

ARMY RESEARCH LABORATORY



# Functional Nanostructures for Induction Heating: A Review of Literature and Recommendations for Research

by Bruce K. Fink, Shridhar Yarlagadda, John Q. Xiao,  
Gary H. Lavery, and John W. Gillespie, Jr.

ARL-TR-2365

November 2000

Approved for public release; distribution is unlimited.

DTIC QUALITY INSPECTED 4

20010215 126

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

# Army Research Laboratory

Aberdeen Proving Ground, MD 21005-5069

---

---

ARL-TR-2365

November 2000

## Functional Nanostructures for Induction Heating: A Review of Literature and Recommendations for Research

Bruce K. Fink

Weapons and Materials Research Directorate, ARL

Shridhar Yarlagadda, John Q. Xiao, Gary H. Laverty, and  
John W. Gillespie, Jr.

University of Delaware

---

## Abstract

---

This report presents the concept for a multidisciplinary research program aimed at establishing the science base for the design and synthesis of magnetic nanoparticles for hysteresis heating, with potential applications ranging from novel composites processing techniques to alternative cancer treatments. Magnetic materials are used in a wide range of applications and designed for maximum efficiency or minimized hysteresis loss. The uniqueness of this project is that, while considerable work has been aimed at reducing hysteresis losses, the converse effect (i.e., increasing hysteresis losses and therefore heat generation) has not been fully studied. Hysteresis-based heating has several advantages over conventional heating techniques, including the fact that it is a very rapid and noncontact process. In addition, the Curie temperature of magnetic materials can also be used as a means of "smart" thermal control. Exploratory basic research through ongoing programs at the U.S. Army Research Laboratory (ARL) has established the feasibility of Curie temperature control and demonstrated the effects of particle size, frequency, and stoichiometry on hysteresis losses. The following scientific barriers are addressed in this report: magnetization dynamics in high-frequency magnetic fields, the effects of magnetic phase transition on hysteresis heating, and the dimensional dependence of Curie temperature in nanoparticles. If carried out, the research program outlined in this report would establish the science base for the design and synthesis of nanoparticles for hysteresis heating applications.

# Table of Contents

	<u>Page</u>
<b>List of Figures .....</b>	v
<b>1. Introduction .....</b>	1
<b>2. Scientific Barriers in Particle Design .....</b>	6
2.1 Issues .....	6
2.2 Particle Synthesis .....	6
2.3 Dynamics of Magnetic Domain Wall Motion .....	9
2.4 Ferromagnetic to Paramagnetic Phase Transition and Superparamagnetic Relaxation .....	14
<b>3. Potential Applications .....</b>	17
3.1 Polymer Processing .....	17
3.2 Selective Cell Death .....	20
3.2.1 <i>Experimental Cell Bioassays</i> .....	21
3.2.2 <i>Heating Tests</i> .....	22
3.2.3 <i>Cell Death Assays</i> .....	22
<b>4. Summary .....</b>	23
4.1 Particle Design .....	23
4.2 Polymer Processing .....	23
4.3 Selective Cell Death .....	24
<b>5. References .....</b>	25
<b>Distribution List .....</b>	35
<b>Report Documentation Page.....</b>	55

INTENTIONALLY LEFT BLANK.

# List of Figures

<u>Figure</u>		<u>Page</u>
1.	Multidisciplinary Research Effort in Hysteresis Heating of Magnetic Nanoparticles for Biological and Polymer Processing Applications. ....	2
2.	Schematic of Domain Wall Motion Due to External Field.....	11
3.	Schematic Representation of the Random Anisotropy Model.....	13
4.	Coercivity vs. Grain Sized for Various Soft Magnetic Materials .....	14
5.	Self-Regulating Temperature Profile for Ferromagnetic Polymer Susceptor .....	18

