PROBABILISTIC INSPECTION STRATEGIES FOR MINIMIZING SERVICE FAILURES

Abraham Brot
TASHAN Engineering Center
Israel Aircraft Industries
Ben-Gurion Airport, Israel

SUMMARY

The **INSIM** computer program is described which simulates the "limited fatigue life" environment in which aircraft structures generally operate. The use of **INSIM** to develop inspection strategies, which aim to minimize service failures, is demonstrated. Damage-tolerance methodology, inspection thresholds and customized inspections are simulated using the probability of failure as the driving parameter.

INTRODUCTION

Aircraft structures generally have a limited fatigue life. Sooner or later, cracks develop at critical locations. These cracks propagate and, unless detected and repaired, will eventually result in a failure. There are three, mutually exclusive, possible outcomes of the fatigue process:

(1) The aircraft may reach the end of its operational life and be retired from service. The retired aircraft may or may not have undetected cracks at critical locations.

(2) A crack may be detected during maintenance operations. The affected part is usually repaired or replaced.

(3) A crack reaches its critical size undetected and the structure fails in service.

It is the aim of the fatigue engineer to minimize the probability of failure during the service life. Damage-tolerance methodology serves this purpose by requiring or encouraging the following:

(1) Moderate stress levels resulting in long crack initiation and propagation lives;

(2) rationally determined NDI methods and intervals;

(3) fail-safe or crack-arrest design features to avoid catastrophic failures.

However, over the past 10-15 years, a trend has developed in which aircraft are being operated much longer before retirement. For many aircraft models, high-time aircraft greatly exceed original design life goals (Reference 1). With increased service usage, the NDI methods and

intervals originally specified may prove to be inadequate for avoiding failures and new strategies must be developed in order to minimize failures in service.

SIMULATION OF THE FATIGUE PROCESS AND ITS DETECTION

A simulation method has been developed to provide strategies for the optimum scheduling of structural inspections. The **INSIM** (**IN**spection **SIM**ulation) computer program has been written to simulate the "limited fatigue life" environment. Using **INSIM**, various inspection methods and intervals can be evaluated for selected parameters, and the resulting probability of failure can be determined.

INSIM contains four probabilistic simulations:

(1) Service life variation is provided by a normal distribution defined by a mean and high-time ($+3\sigma$) expected service life.

(2) Crack initiation life is described by a two-parameter (shape factor and characteristic life) Weibull distribution.

(3) Crack growth variation is characterized by a normal distribution defined by a mean rate and an extreme ($\pm 3\sigma$) variation.

(4) NDI probability of detection is modelled by a three-parameter (shape factor, characteristic length and minimum detectable length) Weibull distribution.

INSIM performs a simulation of a single critical location in an entire fleet of aircraft. Cracks initiate at various times and grow at variable rates in each aircraft. Inspections are performed according to a predetermined schedule, using as many as six different NDI methods. Cracks are detected during these inspections according to the statistical expectation of detection. As the simulation proceeds from aircraft to aircraft, cracks are detected, aircraft are retired from service or failures occur. The computer acts as a scorekeeper, amasses the statistics and summarizes the results. In order to provide statistical significant results, a large number of simulations must be performed. In a typical simulation, 100,000 inspections will be performed for a fleet of 30,000 aircraft.

The program determines, for the parameters selected:

(1) The probability of an aircraft reaching retirement, uncracked at the critical location.

(2) The probability of an aircraft retiring with an undetected crack.

(3) The probability of detecting a crack before it reaches the size dictated by the damage-tolerance regulations.

(4) The probability of detecting a crack larger than the above, but less than the size required for failure.

(5) The probability of a failure occurring during the service life.

Based on these results, optimum NDI methods and intervals can be selected to provide a required level of safety and cost effectiveness. A typical **INSIM** output is shown in Table 1.

The method is especially well suited for developing inspection strategies for multiple-site or widespread fatigue damage situations.

