as the original procedure. One inspector was observed changing detections made by the MOI to no-calls based upon his verification inspections. Apparently, the verification process was setup to be less sensitive than the original MOI inspection.

The one day of training provided to the inspectors was adequate. However, some inspectors expressed discomfort with the MOI because of their lack of experience in using the MOI. Having an inspector perform an inspection on samples with unknown flaws and then allowing the inspector to redo the inspection with the knowledge of crack locations and sizes would help in removing discomfort. This procedure was followed before the laboratory inspection performed by the Sandia technician. The inspector reported feeling more comfortable with the MOI inspection after the feedback process. Detection rates also improved.

3.3 COST-BENEFIT ANALYSIS METHODOLOGY.

Considering the mixed results received in the survey and as part of the validation process, a formal assessment of the economic impact of the MOI is warranted. To more accurately measure the full economic impact of the MOI, a thorough quantitative analysis has been undertaken. Section 3.3.1 presents the net present value methodology that is used in this analysis for measuring the economic benefit of an investment in the MOI. Section 3.3.2 provides the decision criterion for the investment. In section 3.3.3, measurement issues are discussed. Finally, some of the areas that introduce uncertainty to the economic analysis and some ways of approaching uncertainty are discussed in section 3.3.4.

3.3.1 Net Present Value.

Inspection facilities have an incentive to invest in the MOI if the future flow of benefits attributable to the MOI are greater than the future flow of the costs. That is, the investment is expected to generate a positive return. While there are several methods that may be used to make this calculation, many economists and maintenance facility managers agree that the calculation of the *net present value* of an investment is the most useful measurement. Net present value (NPV) measures the expected stream of benefits less the expected stream of costs over the investment lifetime, with future figures discounted so that they reflect the present value of the investment. The calculation is as follows:

$$NPV_i = \sum_{t=0}^{T} \frac{B_{it} - C_{it}}{(1+r)^t} \qquad \text{Equation 3.1}$$

where i indexes the individual maintenance facility
t indexes time
T = useful life of the MOI
B = benefits obtained from using MOI
C = cost of using MOI
r = discount rate.

For a thorough description of the model, see [15]. A more complete discussion of the measurement of these variables follows an explanation of the criterion for choosing to undertake an investment in the MOI.

3.3.2 Investment Criterion.

If the NPV is positive, the future stream of benefits outweighs the future stream of costs and the investment in the MOI is expected to yield a positive return, therefore making it an economically beneficial investment. If NPV is negative, the money could yield a higher return if invested elsewhere, and the investment is not economically justified.

3.3.3 Measurement Issues.

Measurement of the costs and benefits, C and B in equation 3.1, is made on an avoidable and incremental basis. Costs and benefits are avoidable if they are directly attributable to the adoption of the MOI. Incremental measurements are made about a baseline scenario that is likely to occur if the MOI is not purchased. The incremental measurement allows for some costs to be negative. That is, the costs attributable to a new method are lower than those of the baseline scenario. A decrease in cost from the baseline scenario can increase the NPV of the investment and can contribute to the factors that make the MOI economically beneficial. The baseline scenario chosen for this study is the situation where alternative NDI methods are used for performing inspections that the MOI addresses. The industry survey [14] indicates that the principle method currently used is the sliding probe eddy-current technique.

Costs and benefits are measured by a common unit of value to make them comparable. A constant dollar measurement is recommended because it nets out the effects of inflation. To make accurate comparisons of dollar values over time, a constant dollar value is arbitrarily chosen, that is, the value of a dollar in a specific year. In this case, the year 1992 was chosen. Future values are then expressed in terms of the 1992 value of money. This is referred to as the real value, i.e., the value net of inflation.

The time over which the costs and benefits of the MOI are evaluated, T, is called the useful life of the investment. The economic useful life is the period in which the MOI fulfills the requirement for which it is employed at the lowest achievable cost compared with all other available techniques.

The future stream of costs and benefits are discounted by rate r to take into account the preference of current benefits over future benefits. Clearly, $1 today is worth more than $1 next year to most people (and firms), even after the effect of inflation is taken into account. Hence, the net benefits that are realized today are worth more than those enjoyed next year. 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. Generally, this is measured by the market rate of interest that is available on an investment covering a similar time period. Although in the airline industry, the opportunity cost of capital is believed to be considerably higher.

There is no need to account for future inflation in the measurement of costs and benefits over time if all measurements are made in constant dollars, as recommended above. Hence, expected inflation must be netted out of the discount rate and the real rate of return on alternative investments is used as a discount rate.

For a more thorough discussion of measurement issues, see [15].

3.3.4 Uncertainty.

As was previously mentioned, aircraft maintenance facilities are a widely diverse group. Each has unique operations based on its specific requirements. Therefore, the input variables in the NPV calculation are not the same for each facility. The calculation of the NPV in equation 3.1 is defined for an individual facility. Consequently, it is necessary to examine a variety of scenarios based on the different practices witnessed in maintenance facility operations. Descriptions of the variable factors in the cost-benefit analysis are presented in the remainder of this section. A plausible range for each of these factors is examined in the sensitivity analysis. For a generic discussion of the various methods for dealing with uncertainty in cost-benefit analysis, see [15].

3.3.4.1 Fleet Characteristics.

The first obvious difference is that not all facilities operate on the same scale or scope compared to other facilities or compared to its own workload in the past. The size of the fleet and the variety of aircraft models that are inspected in the facility can vary greatly between facilities and within a facility over time. Major carriers tend to perform maintenance on their fleet only, although some have found that it is cost-effective to contract-out their maintenance services to other carriers or third-party maintenance depots. Some carriers have been retiring aging aircraft due to the increasing maintenance burden. Third-party facilities have a wide variety of aircraft to inspect and the scale and scope can change dramatically depending on the market conditions. Therefore, there can be much uncertainty in determining the actual number of aircraft that can be inspected with the MOI on an annual basis.

First, it is necessary to identify the specific models of aircraft that are most likely to be inspected with the MOI. Following is a list of sample applications of the MOI to specific aircraft inspections derived from the survey of maintenance facilities and a review of the FAA and manufacturer documentation of required and recommended inspection procedures (See [16] through [21]). This list should not be construed to be a complete list. The MOI can also be used in routine inspections not included in the list of specific inspections. Nevertheless, the following list is taken as a starting point for the cost-benefit analysis.

- A subset of Boeing 727, 737, and 747 aircraft is required by FAA Airworthiness Directives to undergo regular surface inspections for cracks emanating from the upper row of rivets in the fuselage skin laps after the aircraft has surpassed a threshold number of pressurization cycles. The alternative to performing continued inspections on these aircraft is to perform the modification by replacing the upper row of countersunk rivets with solid universal head (i.e., protruding) rivets. The MOI can be used to perform these lap joint inspections on the countersunk rivet heads. After modification, the MOI cannot be used for crack detection on the lap slices.

- Some B-747s are also subject to a skin inspection on the flat side of the fuselage (aircraft section 41). Both the skin laps at stringer 6 and a portion of the skin area between the lap joints are to be inspected. The MOI can be used for both of these tasks.

- The McDonnell Douglas DC-10 has a number of areas that can be addressed by the MOI. Two of these inspections are on the wing skin cover (at stringers 39 and 41), where two rows of rivets are inspected for cracks. There are also crack inspections on the crown skin and in the aero-break area of the rear spar lower cap and skin that can be addressed by the MOI, although the survey indicated that these are not yet current practice. These inspections are required after a threshold number of pressurization cycles.

- Lockheed has included the MOI as an inspection technique suitable for inspecting the upper surface wing vent stringers 9/10 on the L-1011. In addition, at least one foreign carrier uses the MOI on the L-1011 for detecting cracks in the belly skin in the C-1 cargo compartment and under the floor galley.