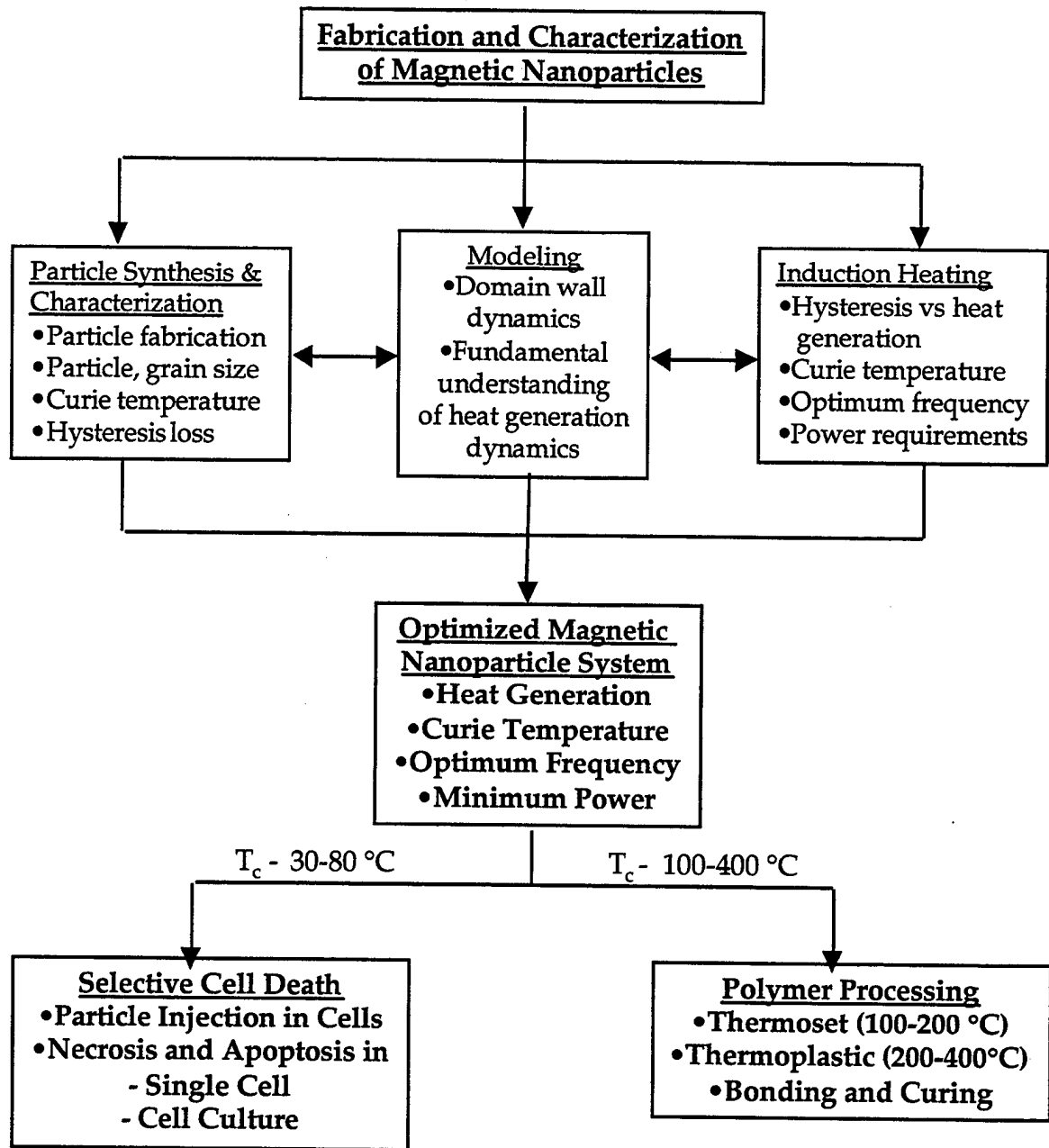
INTENTIONALLY LEFT BLANK.

# 1. Introduction

The goal of this report is to outline the research requirements to establish the science base for the design and synthesis of nanoparticles for hysteresis heating, with potential applications ranging from novel polymer processing techniques to alternative cancer treatments. This report outlines a multidisciplinary research approach encompassing physics, material science, and biology research areas. The proposed research focuses on maximizing hysteresis losses in magnetic particle systems, while research to date has focused on minimizing hysteresis losses. As shown in Figure 1, a multidisciplinary research approach would enable advances in the basic science of hysteresis heating in magnetic nanoparticles and subsequent optimization of these nanoparticles for potential use in biological and polymer processing applications.

Interest in the study of nanostructured materials has increased rapidly during the past several years, stimulated by recent advances in materials synthesis and characterization techniques. These materials are of great scientific interest in developing a better understanding of magnetic phenomena. Their unique structure offers a fertile ground to study size, surface/interface, and intra- and interparticle interaction effects [1-3]. These materials are being used in a wide range of applications, including magnetic tapes, ferrofluids, catalysts, medical diagnostics, drug delivery systems, and pigments in paints and ceramics [1, 2, 4-6]. As never before, magnetic materials are the key to the future of the storage industry [7-13].

