# I. CONCEPT DESCRIPTION

## a. Concept Title - Condition Assessment of Aircraft Structures

## b. Concept OPR

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## c. Background

The prediction of the future failure of structures subject to fatigue is very difficult using conventional techniques. This is primarily due to the fact that the vast majority of structures' fatigue lifetimes (90-95%) are spent in nucleation of very tiny flaws into measurable crack sizes. Due to the large variation in nucleating flaw sizes and the mathematics of flaw growth, the fatigue lifetimes, even of high quality structures, can vary by a factor of as much as 10 to 20 in a small fleet. This large variation in fatigue lifetimes leads to conservative statistics, which often prompts the premature retirement or overhaul of vehicles or other structures, since they focus on the weakest members of the fleet, while the remainder of the fleet is sound.

In the case of military aircraft, structural components are considered primarily in two groups. The first group are those where undergoing NDE/NDI with service life management by current fracture mechanics techniques is feasible, within the limitations of current technical complexities and future service condition predictions. The second group are those where it is not feasible or economical to undergo NDE/NDI, and must be managed by conservative statistical techniques. This results in the grounding of many aircraft at lifetimes that are far short of their inherent lifetime, thus limiting the possibility of fatigue failure in the weakest airframe in the fleet.

The principal nondestructive techniques available at present to indicate hidden cracks, cracks due to widespread fatigue damage, or cracks which are exacerbated by corrosion, are ultrasonic examination, eddy current examination, X-ray examination, dye penetrant examination, and acoustic emission measurements. These techniques are used in a Griffith fracture-mechanics based system to assure structural safety. This is accomplished by modeling crack growth in the structure, based on projected loading patterns and environmental conditions, and determining a maximum acceptable flaw size allowable in the structure, assuming crack growth under the assumed conditions until the next nondestructive inspection period. The nondestructive inspection technique is then used to locate and quantify the size of flaws within the structure, and ensure that flaws larger than the maximum allowable size are not permitted to remain.

The ultrasonic examination, eddy current examination, X-ray examination, and dye penetrant examination techniques are all used to ensure that cracks no larger than the allowable size are allowed to remain in the structure during the nondestructive inspection service interval.

The uncertainties that remain in this system are based on the fact that the crack growth rate projections are only as accurate as the projections of future loading amplitude, frequency, service patterns, and future environmental exposure conditions. Also, significant analytical uncertainties exist with regard to how to treat cracks in the presence of general corrosion and widespread fatigue cracking. Of necessity, to account for these uncertainties, additional conservatism must be

incorporated into the allowable structure flaw size, leading to more frequent and costly nondestructive inspection intervals.

The acoustic emission system more closely resembles the technique presented here, in that it attempts to detect imminent structural failure by using indications of the structure itself, in this case acoustic noise emitted as energy during the cracking process. However, this technique is heuristic at best, having little underlying basis in theory, and has failed to produce a reliable precursor to structural failure in all environments, and can be affected by numerous other variables.

Currently, several models of military aircraft are reaching the limits of their intended calendar service life. Civilian aircraft, with their greater duty cycle of use, tend to approach their design fatigue use limits. Military aircraft, with their lower duty cycle of use, tend to face retirement due to aging phenomena such as corrosion, multiple site damage, and widespread fatigue damage, leading to uncertainty in their remaining safe service life. Consequently, owners of these aircraft are facing the economic penalties of shutting down many healthy aircraft, or of assuming the increasing risk of continued operation under current practices. The legal liabilities of continued uncertain operation tend to force the owners to accept the economic penalties of premature retirement or to look for additional alternatives. Until now, no reliable method for real-time condition assessment has been devised on which to base continued use of structures subject to fatigue.

The techniques described here for directly sensing conditions that indicate impending fatigue failure have been proven to be reliable on other physical and biological systems. They have also been demonstrated in laboratory scale experiments to be able to sense precursors of fatigue, stress corrosion, and low temperature creep failure in fiberglass, aluminum, and steel under pristine conditions, and under conditions of simulated corrosion and multiple site damage. The failure indications were from 1% - 20% of fatigue life in advance of actual failure under constant load. The techniques require measurement of global loadings and local deflections/strains at critical structural locations to indicate the rapidly increasing growth of hidden cracks with sufficient warning time prior to structural failure to take preventative action to correct the problem or retire the structure before failure. The techniques, as described in the referenced report and patent application (US government rights reserved)[1], have been proven on a laboratory scale. They have successfully detected the onset of structural failure due to fatigue cracking (including simulated widespread fatigue cracking and cracking in the presence of corrosion), stress corrosion cracking, and low temperature creep crack growth, with a reasonable degree of forewarning before failure. It is also believed that these techniques will be successful for corrosion fatigue and high temperature creep crack growth.

The techniques are Griffith Energy absorption measurements for structures under load and subject to cracking, based on the concept of $G_{Ic}$ or $J_{ic}$ as critical strain energy release rates. The Griffith critical strain energy release rate criterion for structural failure by cracking states that a crack will begin to extend when the strain energy released from the structure by relaxation during crack extension exactly equals the consumption of energy demanded by the formation of new surface area. This criterion has been established to be a material property, and is stated as:

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[1]Welch, D. E., Hively, L. M., and Ruggles, M. B., *Nonlinear Crack Growth Monitoring*, ORNL-TM-1999/117, Oak Ridge National Laboratory, Oak Ridge, TN, October, 1999.

Where

U= the strain energy within the structure at the point of the beginning of crack extension
a = crack length
dU/da = decrease in internal strain energy during crack extension da for fixed end displacement, or increase in internal strain energy during crack extension da for constant end load.

