1.0 Abstract

The Aerospace Industries Association (AIA) Rotor Integrity Sub-Committee ("industry committee") has proposed an enhanced damage tolerance design strategy for critical rotating titanium parts, in response to recommendations made in the FAA Titanium Rotating Components Review Team Report, December 14, 1990. This design strategy employs a probabilistic relative risk assessment methodology intended to reduce the rate of uncontained rotor events. A key part of constructing this strategy was the development of the hard alpha (Nitrided titanium) anomaly distribution (occurrence rate and size of the anomalies present in the finished part material), and the benchmarks to measure the results of the assessments [engine and component Design Target Risk (DTR) values]. The DTR is the metric that determines the acceptability of new designs and the appropriateness of proposed field actions.

The industry committee put in place our sub-team to establish the hard alpha anomaly distribution and develop a methodology for the committee to determine the DTRs. We developed the distribution through a series of analytical modeling steps, based on behavioral observations, that simulate the manufacturing process of a titanium rotating component from ingot conversion through forging inspection. The simulation incorporates three dimensional size information from detected and analyzed hard alpha, inspection capability, and inspection find rates to determine a baseline distribution shape. The initial estimated distribution was adjusted based on certain Commercial Engine service experience of the industry committee members. This adjustment was necessary since the analytical process involved a set of difficult to evaluate assumptions, leading to multiple potential solutions. Once we established the anomaly distribution, based on the complex set of assumptions and experience, the industry committee determined DTRs for both the engine and individual components. The industry committee arrived at the DTR values by consensus using results of analytical simulations from each member company. The proposed DTRs represent a significant reduction in estimated number of hard alpha uncontained rotor events when compared to the baseline period; 1984 to 1989, as reported in the SAE SP 1270 report.

The steps taken to develop the hard alpha anomaly distribution and the DTR values are presented in this paper. This information is applicable to titanium disk alloys (i.e., Ti 6-4, Ti 6-2-4-6, and Ti 17β) manufactured after 1995.

2.0 Introduction

Historically, the conventional design and life management of aircraft gas turbine engine disks have involved a methodology (i.e., "Safe Life") founded on the premise of nominal material and manufacturing variability (common cause). While the industry has put in place strict material process controls and in-process inspections, gas turbine industry experience demonstrates that material anomalies, while extremely infrequent and sometimes not detectable with standard non-destructive testing (NDT) methods, exist and have the potential to degrade the structural integrity of high energy rotating components.

Damage tolerance is one way of improving recognition of potential anomalies which can result from inherent material structure, material processing, component design, manufacturing or usage. These potential anomalies are addressed through the
incorporation of fracture resistant design, fracture mechanics, manufacturing process control, and/or nondestructive inspection.

The FAA established the Titanium Review Team after the 1989 Sioux City accident to evaluate the material process control, manufacture, and field management of titanium alloy rotating turbine engine components. The FAA Titanium Review Team Report (issued in December 1990) recommended that the industry review available techniques to determine whether the introduction of additional damage tolerance concepts could reduce the rate of uncontained rotor events. The industry established the AIA Rotor Integrity Sub-Committee (“industry committee”) to address this FAA recommendation.

The industry committee concluded that current technology could enhance the conventional design and life management process to address anomalous conditions. It has proposed that an additional damage tolerance element be added to conventional design procedures to augment the FAA and industry efforts to minimize the occurrence of uncontained rotor events. In response to a FAA request for prioritization of this undertaking, the industry committee focused its initial efforts on the issues associated with potential hard alpha in rotors manufactured from titanium alloys (e.g. Ti 6-4, Ti 6-2-4-6, and Ti 17β).

The proposed process change will result in damage tolerance assessments on all new critical titanium alloy rotor designs in the form of fracture mechanics-based probabilistic analyses. The results will be compared against specified Design Target Risk (DTR) values. Designs satisfying the targets will be considered acceptable. If a design does not meet the DTRs, the engine manufacturer has several options to achieve the desired target, including component redesign, material change/process improvements, manufacturing inspection improvements, in-service inspections, and any combinations of the above.

Since the analysis inputs are subject to variability, the results of these assessments are not considered to be “exact” or “absolute”. Never the less they are a “relative calculation” to be used as an engineering guideline by the engine industry to select design and/or field actions which minimize the chances of uncontained rotor events.