Table 1. A Typical Example of INSIM Results

SUMMARY & STATISTICS

Fleet size: 30000   Threshold: 10000   Interval(s): 4000

Mean service life:	29965	High-time aircraft: 45463
Min. crack initiation:	7104	Max. crack initiation: 150598
Min. crack growth:	11376	Max. crack growth: 17285
Inspections performed:	164488	Inspections per aircraft: 5.48

	Number of Aircraft	Percent
Aircraft retired uncracked:	29309	97.70%
Aircraft retired cracked:	494	1.65%
Cracks < Ap detected:	187	0.62%
Cracks > Ap detected:	3	0.0100%
Failures:	7	0.02333%

SELECTING INSPECTION STRATEGIES USING INSIM

The **INSIM** computer program can be used to select inspection strategies that minimize the probability of failure in service. Several examples will be shown to demonstrate this feature.

The Primary Strategy -- Damage-Tolerance Methodology

The damage-tolerance regulations implicitly require the use of moderate stress levels and rationally determined NDI methods and intervals. This results in several benefits such as: long crack initiation lives, long crack growth lives, relatively large critical crack sizes and ample opportunities to detect cracks. Thus, damage tolerance methodology can be considered to be the primary strategy for minimizing service failures.

Figure 1 compares the probability of failure for a typical location designed to damage-tolerance requirements compared to one designed to safe-life requirements.
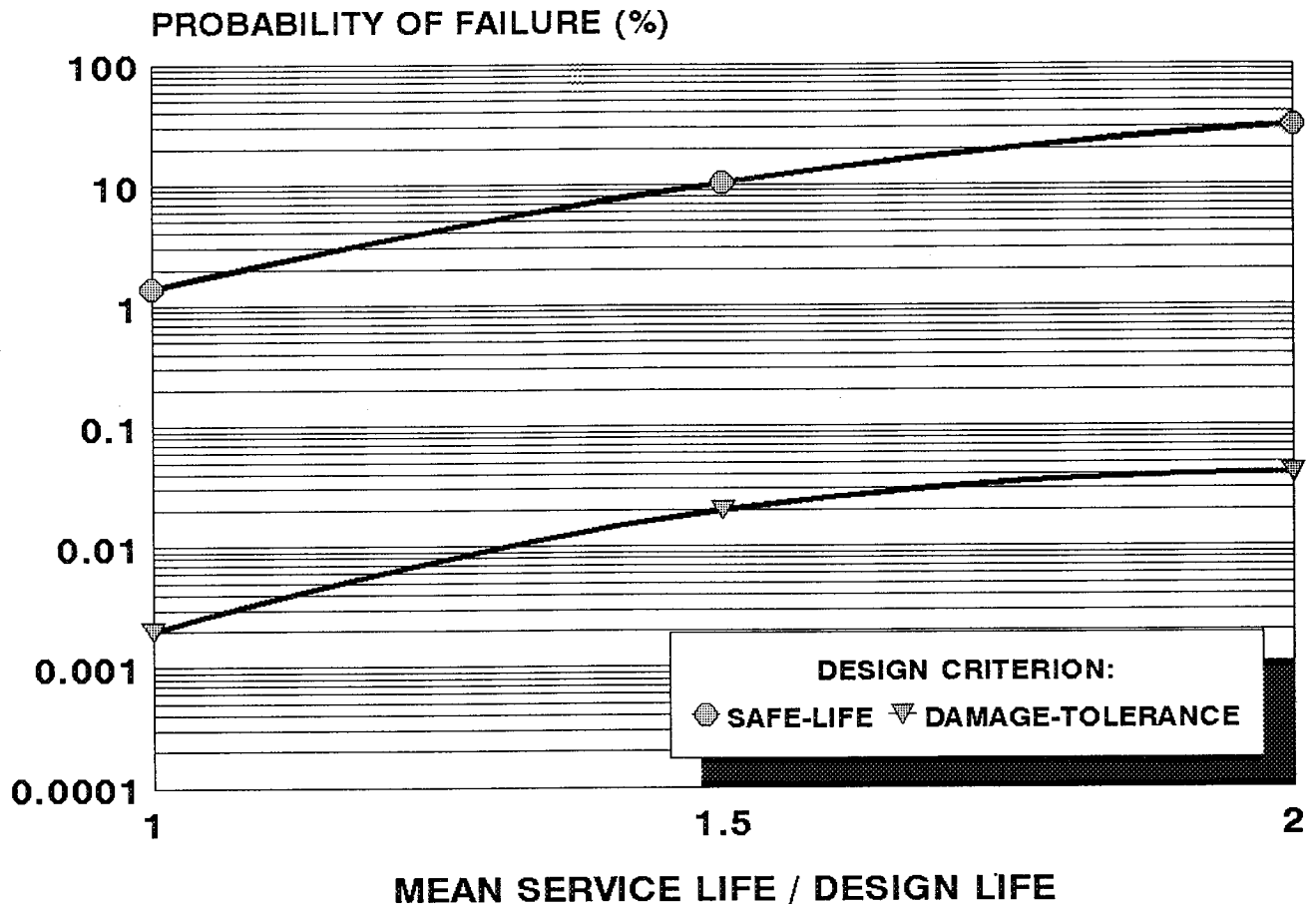