Research on fine magnetic particles started in the late 1940s [14, 15] and peaked in the 1950s. One of the milestones of that development was the emergence of domain theory [16], which led to the concept of single domain particles [17] and magnetic anisotropy contributions, giving rise to permanent magnet behavior [18] and superparamagnetism [19]. Stimulated by the potential application of fine magnetic particles in magnetic recording media [20, 21], most recent studies have concentrated on magnetization and coercivity [1, 2], magnetic reversal mechanism [22-25], and superparamagnetic relaxation [26, 27]. The dynamics of fine magnetic particles, including phenomena such as domain wall resonance and spin resonance, have rarely been



**Figure 1. Multidisciplinary Research Effort in Hysteresis Heating of Magnetic Nanoparticles for Biological and Polymer Processing Applications.**

studied, except in the superparamagnetic region. These phenomena are directly related to the conversion of energy absorbed from external magnetic fields to heat.

In most applications of magnetic nanoparticles, heat generation is not desirable. However, induction-based hysteresis heating has several features that can be exploited for efficient and economical heating. Two applications proposed as part of this effort use hysteresis heating of particles. The first involves induction heating for processing of advanced polymers; the second is targeted at the use of magnetic nanoparticles for selective heating and destruction of cells. The proposed effort addresses the scientific barriers to magnetic nanoparticle design for controlled heating.

Exploratory basic research at the U.S. Army Research Laboratory (ARL) at Aberdeen Proving Ground (APG) and the University of Delaware has established the feasibility of hysteresis heating for polymer processing [28–31], and an invention has been disclosed on this technology [32]. Existing processing techniques for polymers have time and cost limitations that can be overcome by hysteresis heating. In the repair of high-performance polymer composites where the thermal requirements are stringent, self-controlled heating based on the Curie temperature of the material is ideal. In addition, by using nanoparticles as additive fillers, one can easily adapt existing processing techniques for hysteresis-heating-based processing of polymers. New research is required to quantify the heat-generation capabilities of a variety of magnetic nanoparticle systems and the use of Curie temperature as a built-in “smart” thermal control system.

Hyperthermia in the treatment of cancer is well established in terms of the required temperatures and dwell cycles for cellular thermal shock, thermotolerance buildup from heat shock proteins, apoptosis, and rapid thermoablation [33–39]. The most clinically effective and desirable means of imposing thermal energy for hyperthermia is to inject a susceptor material directly into the target cells. This allows localization of thermal energy into the target cells alone. In order to be acceptable for hyperthermia treatment for humans, the susceptor material must be injectable into the cellular structure, must remain localized to the target cells for

subsequent treatment, and must not cause clinical complications. In order to be effective, the susceptor material, or ferrofluid, must be energetically able to remain in suspension, must be capable of rapid heating to the correct “process” temperature to minimize electromagnetic radiation exposure time for the patient, must have a Curie temperature that provides for precise control of temperature, and must have sufficient hysteretic properties such that the volumetric percentage of loading of particles is minimized. Most research to date has focused on the former “acceptability” issues and not on the latter “effectiveness” issues. The proposed work would focus on the latter enabling issues for cancer treatment.

Magnetic materials have been considered for a number of therapeutic applications, including contrast imaging [40], magnetic guidance of drugs or radionucleides to selected target sites [41], and hyperthermic destruction of cells using inductive heating methods [42–44]. The latter application represents an important advance in cancer therapy and is the focus of this report. Two major obstacles to the implementation of such an approach can be imagined: (1) selective targeting of particles to specific cells and (2) optimization of particle and heating parameters to destroy those cells with minimal collateral damage. In addition, there are numerous other considerations, such as toxicity, metabolic clearance of particles, intracellular vs. extracellular efficacy, and precise control of heat production in the target area, vis-à-vis blood flow patterns, tissue density, etc. While many of these issues have been considered [42, 44–46], there has been little systematic investigation of nanoparticle properties in a reproducible bioassay. Thus, one objective of any new research thrust should be to develop such bioassays, based on nanoparticle-induced hyperthermic cell death.

Used in a wide range of applications, magnetic materials are designed for maximum efficiency or minimized power loss. One mechanism of power loss in these materials is magnetic hysteresis loss, which results in heating of the material. While considerable work has been aimed at reducing hysteresis losses, the converse effect—i.e., increasing hysteresis losses and therefore heat generation—has not been fully studied.

Hysteresis-based heating has several inherent advantages over other heating techniques.

- Energy input is noncontact.
- Heating can be very rapid ( $\sim 50$  °C/s).
- Heating can be self-controlling based on the Curie temperature of the material.

In order to fully exploit the potential of hysteresis heating, work is necessary to understand the relationships between hysteresis heating and material parameters, such as composition and particle size. Nanoscale particles allow us the flexibility of (1) using size-property relationships to maximize hysteresis losses, (2) minimizing eddy current losses such that Curie temperature can be for smart temperature control, and (3) maximizing particle-polymer interphase to optimize thermal and mechanical properties.