Once a set of specific inspections for which the MOI is applicable is identified, the next step is to determine the approximate number of aircraft that are required to undergo inspections for which the MOI can be used. Table 3.1 presents an inventory of the aircraft models that are cited in the list above for the major domestic carriers. Also included is the average age of individual carriers' fleets.

Age is an important factor in determining the number of aircraft to be inspected with the MOI, because all the sample inspections listed above are required to start at a threshold number of pressurization cycles. Without that information, aircraft age can act as a proxy for pressurization cycles to determine the number of aircraft that are expected to undergo specific inspections. The information in table 1 is combined with the specific inspection protocols to determine a potential scale of use for the MOI.

In this study, it is necessary to specify the aircraft models on which the MOI is expected to be used and to determine the average number of aircraft that are expected to undergo these inspections in a given year. These numbers are then varied to incorporate facilities that may perform more or fewer inspections than the industry average.

TABLE 3.1 *FLEET SIZE AND AVERAGE AGE OF SELECTED AIRCRAFT MODELS/MAJOR DOMESTIC CARRIERS*

		B-727*		**B-737***		**B-747***		**DC-10**		**L-1011**
Carrier	**#**	**Av.Age**	**#**	**Av.Age**	**#**	**Av.Age**	**#**	**Av.Age**	**#**	**Av.Age**
AAL	164	19.1	11	22.6	2	11.3	59	17.6	0	--
AMW	0	--	29	12.4	4	12.3	0	--	0	--
CAL	110	18.1	39	22.3	9	19.7	17	16.8	0	--
DAL	129	14.4	59	6.9	0	--	0	--	40	11.5
NWA	69	17.0	0	--	40	14.6	24	17.8	0	--
SWA	0	--	54	10.4	0	--	0	--	0	--
TWA	65	20.0	0	--	15	20.5	0	--	45	15.0
UAL	129	17.5	74	15.0	25	17.7	57	15.3	0	--
USA	46	17.7	81	11.9	0	--	0	--	0	--
Average**	79	17.6	50	13.0	16	16.3	39	16.7	43	13.4

Source: Avitas Data based on 3rd quarter, 1991.

* Only the -100, -200, and -SP series of the B-727, -737, and -747 aircraft are included in census because these are the aircraft that are affected by the inspection requirements.

** Averages are calculated over the group of carriers that operate the specific model. Therefore, the zero values are not included in the averages.

3.3.4.2 Flexibility in Inspection Scheduling and Work Practices.

Another variable factor is the capability of facilities to take advantage of new techniques that allow inspectors to perform their duties more quickly, therefore improving their productivity. For example, NDT managers at some facilities doubt that they are able to achieve the full benefit from inspection time savings. They don't believe that the time saved with faster inspection methods can actually be transformed into productivity improvements because their inspectors cannot perform other tasks with the time saved. They are also not convinced that faster inspections can achieve shorter aircraft downtimes (See [14]).

The concerns expressed by NDT managers reflect an inflexible environment regarding the implementation of advanced technology. The possibility of rescheduling inspections to take advantage of faster inspections by minimizing downtime may not be encouraged. Also, rigid task definitions in a maintenance facility may not allow inspectors to perform a variety of duties. Some facilities, on the other hand, are able to take advantage of faster inspection techniques by cross-training mechanics and inspectors to do a multitude of tasks. One carrier facility did not replace a retiring inspector when they purchased the MOI. Another justified their purchase of the MOI with figures that showed an investment payback in less than a year, based on faster inspections and elimination of paint removal. Clearly, these facilities are responding to competitive pressures by enforcing flexibility in their inspection scheduling and work practices.

Some facilities, especially third-party maintenance facilities, compete based on how fast they can perform inspections. In this case, downtime savings is clearly an important factor. In other situations, the MOI inspections are performed while the aircraft is down for other reasons and any time savings with the MOI do not effect the total downtime for the aircraft. In this case, though, faster inspections may allow the planning department more flexibility in scheduling MOI inspections, therefore providing the opportunity for aircraft downtime to be minimized. It would be neglectful to omit the potential downtime savings accrued from shorter inspection times.

The economic case for new NDI equipment that allows for faster inspections, such as the MOI, is greatly advanced with more flexible work assignments and inspection schedules. Also, the reduced training requirements can yield economic benefits if cross-training is allowed. The analysis in this report concentrates on a *competitive scenario* defined as a facility where productivity improvements and decreased aircraft downtime derived from faster inspection techniques are realized and the lower training requirement is observed by cross-training. A less than optimal scenario, the *semi-competitive scenario* is also examined. This scenario is defined as a facility where cross-training is not allowed, downtime is not affected, and only 50 percent of the productivity improvements are realized. The two scenarios examined in the cost-benefit analysis are summarized in table 3.2.

TABLE 3.2 SCENARIOS EXAMINED IN THE COST-BENEFIT ANALYSIS

Competitive Scenario	***Semi-Competitive Scenario***
1. 100 percent of labor savings is realized 2. Cross-trained inspectors employed 3. Aircraft downtime is affected	1. 50 percent of labor savings realized 2. No cross-trained inspectors 3. Aircraft downtime not affected

3.3.4.3 Time Savings.

The degree of time savings achievable with the MOI can vary depending on the conditions of the individual facilities and the aircraft to be inspected. For example, some hangars are furnished with docking stations that can preclude inspectors from continuous access to the full side of the fuselage, especially when considering the need for an umbilical power cord with the MOI. Alternatively, in other hangars, the aircraft may be accessed with a cherry picker, which is equipped with an electrical outlet. Clearly, the two environments can have very different effects on the level of time savings that is achievable with the MOI.

Another significant factor that affects the time savings is whether it is necessary to strip the paint or decals from the inspection area when using the traditional eddy-current methods of inspection. In the Boeing procedures for the lap joint inspections using the eddy-current technology, it is not a requirement that paint or decals be removed each time the inspection is performed, although it is required in some circumstances. The procedures for each aircraft model vary. The service bulletin for the B-737 lap skin inspections explicitly states "if more than two coats of paint are applied, the paint should be stripped from the joint to be inspected [16]." In other documents for the B-727 and B-747, it is stated that the rivet head must be visible to do the inspection with eddy-current methods. If the paint or decal on the inspection area is thick enough to make the rivet heads not visible, then the paint must be removed to use the sliding probe and the pencil probe/template methods.

It is not necessary for the inspector to see the rivet heads to use the MOI effectively. The MOI is able to inspect through a thicker coating of paint or decals because the image of the rivet head is visible on the MOI monitor. Therefore, a large amount of labor and material cost can be avoided with the MOI if the inspection requires paint or decal stripping and re-application when using the traditional eddy-current methods on Boeing aircraft. Both the Boeing [6] and the Douglas [7] procedures require that the paint or decal thickness does not exceed 0.015 inch when using the MOI.

The average inspection time savings can be greatly improved if either the full length of the fuselage is easily accessible or if the need to strip paint or decals can be avoided. The sensitivity analysis considers how different degrees of the inspection time savings and avoidance of the need to strip paint on Boeing 747's within the representative fleet affect the overall economics of the MOI. The sensitivity analysis includes only the Boeing 747 in the paint strip avoidance scenario as the requirements (greater than two coats or not being able to see rivets) for stripping paint to use eddy-current procedures are made explicit in the Boeing 747 documentation.

