Risk Analysis to Over-fly an IAT-Based F-22 Structural Inspection Requirement

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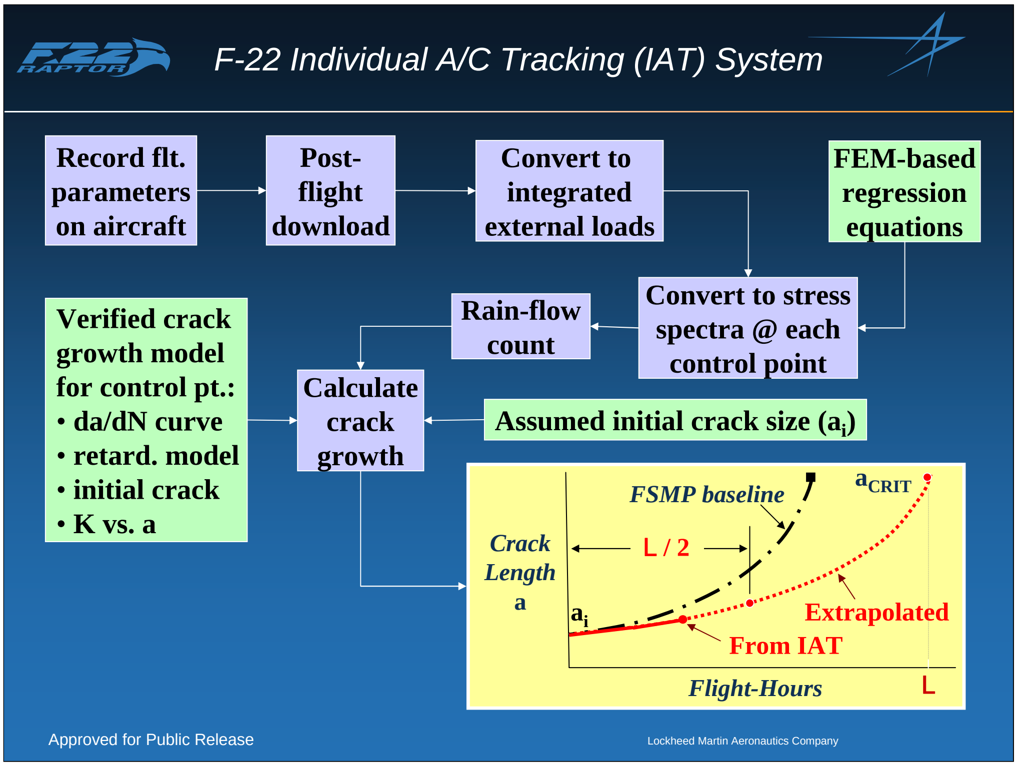
Abstract

To optimize fleet readiness, F-22 structural inspections are scheduled in groups called Planned Maintenance Packages (PMPs). Many independent individual aircraft tracking (IAT) crack growth models are used to track usage severity and adjust inspection interval requirements at individual inspection locations. The sophistication of these models provides the F-22 IAT program with unprecedented fidelity. At the same time, the resulting variability of the required inspection times from location to location within a PMP tends to complicate fleet management. Inevitably for some individual aircraft, high usage rates occur at one or two inspection locations within a PMP, accelerating the inspection requirement at those locations. Meanwhile, on the same aircraft, low usage rates at other locations within the same PMP could allow delay of those inspections. For fleet readiness, a critical objective is to keep the inspections grouped in PMPs (with very rare interjection of an individual inspection) and avoid accelerating an entire PMP to accommodate an isolated high-usage inspection location. Therefore, requests are made to the Structural Integrity engineer to "over-fly" IAT-required inspections at the high-usage inspection locations, delaying those one or two inspections until several other inspections in their PMP are due.

The challenge for F-22 Structural Integrity is to establish a process that approves over-fly requests whenever possible, but without compromising the required level of aircraft structural integrity. A risk analysis rationale, process, and criteria are presented that meet this challenge. In this process the total risk is considered for all inspections in a PMP for a given aircraft. The IAT-based requirements for next inspection are different for every inspection location in the PMP, but the PMP concept proposes to inspect all at the same time. If the proposed timing for the PMP involves an over-fly, most locations would be inspected early compared to their individual requirement, but one or two would be inspected later than the IAT requirement. A risk analysis compares the increase in probability of structural failure due to these one or two locations to the decrease due to the many locations inspected early. If the estimated decrease in risk offsets the estimated increase, then the proposed PMP as a whole is a risk reduction, and the over-fly request is approved.

The paper presents the details of the risk analysis process and its success to date as a rationale for approving F-22 over-fly requests.

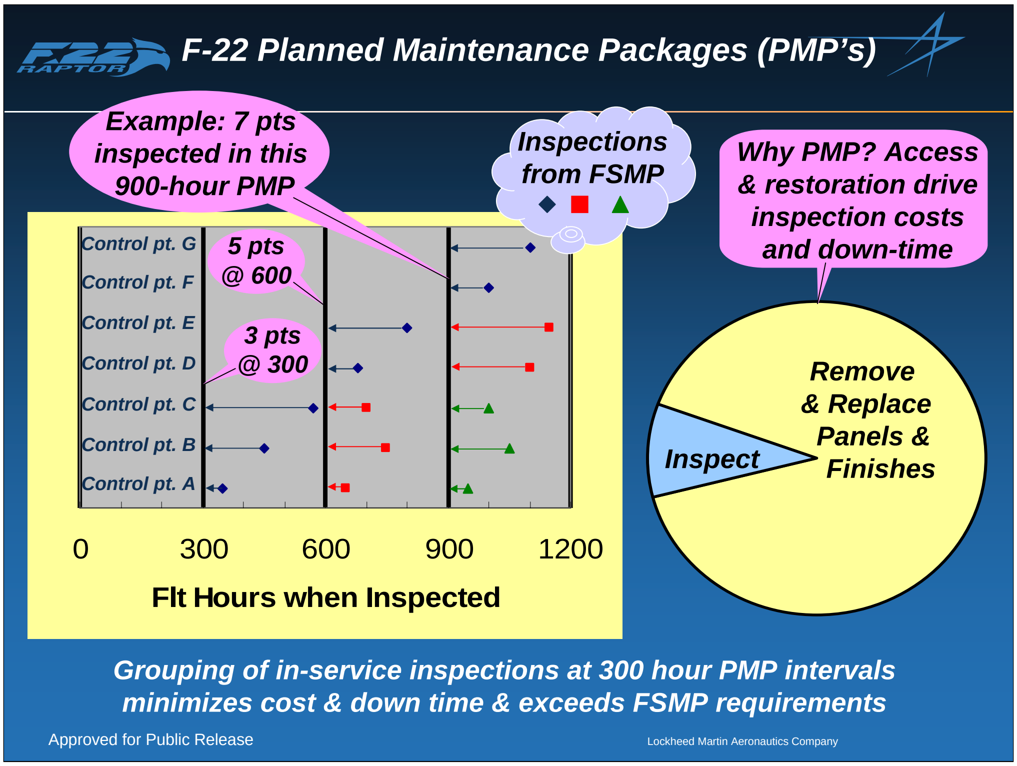


The F22 Individual Aircraft Tracking (IAT) program uses measured flight parameters to calculate crack growth at hundreds of control points on each individual aircraft. The Flight data recorder on the aircraft records the actual time-correlated sequence of values of numerous airplane parameters. After each flight these data are downloaded to a ground processor. Typically, IAT loads equations, derived from flight test data, convert the parameter data to spectra of integrated external loads (e.g., wing root bending moment). IAT stress equations, obtained from the airplane finite element model (FEM) by regression, convert the loads spectra to a spectrum of local stresses at each control point. The verified crack growth analysis model at each control point calculates crack growth for the assumed initial flaw.