The industry committee put in place our sub-team to establish the hard alpha anomaly distribution and develop a methodology for the committee to determine the DTRs.

The scarcity of hard alpha data combined with the issue that the available data was not in the appropriate form, suggested the need for an analytical process to estimate the appropriate data to develop and validate the hard alpha anomaly distribution. The titanium hard alpha anomaly distribution was developed through a series of analytical modeling steps, based on behavioral observations, that simulate the manufacturing process from billet conversion to final machining. The simulation incorporates three dimensional size information from detected and analyzed hard alpha, inspection capability (agreed to by the industry committee), and inspection find rates to determine a baseline distribution. The final distribution was estimated by adjusting the hard alpha frequency of the baseline distribution to achieve an approximate correlation with commercial engine service experience for a baseline period, 1984 through 1989, as reported in SAE SP 1270. This adjustment attempted to reconcile an analytical process that involved an initial set of assumptions that were difficult to validate, and led to multiple solutions.

Once the anomaly distribution was established, the industry committee determined Design Target Risk (DTR) values specifically for hard alpha anomalies. Targets specific to hard alpha were necessary since the process to determine the DTRs used the estimated hard alpha anomaly distribution as an input. The industry committee arrived at the DTR values by consensus using results of analytical simulations from each member company. The proposed DTRs represent a significant reduction in estimated number of hard alpha uncontained rotor events when compared to the baseline period.

3.0 Review of Available Data

Our goal was the development of a hard alpha anomaly distribution that applies to fully machined finished components for future engine designs. Unfortunately, as in many undertakings of this nature, the requisite data did not exist to directly determine this distribution, which required size and frequency data for the rare hard alpha present in finished parts. The available data were for anomalies found by inspection and removed from the in-process material. Specifically this information included the following:

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† The term absolute typically describes risk analysis that includes an accurate portrayal of all significant variables and is rigorously calibrated to past experience.
Jet Engine Titanium Quality Committee (JETQC) data for double and triple vacuum arc remelt (VAR) titanium alloys (e.g. Ti 6-4, Ti 6-2-4-2, and Ti 17\(\beta\)). The data was recorded from 1990 to mid 1992 and consisted of:

- The number of billet and bar hard alpha ultrasonic inspection finds
- The weight (in pounds) of material inspected
- Two dimensional size data (radial and circumferential) for all of the hard alpha finds. (note: sometimes including an estimate of the axial length) See Figure 3.1
- Three-dimensional size data (radial, circumferential, and axial) for a limited number of finds. Size data was based on detailed metallurgical sectioning of the hard alpha.

**Figure 3.1. Hard Alpha Reference Directions Inside the Billet or Bar**

![Hard Alpha Reference Directions](image)

- Probability of Detection (POD)\(^4\) estimates for the in-process billet and bar ultrasonic inspections
- Estimate of the number of sonic shape\(^\ast\ast\) hard alpha finds
- Hard alpha find data from titanium rotor proof testing\(^\dagger\dagger\)

Individual sub-team member’s review of the available data revealed several significant observations regarding the development of the hard alpha anomaly distribution. They were:

1. Hard alpha were deformed in the billet and bar proportional to the amount of elongation in the ingot to billet/bar transformation.
2. The find rate (number of hard alpha per unit weight) for bars was greater than the find rate for billets.
3. Sonic shape finds were no more than 10 % of the billet finds.
4. There were indications of an underlying hard alpha distribution that ultrasonic inspection apparently did not detect.

A sub-team member made the first observation based an analysis of the JETQC hard alpha three dimensional size data which showed that hard alpha detected in bars tended to be more elongated in the axial direction than those detected in billets. In addition, the hard alpha cross sectional area in the circumferential-radial plane was typically larger for the billet finds than it was for the bar finds. This was true for both the two and three dimensional JETQC data. These observations suggested that the ingot to billet/bar transformation stretched the hard alpha in the axial direction during the ingot to billet/bar transformation and the amount of deformation was a function of the amount of ingot to billet/bar elongation.