The following outlines a three-step research effort on the design and application of hysteresis heating of magnetic nanoparticles.

- (1) Establish the science base to understand the hysteresis behavior of magnetic nanoparticles as a function of particle parameters, magnetic field, and frequency.
- (2) Develop materials by design based on the physics of magnetic particles. With the science base established, given the heating requirements for specific applications, one can easily determine the specific material parameters to be used; this will involve fabricating of nanoparticles of a variety of compositions and particle sizes, characterizing of the magnetic and heating properties, and theoretical modeling to optimize particle preparation.
- (3) Identify and demonstrate two potentially high-gain applications using the following nanoparticles:

- Curie temperature control-based polymer processing, and
- selective cell death—necrosis and apoptosis.

## 2. Scientific Barriers in Particle Design

**2.1 Issues.** For these objectives to be met, several basic issues in the physics of magnetic particles must be addressed.

- Development of reliable and controllable methods to synthesize nanoparticles.
- Development of an understanding of the magnetization dynamics in high-frequency magnetic fields, with the ultimate goal being to maximize the energy loss, which is minimized in traditional applications. These high-frequency behaviors, which have rarely been studied, are of great scientific interest, relating magnetic tunneling, domain wall damping, and domain wall resonance phenomena.
- Investigation of the effects of magnetic phase transition on hysteresis heating (energy loss); the magnetic transition of a nanoparticle encompasses ferromagnetic, superparamagnetic, and paramagnetic phases.
- Application-based identification of particle composition, size, microstructure, induction power, and frequency for maximum heat generation or power loss at a specified Curie temperature. The Curie temperature is chosen based on the applications; 100–400 °C for polymer processing and 30–80 °C for cell death studies.

**2.2 Particle Synthesis.** There are numerous techniques for preparing fine particles [1, 2]. These include electrodeposition [47], reducing transition metal ions by  $\text{NaBH}_4$  or  $\text{KBH}_4$  [48–51], sol-gel processes [52], spark erosion [53–55], aerosol pyrolysis [56], gas evaporation [20, 57], sputtering [26, 58], gas and water atomization [59], reverse micelle techniques [60–63], and mechanical ball milling (MB) [64–66]. MB, unlike many of the aforementioned methods,

produces its nanostructures not by cluster assembly but by the structure decomposition of coarse-grained structures as the result of severe plastic deformation in a cyclic process. This has become a popular method to make nanocrystalline materials because of its simplicity, the relatively low cost of the equipment needed, and the applicability of the method to essentially all classes of materials. Another major advantage is the potential for easily scaling up to tonnage quantities of materials for various applications.

It is necessary to first distinguish between nanoparticles and nanograin/nanocrystalline particles. The former refers to particles of nanometer size that generally consist of a single grain, and the latter to particles consisting of many grains of nanometer size. The nanograin particle may not be nanometer in size. For brittle materials, such as oxides, nitrides, carbides, and rare earth-transition metal intermetallic compounds, MB can indeed produce nanoparticles [67], whereas for ductile materials, straight MB will produce only nanograin particles because of the excessive cold welding. The nanoparticles can, however, be fabricated either using various surfactants (hexane) [68–70] or milling the material in an oxygen or hydrogen atmosphere and deoxidizing/dehydriding the final powders [59]. Both nanoparticles and nanograin particles are relevant to this research, as discussed in the following paragraphs.

A detailed microscopic model of the development of a nanocrystalline structure by MB is still lacking, although there is some agreement on the phenomenological model, which comprises three stages [64, 65].

- (1) Deformation Stage—the deformation is localized in shear bands containing a high dislocation density.
- (2) Nanograin Formation—dislocations annihilate and recombine to form nanograins with small-angle grain boundaries. Further milling extends this structure throughout the sample.

- (3) Nanograin Randomization—the orientation of the grains becomes random, probably through grain boundaries by sliding or rotating.

These deformation processes are important for fundamental studies of extreme mechanical deformation and for developing a nanostructured state of matter with particular physical and chemical properties. The mechanisms of dislocation vs. grain boundary deformation can be distinguished by studying the atomic-level lattice strain ( $\epsilon$ ) and the stored enthalpy ( $\Delta H$ ) as a function of reciprocal grain size. At stage 1, both lattice strain and enthalpy depend weakly on grain size. A large jump in the values of  $\epsilon$  and  $\Delta H$  signifies the transition into stages 2 and 3. Finally, both  $\epsilon$  and  $\Delta H$  reach a maximum value before decreasing. The causes of such maxima are still under debate [66, 71–74]. It is important to identify the microstructure in which optimal magnetic properties can be realized.