The severity of the usage is compared to the F-22 Force Structural Maintenance Plan (FSMP) baseline using a severity ratio. Severity ratio is the ratio of actual hours to FSMP hours for the same calculated growth increment. All the severity ratios for that control point for aircraft at the same base are combined to calculate a weighted average usage severity. This base average is used for extrapolation. For the individual aircraft control point shown above, extrapolation to critical crack size provides an estimate of the crack growth life (***L***) for that control point on that aircraft.

The standard requirement for time to next inspection is half the IAT crack growth prediction, ***L/2***. This requirement is based on actual measured usage, and therefore it supersedes the FSMP inspection interval, which was derived for an assumed baseline spectrum.

In general each control point on an aircraft is responds to a different set of dominant loads and has its own unique stress equation and crack growth equation. Thus the usage severity can vary significantly between control point locations on the same aircraft.



On F-22, it is the removal and restoration of access panels and final finishes, not the inspections themselves, that drives the time required to implement inspections. Therefore, F-22 structural inspections are scheduled at 300 flight-hour intervals and grouped in packages called Planned Maintenance Packages (PMPs). Using PMPs, several inspections requiring the same panel removals can be consolidated, saving inspection costs and down time.

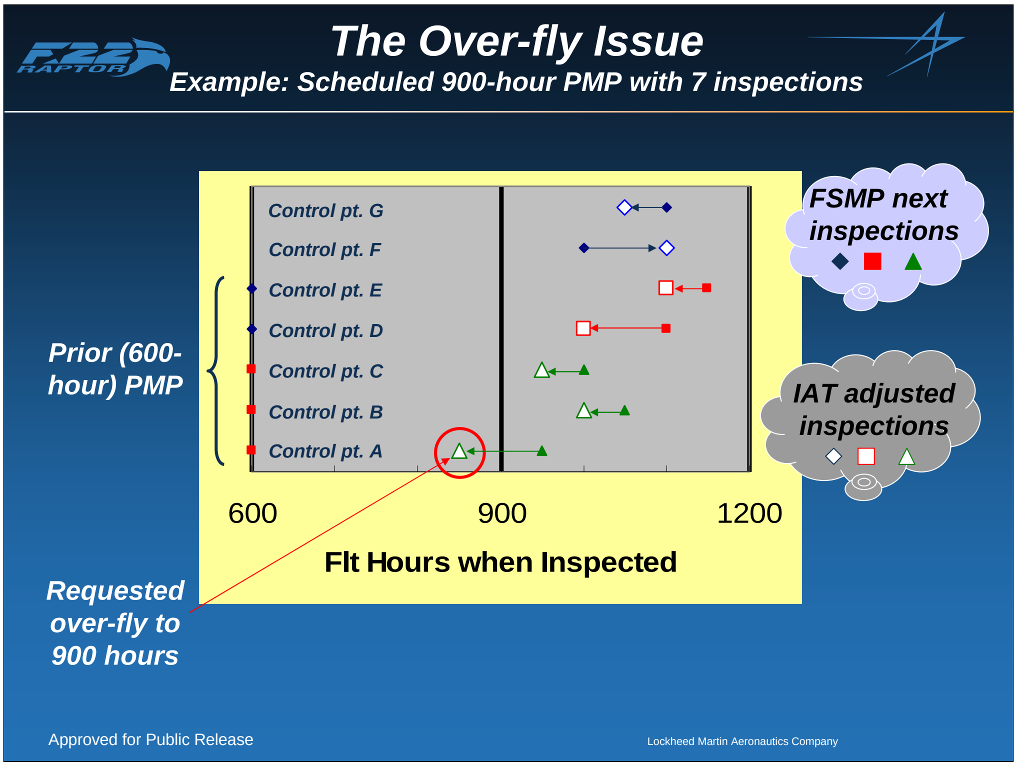
Major structural design changes of F-22 have tended to be implemented at the same time, resulting in "blocks" of aircraft with essentially identical structural details. Therefore content of a particular PMP (e.g., the 600 hour PMP) is the same for all individual aircraft within a "block." However, the contents of the 300 hour, 600 hour, 900 hour, etc. PMPs will all differ from one another.

To illustrate, shown above is a fictitious example of a 300, 600, and 900-hour PMP. The blue diamond-shaped points depict FSMP-required initial inspection times for control points A through G. For Points A, B and C the FSMP inspection times are between 300 and 600 hours. With the PMP concept, scheduling of these 3 inspections is pulled back to 300 hours, and they constitute the 300-hour PMP. Similarly, first inspections of control points D and E are scheduled in 600-hour PMP, and first inspections of F and G are scheduled in the 900-hour PMP.

The square red points depict second inspection requirements. After the first inspection, the FSMP interval is measured from the time the preceding inspection was actually accomplished. For example the second intervals for points A, B and C are measured from the 300 hour PMP. They, along with the first inspections of points D and E, constitute the 600-hour PMP.

By similar logic, the 900-hour PMP in this example consists of the third inspections of Points A, B, and C, the second inspections of Points D and E, and the first inspections of points F and G.

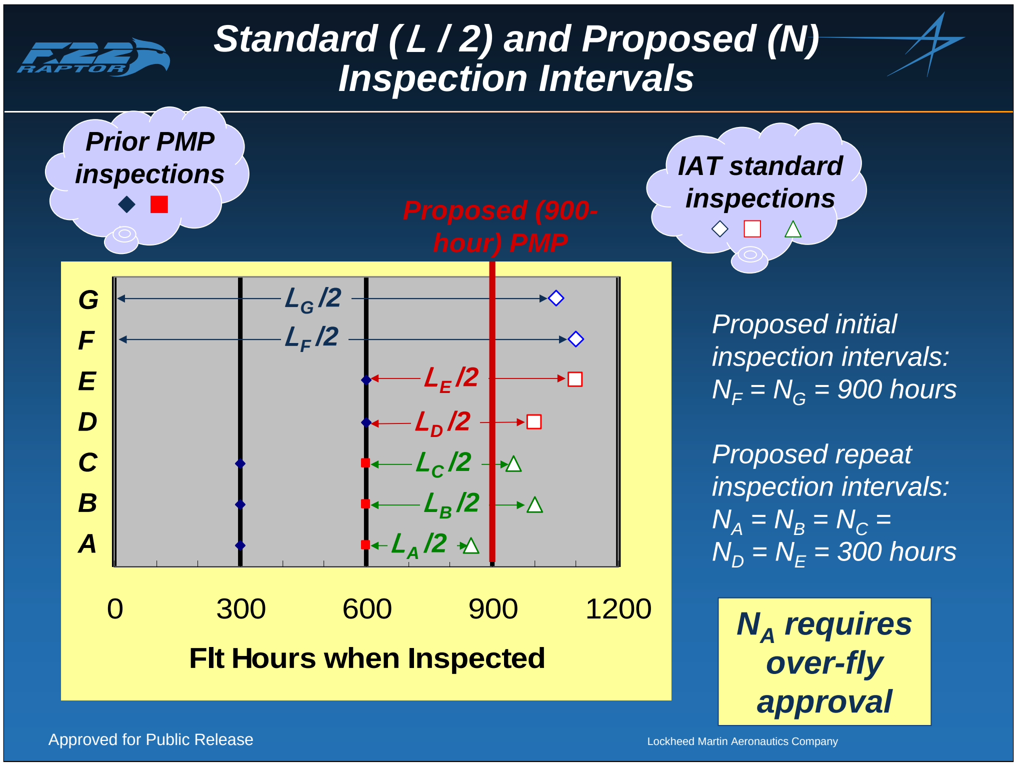
The inspection intervals in the FSMP are used to pre-group the PMPs. Consider next how revised interval requirements based on IAT data might affect the 900-hour PMP in this example.