**Figure 3.2. Hard Alpha Deformation Schematic**

![Hard Alpha Deformation Schematic](image)

\(^4\) POD is a quantitative statistical measure of the probability of detecting a particular type of material anomaly over a range of sizes for a specific non-destructive inspection technique.  
\(^\ast\ast\) A geometric shape machined from a forging to enable ultrasonic inspection of the material.  
\(^\dagger\dagger\) Component spin test at elevated conditions to screen for anomalies in the material that could be detrimental in service. This test is conducted after ultrasonic inspection and prior to field service.

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axial dimension required to calculate the equivalent volume and associated diameter for the hard alpha anomaly in the ingot.

After considerable experimentation with more complex relationships the team member concluded that a simple model was the most appropriate. We adopted the following model based on our team member’s recommendation:

\[ L_{HA_b} = D_{HA_i} \times \left( \frac{D_i}{D_b} \right)^{0.364} \]

Where \( L_{HA_b} \) is the length of the hard alpha in the billet, \( D_{HA_i} \) is the diameter of the hard alpha in the ingot, \( D_i \) is the ingot diameter, and \( D_b \) is the billet or bar diameter.

Figure 3.3. Hard Alpha Elongation Model

The team member’s second observation suggested that hard alpha in a bar was more inspectable than in a billet. As billet and bar material generally comes from the same ingot source, the team member concluded, on the average, bars should not contain any more hard alpha than the billets. Three contributing factors are: 1) hard alpha deformation in a bar creates a larger inspectable cross-sectional area than in the billet; 2) the bar material was inspected with a more sensitive ultrasonic inspection; and, 3) the smaller diameter of the bar means there is less material to inspect through. Overall, this member’s observation supported the argument that the find data could not be used directly to determine the hard alpha distribution present in finished parts. We adopted our team member’s conclusion.

The sub-team used the first two observations as fundamental building blocks for construction of the simulation model and the third and fourth observations as process checks on the results estimated by the model.

4.0 Development of the Baseline Distribution

The hard alpha deformation model combined with the observed effects of the in-process ultrasonic inspections provided the foundation for developing a simulation model to determine the required data for estimating the hard alpha distribution. However, our sub-team as well as the total industry committee recognized that an analytical procedure alone may not yield the final distribution, due to the uncertainty in the data and the process itself. Therefore, the industry committee anticipated a need to correlate with field experience of in-service components.

The steps we used to establish the final hard alpha distribution are discussed in sections 4.1 through 4.4.

4.1 Titanium component manufacturing process model description

Figure 4.1 shows the titanium component process model we developed to estimate the required data for the baseline hard alpha anomaly distribution. The model assumes that both bar and billet material originate from the same initial ingot distribution, frame 1. From this point the model splits into paths, one for billet material and one for bar. In frames 2 and 3 the deformation model is applied to create the billet and bar pre-inspected distributions. In frames 4 and 5, each distribution is inspected with the appropriate ultrasonic inspection POD curve [\#2 flat bottom hole (FBH) for the bar and \#3 FBH for the billet]. These inspections yield two types of data, estimated number of billet and bar finds, and the post inspected billet distribution. Frame 6 represents the pre-inspected sonic shape distribution, we assumed that the forging process had little impact on the hard alpha size and shape. In frame 7 performing the ultrasonic sonic inspection with the appropriate POD curve (\#3 FBH) results in the post-sonic or baseline finished part distribution and an estimated number of sonic inspection finds, shown in frame 8.

‡‡ Ultrasonic calibration standard consisting of a block of material containing holes of varying diameters. The diameters of the holes are specified in multiples of 1/64”.

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4.2 Derivation of the Baseline Anomaly Distribution

Derivation of the baseline hard alpha distribution breaks down into 5 main steps.

1. Construction of an ingot relative size distribution, based on three-dimensional JETQC data, and the #2 and #3 flat bottom hole POD curves.

2. Conversion of the ingot relative size distribution to billet and bar relative size distributions implementing the deformation model.

3. Estimation of the number of billet and bar finds and post inspected billet distribution, applying the appropriate POD curve.

4. Determination of the position of the ingot distribution (on the probability axis) that achieves a match with the number of finds in the JETQC data for both the billet and bar material.

5. Conformation of results against the sonic shape inspection find rate and the undetected hard alpha distribution.

The following discussion is further elaboration on the above steps.