Magnetic particles can be fabricated using a shake mill and a computer-controlled attrition mill. The latter has a variable rotor speed of up to 1,500 rpm, with a capacity up to 500 cm<sup>3</sup>. Particles can be made in vacuum, gas atmosphere, or solution. For alloys, small particles are made either through mechanical alloying (mixing powders) or milling down the alloys, which are made using arc melting or vacuum-induction furnaces. Magnetic oxide particles, which may be more friendly to biological cells, can also be made using powders, which are readily available. To achieve the nanoparticle size for ductile materials, two methods will be used. Materials can be ball-milled in an oxygen or hydrogen environment. The interstitial oxygen/hydrogen or oxides/hydrides tend to make materials brittle. The final nanoparticles will be treated in a high vacuum to remove/disassociate the oxygen or hydrogen. An alternative way to fabricate nanoparticles is to add surfactants, usually a hexane solution, during the ball milling. For example, extremely soft aluminum and magnesium powders can be milled to form small alloy particles in the presence of sodium-1, 2 bis (dedecyl carbonyl) ethane-1-sulfonate or lithium-1,2 bis dodecyloxycarbonyl sulfasuccinate [68], and (Co-Fe)<sub>75</sub>Si<sub>15</sub>B<sub>10</sub> soft magnets can be milled down to about 100 nm in diameter in the presence of sodium-1,2 bis (dedecyl carbonyl) ethane-1-sulfonate or ammonium dihexadecyl dimethylacetate.

Particle size and grain size can be characterized using x-ray, electron microscopy, and particle analyzers (GALAI CIS100 and Brookhaven Instrument B1-XDC). The GALAI CIS100 analyzer measures particles from 0.5 to 600  $\mu\text{m}$  in size by measuring the rotating laser time of shadowing, with additional particle shape analysis using a rapid video microscope picture analyzer. The Brookhaven analyzer uses centrifugal analysis with an x-ray detector and is capable of measuring particles from 10 nm to 10  $\mu\text{m}$  in size. The stored enthalpy will be measured using differential scanning calorimetry (DSC) by integrating the exothermal signals. The structure will be carefully characterized and optimized to produce maximum heat. Such optimization can be achieved through adjusting rotor speed and adding appropriate surfactants.

A common problem encountered with milling fine particles is the potential for significant contamination from the milling media (balls and vial) or atmosphere. Such contamination can be significantly reduced using a low-energy mill [66], which can be achieved in our attrition mill by reducing the rotor speed. It has recently been shown [73] that the minimum nanocrystalline grain size for a number of elements milled in a low-energy mill is comparable to that from a high-energy mill [71, 74, 75]. Surfactants may also be used to minimize contamination. For example, boric acid and borox were quite effective in reducing iron contamination [76]. Our attrition mill is also capable of fabricating materials in a vacuum environment, thus minimizing atmospheric contamination.

**2.3 Dynamics of Magnetic Domain Wall Motion.** Many of the specific applications of magnetic materials depend on their behavior at high frequencies. When subjected to an alternating field, magnetic permeability shows dependence on several magnetization mechanisms. As the field frequency increases, magnetic moments are unable to follow the applied field because of "microeddy currents" generated by the ac field near the domain walls. Consequently, there is a lag between the applied field and the magnetization of the material, resulting in hysteresis-type behavior. The permeability becomes a complex number, and the imaginary part of the permeability corresponds to the energy dissipation. This energy dissipation appears in the form of heat and is commonly called hysteresis heating. In all nonheating

applications, hysteresis heating should be minimized; however, the proposed applications require the converse (maximum hysteresis heating and desired Curie temperature  $T_c$ ).

The frequency spectrum for each magnetization mechanism is different, since each has a different time constant. In bulk materials, such as ferrites, the low-frequency (MHz) peak is associated with domain wall dynamics and the high-frequency peak, usually in the GHz range, with spin resonance. There are very few studies on the dynamics of magnetic particles, and the emphasis was exclusively on quantum tunneling behavior, which appear at sub-Kelvin temperature and low frequency (<1 MHz) [77, 78]. The study of particle dynamics will not only lead to a new understanding of their behavior in ac fields, but also significantly impact both heating and nonheating applications, as more materials based on particles are used.