Figure 1. Effect of mean service life on the probability of failure.

The safe-life requirements assume a mean crack initiation life of two design lifetimes and an inspection interval of half the design lifetime. Implementation of the FAR-25 damage-tolerance requirements resulted in a 21% reduction in allowable stress level and set an inspection interval of 20% of the design lifetime.

Figure 1 shows that the probability of failure, for a mean service life equal to the design life, is 1.4% for the safe-life design while it is only 0.002% for the location designed according to the damage tolerance criterion. As the mean service life of the fleet increases, so does the probability of failure increase. Figure 1 indicates, for a mean service life equal to twice the design life, the probability of failure is 31% for the location designed to the safe-life criterion. The corresponding value for the location designed to be damage-tolerant is only 0.04%.

There is a commonly expressed belief that a structure, designed to the damage-tolerance requirements, is not affected by an extension in service life, since the assumed fatigue damage reverts to a predetermined value after each inspection that did not detect a crack. If this is true, there need not be any limitations on the acceptable service life of an aircraft. Even without considering corrosion damage, which is time dependant, the total life view of INSIM shows that this premise is not true, and the probability of failure increases with increased service life. This is obviously due to the fact that, for the overwhelming number of locations (more than 99%), aircraft can be expected to retire from service without any cracks being detected, as is shown in Table 2. As the service life increases with respect to the design life, less aircraft retire without cracks being detected. Most of the difference is reflected by the number of cracks detected by NDI. However, it is inevitable that some of the difference is accounted for by unsuccessful inspections which lead to service failures. Therefore, it is clear that the probability of failure increases with service usage -- even in locations designed according to the damage-tolerance criteria.

TABLE 2. Typical Distribution of Possible Outcome at a Location

POSSIBLE OUTCOME AT LOCATION	MEAN SERVICE LIFE / DESIGN LIFE		
	1.0	1.5	2.0
Retired from service before detection of crack	99.97%	99.73%	99.06%
Crack detected by NDI	0.03%	0.25%	0.90%
Failure in service	0.00%	0.02%	0.04%
T O T A L	100.00%	100.00%	100.00%

As usage severity increases, it can be expected that the probability of failure will increase. This is illustrated in Figure 2 for locations designed according to the safe-life and damage-tolerance criteria. Usage severity is characterized here by an increase in the spectrum stress level. As is shown in Figure 2, under a 20% increase in usage severity, the probability of failure for the safe-life design can reach 55%. For the damage-tolerance design, even under these adverse conditions, the probability of failure only reaches 0.13%.