**Step 1 - Construction of the ingot relative size distribution.** We estimated the ingot relative size distribution using the JETQC three-dimensional billet and bar find data and associated inspection POD. Two-dimensional size information was also available, however a strong correlation between the two-dimensional and three-dimensional sizes did not exist. Therefore, we did not use the two-dimensional size data for this purpose.

The analytical process involved estimating the pre-inspected number of hard alphas for a given size as a function of the ultrasonic inspection. First, we calculated the hard alpha ellipsoidal cross sectional area presented to the inspection field. We used the root mean square of the radial and circumferential dimensions due to the uncertainty in the melter’s reporting of the actual orientation of these two dimensions.

\[
A_{HA} = \frac{\Pi}{4} \times Axial \times \sqrt{Radial^2 + Circumferential^2} \div 2
\]

We screened the area of each anomaly in the billet against the appropriate POD curve (#2 or #3 FBH) to estimate how many anomalies were present prior to the inspection as shown in Figure 4.2. For example, if the POD for a given find size is 50% this implies that a second anomaly of this size existed in the
pre-inspected material. The screening process for each find is characterized by the following expression:

$$\text{Number of Anomalies}_{HA} = \frac{1}{\text{POD}_{HA}}$$

Step 2 - Conversion of ingot to billet/bar distributions. Once we established the ingot relative size distribution, we applied the deformation model to transform the ingot distribution into billet and bar distributions as shown in Figure 4.4. We used the average ingot, billet, and bar diameters from the complete set of two dimensional JETQC finds to accomplish this result.

Step 3 - Estimation of inspection finds and post inspected billet distribution. We estimated the number of hard alpha finds from billet and bar inspections by screening the above billet and bar distributions with the appropriate ultrasonic inspection POD curve (#3 FBH and #2 FBH for billet and bar respectively) as shown in Figure 4.5. We conducted the screening process through numerical integration of the pre-inspected distributions with the appropriate POD curves per the following expressions:

$$\text{Remaining}_{HA} = \sum (\text{Total}_{HA} - \text{Total}_{HA_{i+1}}) \times \left[1 - \text{POD}\left(\frac{x_i + x_{i+1}}{2}\right)\right]$$

$$\text{Found}_{HA} = \sum (\text{Total}_{HA} - \text{Total}_{HA_{i+1}}) \times \text{POD}\left(\frac{x_i + x_{i+1}}{2}\right)$$
We compared the estimated find rates to find rates reported by the JETQC.

Bar = 1.0 finds/million pounds  
Billet = 0.6 finds/million pounds

**Step 4 - Determining the position of the distribution.**
The sub-team determined the final position of the baseline distribution using an iterative process. We adjusted the ingot distribution hard alpha frequency (shifted up or down on the exceedence axis as shown in Figure 4.6) and repeated steps 2 and 3 until we achieved a match with the JETQC find rate data. By forcing a match to the JETQC frequency data, we essentially transformed the relative size distribution into an exceedence distribution per unit volume.

After several iterations of this process, it became apparent that we could not achieve a simultaneous match to the JETQC billet and bar finds, and we had a problem with the model. We decided to investigate the effects of potential variation in the POD curves. While the problem could have been caused by several other variables, we believed it was appropriate to explore the effects of variation in the POD. We made our decision based on our knowledge of the limited amount of data available to estimate the POD curves, therefore, causing uncertainty in these estimates. Future plans, as discussed in section 8.0, include the evaluation of how other variables effect the solution.

Our investigation included the variation in the POD curve mean and standard deviation, and a cap on the maximum achievable POD. [We explored the cap to assess the possibility that larger anomaly sizes saturate the ultrasonic inspection beam, thus after a certain size the POD would not increase]. The billet #3 FBH and bar #2 FBH curves were modified on a consistent basis. These studies resulted in a range of possible anomaly distributions which all “fit” the analytical model.

**Step 5 - Checks against other independent data.** In all cases, our estimated number of finds at the sonic shape was less than 10% of the billet finds, meeting the sonic find check. In addition, the distributions we derived by using the cap POD curves coincidentally displayed the characteristics of the underlying hard alpha distribution not detected by ultrasonic inspection. This observation influenced the industry committee’s final selection of the distribution, as discussed in the next section.