Consider a  $180^\circ$  domain wall, as shown in Figure 2; an external magnetic field  $H(x,z)e^{i\omega t}$  exerts a pressure on and bows the Bloch wall, displacing it a distance  $h(z)$  in the x-direction. These displacements approximately obey the equation [79, 80]

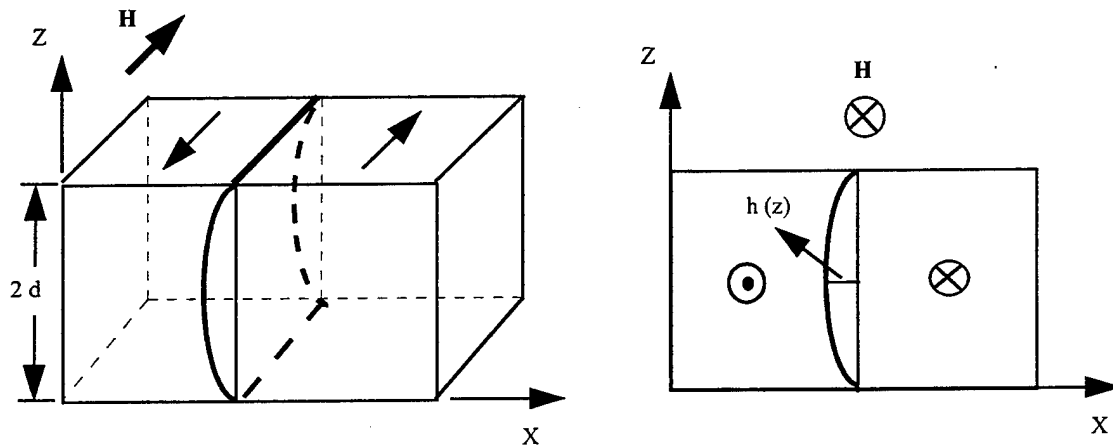
$$\gamma \frac{d^2 h}{dz^2} - m \frac{d^2 h}{dt^2} - \beta \frac{dh}{dt} - \alpha h = -2M_s H(h), \quad (1)$$

where all the coefficients are defined per unit area. The first term represents the wall energy, and  $\gamma$  is the wall surface tension. The second term is the wall inertia, and  $m$  is the effective wall mass. The third term is the relaxation damping term opposing wall propagation, and the last term is associated with wall pinning due to defects, expressed as a restoring force. The equation resembles a harmonic oscillator and has no analytical solution. Many assumptions have been made in order to solve the equation—e.g., either rigid or flexible plane walls (no bowing) were used in the Polivanov model [81] and the Pry and Bean model [82], respectively. In the models where wall bowing is considered, a linear response approximation was always used [79] (either  $H$  is not a function of  $h$  or only a linear term is considered).

Most recently, in an attempt to explain results on the frequency response of iron-cobalt soft magnetic materials at high temperatures [83], Chui reconsidered the problem [84]. Consider the situation shown in Figure 2; in addition to equation (1), the equation for H was also derived as follows:

$$\frac{\partial H}{\partial t} = \frac{c}{4\pi\sigma} \left\{ \frac{\partial^2 H}{\partial z^2} + \left[ 1 + \left( \frac{\partial h}{\partial z} \right)^2 \right] \frac{\partial^2 H}{\partial x^2} - 2 \frac{\partial h}{\partial z} \frac{\partial^2 H}{\partial x \partial z} + \left[ \left( \frac{c^2}{4\pi\sigma} \right)^{-1} \frac{\partial h}{\partial t} - \frac{\partial^2 h}{\partial z^2} \right] \frac{\partial H}{\partial x} \right\}, \quad (2)$$

where  $\sigma$  is electric conductivity. To avoid any simplifying assumptions, a numerical method was used to solve the equations. Similarly, core losses, which correspond to heat generation, can also be calculated by integrating  $jE = \sigma E^2$ . The electric field E can be calculated using  $\nabla \times E = 1/c(\partial B/\partial t) = M_s/c(\partial h/\partial t)$ . The first-order approximation, in the case shown in Figure 2, leads to  $\nabla \times E \approx 2E$ , and core loss will be proportional to the domain wall speed  $(\partial h/\partial t)^2$ . However, a detailed solution should be obtained by solving equations (1) and (2) self-consistently.