PROBABILITY OF FAILURE (%)
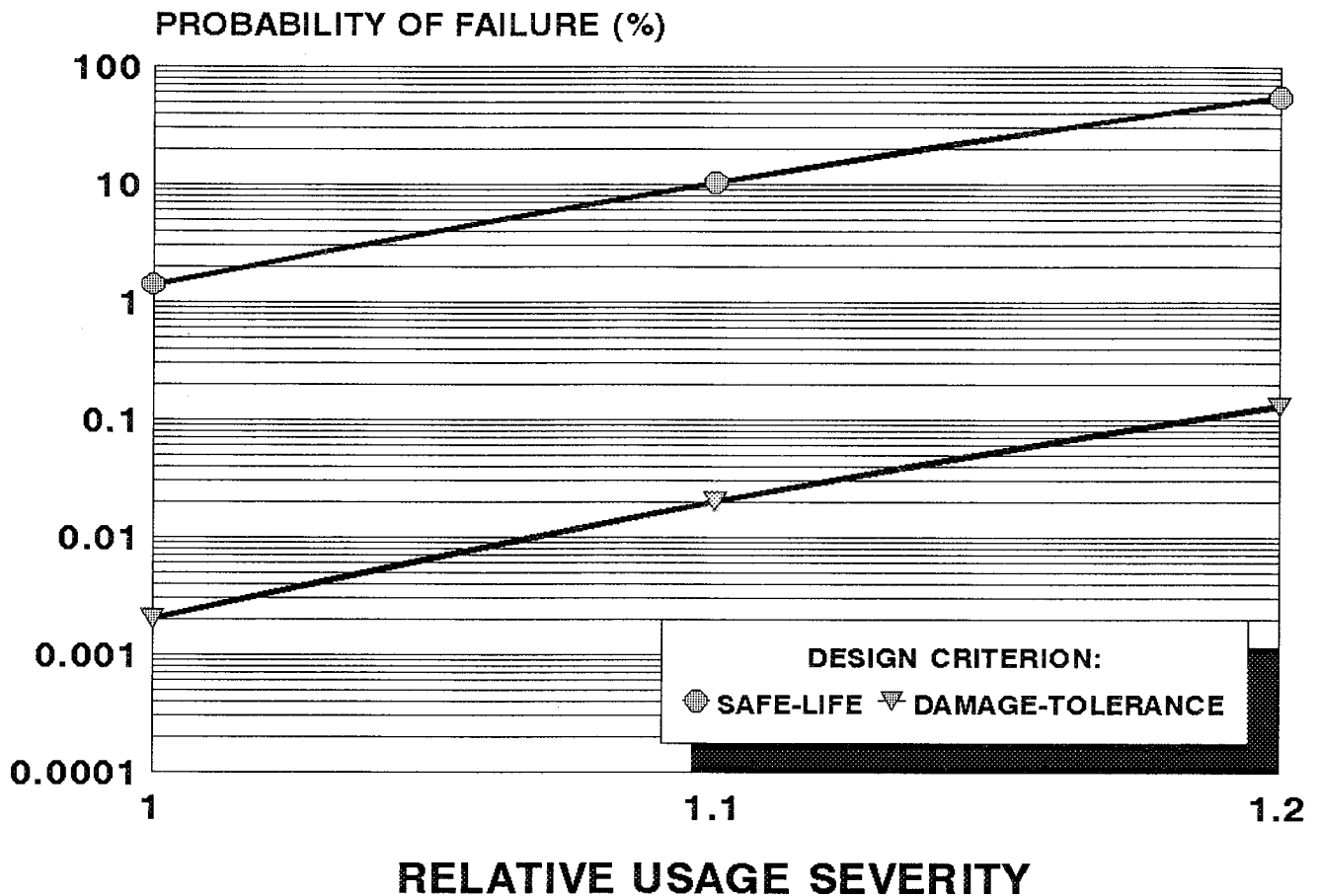

RELATIVE USAGE SEVERITY

Figure 2. Effect of usage severity on probability of failure.

These studies, assisted by the **INSIM** program, demonstrate that the damage-tolerance methodology can be considered to be the primary strategy for minimizing service failures. As is shown in Figures 1 and 2, even under adverse conditions of extended service life and usage severity, reasonable probabilities of failures can still be achieved.

The Inspection Threshold -- Friend or Foe?

It is FAA practice to permit, under certain circumstances, delaying the initial inspection to 50% of the design life (See Reference 2). This initial inspection is often called the "inspection threshold".

The concept of an inspection threshold obviously appeals to the manufacturer and operator, who can delay maintenance to a later date. It is assumed that there is only a very small probability that cracks will be detected early in an aircraft designed to be damage-tolerant. Therefore, the initial inspection can be safely delayed until 50% of the design life has been reached.