The open points plotted above show the adjustments to the FSMP intervals due to individual aircraft tracking data. In the example, IAT-measured actual usage is more severe than FSMP baseline for six of the 7 points, and the inspection is required earlier than the FSMP projection. Meanwhile at Point F, actual usage is less severe.

Focus on Control Point A. Based on FSMP its required inspection interval is 350 hours, measured from the time it was previously inspected (in the 600-hour PMP). More severe IAT-measured usage on this aircraft has reduced the repeat inspection interval requirement to 250 hours, 50 hours earlier than the planned 900-hour PMP.

For fleet readiness, a critical objective is to keep the inspections grouped in PMPs (with very rare interjection of an individual inspection) and avoid accelerating an entire PMP to accommodate an isolated high-usage inspection location. Typically therefore, a request would be made to the Structural Integrity engineer to “over-fly” the IAT-required 250-hour inspection requirement at Location A until the pre-scheduled date of the 900-hour PMP.

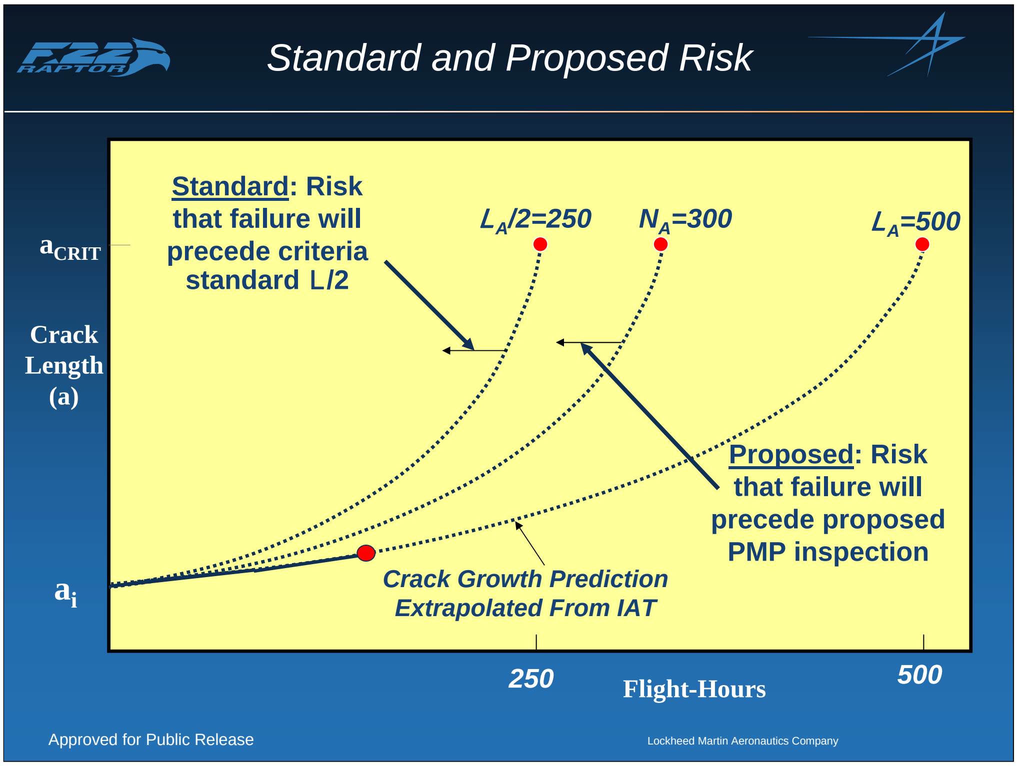


Two types of inspection intervals are involved in the PMP process.

The Standard inspection interval reflects the USAF standard requirement: The Standard inspection interval is required to be half estimated number of hours (***L***) for the crack to grow from assumed initial size to critical size.

For F-22 the proposed interval is determined by the PMP process and is some integer multiple of 300 hours. For the repeat inspections at Points A through E above the proposed interval is 300 hours. For the initial inspections of Points F and G the proposed interval is 900 hours.

PMP groupings are done conservatively based on the FSMP, so that the proposed inspection intervals are all shorter than the FSMP standard required interval. A structural integrity issue arises when (as in the case of Point A) IAT introduces a new standard interval that is not only shorter than the FSMP interval, but also shorter than the proposed PMP interval.



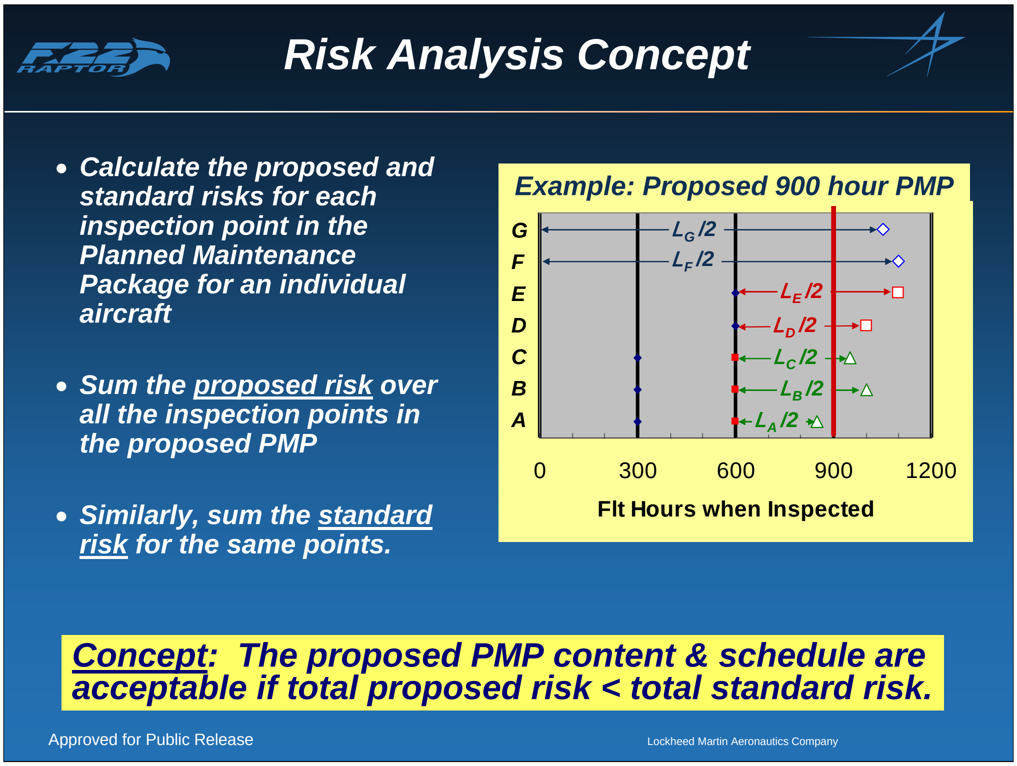
Define "proposed risk" at each inspection point as the probability that a flaw that was not detected in the previous inspection will grow to catastrophic failure before the proposed PMP inspection.