3.3.4.4 Discount Rate.

There exists a great deal of debate over the appropriate discount rate to be used in private sector investment analysis. As was described in the previous discussion of the discount rate, the opportunity cost of capital is the appropriate measurement. In a situation with free capital markets, this can be measured by the market rate of return on an equivalent length alternative investment. The recommended annual discount rate for FAA investments is 10 percent [22]. In practice, the airline industry experiences a much higher opportunity cost of capital, resulting in a more conservative outlook for the present value of future benefits. Current opportunity cost of capital estimates in the airline industry received from members of the Air Transport Association (ATA) range up to 34 percent annually. Both the FAA-recommended rate and the more conservative ATA estimates are examined in the sensitivity analysis.

3.3.4.5 Expanded Applicability.

To present realistic assumptions, the economic analysis concentrates on a select group of inspections for which the MOI is already approved and currently used. However, there is the possibility that the MOI will become more broadly applicable to other inspections in the future. The developers of the MOI are currently working with manufacturers, maintenance facilities, and the FAA to assess the MOI for use on corrosion and subsurface flaw detection. The outcome of these investigations is uncertain. Therefore, it is not recommended to include these potential MOI applications in the formal cost-benefit analysis, although a broader range of possible future applications is examined in the sensitivity analysis.

3.4 DATA ACQUISITION.

The three main data sources that have been used for the cost-benefit analysis are a qualitative survey of maintenance facilities regarding current practices in the industry, a field collection of data from a number of maintenance facilities, and a review of the FAA and manufacturers' guidelines for inspections. A description of the data disclosed by each of these sources is listed in this section.

3.4.1 Survey of Industry Practices.

Thirteen maintenance facilities in the commercial and military sectors have been surveyed either in person or by written and telephone communication. The results of the survey are mainly qualitative and describe the scenarios that are most likely for current and future use of the MOI. The facilities contacted include military, airline and third-party maintenance facilities. Complete results of the survey can be found in [14]. A brief summary of the survey is given in section 3.2.

3.4.2 Field Inspection Data.

Quantitative data were collected on inspection times and PoD for both the MOI and the traditional eddy-current methods in the field experiments described in sections 2.1 and 2.2. The field data represents reliability that is available to the entire industry. It is comprised of data from both airlines and third-party maintenance facilities. Both users and non-users of the MOI were included in the study. See section 2.2.2 for a more thorough description of the field data results.

3.4.3 Documentation Review.

A review of the relevant FAA and manufacturer documentation has been undertaken to define the regulatory and advisory procedures with which the maintenance facilities comply. This review is necessary to define the scope of use for the MOI and alternative methods. Also, it has been necessary to examine the current size of the fleets that may be affected by the MOI.

3.5 DATA CHARACTERISTICS FOR A REPRESENTATIVE FACILITY.

In this section, a representative facility is defined. The diversity in maintenance operations causes many of the factors to have a range of plausible values rather than a specific fixed value. Therefore, a representative facility is chosen to perform a cost-benefit analysis for a specific case. The representative facility cost-benefit analysis data inputs are discussed in sections 3.5.1 through 3.5.12. Factors subject to variability in the aircraft maintenance industry are included in the discussion to represent the diversity of practices. In table 3.3, the characteristics for the representative facility are listed. The fixed factors, such as the equipment cost of the MOI, are held constant throughout the analysis. The uncertain factors, denoted with an asterisk, are varied in the sensitivity analysis.

TABLE 3.3 DATA INPUTS FOR THE COST-BENEFIT ANALYSIS OF THE MOI FOR A REPRESENTATIVE FACILITY

Costs:		
	Equipment Cost	$30,000
	Training Requirement per Inspector (hrs.)	12
	Number of Inspectors Trained	4
Benefits:		
*	Inspection Time Savings (MOI vs. sliding probe)	20%
	Average Hourly Wage of NDT Inspectors	$30
	Average Hourly Wage of Non-NDT Inspectors	$20
	Selected Inspections and Baseline Times (man-hours per aircraft):	
	B-747 Lap Joints	56
	B-747 Section 41:	
	Fuselage skin area	24
	Stringer six lap joints at BS 340-400	8
	Stringer six lap joints at BS 400-520	4
	DC-10 lower wing skin at stringer 39 (per wing)	11
	DC-10 lower wing skin at stringer 41 (per wing)	9
*	Number of Aircraft Inspected:	
*	B-747 Lap Joints	12
*	B-747 Section 41	22
*	DC-10 lower wing skin at stringer 39	35
*	DC-10 lower wing skin at Section 41	31
	Modification Performed	no
*	Number of Planes Requiring Paint or Decal Removal	0
	Improved PoD	no
Competitive Scenario:		
*	Proportion of Labor Savings Realized	100%
	Training Time Savings Per Inspector (man-hours)	28
*	Downtime Savings	yes
	Value of aircraft downtime per hour (for early series B-747-100, -200 and DC-10)	$200
*	Annual Discount Rate	10%
	Annual Inflation Rate	4%
	Useful Life (years)	10

* indicates that the assumption will be varied in the sensitivity analysis in the next section.

3.5.1 Investment Cost.

Employing the MOI as an inspection technique involves investment in both physical capital and human capital. The physical capital cost is the cost of the actual equipment. The cost of the MOI in 1992 dollars is approximately $30,000. No extra equipment is required to operate the MOI. The human capital element entails training inspectors to use the MOI. This consists of a twelve hour training session per inspector. It is assumed that initially four inspectors receive MOI training. NDT inspectors have already undergone eddy-current training and it is necessary for them to have eddy-current training for other inspections, so the total avoidable cost for four NDT inspectors to undergo a 12-hour training session is 48 man-hours. The benefit of cross-training general inspectors to use the MOI is discussed in section 3.5.9.

3.5.2 Inspection Time Savings.

The operating cost is the continuing cost of using the MOI over time. The operating cost of using the MOI is believed to be lower than that of the traditional eddy-current methods because the MOI is a faster inspection technique. Therefore, the incremental operating cost of using the MOI is represented by the estimated time savings that the MOI can generate.

While the survey respondents revealed a wide range of time savings estimates, the field data was the most useful measurement for the cost-benefit analysis because it represented an average time savings across the entire industry. The field data include the times of sample lap joint inspections performed at three different aircraft facilities with both the sliding probe eddy-current device and the MOI. As was described in section 2.1.2, the sample lap joints were configured to simulate the fuselage of an actual aircraft. The inspections were performed by NDT inspectors in their regular hangar environment.

The results from the field data discussed in section 2.2.2 indicate that the time savings averaged over the three facilities where the MOI was implemented into the study was 13 percent. When discounting one extreme inspection time, an average of approximately 20 percent time savings results from using the MOI rather than the sliding probe. The survey indicates that there are situations where a higher rate of time savings is achievable. Estimates of up to 50 percent have been cited. This may be especially true for facilities that use the pencil probe/template eddy-current procedure for these inspections. Because of the variability, 20 percent is used for the base case and different levels of time savings are analyzed in the sensitivity analysis, with the effects on the NPV discussed. Also, the possible times savings represented by the avoidance of stripping paint from the inspection area is considered separately in section 3.5.6.

3.5.3 Average Inspector Wage.

In 1990, the median annual income for aircraft mechanics was $30,000, with the top 10 percent earning $45,000 per year [23]. Including an extra 28 percent for benefits and inflating to 1992 levels, the cost to employers per man-hour translates to a median wage of approximately $20 and a top 10 percent wage of $30. Because most NDT inspectors have attained a high level of seniority, it is plausible to assume that the majority are in the top 10 percent of the aircraft mechanics earnings scale. Therefore, $30 per man-hour is assumed to be the average wage of NDT inspectors. The median mechanics' wage of $20 per man-hour is used to determine the cost per man-hour of stripping and repainting aircraft.