This premise has been studied, using the **INSIM** computer program, and the results are shown in Figure 3. The parameters used are typical results for a location designed to be damage-tolerant. The mean service life was taken to be equal to the design life. Inspections are performed, after the threshold inspection, at intervals of 20% of the design life.
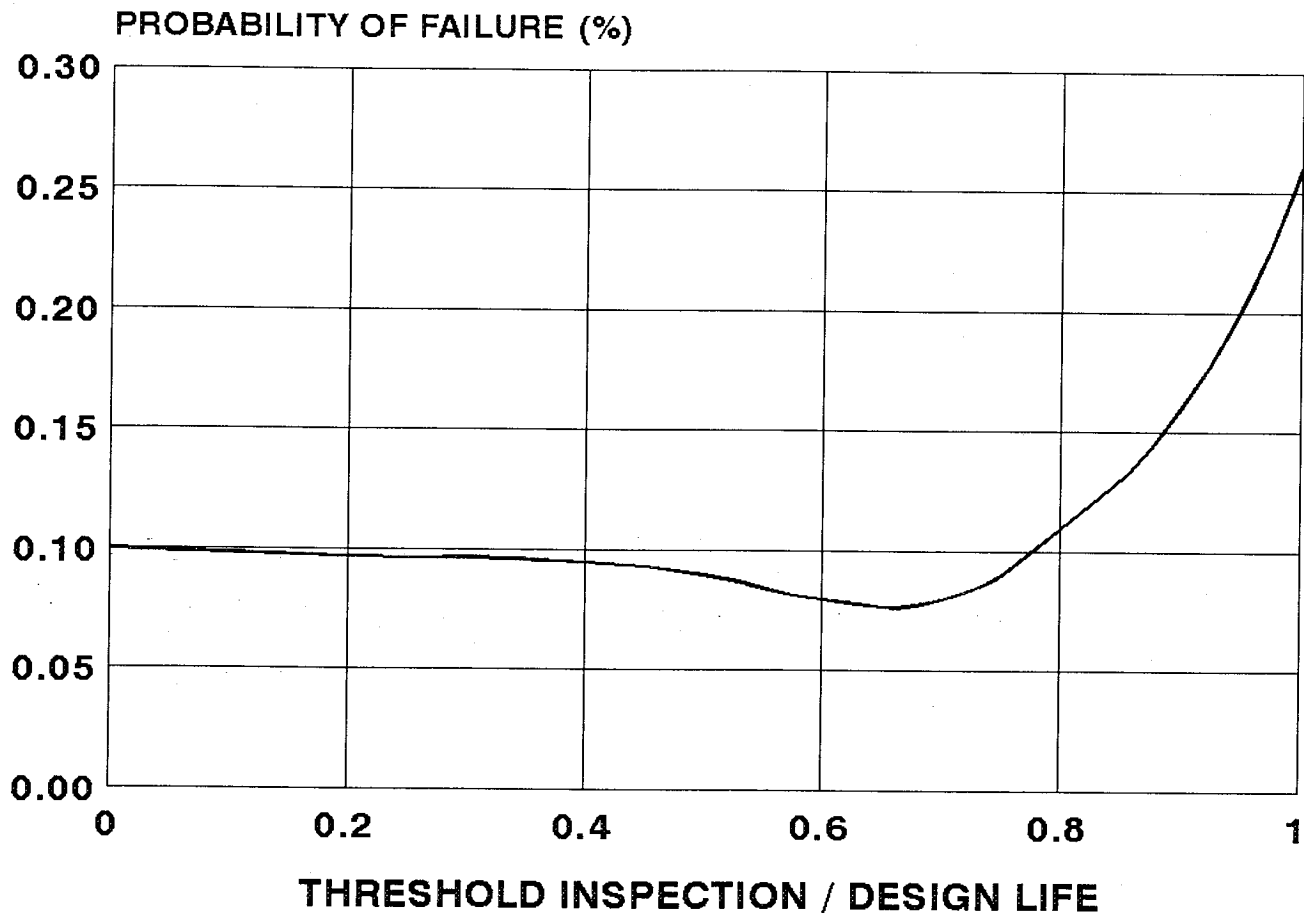

Figure 3. Effect of threshold inspection on the probability of failure.