**4.3 Field Experience Calibration**
Recognizing the limitations of the process for determining the distribution, our sub-team recommended to the industry team that we use each industry committee member’s titanium rotor event rate experience to select the final shape and position of the distribution. The industry committee adopted our recommendation. From the range of possible solutions, we determined a best estimate of an upper-bound and lower-bound distribution as shown in Figure 4.7.

Since the parts with field experience (to be used for correlation) were manufactured prior to 1990,
we created upper and lower bound distributions representative of the manufacturing processes for that hardware. We generated a family of upper-bound and lower-bound curves, which reflected typical ultrasonic inspection levels that were generally performed during this period. Also, we adjusted the frequency values to reflect the melting practices of the period, including double VAR, triple VAR, etc., based on limited industry data.

We provided this family of curves to the industry committee member companies so that they could perform probabilistic assessments and compare estimated number of events to their specific actual field experience. Each company then noted which curve, upper-bound or lower-bound, best represented its experience and reported how to adjust the exceedence axis (or hard alpha frequency) of the curves to achieve correlation.

We compiled the responses and provided them to the industry committee for review. The industry committee reached a consensus agreement to use the lower-bound curve with a 3 X increase on the exceedence values (or hard alpha frequency) as shown in Figure 4.8. The industry committee concluded that the lower-bound curve shape best represented the effects of in-process inspections and the underlying distribution of hard alpha not detected by ultrasonic inspection.

Because of the manner in which the final distribution was derived, we consider it to be approximately correlated to industry experience.

A considerable amount of time had elapsed from the initial development of the hard alpha distribution to the time the industry committee planned to submit their damage tolerance proposal to the FAA. Recognizing that the JETQC had collected more data over this time interval, we decided to review their most recent database to determine if a significant change in hard alpha find rates had occurred. Our analysis of the updated database showed an approximate 50% reduction for rotor grade material. We proposed to the industry committee that the 1990 hard alpha be updated to reflect our findings. The industry committee agreed to modify the 1990 distribution prior to submitting their recommendations to the FAA.

We updated the 1990 distribution by scaling its exceedence values (or hard alpha frequency) down by the ratio of the change in hard alpha rates from 1995 to 1990 (0.54). This modified distribution became the post 1995 hard alpha distribution, as shown in Figure 4.9.

5.0 Design Target Risk (DTR)
With the hard alpha distribution complete, we developed an approach for the industry committee to generate data that they could use to establish component and engine level DTRs for the design of new titanium rotating parts. The approach consisted of analytical studies conducted by each industry committee member that simulated goal reductions in the industry hard alpha event rate. The industry committee arrived at the DTRs by consensus using the results of these analytical reduction studies.

The industry committee’s goal was to develop DTR levels that would provide a substantial reduction in the hard alpha related event rate for the new engines in the future fleet relative to the existing commercial fleet characterized by the SAE SP 1270 reporting period. Absolute DTRs were not possible due the uncertainty of the inputs to the probabilistic
assessments, particularly the hard alpha distribution. Therefore, the industry committee concluded that only a relative reduction had validity. Reduction targets of 3, 6, and 15 X were selected to guide the simulation process. The industry committee’s intent was to make the maximum reduction consistent with the practical constraints of engine design and commercial engine use.

During the SAE SP 1270 reporting period the commercial transport fleet accumulated 220 million engine flight cycles and experienced 3 titanium melt related events. For the purposes of this simulation the industry committee assumed that the size of the commercial fleet will double in the next 20 years. They selected a six year time period to define the future fleet, consistent with the SAE reporting period, which suggested that the fleet would accumulate 440 million engine flight cycles. The industry committee also assumed that new engines designed to the damage tolerance criteria would account for 1/2 of the engine cycles of the future fleet, or 220 million engine flight cycles.

Each industry committee member independently estimated reductions in event rates by comparing the estimated event rate of two hypothetical fleets, one representing titanium components in operation at the time of the SAE SP 1270 report period (existing fleet) and the other made up of new parts designed to the proposed damage tolerance criteria (future fleet). The hypothetical fleets were based on each member’s own components, essentially assuming that the commercial fleet was made up of 100% of their engines.