**Figure 2. Schematic of Domain Wall Motion Due to External Field.**

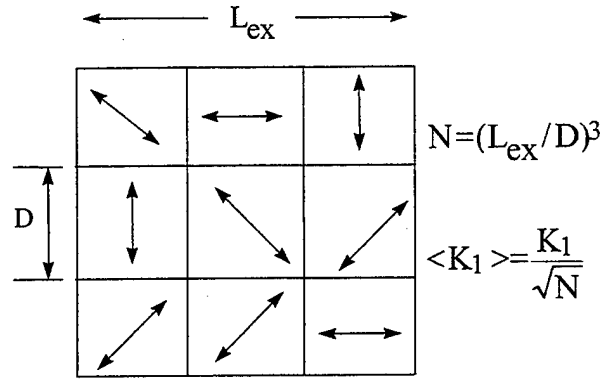
With some modifications, the previous method can be applied to magnetic particles. Particularly, anisotropy and dipolar energy, which scale with particle size, have to be considered.

The interplay between exchange interaction, anisotropy, and dipolar interaction leads to the formation of edge domains. The formation of edge domains and magnetization reversal mechanisms have recently been studied theoretically with the Monte-Carlo simulation by Chui using  $4 \times 4 \times 12$  "block spins" in nanosize thin films [85], particles, and nanowires [86]. The finite element block spin, in which all atomic spins are aligned, is chosen so that the detail of domain formation can still be clearly seen, and the computing power (time) is minimized. Consequently, a relatively large sample can be simulated. For example, the block spin of soft magnetic materials is chosen to be much larger than that in hard magnetic materials.

It is crucial to relate the heat generation (core loss) to material parameters (exchange coupling constant [J], anisotropy constant [ $K_1$ ], and microstructure, such as grain size and particle size). The wall energy  $\gamma$  in equation (4) is related to  $(JK_1)^{1/2}$ , and the restoring force will include the dipolar term.

For nanoparticles where only a single domain exists, the coherent rotation is believed to be due to the reversal mechanism [23, 24, 87]. However, recent theory has suggested that even in very small particles, edge domains exist [86]; in most experiments, domains always nucleate because of impurities, dislocations, and surface boundary effects. In MB samples, the impurities and dislocations are expected to be high, and magnetization reversal is almost certainly due to domain wall motion. The theoretical approach presented for the dynamics of magnetic domain wall motion is thus applicable to our study.

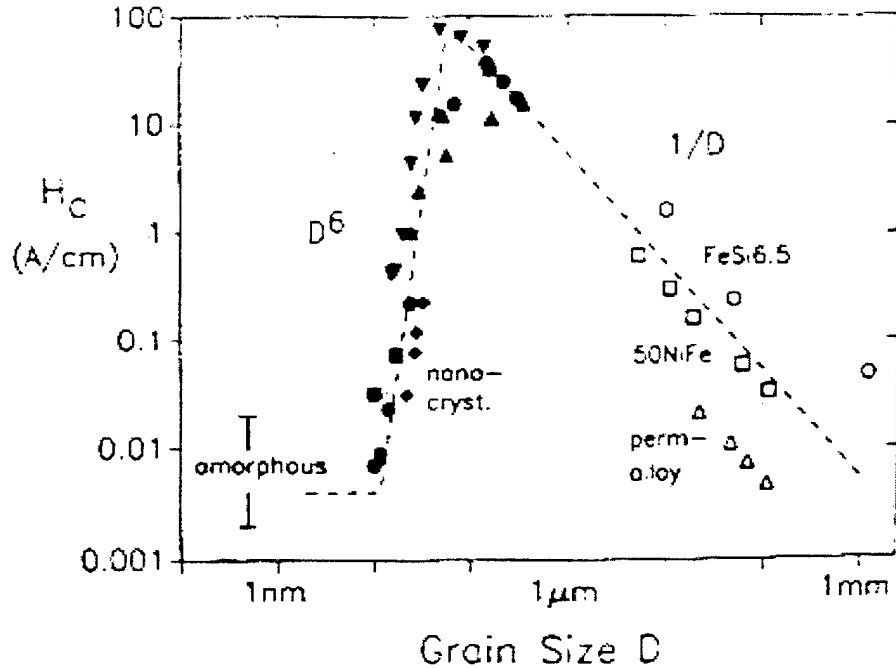
For nanocrystalline particles, domain walls can easily nucleate and move rapidly because of a much smaller effective anisotropy  $K_1$ . Therefore, significant heat generation is expected from these nanocrystalline particles. The effective anisotropy and dipolar interaction can be calculated using a random anisotropy model that was originally developed by Cullin, Yu and Cullen [88] and Alben, Becker, and Chui [89] for amorphous materials. The basic idea, sketched in Figure 3, starts from an assembly of ferromagnetically coupled grains of size  $D$  with magnetocrystalline anisotropies of  $K_1$  oriented at random. The effective anisotropy affecting the magnetization process results from an average over the  $N = (L_{ex}/D)^3$  grains with the volume