Figure 3 indicates that the probability of failure remains nearly constant for conditions ranging from no threshold inspection to delaying the threshold inspection to 75% of the design life. In fact, for threshold inspections between 40% and 70% of the design life, there is a slight reduction in the probability of failure. This unexpected phenomenon can be explained by the fact that the presence of a threshold inspection may place the remaining inspections at points on the crack growth curve where crack detection is more probable. Only when the threshold inspection is scheduled for later than 75% of the design life does the probability of failure begin to rise rapidly.

As a result of this study, and similar studies performed using **INSIM** over a wide range of parameters, it can be concluded that there is no adverse effect in scheduling the threshold inspection at 50% of the design life for aircraft that have been designed to damage-tolerance requirements.

Customized Inspections for Minimizing the Probability of Failure

In spite of the virtues of the damage-tolerance methodology in minimizing the probability of failure, adverse situations exist in which conventional inspection intervals are insufficient. In such a case, **INSIM** can be used to select a customized inspection schedule which will reduce the probability of failure to an acceptable level. This will be demonstrated using two examples.

The first example deals with a 2024-T3 plate having several fastener holes. A crack will develop at one fastener hole, eventually severing the ligament and then continue to grow from the opposite side of the hole. The crack continues to grow until it reaches a size critical under service loads, and then failure occurs. Using conventional damage tolerance criteria, the threshold inspection was selected to be 50% of the design life and subsequent inspection intervals were selected to be 20% of the design life, using a liquid penetrant NDI method. Figure 4 indicates the probability of failure for this location which is designated location "A".

When the mean service life equals the design life, Figure 4 indicates that the probability of failure would be 0.05% without any inspections. This is due to the relatively large mean crack initiation life of nearly four design lifetimes. When the inspections prescribed by the damage tolerance criteria are applied, the probability of failure drops to 0.01%.

As the mean service life increases, the probabilities of failure likewise increase, as is illustrated in Figure 4. When the mean service life reaches twice the design life, the probability of failure is 0.55%, even though the inspections are performed in accordance with the damage tolerance requirements. This probability of failure is excessive, and should be reduced. Several customized inspection schedules were studied with the assistance of **INSIM**. Table 3 describes the customized inspection schedule which seemed to be the most cost-effective.
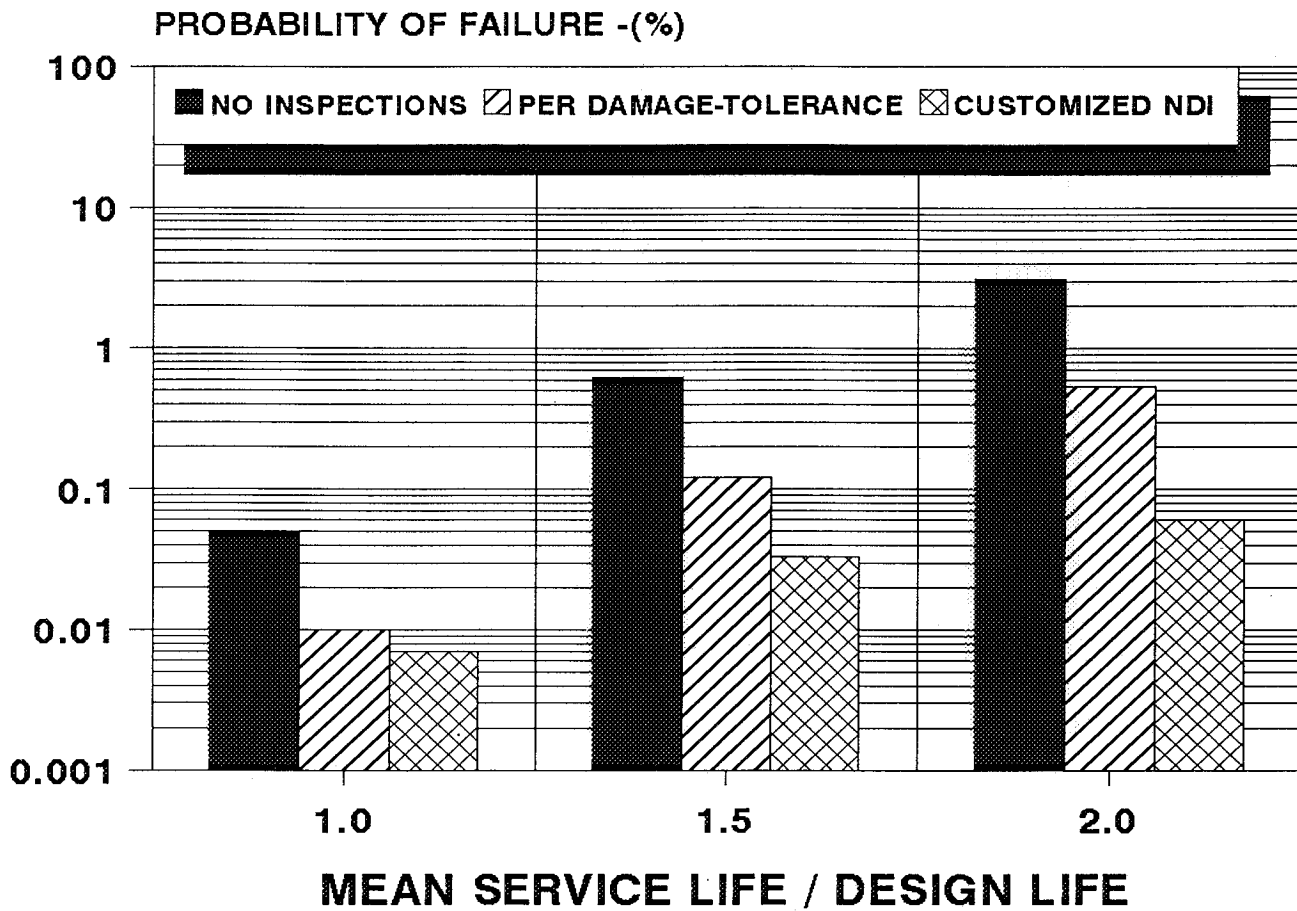
PROBABILITY OF FAILURE -(%)