Each industry committee member computed the number of engine components in its hypothetical commercial fleets based on its cyclic mix of engines, number of titanium stages in each engine, and the individual component life limits, so that the total number of engine cycles was 250 million (The industry committee agreed to use 250 million engine flight cycles to simplify the calculations). The following tables provide an example of how the industry committee members determined the engine cyclic mix and number of components to populate their hypothetical fleets.

### Example - Engine Cyclic Mix

<table>
<thead>
<tr>
<th>Engine</th>
<th>Cyclic Mix</th>
<th>Engine Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENG - 1</td>
<td>20%</td>
<td>50 E06</td>
</tr>
<tr>
<td>ENG - 2</td>
<td>80%</td>
<td>200 E06</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>250 E06</td>
</tr>
</tbody>
</table>

### Example - Total Number of Components In the Fleet

<table>
<thead>
<tr>
<th>Engine</th>
<th>Titanium Stage</th>
<th>Life Limit</th>
<th>Engine Cycles</th>
<th>Calculated # of Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENG - 1</td>
<td>1</td>
<td>20000</td>
<td>50 E06</td>
<td>2500</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>20000</td>
<td>50 E06</td>
<td>2500</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>10000</td>
<td>50 E06</td>
<td>5000</td>
</tr>
<tr>
<td>ENG - 2</td>
<td>1</td>
<td>20000</td>
<td>200 E06</td>
<td>10000</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>10000</td>
<td>200 E06</td>
<td>20000</td>
</tr>
<tr>
<td>Total Fleet</td>
<td></td>
<td></td>
<td></td>
<td>40000</td>
</tr>
</tbody>
</table>

Once the industry committee members defined the mix and number of components in their hypothetical fleets, they selected the appropriate anomaly distribution and estimated the probability of fracture (POF) for each component in the hypothetical existing fleet. Field inspections were included as applicable. The committee members classified each titanium component by material melt process, time period, and level of in-process inspection using categories established during the hard alpha distribution development as discussed in section 4.3. The estimated number of events (ENE) was then calculated using the following expression:

\[
ENE = \sum_{j=1}^{E} \sum_{i=1}^{n} (POF \times N \times Limit)
\]

Where POF is the component probability of fracture (events/part cycle), E is the number of engines, j is an individual engine, n is the number of titanium stages per engine, N is the total number of components in the fleet for a given stage, Limit is the component service life limit. This ENE calculation provided a baseline number of events for the existing fleet that was used as a benchmark to calculate the potential reductions for the future fleet.

Next each industry committee member changed the material for each part to the 1990 vintage and recalculated the event rate to reflect the improvements in material processing. If the baseline to 1990 material event rate reduction was less than the target value, each industry committee member determined a maximum component POF such that the target reduction was achieved. The maximum component POF was established by replacing the higher risk parts with lower risk parts until the target was met, essentially assuming redesign, as shown in Figure 5.1.
Each industry committee took the component DTR as the maximum component POF allowed in order to meet the event rate reduction goal. They then computed the POF for each engine by summing the individual component POF values for an engine using the capped values from the component DTR exercise. Each industry committee member took the maximum engine POF as the engine level DTR.

A member of our sub-team assembled all of the results from each industry committee member and presented them to the industry committee for review. The entire industry committee evaluated the combined results and agreed to the following values for engine and component level DTRs.

<table>
<thead>
<tr>
<th>Level</th>
<th>DTR (Events/Part Cycle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>5.0 E-09</td>
</tr>
<tr>
<td>Component</td>
<td>1.0 E-09</td>
</tr>
</tbody>
</table>

The estimated event reduction based on the above values was different for each individual company, as a function of its particular mix of component characteristics (vintage of material, component stress levels, number of engines, etc.). The range of reduction for the industry was approximately 3 to 10 X. The industry committee gave greater weight to results from engine companies with more component experience during the 1984 through 1989 time period. For those engine manufacturers the reduction could be as high as 8 to 10 X.

6.0 Customization and/or Future Modifications

Since the titanium hard alpha distribution is only “roughly” correlated to industry experience, and the industry committee based the DTR values on studies using the hard alpha distribution, these DTRs are not “absolute” values. In addition, this integrated approach of developing the DTRs from analytical studies using the hard alpha distribution suggests that the DTRs and hard alpha distribution are highly interdependent. Therefore, the industry committee recommends that any company specific anomaly distributions be developed using a methodology similar to that described in this paper. Failure to do so may result in component estimated event rate reductions inconsistent with those previously stated.