Define "standard risk" at each point as the probability that a flaw that was not detected in the preceding inspection would grow to catastrophic failure before its required standard L/2 interval.

The IAT-based crack growth prediction is 500 hours for Inspection Point A in the 900-hour PMP example, so the standard inspection interval is 250 hours. The standard risk is the risk that failure will precede 250 hours. The proposed interval for Point A is the 300-hour interval between PMPs. Clearly, the proposal to wait another 50 hours to inspect would add risk for point A.

Conversely, it is proposed to inspect the other inspection points in the same PMP earlier than the standard required time (L/2) for those points. For those points, the standard risk is greater than the proposed risk.

For the total PMP package, might these proposed changes in risk offset one another?

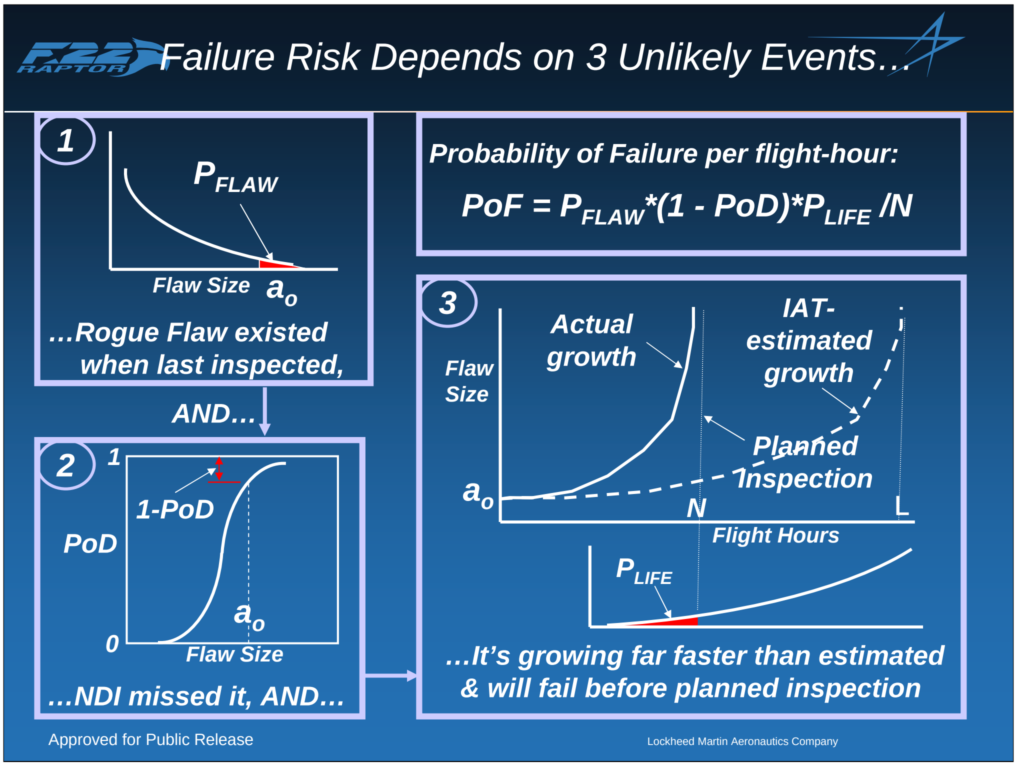


A request to over-fly the standard inspection requirement at inspection point A raises a structural integrity issue for the individual airplane under consideration. To address this issue, a global viewpoint is helpful. The structural integrity goal in scheduling inspections is to meet or exceed the safety requirements for the entire airplane. Thus in reviewing the proposed inspection package for acceptability, it is logical to consider the risk impacts of that airplane's 900-hour PMP in its entirety.

Consequently to address an over-fly issue, a comparative risk analysis approach is applied to the proposed PMP on the individual aircraft as follows:

- Estimate the risk of failure at each inspection point in the PMP, first assuming the proposed inspection interval, and then assuming the standard ***L/2*** interval.
- For the given aircraft, sum the proposed risk over all the inspection points in the proposed PMP package.
- Similarly, sum the standard risk for the same points.

The proposed PMP content & schedule (including the over-fly point) could be considered acceptable if the total proposed risk is less than the total standard risk.



Damage tolerance failure can occur during time interval (N) between inspections only if all the following occur:

1. A flaw exists at the beginning of time interval N, <u>AND</u>
2. The inspection at that time fails to detect the flaw, <u>AND</u>
3. The undetected flaw grows to failure within time interval N

Thus, probability of failure (***PoF***) is basically the product of 3 probability numbers

$$PoF = P_{FLAW}*(1 - PoD)*P_{LIFE} /N$$

PoF = Mean failure probability per flight-hour (during time interval of ***N*** flight-hours) due to an undetected flaw

P_{FLAW} = probability that the flaw exists or develops (by the beginning of time interval ***N***)

(1-PoD) = Probability flaw (if present) was not detected: The complement of Probability of Detection (PoD)

N = Time interval (flight-hours) between inspections

P_{LIFE} = Probability that the flaw (if present & undetected) will grow to failure before the planned inspection

The next few charts discuss how to estimate the P_{LIFE} term in the probability of failure equation.