Figure 4. Probability of failure for location "A".

TABLE 3. Customized Inspection Schedule for Location "A"

(All inspections are performed using liquid penetrant)

SERVICE LIFE / DESIGN LIFE	INSPECTION INTERVAL / DESIGN LIFE
0.50	Threshold Inspection
0.50 - 1.00	0.20
1.00 - 1.50	0.15
1.50 - 2.00	0.10
2.00 -	0.05

The customized inspection begins with the conventional threshold and inspection interval, as dictated by damage-tolerance requirements. With each extension in service life, the interval is reduced, as is shown in Table 3. Figure 4 describes the effect of the customized inspection schedule on the probability of failure. When the mean service life equals the design life, the customized schedule has no real effect. However, when the mean service life reaches 1.5 times the design life, the probability of failure is reduced from 0.12% to 0.033%, as is shown in Figure 4. When the mean service life reaches twice the design life, the customized inspections reduce the probability of failure from 0.55% to 0.06%. This is a very significant reduction in the probability of failure. This example demonstrates how a specific inspection strategy, of reducing the inspection interval as service life is extended, can be selected to minimize the probability of failure.
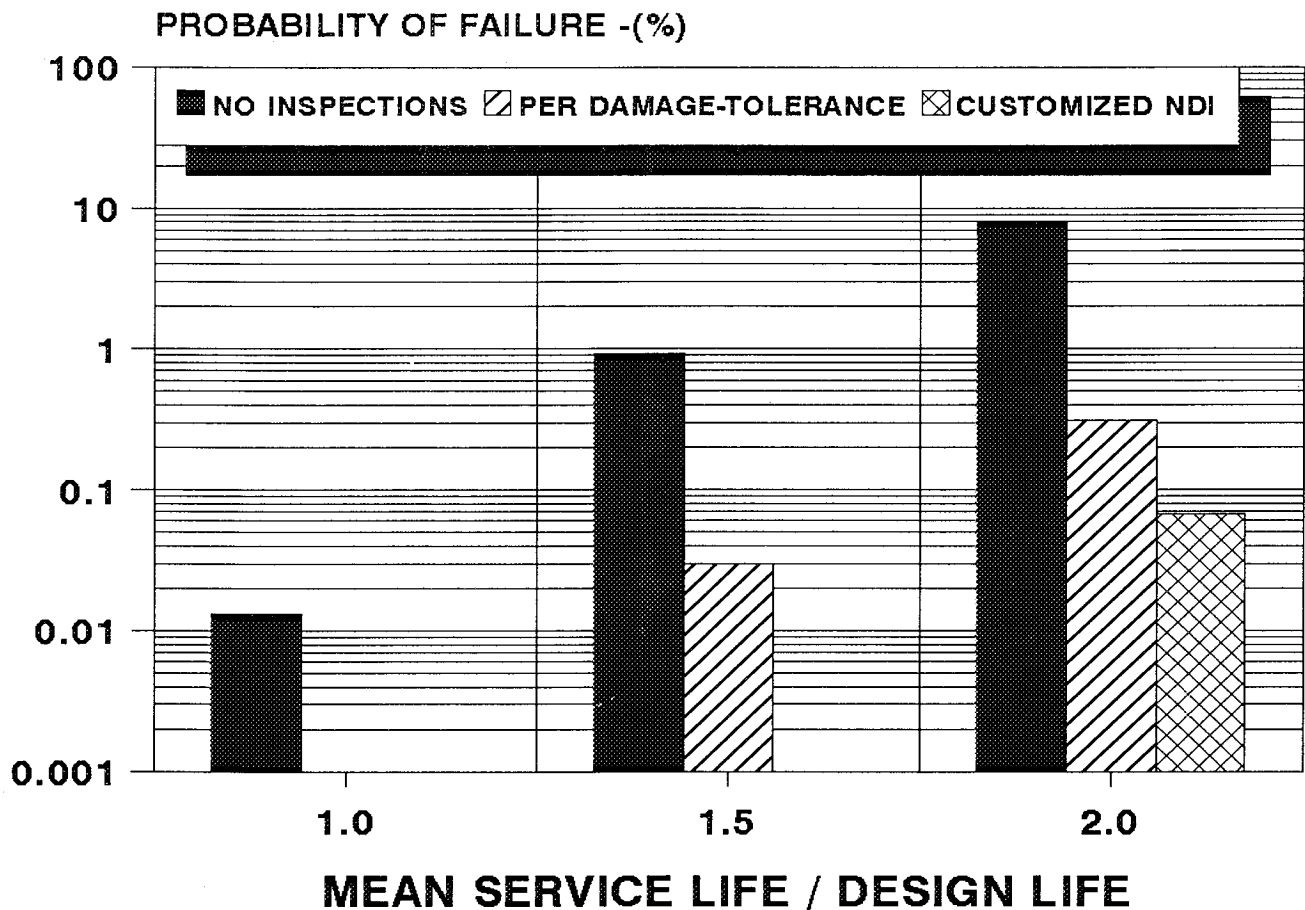
PROBABILITY OF FAILURE -(%)

Figure 5. Probability of failure for location "B".

The second example deals with a 7475-T73 wing skin panel at an access hole. Cracks developing at the edge of the hole will propagate and eventually result in a failure of the panel. Conventional damage tolerance analysis set the threshold inspection at 50% of the design life and the inspection interval at 15% of the design life. Inspections are to be performed visually. Figure 5 describes the probability of failure for this area, which is designated location "B".

When the mean service life equals the design life, Figure 5 indicates that the probability of failure is only 0.013% even without any inspections. When the above inspections are performed, the probability of failure is virtually zero.

However, as the service life increases, the situation begins to deteriorate. When the mean service life equals twice the design life, the probability of failure increases to 8.0% for no inspections and 0.31% when the prescribed inspections are performed, as is shown in Figure 5. By using **INSIM** to study various inspection strategies, it was concluded that the addition of an ultrasonic inspection, at the end of each design life, would reduce the probability of failure significantly.

Figure 5 indicates that when the mean service life is twice the design life, this supplementary inspection will reduce the probability of failure from 0.31% to 0.067%.

These two examples demonstrate two ways that customized inspections can be used to reduce the probability of failure significantly. The first method is to continuously reduce the inspection interval as the service life increases beyond the originally determined design life. The second method is to add supplementary inspections at specific intervals of service usage. In both cases the INSIM computer program was used to evaluate the improvement to the probability of failure.

REFERENCES

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