It is assumed that inspectors' wages increase by the inflation rate over the investment lifetime. Therefore, the real value remains unchanged.

3.5.4 Selected Inspections and Baseline Times.

As discussed in section 3.3.4, Airworthiness Directives and Service Bulletins that call for inspections for which the MOI can be used include lap joint inspections on Boeing 727, 737, and 747 aircraft. The survey of the industry indicates that most carriers have performed the modification on the B-727 and B-737 lap joints. Evidence of the DC-10 applications in the field is limited to the two wing inspections. At the time that this report went into publication, another DC-10 application on the crown skin was under investigation, but not yet put into practice. The survey provided no evidence that the L-1011 application is currently adopted in any domestic maintenance facilities.

The representative facility is assumed to have modified all of its B-727 and B-737 lap joints, but is able to use the MOI on its B-747s. It is also assumed that the representative facility uses the MOI for the under wing inspections on DC-10s. The specific inspections that are included in the cost-benefit analysis of the representative facility are summarized below. (See [17] through [21])

- **B-747 lap joints** - For production line numbers 001-200, conduct a high-frequency eddy-current (HFEC) inspection for cracks emanating from the upper row fasteners on all upper lobe skin lap joints forward of BS 1000 and aft of BS 1480. Begin this inspection when the aircraft has accumulated 15,000 pressurization cycles and repeat every 4,000 pressurization cycles forward of BS 1000 and every 6,000 pressurization cycles aft of BS 1480. In lieu of continued reinspections, modification of lap joints is possible by installing protruding head rivets. (Airworthiness Directive 90-15-06, Boeing Service Bulletin 747-53-2307).

- **B-747 stringer 6 lap joints at Section 41 -**

  1. **Body Station (BS) 340-400 -** For production line numbers 001-603, conduct a HFEC inspection for cracks emanating from the upper row fasteners on the left and right stringer 6 of the fuselage skin lap splice between BS 340-400. Begin this inspection when the aircraft has accumulated 10,000 pressurization cycles and repeat every 3,000 pressurization cycles. Modification of the lap joint with protruding head rivets or an external doubler is recommended at the accumulation of 20,000 flight cycles. (Airworthiness Directive 90-23-14, Boeing Service Bulletin 747-53-2253).

  2. **Body Station (BS) 400-520 -** For production line numbers 001-628, conduct a HFEC inspection for cracks emanating from the upper row fasteners on the left and right stringer 6 of the fuselage skin lap splice between BS 400-520. Begin this inspection when the aircraft has accumulated 13,000 pressurization cycles and repeat every 5,000 pressurization cycles. Modification of the lap joint with protruding head rivets or an external doubler is recommended at the accumulation of 23,000 flight cycles. (Airworthiness Directive 89-05-03, Amendment 39-6146, Boeing Service Bulletin 747-53A2303).

- **B-747 Section 41** - For production line numbers 001-430, conduct a HFEC inspection for cracks in the fuselage skin from BS 220-520 (Section 41) between stringers 6 and 14 excluding the lap joints. Begin this inspection at 12,000 pressurization cycles and repeat every 2,000 cycles. In lieu of continued reinspections, modification of skin panels is possible by installing new ones. (Airworthiness Directive 90-26-10, Boeing Service Bulletin 747-53A2321).

- **DC-10 lower wing skin at stringer 39** - Conduct a HFEC inspection of the lower wing spanwise skin splice at stringer 39 on both wings. Begin this inspection at 17,958 pressurization cycles and repeat every 4,000 cycles. Inspect 100 percent of DC-10s in this area. (PSE Number 57.10.005/.006).

- **DC-10 lower wing skin at stringer 41** - Conduct a HFEC inspection of the lower wing skin and stringer at Section 41 outboard of the pylon on both wings. Begin this inspection at 19,520 pressurization cycles and repeat every 7,290 cycles. Inspection of a fleet is based on sampling, with 88 percent required for sampling. (PSE Number 57.10.017/.018).

Manufacturer estimates of the time taken to perform the above inspections with traditional eddy-current devices are listed in table 3.3. These figures are used for the baseline scenario. The MOI is assumed to perform the inspections 20 percent faster.

Other applications of the MOI are possible. The MOI can be used in place of eddy-current techniques for routine inspections not directed by specific ADs or SBs. In the future, applications in the area of corrosion detection, where most inspections are performed visually, may be possible. The number of inspection man-hours for the MOI is varied in the sensitivity analysis to reflect the possible effects of broader use of the MOI.

3.5.5 Number of Inspections.

An estimate of the number of inspections expected to be undertaken with the MOI is used in combination with the inspection times to measure the scale in which the MOI will be used. The number of inspections is based on two components; the baseline number of aircraft to be inspected with the MOI and the number of continuing inspections required over time.

The average domestic fleet size of B-747 aircraft that are required to undergo the lap joint inspections is 12, with a range from 0 to 17. (See service bulletin listing of the number of planes affected by each inspection procedure.) The Section 41 inspections on the B-747 are required for a larger group of aircraft, with an average number per carrier of 22, and a range from 0 to 34. (See service bulletin listing of the number of planes affected by each inspection procedure.) These inspections are only required on early production line models, as cited in the inspection description above. The DC-10 inspections on the lower wing at stringer 39 are required for all aircraft with usage cycles exceeding the threshold. The average domestic carrier fleet size of DC-10s is 35, with a range from 0 to 59 (see table 3.1). The DC-10 lower wing inspections at stringer 41 are required for 88 percent of the DC-10s.

The representative facility performs inspections on the average number of aircraft listed above. This precludes the example of a large carrier or third-party facility that maintains a larger number of aircraft. To include this possibility in the analysis, the maximum numbers are examined for all models in the sensitivity analysis. In this model, if a carrier or third-party facility doesn't perform maintenance on any of these aircraft models, then the net benefits of the MOI are negative.

The inspections listed above are required only after some threshold number of pressurization cycles. The average age is the best available estimate to determine the number of aircraft that are affected by the relevant inspections. The average ages of in-service aircraft are found in the census data reported in table 3.1. Airworthiness directives (ADs) specify the threshold number of pressurization cycles that an aircraft is allowed to attain before undergoing the inspections. The oldest Boeing 747s have each averaged 738 cycles a year and the oldest DC-10s have logged 1,118 cycles annually [24]. The average age figures in the census are adjusted by the average cycle per year figures to estimate the average number of pressurization cycles for the fleet aircraft that are subject to the inspection.

The average ages in table 3.1 indicate that many of the current fleet of B-747s and DC-10s are already beyond the threshold of allowable pressurization cycles. Because the aircraft age data are averaged, though, there are obviously some aircraft that are not obliged to be inspected immediately. For the representative facility, it is assumed that 70 percent of the fleet of both B-747s and DC-10s need to be inspected in the first year and inspections on the remaining 30 percent are evenly distributed over the next nine years.

Finally, repeat inspections must be taken into account. Frequency intervals for repeat inspections are also found in the ADs and they are included in the inspection descriptions. In this example, each aircraft that is inspected initially, also undergoes repeat inspections over the 10-year estimation interval, according to the time intervals prescribed in the ADs.

For the B-747 inspections, there are alternatives offered to continuing repeat inspections. These are called modifications or terminating orders. The modifications are often economically attractive alternatives to the carriers, but will negate any economic benefit from the MOI. If the modifications are performed, the inspection is either terminated or it must be performed with an alternative technique. In the lap splice inspections, the modification options consist of removing the top row of countersunk rivets and replacing them with protruding head rivets, or adding a specified external doubler to the skin lap splice. In either case, future inspections cannot be undertaken with either the MOI or the sliding probe because of the uneven skin surface that results from the modification. If a modification is chosen instead of the inspections, then there are no benefits from the MOI for that specific application.