Using this technique for fatigue loading, the energy input into the structure during each cycle is measured by integrating the global load and the local critical deflection. Then, during the unloading portion of the cycle, the global load and the local critical deflection are again integrated, and by subtracting the two we obtain a net residual energy input into the local structure area during each fatigue cycle. For structures which are loaded principally in the elastic regime (as most structures are), this energy will consist principally of two components. These are the thermoelastic damping component, representing the cumulative effect of adiabatic tension followed by thermal expansion, then adiabatic compression followed by thermal contraction. The second component is the incremental consumption of new surface energy by the slowly increasing crack size.

### d. Laboratory Research

Laboratory experiments performed by ORNL have shown that the initial crack size, and hence the initial crack growth energy component, is small compared to the damping energy component for new undamaged structures. By monitoring the hysteresis strain energy (energy consumed per fatigue cycle) vs. number of cycles, we initially see a relatively constant level of energy consumption (due to damping alone). However, as the internal critical crack grows larger, the crack growth energy consumption component grows larger compared to the constant damping energy component, so that the curve of overall energy consumption begins to rise noticeably near the end of life. It is this **increase** in strain energy consumption, rather than the level of strain energy consumption itself, which is used as the indicator of the approach of structural failure. Therefore, it may be applied to any structure, and at almost any point in a structure's lifetime. We have tested the technique in Mode I and Mode III cracking, and for tensile, compressive, flexural, and torsional loadings.

ORNL has established a reliable statistical indicator that indicates the point at which the end of

This proposed project will be conducted jointly by the 134th Air Refueling Wing (ARW) and the Engineering Technology Division (ETD) of the Oak Ridge National Laboratory (ORNL). The ETD has recently completed a one-year research and development program to prove the effectiveness of this technology in a laboratory scale effort[1], and has applied for patent protection for this technology with US government rights reserved.

**e. Objective**

The objective for this project is to demonstrate, on a fleet-wide basis, a technology for monitoring a selected flight safety related structural element on the KC-135 fleet of aircraft for the approach of a crack-dominated failure mode. This will allow remedial action (repair or replacement) to be taken prior to the actual occurrence of failure of that element. This technology will be compared to the baseline method of structural integrity assurance currently in use for this element, and will be gradually introduced as its reliability indicates its ability to improve the structure's safety assurance.

**f. Approach**

The strategy for beginning implementation of this technology for assurance of structural safety of military aircraft while extending their useful life will be based on a three-step implementation program. The program will utilize the resources provided by the established partnership between ORNL and the nearby 134th Air Refueling Wing of the Tennessee Air National Guard's fleet of eleven KC-135E aircraft at McGhee-Tyson Air Base.

The first implementation step will require laboratory testing of a selected structural life-limiting element from actual flight hardware, under simulated flight loading and environmental conditions. Suitable KC-135 structural elements could be fuselage longeron stringer ties, aft pressure bulkheads, or wing spars.

The second implementation step will require prototype flight monitoring of this selected structural element in a test bed of actual military aircraft, as a supplement to conventional fracture mechanics based flight safety assurance practices. In this phase, the results of this new technique can be validated by comparison to existing flight safety assurance fracture mechanics techniques.

The third implementation step will require migration of the proven implemented technology to depot maintenance implementation for the chosen aircraft fleet at large. This step would be coordinated with the OC-ALC for the KC-135 depot maintenance implementation.

**g. Expected Results**

This technology will improve the ability to monitor the effect of cracks due to either hidden corrosion or stress-corrosion cracking, cracking in multi-layer structures, or cracks in fastener holes in multi-layer structures on aircraft structural life. It will also provide useful information with regard to the approach of the end of structural life due to crack-dominated failure mechanisms.

The best estimate of cost avoidance or savings is that a 50% improvement in overall KC-135 fleet-average airframe lifetime limited by crack-failure, with no reduction in flight safety, can be achieved within 10 years. It is also estimated that the frequency, and hence cost, of nondestructive

inspections can be reduced, as confidence is gained in the ability to detect significant hidden crack growth.

**h. Initial Aircraft MDS on which EMD will be accomplished: KC-135**

i. **Is the technology applicable to other aircraft MDS=?:** Yes

Any aircraft consisting of metallic or composite load bearing structures subject to crack-dominated failure modes can benefit from this technology.

**j. Targeted level of implementation:**

Depot level maintenance, with possible extension to field level maintenance.

k. **Project start date:** 1 Oct, 2000

l. **Projected duration of EMD in years:** Three years

**m. Contract Vehicle:**

The funding vehicle for this project is anticipated to require a MPIR between ORNL and either the TN-ANG, the OC-ALC, and/or the AAPO.

## II. Funding Information

**a. EMD Cost**

| FY | INITIAL FUNDING | ADJUSTMENT |
|---|---|---|
| FY01 | $500K | |
| FY02 | $750K | |
| FY03 | $750K | |

## III. Implementation and Sustainment

a. **Where will the new capability be implemented after EMD?**

The targeted implementation center will be the Oklahoma City Air Logistics Center, as the lead depot maintenance center for the KC-135 aircraft.

**b. Who will provision for initial spares, follow-on spares, technical orders, training, manpower, and spare parts?**

The C/KC-135 SPD will be responsible for operation and maintenance of the equipment. Provisioning will be accomplished via provisioning conferences pending receipt of source documentation.

c. **Who would prepare POM submission if EMD proves successful?** C/KC-135 SPD

IV. **Project Signatures and Approval Authority**

**Project OPR:** _____

**SPD Concurrence:** _____