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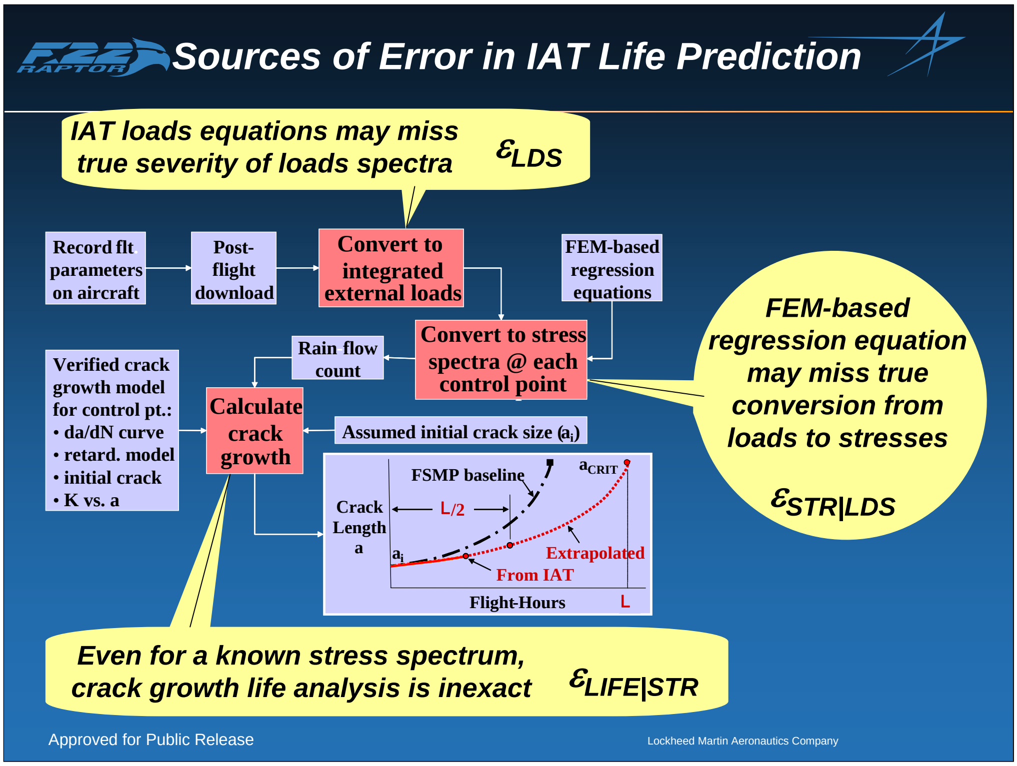
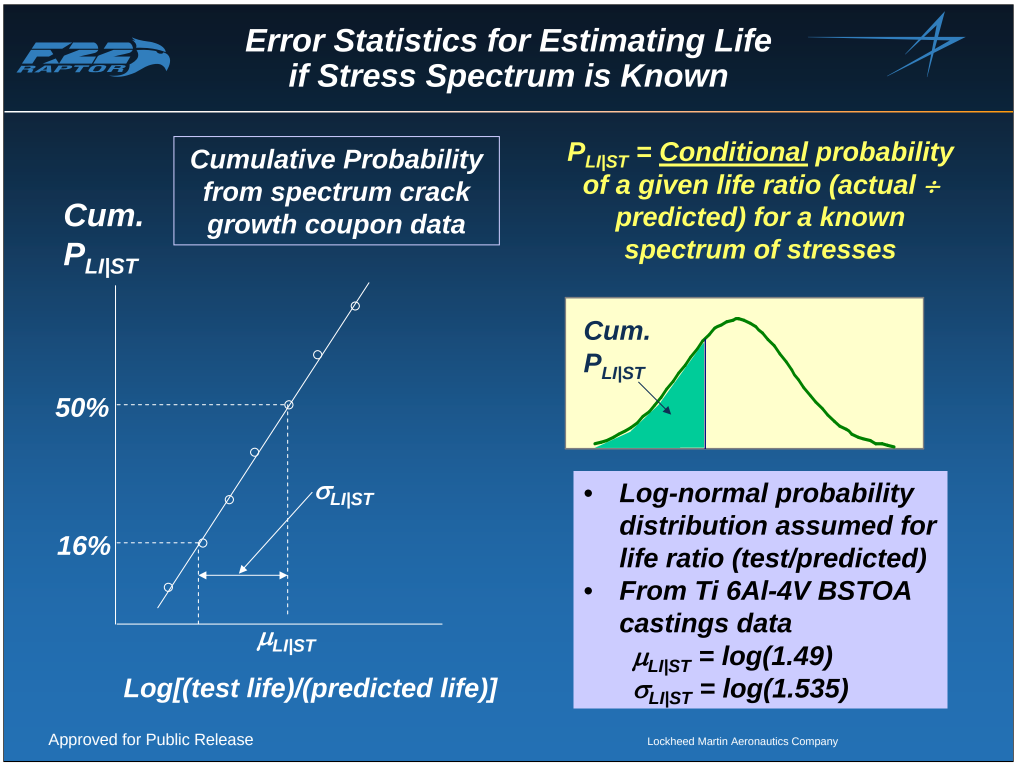
*<u>Note</u>: Rigorously, **PoF** is the integral of the above equation for an estimated distribution of flaw sizes existing at the beginning of the inspection interval. Here, early in F-22 life, discrete rogue flaw size is used as an approximation.*



P_{LIFE} is the probability that the flaw (if present & undetected) will grow to failure within time interval N, even though the IAT predicted life is L. Such an unexpected shortfall to the IAT predicted life is always a remote possibility because of error (including normal scatter) in life prediction. There are 3 primary sources of error in calculating crack growth life with the F-22 IAT system:

- Error in the IAT loads equations that calculate external loads spectra from measured flight parameters
- Error in the IAT stress equations that convert external loads to the corresponding internal stresses and stress intensity factors that drive crack growth
- Error in the IAT crack growth equations that transform a stress spectrum into the corresponding crack growth life

These 3 sources of error are assumed to be statistically independent component parts of the total error represented by P_{LIFE}.

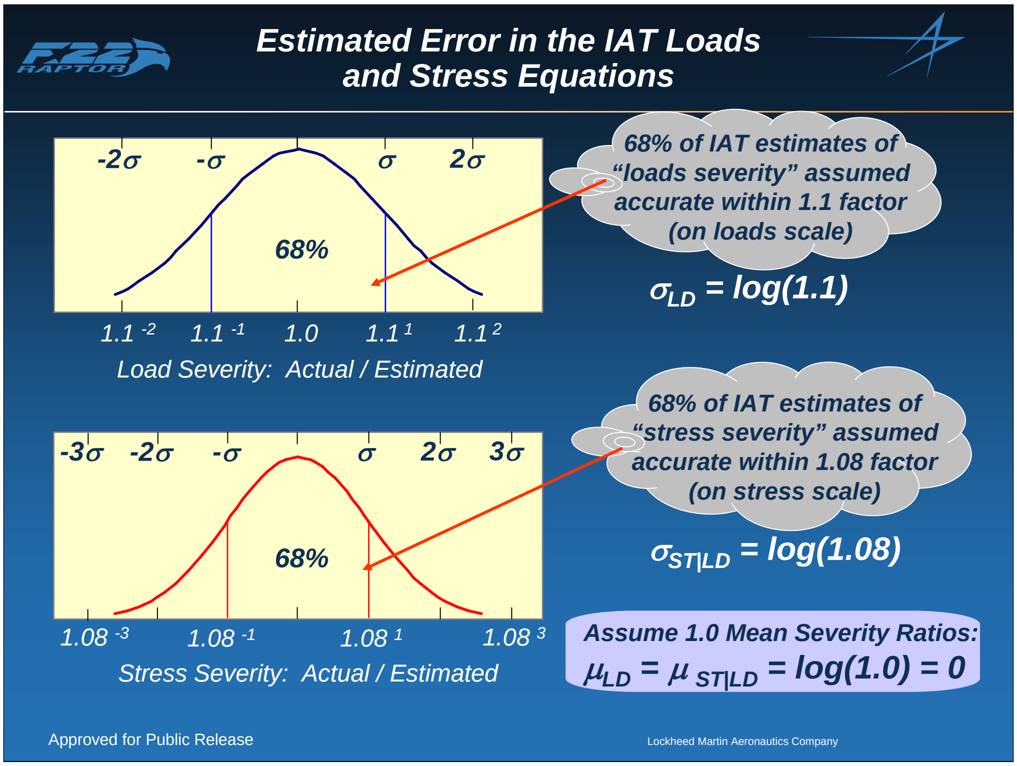


In the case of coupon crack growth tests, the loads are specified and the stress analysis is very accurate. Therefore errors in life prediction for test coupons provides a measure of the error statistics of damage tolerance life prediction methodology for known stress spectra.

Here the life ratio (test ÷ predicted) for a set of spectrum crack growth tests is plotted on a lognormal probability plot. A life ratio of 1.0 is a perfect prediction. Ratios less than 1.0 indicate shorter life than predicted. The abscissa of the graph is the cumulative probability that the life ratio is at least the value indicated. The 50% probability point is the mean. The slope determines the standard deviation. One standard deviation is the mean minus the 16th percentile value.