3.5.6 Number of Planes Requiring Paint/Decal Removal.

There is no *a priori* method of determining what aircraft are subject to paint/decal stripping before inspection with the traditional eddy-current methods. The feedback from the industry indicates that it is quite small, although at least one facility found it necessary to strip the paint on all its aircraft subject to the skin lap inspections. Some aircraft may need to have the paint stripped for other reasons, so the incremental cost of paint stripping and repainting may be nil.

However, operators are eager to extend the cycle between paint jobs on their aircraft and any method that allows them to do so is attractive.

In certain situations, the need to strip paint or decals can be avoided when using the MOI and a large part of the inspection preparation time can be eliminated. The lap joints on the B-747 span the entire upper half of the fuselage. According to the feedback from the survey, the difference between stripping just the lap joints and stripping the entire fuselage is small. Many airlines commented that they would rather strip the entire fuselage for aesthetic reasons. The estimated labor cost of stripping an entire B-747 fuselage is approximately 1800 man-hours.

It is assumed that none of the representative facility's fleet of B-747s need to have the paint or decals stripped for the inspection with traditional eddy-current methods. Therefore, any savings that the MOI can generate by eliminating the need to strip the fuselage are not included in the NPV calculation. This assumption is relaxed in the next section to include scenarios where 3 of the B-747s in the fleet of the representative facility require paint or decal removal with the traditional methods.

3.5.7 Improved Reliability.

The field inspection results reported in section 2.2.2 indicate that there is no significant difference in the probability of detecting flaws with the MOI than with the sliding probe eddy-current methods. Therefore, the economic impact of a different PoD is not estimated in the cost-benefit analysis.

3.5.8 Proportion of Labor Savings Realized.

An assumption is made on the ability of the representative facility to transform time savings into labor savings. The competitive and semi-competitive scenarios defined previously are therefore implemented by assuming that a specific level of labor savings is achieved by the facility. In this case, the competitive scenario is assumed and 100 percent of the time savings are translated to productivity improvements. This assumption is changed to reflect the impact of the semi-competitive scenario where only 50 percent of productivity improvements are realized.

3.5.9 Number of Inspectors Cross-Trained.

The practice of cross-training inspectors is another assumption implicit in the competitive scenario. If a facility cross-trains non-NDT inspectors or mechanics to perform MOI inspections only, it can save the training costs that are required for eddy-current training. ATA Specification 105 [25] outlines a 40-hour eddy-current training course as a recommendation to the industry. The producers of the MOI recommend a training course of only 12 hours for the MOI. Therefore, 28 hours of training costs per inspector can be saved if cross-training is allowed.

The survey of the industry indicates that some facilities do use cross-trained personnel to perform MOI inspections. Usually the inspection team consists of one NDT inspector and one mechanic or general inspector that is cross-trained to use the MOI. For this reason, in the competitive scenario, it is assumed that two of the four inspectors trained to use the MOI are not NDT inspectors, causing lower training costs than if all four were NDT inspectors. This assumption is removed for the semi-competitive scenario where cross-training is not allowed and all MOI inspectors are also trained eddy-current inspectors.

3.5.10 Downtime Savings.

The final assumption of the competitive scenario is that inspection time savings can be translated into shorter aircraft downtimes. There are two possible scenarios for which the airline industry estimates the cost of out-of-service aircraft; planned downtime and unplanned downtime. Because the MOI inspections are planned inspections, it is appropriate to calculate the cost of planned downtime savings. This is estimated by pro-rating the lease cost of the same model aircraft on an hourly basis. Lease rates are estimated to be $150,000 per month for older models of both the B-747-100 and -200 and the DC-10 [26]. These figures pro-rated to an hourly basis are reported in table 3.3. This is the method used by many carriers to calculate the cost of planned out-of-service aircraft.

3.5.11 Discount Rate.

The opportunity cost of capital recommended for Government investment in commercial or industrial products and services is 10 percent [17]. The recommended inflation rate is 4 percent, resulting in a real rate of return of 6 percent to be used as the discount rate. It has already been mentioned that the airline industry estimates a much higher opportunity cost of capital, up to 34 percent. Therefore, the net present value is calculated under both the Government rate and the industry rate in the sensitivity analysis.

3.5.12 Useful Life.

The economic useful life of the investment is estimated to be 10 years. This is the recommended figure for FAA investments in mechanical equipment, according to the Department of Transportation [27].

3.6 RESULTS.

The results of the cost-benefit analysis are presented in two sections. The representative facility defined in section 3.5 is evaluated using the net present value criteria and the results are presented in section 3.6.1. The assumptions of the representative facility are individually relaxed to include a wider variety of possible facility characteristics and the results of the sensitivity analysis are presented in section 3.6.2.

3.6.1 Representative Facility.

The assumptions listed in table 3.3 define the representative facility, which is examined first. The results are presented under the two scenarios defined in table 3.2; the competitive scenario and the semi-competitive scenario. Under the relatively conservative assumptions listed in table 3.3 and using equation 3.1, the NPV calculations and payback periods are listed in table 3.4.

Figures 3.1a and 3.1b are disaggregated into annual terms over the life cycle of the investment. A table of the specific data inputs used for the calculations can be found in Appendix A.