7.0 DTR Application and Projected Impact

As noted in the introduction, the industry committee has proposed fracture mechanics based probabilistic assessments to evaluate the damage tolerance capability of future titanium rotating component designs. Action to reduce the relative risk of a future rotor design should be based on whether or not the design satisfies the component and engine level DTRs. The role of the two DTRs will be a function of the component relative risk profile for the engine. The engine DTR will typically control the overall relative risk, while the component DTR prevents concentration of relative risk into one single component.

We considered two examples to illustrate the application of the DTRs. The first is a hypothetical engine with titanium components that have a high/low relative risk profile, and the second is an engine with a uniform component relative risk (or POF) profile.

Probabilistic assessment results for the first example, are shown as the black bars in Figure 6.1. The POF for components 1 and 2 are higher than the rest of the parts, and exceed the component and engine DTRs of 1 E-09 (events/cycle) and 5E-09 (events/cycle) respectively. Since the DTRs are exceeded, redesign or a field plan should be considered. Quantitative trade studies can be performed to determine the influence of key variables such as
potential inspection methods, inspection frequency, stress levels, material selection, and life limits. Variations of these design and/or field management actions can be evaluated to achieve the DTRs.

Assuming these evaluations yield the results denoted by the shaded bars in Figure 6.1 for components 1 and 2, the engine POF would be 2.8 E-09 (events/part cycle), which is less than the 5.0 E-09 (events/part cycle) DTR. Thus, both the component and engine DTRs would be satisfied.

In the second example the initial probabilistic assessment results, again shown as the black bars in Figure 6.2, depict a uniform component POF profile.

In contrast to the first example, all of the components are at the same POF and exceed the component DTR. Like the first example, the engine DTR has not been achieved. In this case, redesign or a field action plan should be considered for all of the components. Assuming the shaded bars in Figure 6.2 denote the results of a first pass at such actions, all of the parts meet the component DTR. However, the engine POF is still greater than the engine DTR [(10 E-09 (event/part cycle) vs. 5 E-09 (events/part cycle)] and further action should be considered. Assuming the open bars in Figure 6.2 denote the results of additional action, the engine POF drops to 5 E-09 (events/part cycle). Thus both the component and engine DTRs are satisfied.

Reference 5 contains detailed examples of the fracture mechanics-based probabilistic assessment process, the accompanying methodology, and standardized input data.

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### Figure 6.2. Second Example of DTR Application

- **Initial POF**
- **First Pass POF**
- **Final POF**

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### 8.0 Future Work

Realizing the importance of this effort, the FAA awarded a grant to Southwest Research Institute which, teamed with four members of industry (AlliedSignal, Allison, GE Aircraft Engines, and Pratt & Whitney), is working to further develop the hard alpha anomaly distribution, as well as completion of several other related tasks. In addition the Engine Titanium Consortium (ETC), also sponsored by the FAA, is working to improve the quality of the POD estimates used in the development of the hard alpha distribution and the damage tolerance probabilistic assessments. A future update to the hard alpha distribution is planned to be completed in the next two to three years.

### 9.0 Acknowledgments

The authors acknowledge the significant amount of time and resources that each member company of the AIA Rotor Integrity Sub-Committee put into development of the hard alpha anomaly distribution and the DTRs. Industry members of the AIA Rotor Integrity Sub-Committee are: AlliedSignal, Allison, GE Aircraft Engines, MTU, Pratt & Whitney, Pratt & Whitney of Canada, Rolls Royce, SNECMA, Sundstrand, and Williams International.

In addition, the authors acknowledge the excellent team work, cooperation, and technical creativity of the individual sub-team members. The sub-team membership consisted of Dr. Joseph Casey (GEAE), Barry Kalb (GEAE), Nichola Little (GEAE), Mike McNelly (Allison), Gary Peters (P&W), Nick Provenzano (Allison), and Jon Tschopp (GEAE).

### 10.0 References

4. Hard alpha find data provided by the Jet Engine Quality Committee (JETQC) for the 1990 through 1995 time period.