Pending more a complete review of spectrum crack growth data, the mean and standard deviation for the probability distribution $\boldsymbol{P_{LI|ST}}$ listed above are from Ti 6Al-4V BSTOA castings data discussed in the following Reference:

Reference: T. R. Brussat and P. J. Caruso "Probability of Failure Analysis for Fracture Critical F-22 Titanium Castings" presented at 2001 USAF Aircraft Structural Integrity Program Conference, Williamsburg, VA, 11-13 December 2001

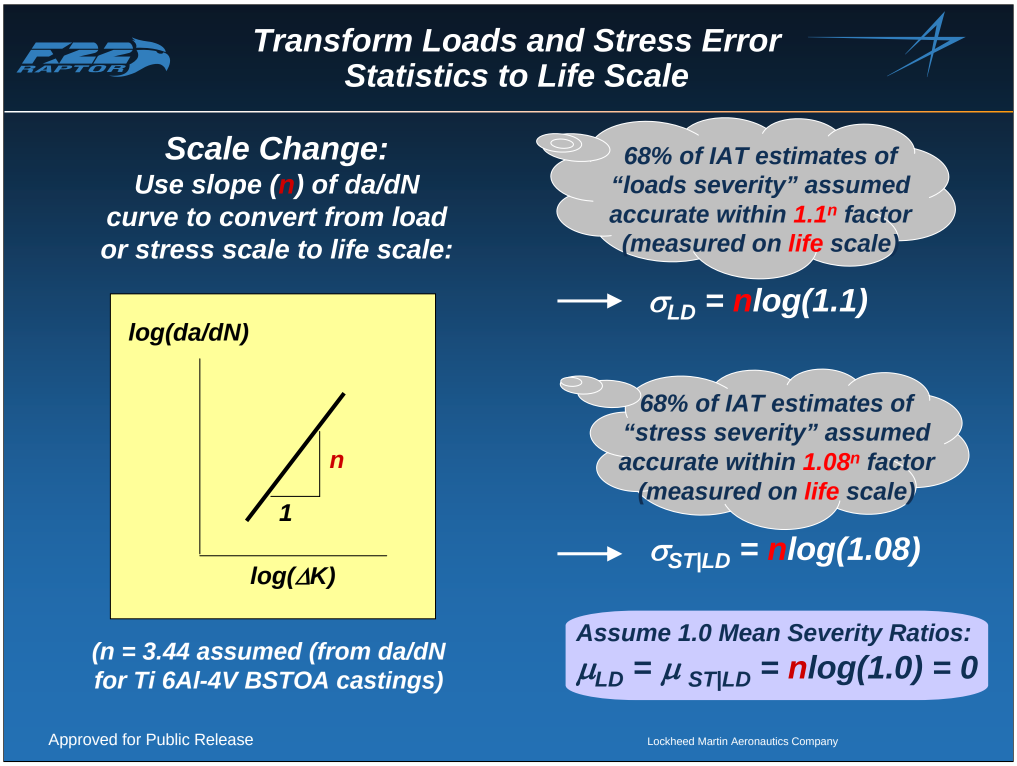


Currently the other two error terms for $\boldsymbol{P_{LIFE}}$ are estimated by engineering judgment.

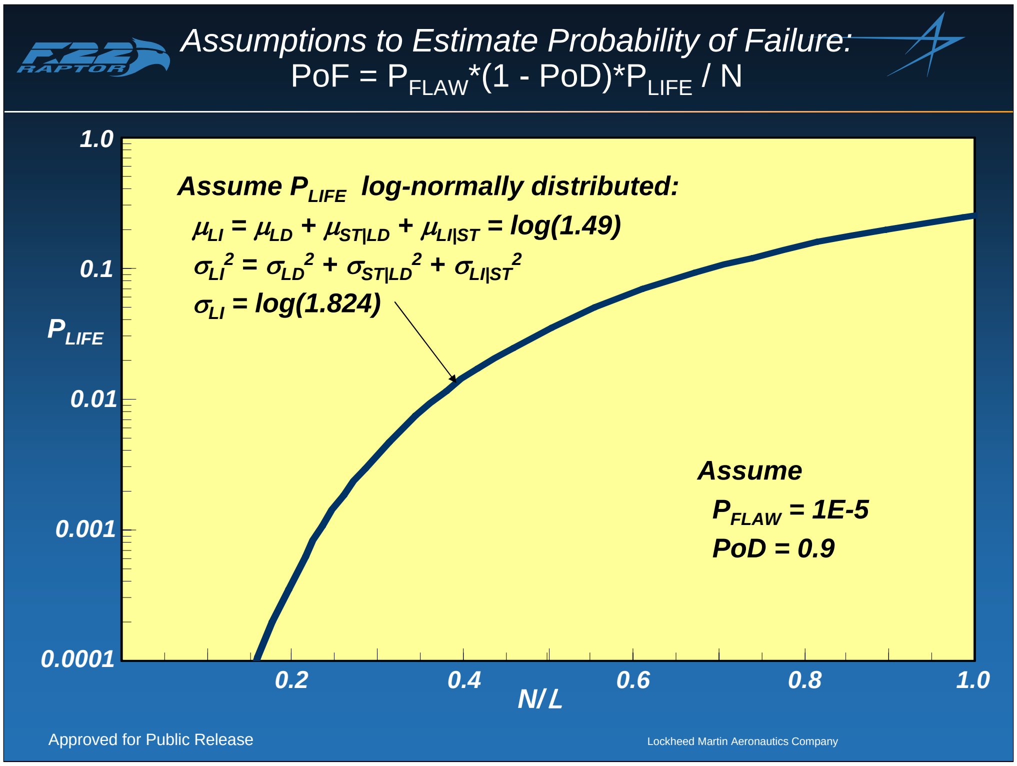
A loads severity ratio (actual ÷ calculated is used as a measure of the loads equations errors in IAT. Similarly, a stress severity ratio (actual ÷ calculated) is used as a measure of the errors resulting from converting a spectrum of known loads to an estimated stress spectrum.

The error estimates currently used are believed to be conservative. It is estimated that 68% of loads spectrum estimates (derived from measured flight parameters) are within ±10 percent of the actual loads spectrum severity. Similarly, for known loads, it is estimated that 68% of stress spectra estimates are within ±8 percent of actual stress spectrum severity. The 68% corresponds to ±1 standard deviation for a lognormal distribution.

To meet these assumptions it is not necessary that, for example, 68% of the individual loads are accurate within 10 percent. Spectrum severity reflects the cumulative effect of all estimated loads cycles in the spectrum. This error is smaller than the error of the individual loads, due to the canceling effects of over- and under-predicting individual loadings in the spectrum.



Note that these estimated standard deviations for loads and stresses are scaled as load or stress ratios, not life ratios. To express these as life ratios, the load and stress ratios must be transformed. The dominant log-log slope (n) of the da/dN curve provides a straightforward way to accomplish this scale transformation. The severity ratios are raised to the nth power. Equivalently, the means and standard deviations for the log-normal probability distribution are multiplied by n.



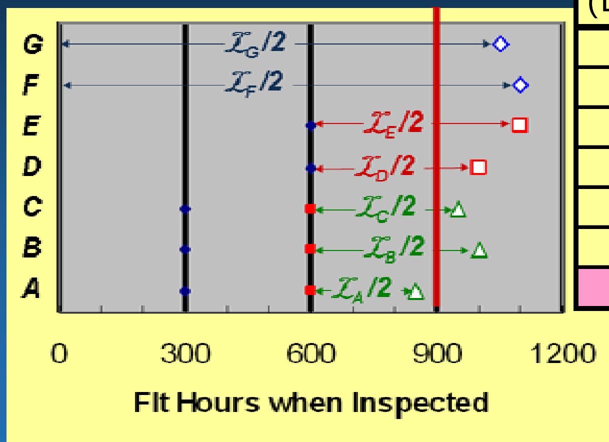
The measures of each of the 3 independent sources of statistical error of $\boldsymbol{P_{LIFE}}$ are now compatible (log of a life ratio). Therefore the following can be inferred:

- The total error in a life prediction is the sum of the 3 errors
- The total mean of $\boldsymbol{P_{LIFE}}$ is the sum of the means
- The total variance is the sum of the variances

The IAT life ratio (actual ÷ predicted) is assumed to be log-normally distributed, with the mean and variance equal to the totals described above. For that probability distribution, risk of failure at any control point is greatest just before the inspection. In the F-22 risk analysis, $\boldsymbol{P_{LIFE}} \div \boldsymbol{N}$ is the maximum probability per hour, not the average over the inspection interval. Thus, if a rogue flaw with predicted life ***L*** existed and was not discovered in the preceding inspection, $\boldsymbol{P_{LIFE}}$ (from the above plot) divided by the inspection interval provides the probability of failure during the final hour of inspection interval ***N***.