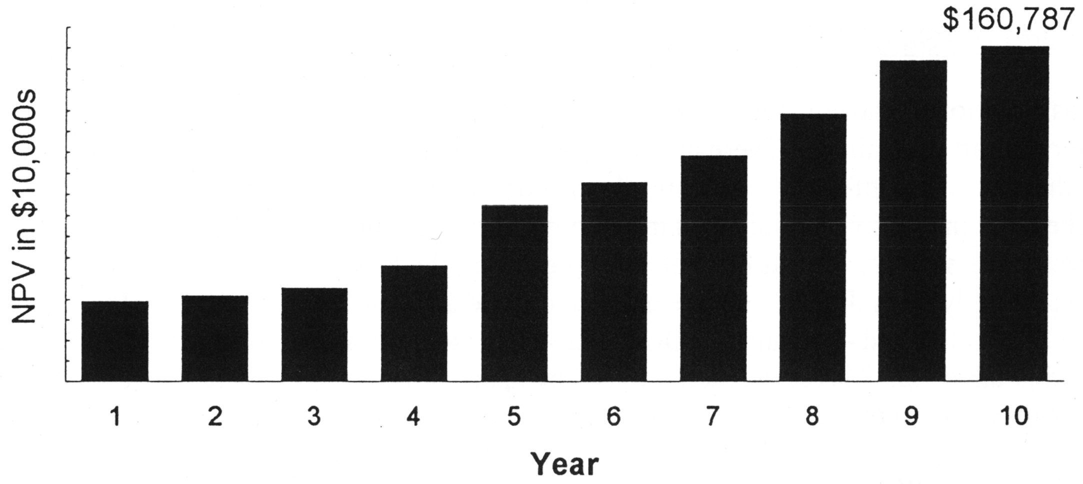

FIGURE 3.1a CUMULATIVE NPV OVER LIFETIME OF INVESTMENT - COMPETITIVE SCENARIO

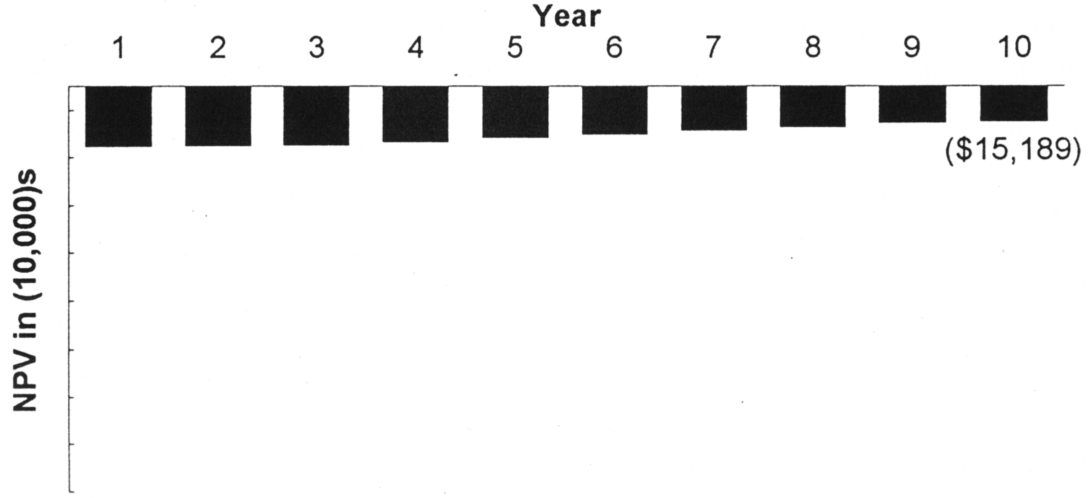

FIGURE 3.1b CUMULATIVE NPV OVER LIFETIME OF INVESTMENT - SEMI-COMPETITIVE SCENARIO

TABLE 3.4 NPV AND PAYBACK PERIODS FOR THE SPECIFIC CASE

Competitive Scenario	
NPV	$160,787
Payback Period	< 1 year
Semi-Competitive Scenario	
NPV	($15,189)*
Payback Period	> 10 years

* Parentheses indicate a negative value throughout this report

Clearly, the assumption of the competitive scenario has a strong impact. Not only does it generate a positive return on the investment in less than a year, but also continues to generate savings over the life cycle of the investment, resulting in a cumulative NPV at the tenth year of $160,787. Figures 3.1a and 3.1b display the cumulative NPVs over the lifetime of the investment under both scenarios. Without the competitive assumption, the NPV is negative throughout the life cycle of the investment, as indicated in figure 3.1b. Although it increases over the life cycle, the incremental annual increases are so small that the overall impact on the NPV is negligible, resulting in a negative NPV at the end of the useful life. The incremental increases to the NPV over time are greater in the competitive scenario than in the semi-competitive scenario.

Because of the large impact the competitive scenario displays, it is useful to disassemble the competitive scenario to examine the impact of the individual assumptions that are made. Each of the individual assumptions of the competitive scenario are eliminated one at a time, keeping the other assumptions constant. The resulting effect on the NPV is reported in table 3.5.

TABLE 3.5 EFFECT OF INDIVIDUAL ASSUMPTIONS IN THE COMPETITIVE SCENARIO ON NPV

Competitive Scenario	***NPV = $160,787***
No Cross-training	$159,667
50% Productivity Improvement	$144,536
No Downtime Savings	$2,182

The information in table 3.5 indicates that the downtime savings generates by far the largest contribution to the NPV. The other two assumptions are relaxed with a relatively small impact on the NPV. The downtime savings assumption has the strongest effect on the NPV for the representative facility.

Two extreme cases have been presented. First, all the potential time savings are translated into decreased aircraft downtime. Second, none of the potential savings are considered. A more realistic scenario can be found somewhere between the two extremes. Figure 3.2 plots the total range of achievable downtime savings as a percentage of potential against the cumulative NPV. In this scenario, the 50 percent productivity improvement and no cross training assumptions are retained, but the achievable downtime savings is varied. From this graph, one can deduce the threshold level of actual downtime savings as a percentage of potential downtime savings that is required for the MOI to generate an acceptable return, i.e., a positive NPV.

Figure 3.2 shows that the total NPV increases as a larger proportion of downtime savings becomes realized. The threshold value, the percentage of achievable downtime savings where the NPV becomes positive, is just under 10 percent. If 10 percent of the total time saved with the MOI can be translated into decreased aircraft downtime, under the assumptions of the representative facility, then the investment is economically beneficial.

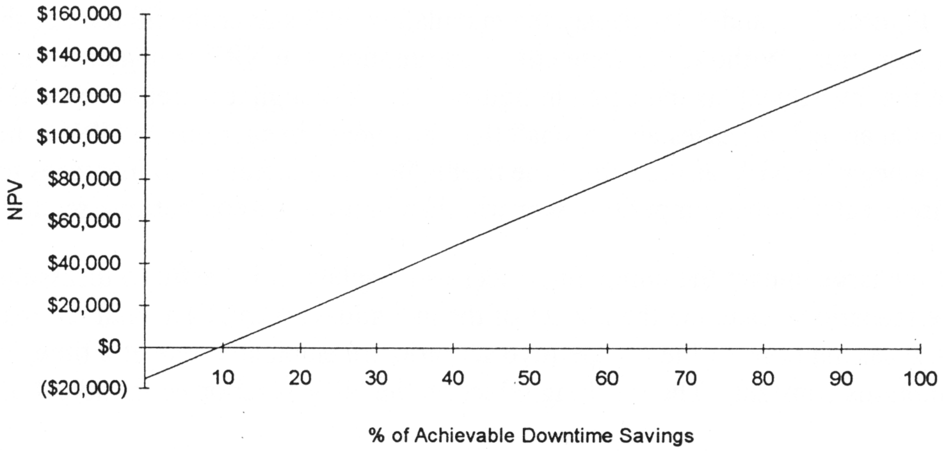

FIGURE 3.2 EFFECT OF ACHIEVED DOWNTIME SAVINGS ON NPV

To summarize the findings in this section, under the relatively conservative conditions of the representative facility, the MOI is cost-effective under the competitive scenario, specifically when the generated inspection time savings are translated into at least a 10 percent improvement in aircraft downtime. The benefits from cross-training and inspector productivity improvements have a minimal impact on NPV. Consequently, one of the criteria for the representative maintenance facility to benefit from an investment in the MOI is that it is able to optimize its inspection scheduling to take advantage of the effects of decreased downtime.

3.6.2 Sensitivity Analysis.

Up to this point, the assumptions listed in table 3.3 have remained fixed, other than those used in the competitive scenario. It has been discovered that under relatively conservative conditions, the MOI is cost-effective when the inspection time savings that it generates can be translated to a minimal improvement in aircraft downtime. Now the starred assumptions in table 3.3 are relaxed to examine the impact on the NPV of a number of different practices that currently exist in aircraft maintenance facilities.

The results of the sensitivity analysis are provided in table 3.6. The representative facility is chosen as the basis for comparison with the characteristics listed in table 3.3. Each assumption is varied individually to examine their isolated effect on the NPV. The NPV values reported in table 3.6 are interpreted as the representative facility with one characteristic varied to accommodate alternative values. NPVs for both the competitive and the semi-competitive scenarios have been calculated.

TABLE 3.6 RESULTS OF SENSITIVITY ANALYSIS ON NPV

	NPV in dollars Competitive Scenario	 Semi-Competitive Scenario
Representative facility	160,787	(15,189)
As representative facility, but paint stripping avoided on 3 B-747s	1,996,787	92,811
As representative facility, but time savings increased to 50% with MOI	447,447	9,187
As representative facility, but for a fleet of 40 B-747s and 59 DC-10s	276,274	(5,835)
As representative facility, but with a 30% discount rate	80,710	(21,941)
As representative facility, but MOI can be used for additional inspections totaling twice as many inspection man-hours	280,112	1,602

The results of the sensitivity analysis indicate that varying the uncertain assumptions listed in table 3.3 has no effect on the investment decision under the competitive scenario. The NPV remains positive for each assumption that is varied. Indeed, the NPV increases for most of the assumptions. Recall that the criterion to invest in the MOI is that the NPV is positive. Therefore, in the competitive scenario, relaxing the assumptions made in table 3.3 does not affect the sign of the NPV in any case. The MOI is always a beneficial investment in the competitive scenario.

