# ARL BAA WHITE PAPER/RESEARCH PROPOSAL COVER PAGE

**THIS IS A** (Mark One): __X__ White Paper Submission ____ Research Proposal Submission

**Research Topic Area Number: ___4.1, 4.2__**

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**Research Area** (Mark One Below)**:**

____ Information Science & Technology
____ Sensors & Electron Devices
____ Survivability/Lethality Analysis
__X_ Weapons & Materials Research
____ Corporate Information & Computing Ctr.

**Offerors Name and Address:**

**_Engineering Technology Division_____**
**Oak Ridge National Laboratory_____**
**_Oak Ridge, TN 37831-8066_____ _**
**_____**

**Federal TIN:**

**Duns Number:**

**Cage Code:**

**Type of Business (check all that apply):**

____ Large Business ____ Woman-owned
____ Small Business
____ Small Disadvantaged Business
____ Educational Inst
____ HBCU/MI
____ Domestic Firm performing Outside U.S.
__X Other, Non-Profit
____ Foreign Concern/Entity

**Are you registered in the CCR?** ____ Yes ____ No

**Type of Instrument** (Mark One Below)**:**

__X_ Contract
____ Grant
____ Cooperative Agreement
____ Other Transaction

**Data Rights and Government Furnished items:**
*(Circle all that apply:)*
White Paper/Proposal contains: **government purpose rights data**
White Paper/Proposal requires Government Furnished: **Equipment** in performance.

**Title of White Paper/Proposal:**
**__Nonlinear Crack Growth Monitoring_____**
**_____**

**White Paper/Proposal Valid Until: _Unlimited__ Total Estimated Cost: $_1.5M_____**

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**Nonlinear Crack Growth Monitoring for**
**Structural Assessment of Military Hardware**

This concept will address the structural problem of failure due to cracks which are either hidden, in the presence of corrosion, due to stress-corrosion cracking, cracking in multi-layer structures, or cracks in fastener holes in multilayer structures. It will also provide useful information with regard to Usage monitoring/data recording.

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 to successfully detect 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:

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

[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.

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.

Our experiments 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 plotting 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 and larger, the crack growth energy consumption component grows larger and 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.

We have established a reliable statistical indicator, which indicates the point at which the end of structural fatigue life is near. This indicator provides an indication of approaching failure at between 1% and 20% of fatigue lifetime before structural failure. In 50-60 experiments with steel, aluminum, and fiberglass materials, no false positive indications (indications without being closely followed by structural failure) or false negatives (failure to indicate before fatigue failure) were noted.

The technique described may be implemented either as a continuous online monitoring system adapted to the military structure itself, or as a series of periodic loading tests applied during routine maintenance to measure the response of the structure to standard loadings.

## 1. Implementation Cost/Strategy

The strategy for beginning implementation of this technology for assurance of structural safety of US Army military structures while extending their useful life will be based on a three-step implementation program, utilizing the resources provided by the previously established partnership between ORNL and the Army Research Laboratory during the 1993-1995 program on Insensitive Munitions with Dr. Robert Frey.

The first implementation step will require laboratory testing of a selected structural life-limiting element from actual military hardware, under simulated operational loading and environmental conditions. Suitable structural elements could be artillery or tank gun barrels, helicopter transmission elements, or vehicle components.

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

The third implementation step will require migration of the proven implemented technology to routine maintenance implementation for the chosen military hardware at large. This step would be coordinated with the ARL and the military hardware Program director.

This program is envisioned to require three years and a cost of $1.5M.

2. **Payoff**

The prediction of the future failure of structures subject to fatigue is very difficult. 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 hardware, structural components are considered primarily in two groups: 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, and those where it is not feasible or economical to undergo NDE/NDI, and must be managed by conservative statistical techniques. This results in the replacement of many structures at lifetimes that are far short of their inherent lifetime, thus limiting the possibility of fatigue failure in the weakest member in the group.

Currently, many elements of military hardware are reaching the limits of their intended calendar service life. Civilian structures, with their greater duty cycle of use, tend to approach their design fatigue use limits, while military structures, 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 structures are facing the economic penalties of shutting down many healthy structures, 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

The best estimate of cost avoidance or savings is that a 50% improvement in overall group-average structure lifetime limited by fatigue cracking, with no reduction in structural safety, can be achieved within 10 years. It is also estimated that, as confidence is gained in the ability to detect significant hidden crack growth, the frequency, and hence cost, of nondestructive inspections can be reduced.

## 3. Background Research

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 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, which 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 frequency and 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, and has failed to produce a reliable precursor to structural failure in all environments, and can be affected by numerous other variables.

## 4. Deliverables and Targeted User

The deliverable for the initial implementation program would be a specification and prototype system for implementation on a chosen military structural element. It would also include assistance in incorporation into the structural safety assessment system of this hardware. The targeted user would be the depot maintenance center.

## 5. Applicability to multiple weapons systems

The techniques described in this paper will be applicable to assisting the fracture-mechanics based structural safety monitoring of all military structural components that are subject to failure by cracking.