Two more assumptions are required to completely quantify all terms in the equation for risk of failure (***PoF***). Standard assumptions are selected for the probability of existence of the rogue flaw ($\boldsymbol{P_{FLAW}}$) and the probability of detection (***PoD***) in the preceding inspection. Note that these two assumed values have the same effect on proposed risk as they have on standard risk. Therefore, if applied uniformly to all points in a PMP, the selected values of $\boldsymbol{P_{FLAW}}$ and ***PoD*** do not affect the ratios of proposed risk to standard risk.

Example: Risk Assessment for Proposed 7-Item 900-hour PMP



Standard (L/2) Interval	Proposed Interval
1050	900
1100	900
500	300
400	300
350	300
400	300
250	300

Proposed Over-fly Point

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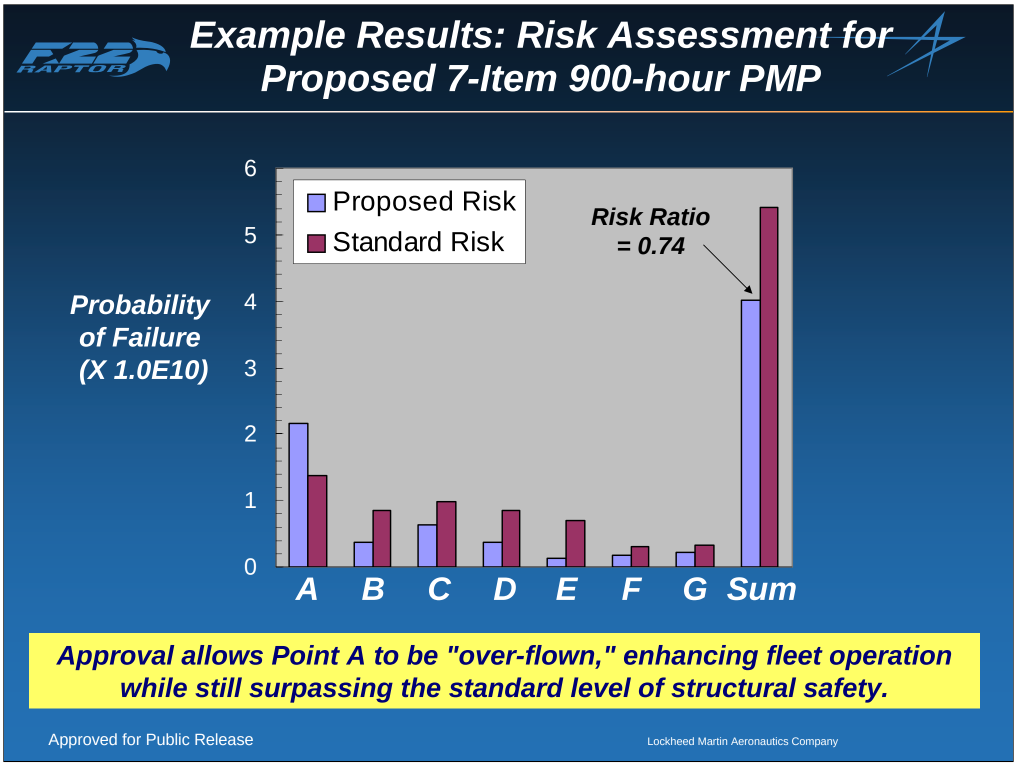
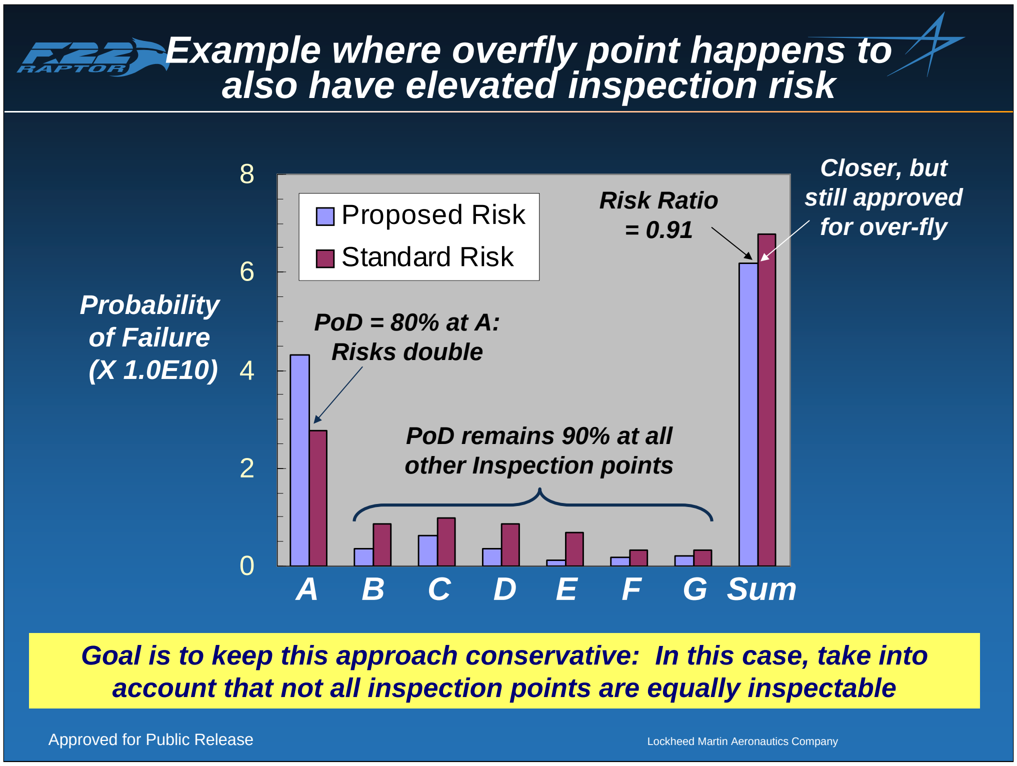
The risk assessment can now be applied to the earlier example of a 900-hour PMP with a proposed over-fly. The standard required inspection interval is listed here for each of the inspection points A through G. The proposed intervals are also listed – either 300 hours for the five points previously inspected in the 600-hour PMP, or 900 hours for the points not previously inspected. Point A is a proposed over-fly, because the proposed inspection interval is shorter than the standard requirement.



This chart summarizes the results of the risk analysis for this example. When risk is calculated for each control point, the proposed risk for Point A is higher than its standard risk. At the same time the proposed risk is lower than the corresponding standard risk for each of the other 6 points. When all proposed risks are summed and compared to the summation of standard risk for the entire PMP, the proposed risk is smaller. The risk ratio (proposed ÷ standard) is only 0.74. Thus the proposed over-fly can be approved, because the total PMP (being 26% lower risk) surpasses the standard safety requirement.