In the semi-competitive scenario, there are three instances where varying the assumptions causes a change in the investment decision. The NPV is negative for the representative facility under the semi-competitive scenario, unless paint stripping is avoided on 3 B-747s, the facility is able to achieve a 50 percent time savings with the MOI, or the applications of the MOI are expanded so that it is used for twice as many inspection man-hours. Each of these is explained below.

3.6.2.1 Avoidance of Paint Stripping.

Paint and decal stripping have such a strong effect on the NPV because it is a very labor intensive process and because it also effects aircraft downtime. It is very expensive to strip paint, especially for lap joint inspections on B-747s, where the paint must be stripped from almost the entire aircraft. Inspections with traditional eddy-current methods are often scheduled to be coordinated with painting requirements. Repeat lap joint inspections occur nominally every 5 years, although operators would like to extend the paint cycle on their aircraft to 6 to 8 years. If this is achieved, the need to strip paint for the traditional eddy-current methods would add to the cost of the baseline scenario and the MOI would become even more cost-effective, as indicated in table 3.6. In other words, investment in the MOI could allow for an extension of the paint cycle and the savings that this would generate.

As was discussed in section 3.3.4.3, paint/decal stripping is not required for every inspection of B-747 lap joints with the traditional eddy-current methods. The Boeing procedures simply state that the rivets must be visible. There is no methodological way to determine when it is necessary to strip paint. The survey yields a variety of responses regarding the necessity to strip paint and/or decals. Therefore, the avoidance of surface stripping with the use of the MOI is presented in this report as a possibility only.

TABLE 3.7 NPVs WHEN PAINT STRIPPING IS AVOIDED WITH MOI

# of Planes	Competitive Scenario	Semi-Competitive Scenario
0	122,993	(16,468)
1	734,993	19,532
2	1,346,993	55,532
3	1,958,993	91,532

It is assumed that the representative facility does not find it necessary to strip any of their aircraft for the traditional eddy-current methods in the results reported in section 3.6.1. Table 3.7 shows the effect on NPV had the representative facility found it necessary to strip one, two, or three planes under both scenarios. Even if no planes need to be stripped for inspections under the competitive scenario, the NPV is positive. Under the semi-competitive scenario, if paint stripping is avoided for at least one aircraft, the MOI is cost-effective for the representative facility. If one or more of the twelve aircraft that the representative facility inspects needs to have paint removed for traditional eddy-current inspections, then the MOI is a worthwhile investment in the semi-competitive scenario.

3.6.2.2 Degree of Achievable Time Savings.

Another factor that, when varied, switches the investment decision is the degree of time savings achievable with the MOI. If, for example, the representative facility replaces the pencil probe/template method with the MOI, the time savings may be greater than 20 percent. Figure

3.3 displays the impact on NPV when the percentage time savings varies from zero to 50 percent. Both the competitive and the semi-competitive scenarios are displayed. Under the competitive scenario, less than 10 percent time savings generates a positive NPV for the representative facility. Under the semi-competitive scenario, this is increased to approximately 40 percent. If the inspection time can be cut in half, the MOI is cost-effective for the representative facility even under the semi-competitive scenario.

3.6.2.3 Further Application of the MOI to Other Inspections.

The inspections included in the analysis of the representative facility are based on evidence of the current practices in the aircraft maintenance community. This precludes any other applications for which the MOI may be used currently or in the future. Some facilities may find more uses for the MOI than those described in the representative facility. Also, further applications may be discovered by the developers of the MOI, aircraft manufacturers, or maintenance facilities themselves. It has already been mentioned that the developers of the MOI are currently working with aircraft manufacturers to identify some applications for corrosion detection. No applications of the MOI to corrosion detection have been approved by any aircraft manufacturers to date.

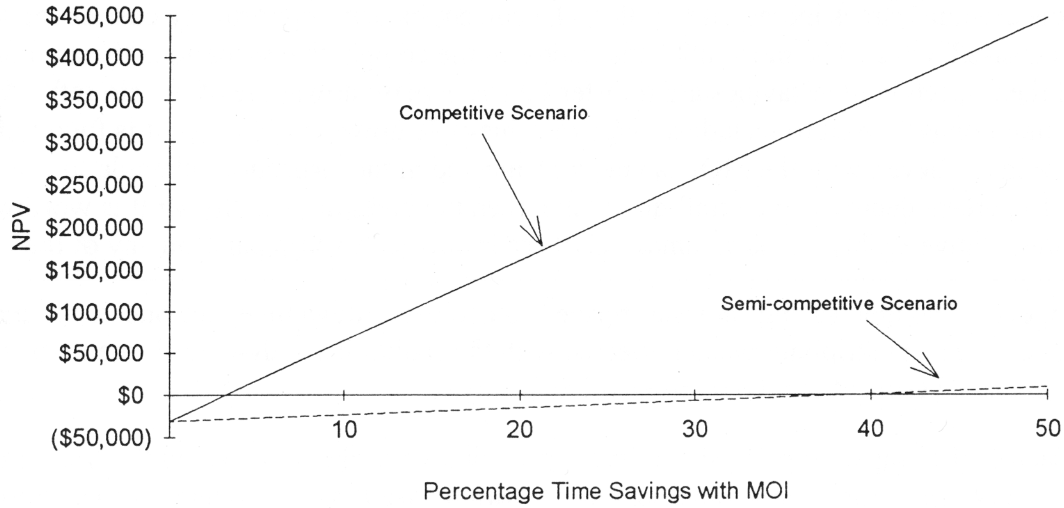

FIGURE 3.3 NPV VERSUS PERCENTAGE TIME SAVINGS

The possibility of additional or future applications is incorporated into the cost-benefit model by doubling the number of inspection man-hours that are addressed by the MOI. This is a simplistic assumption, as it assumes that the future applications replace the same technology, that is the eddy-current method using the sliding probe. Most corrosion detection is currently done visually and occurs at times of heavy maintenance. Thus, the incorporation of the MOI for specific corrosion detection tasks could impact aircraft preparation times as well as inspection times. No assumptions of future impact are made at this time. Nevertheless, even in the semi-competitive scenario, twice as many inspection man-hours addressed by the MOI results in a positive NPV.

The economic case for the MOI would be advanced if it were applicable to inspections other than those incorporated in the representative facility that resulted in at least twice as many inspection man-hours.

3.7 SUMMARY OF ECONOMIC ANALYSIS.

The cost-benefit analysis has sought to analyze the effects of the individual factors that contribute to the cost-effectiveness of the MOI. The possible returns to the investment have been calculated using the net present value methodology for a representative facility. A number of different scenarios have been analyzed, based on the current practices in aircraft maintenance. Data on inspection times and probabilities of detection collected in the field experiment have been used to examine the average time savings achievable with the MOI. Inspection procedures that are currently approved and practiced by the industry are examined in the cost-benefit analysis. Several of the factors have been varied to represent the different practices found in the industry.

The results indicate that there are two factors that have the strongest effect on the decision of the representative facility to invest in the MOI. First, in the competitive scenario, the representative facility always finds the MOI cost-effective and receives the payback in less than a year. Even when the discount rate is increased to reflect the current industry opportunity cost of capital, the MOI is cost-effective. The most influential factor in the competitive scenario is the assumption that all the inspection time savings are transferred to decrease downtime of the aircraft. When this assumption is relaxed to include a range of achievable downtime savings, it is found that if the time savings achieved with the MOI can be implemented in the inspection schedule to achieve at least a 10 percent decrease in aircraft downtime, then the investment in the MOI is worthwhile for the representative facility. This assumes that there is no need to strip paint on any of the B-747s.