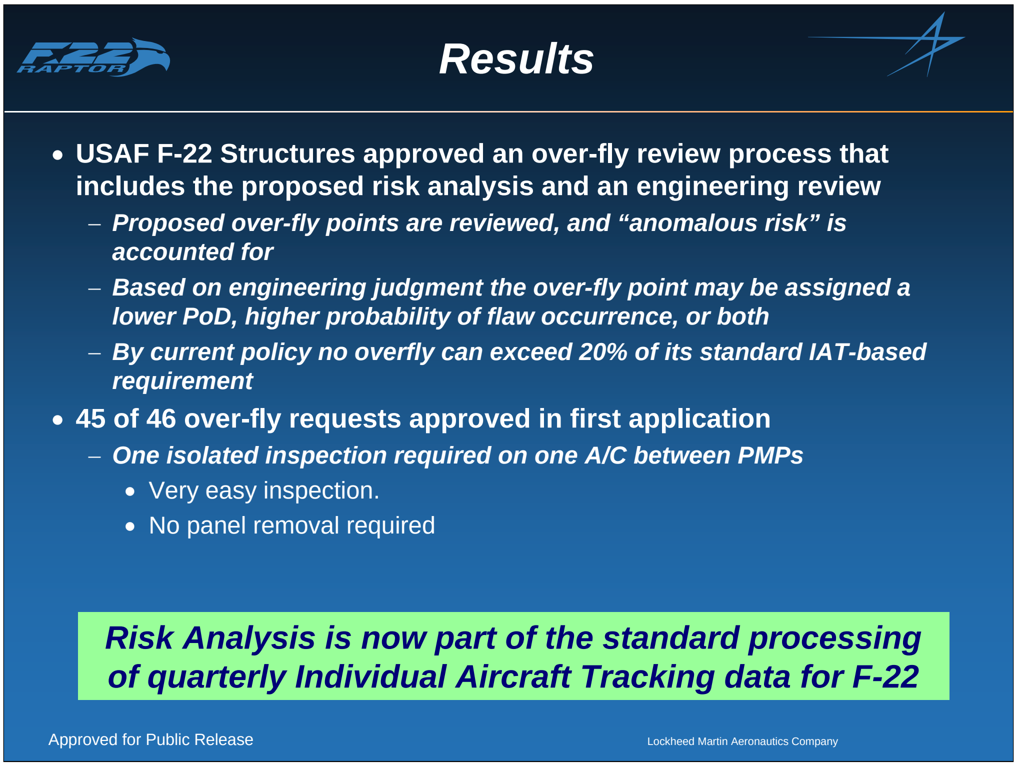
It is assumed here that all seven points in the PMP have equivalent probability of flaw occurrence and probability of detection. The F-22 process also addresses cases when this may not be a safe assumption.



In addition to the risk analysis, an engineering review is conducted of each F-22 over-fly request. For example, if the proposed over-fly point is a point known to be difficult to inspect, a lower probability of detection will be assigned to that point and the risk calculations will be repeated.

To illustrate, the preceding analysis was repeated assuming 80% PoD at inspection Point A. PoD = 90% was again assigned to the other six points.

For Point A, the proposed and standard risks both double. The incremental difference between proposed and standard risk for Point A also doubles. When risks are summed, the risk ratio for the total PMP increases from 0.74 to 0.91. Despite the reduced PoD, the risk ratio is still less than 1.0. Unless over-ruled by other considerations in the engineering review, the over-fly can still be approved.



The above risk analysis approach and rationale was developed to process over-fly requests in connection with the F-22 Planned Maintenance Package (PMP) inspection approach. USAF F-22 Structures approved an over-fly review process that includes the proposed risk analysis and an engineering review of each proposed over-fly point. In this review, engineering judgment is applied to account for any anomalous risks that might be associated with the over-fly point. Based on engineering judgment the over-fly point may be assigned a lower probability of detection, higher probability of flaw occurrence, or both. To avoid extrapolating the risk analysis philosophy beyond intended limits, current policy permits no over-fly to exceed 20% of its standard IAT-based requirement.

This risk-analysis-based process is now part of the standard processing of quarterly Individual Aircraft Tracking data for F-22 and has already had a major positive impact. In its first application, 45 of 46 over-fly requests were approved. The one isolated inspection that was required on one A/C between PMPs was a very easy inspection, in that no panel removal and restoration was required.

F-22 RAPTOR

Recommended Future Work

1. ***Improve risk analysis methodology & data:***
   - **Develop statistical data for P_{LIFE} using:**
     - Regression statistics for the IAT loads and stress equations
     - Predicted life vs. test life from existing spectrum crack growth tests
   - **Incorporate estimated flaw size distribution in place of single discrete flaw size in calculation of risk**
2. ***Improve IAT accuracy by updating FSMP inspection intervals with new baseline operational spectrum***
3. ***After 1 and 2, develop an engineering process to permit delay of any PMP based on risk ratio (proposed ÷ actual) of less than 1.0***

Current quantitative assumptions are judged adequate for use very early in durability life of F-22

The current quantitative assumptions are judged adequate for use very early in durability life of the F-22, while the dominant risk is from a possible rogue flaw. As the fleet begins to age, the following are recommended:

1. <u>Improve risk analysis methodology & data</u>:
   a. Develop statistical data for P_{LIFE} using:
      - Regression statistics for the IAT loads and stress equations. These statistics can be analyzed to update the assumed error terms from the loads and stress equations.
      - Predicted life vs. test life from existing spectrum crack growth tests. F-22 has a significant amount of data for each major structural metallic material.

   b. Incorporate estimated flaw size distribution: As noted earlier, the rigorous way to calculate probability of failure (***PoF***) is to integrate the equation used here over a distribution of flaw sizes, including durability flaws that may develop by fatigue and cumulative effects of past inspections.
2. <u>Improve IAT accuracy by updating FSMP inspection intervals with new baseline operational spectrum</u>. The IAT-estimated F-22 life calculations can be expressed as deviations from baseline life. When baseline is modified to closely match usage, these deviations, and the errors in estimating the deviations, will be reduced.
3. <u>After 1 and 2, expand the role of the risk analysis</u>. Develop an engineering process to permit delay of any PMP based on risk ratio (proposed ÷ actual) of less than 1.0

Conclusions

- **This Risk Analysis approach, in conjunction with F-22 Planned Maintenance Packages and Individual Aircraft Tracking:**
  - ***Maintains standard required levels of structural safety***
  - ***Optimizes scheduling of structural inspections:***
    - More uniform PMP intervals
    - More uniform content (for all A/C in a design block) of a given PMP inspection package
    - More flexibility in managing the operational F-22 fleet
  - ***Reduces down time for inspections***
    - Dramatically reduces risk that isolated pre-PMP inspections will be required

Maintains safety, simplifies planning, standardizes inspection packages, saves costs, maximizes readiness

A risk analysis approach has been described for reviewing requests to over-fly an IAT-based structural inspection requirement. This approach is used in conjunction with F-22 Planned Maintenance Packages and Individual Aircraft Tracking.

First and foremost, this approach is designed to maintain standard required levels of structural safety. Within that constraint, it is intended to simplify planning and standardize inspection packages (by keeping the PMP intact), save inspection costs, and minimize aircraft down time. Initial application has demonstrated that this process can dramatically reduce the risk that extra inspections will be required between PMPs, thus helping to keep the F-22 fleet fully operational and ready for deployment in the defense of freedom.