Second, even if no time savings are transformed to decreased downtime, but one or more of the B-747s require paint stripping when inspected with the traditional eddy-current methods, the MOI is a beneficial investment for the representative facility.

Other factors that impact the decision of the representative facility to invest in the MOI are the percentage of inspection time savings achievable with the MOI and the number of inspections for which the MOI is applicable. Even in the semi-competitive scenario, when the inspection time can be cut by 40 percent with the MOI or when the applicable inspection times (in man-hours) are doubled, the MOI is a cost-effective investment in the representative facility.

The economic study indicates that several variables in this analysis affect the investment decision. The results lead to the following statements. First, the ability to decrease aircraft downtime with faster inspection techniques is an important component for the realization of the benefits of the MOI. Second, if the B-747s that require lap joint inspections need to be stripped of paint and decals when using the traditional eddy-current methods, the MOI can strongly effect the cost in labor and downtime of the inspections. Third, broader applications of the MOI to other inspections, especially corrosion detection, would further the economic case for the MOI greatly. Fourth, if a facility finds that it can perform MOI inspections in half the time it takes to perform eddy-current inspections, then the economics of the MOI is greatly affected. Finally, factors such as the discount rate, the fleet size, the proportion of time savings that is transferred to inspector productivity improvements, and the potential benefits from cross-training inspectors have a less profound effect. When each of these factors is varied to encompass a plausible range of values, they do not affect the overall decision to invest in the MOI.

The above results presume that the facility performs maintenance on the affected aircraft, specifically the B-747 and the DC-10. If the facility maintains less than the industry averages or has performed the modifications on the B-747s, the cost-effectiveness of the MOI diminishes.

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APPENDIX A DATA INPUT TO ECONOMIC ANALYSIS

MOI COST-BENEFIT ANALYSIS FOR THE REPRESENTATIVE FACILITY IN THE COMPETITIVE SCENARIO

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	
COSTS											
Investment Cost:											
Equipment	($30,000)										
Training:											
Number of Inspectors	4										
Training Requirement (hrs.)	12										
Initial Training Costs	($1,440)										
Total Investment Cost	($31,440)										
Operating Cost:											
Inspection Time Savings	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	
Number of Inspectors	4	4	4	4	4	4	4	4	4	4	
Avg. Wage of NDT Inspectors	$30	$30	$30	$30	$30	$30	$30	$30	$30	$30	
Avg. Wage of Mechanics	$20	$20	$20	$20	$20	$20	$20	$20	$20	$20	
Aircraft to be Inspected:											Total:
Number of B-747s for Lap Joints	8	0	1	0	1	0	1	0	1	0	12
Number of B-747s for Section 41 Area	15	1	1	1	0	1	1	1	0	1	22
Number of DC-10s for Str39 Lower Wing	26	1	1	1	1	1	1	1	1	1	35
Number of DC-10s for Str41 Lower Wing	22	1	1	1	1	1	1	1	1	1	31
Repeat Inspections:											
B-747 lap joints						8	1	1	1	1	
B-747 Section 41				16	1	2	17	2	2	3	
DC-10 Lower Wing at Stringer 39					27	2	2	2	28	3	
DC-10 Lower Wing Skin at Stringer 41								23	2	2	
B-747 Stringer 6 Lapjoint - BS 340-400 (both sides)					15	2	2	2	16	2	
B-747 Stringer 6 Lapjoint - BS 400-520 (both sides)								16	1	2	

Appendix A. Data Input to Economic Analysis (continued)

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Inspection Times (per aircraft):										
B-747 Lap Joints	56	56	56	56	56	56	56	56	56	56
B-747 Skin on Section 41	24	24	24	24	24	24	24	24	24	24
DC-10 Lower Wing at Str 39 (both wings)	22	22	22	22	22	22	22	22	22	22
DC-10 Lower Wing at Str 41(both wings)	18	18	18	18	18	18	18	18	18	18
B-747 Stringer 6 Lapjoint - BS 340-400 (both sides)	8	8	8	8	8	8	8	8	8	8
B-747 Stringer 6 Lapjoint - BS 400-520 (both sides)	4	4	4	4	4	4	4	4	4	4
Total Man-hours Spent on B-747	988	36	92	420	200	548	572	220	292	188
Total Man-hours Spent on DC-10	968	40	40	40	634	84	84	498	692	142
Total Inspection Time Savings (hrs)	391.2	15.2	26.4	92	166.8	126.4	131.2	143.6	196.8	66
Prop'n. of Labor Savings Realized	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Value of Inspection Time Savings	$11,736	$456	$792	$2,760	$5,004	$3,792	$3,936	$4,308	$5,904	$1,980
Paint Stripping/Repainting:										
B-747 lap joints										
Strip Time per Aircraft	1080	1080	1080	1080	1080	1080	1080	1080	1080	1080
Repaint Time per Aircraft	720	720	720	720	720	720	720	720	720	720
Strip/Repaint Cost per Plane:	$36,000	$0	$36,000	$0	$36,000	$0	$36,000	$0	$36,000	$0
Number Requiring Paint Stripping	0	0	0	0	0	0	0	0	0	0
Total Strip/Repaint Cost	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Benefits From Cross-Training:										
Number of Inspectors	2									
Training Time Savings	28									
Savings from Cross-training	$1,120									

Appendix A. Data Input to Economic Analysis (continued)

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Downtime:										
Elapsed Time of Inspection										
B-747 Lap Joints	14	14	14	14	14	14	14	14	14	14
B-747 Section 41	12	12	12	12	12	12	12	12	12	12
B-747 Section 6 Lap Joints (BS 340-400)	8	8	8	8	8	8	8	8	8	8
B-747 Section 6 Lap Joints (BS 420-500)	4	4	4	4	4	4	4	4	4	4
DC-10 Underwing Str 39	22	22	22	22	22	22	22	22	22	22
DC-10 Underwing Str 41	18	18	18	18	18	18	18	18	18	18
Paint Removal and Repainting Time Savings	0	0	0	0	0	0	0	0	0	0
Elapsed Inspection Times Savings	288	12.8	15.6	51.2	156	52	71.2	128	175.2	48
Value of Downtime per Hr. (B-747)	$200	$200	$200	$200	$200	$200	$200	$200	$200	$200
Value of Downtime per Hr. (DC-10)	$200	$200	$200	$200	$200	$200	$200	$200	$200	$200
Total Potential Downtime Savings	$57,600	$2,560	$3,120	$10,240	$31,200	$10,400	$14,240	$25,600	$35,040	$9,600
Downtime Included (0=no, 1=yes)	1	1	1	1	1	1	1	1	1	1
Total Downtime Savings	$57,600	$2,560	$3,120	$10,240	$31,200	$10,400	$14,240	$25,600	$35,040	$9,600
Total Operating Cost Savings	$70,456	$3,016	$3,912	$13,000	$36,204	$14,192	$18,176	$29,908	$40,944	$11,580
Discount Rate	6%	6%	6%	6%	6%	6%	6%	6%	6%	6%
Annual Discounted Net Benefits	$39,016	$2,845	$3,482	$10,915	$28,677	$10,605	$12,813	$19,891	$25,689	$6,854
Cumulative Discounted Net Benefits	$39,016	$41,861	$45,343	$56,258	$84,935	$95,540	$108,353	$128,244	$153,933	$160,787
Net Present Value	$160,787									

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