**Figure 3. Schematic Representation of the Random Anisotropy Model.**

$V = L_{ex}^3$ , where  $L_{ex} = (A/K_1)^{1/2}$  is the ferromagnetic exchange length and  $A$  the exchange stiffness. For a finite number ( $N$ ) of grains, there will always be a preferred direction determined by statistical fluctuations. Consequently, the resulting anisotropy density  $\langle K_1 \rangle$  is determined by the mean fluctuation amplitude of the anisotropy energy of the  $N$  grains (i.e.,  $\langle K_1 \rangle \approx K_1/\sqrt{N}$ ). This random anisotropy model was applied to explain the behavior of nanocrystalline materials by Herzer [90, 91] using a dimensionality-like argument. The average magnetocrystalline anisotropy,  $\langle K_1 \rangle$ , is predicted to scale with the structural correlation length  $D$  as  $\langle K_1 \rangle \propto K_1(D/L_{ex})^6$ , and coercive field and permeability is thus scaled with  $D^6$ . Experimental data shows this correlation (Figure 4). The dipolar term ( $g$ ), which scales with grain size as  $g_0(L_{ex}/D)^3$ , can also be included in simulations.

The frequency spectrum of nanocrystalline particles and nanoparticles can be simulated as a function of external field, frequency, anisotropy constant, and particle and grain size. In particular, the peak in the complex component of permeability, which signifies domain wall resonance, can be investigated as a function of these parameters. The information on particle and grain size can be used to design the structure, and material composition can be selected based on exchange and anisotropy constants. The induction system parameters, such as field and frequency, will be optimized to maximize heating. The core loss and permeability spectrum of the designed material can be measured using a high-frequency hysteresis loop tracer and an impedance analyzer.



**Figure 4. Coercivity vs. Grain Size  $D$  for Various Soft Magnetic Materials: Fe-Nb-Si-B ( $\blacktriangle$ ), Fe-Cu-Nb-Si-B ( $\bullet$ ), Fe-Cu-V-Si-B ( $\blacklozenge$ ), Fe-Zr-B ( $\blacksquare$ ), Fe-Co-Zr ( $\blacktriangledown$ ), FeNi-Alloys ( $\Delta$  and  $\square$ ), and FeSi 6.5 weight-percent ( $\circ$ ).**

**2.4 Ferromagnetic to Paramagnetic Phase Transition and Superparamagnetic Relaxation.** The second-order magnetic transition from the ferromagnetic to the paramagnetic phase is characterized by the  $T_c$ , above which no energy will be absorbed from the external magnetic field and thus no heat will be generated. When nanoscale magnetic particles are embedded in an insulating matrix, negligible heat will be generated from eddy currents. Therefore, the  $T_c$  can be used as a smart temperature controller, above which heat generation will automatically shut off.

The  $T_c$  can be varied by alloying different materials or using different particle sizes. The latter has not been studied, mainly due to superparamagnetic relaxation. For a single domain particle, when thermal energy is high enough to overcome the energy barrier that restricts the spins from switching direction, the magnetic moments within a particle can rotate rapidly in unison [92–94]. This behavior resembles the paramagnetic phase, except that the particle carries

a giant moment (sum of individual atomic moments in the whole particle), hence the term “superparamagnetism.” The susceptibility ( $\chi$ ) in a paramagnetic phase can be written as

$$\chi \text{ (emu/V)} = \frac{N(p_{\text{eff}} \mu_B)^2}{3k_B (T - q)}, \quad (3)$$

where  $N$  is the number of paramagnetic moments of an effective atomic moment  $p_{\text{eff}} \mu_B$ , and  $k_B$  is the Boltzmann constant. In the case of a superparamagnet,  $N$  is the number of magnetic particles per unit volume and  $p_{\text{eff}} \mu_B$  is the magnetization of the magnetic particles, which is many times higher than the atomic moment. Clearly, the slopes associated with two phases in the  $1/\chi$  vs.  $T$  curve will be different, and the  $T_c$  can thus be determined. It should be pointed out that the particle size distribution may complicate the analysis. However, since the moments associated with the two phases are very different, the determination of  $T_c$  is possible. As an independent check,  $T_c$  can also be measured using DSC [95] and by performing specific-heat measurements.

It is important to determine whether the superparamagnetism will affect induction heating, which is typically carried out in the kHz–MHz frequency range. The simplest form of the superparamagnetic relaxation time ( $\tau$ ) can be described by the Arrhenius relation [87]

$$\tau = \tau_0 \exp(KV/k_B T), \quad (4)$$

where  $\tau_0$  is the characterization time and  $KV$  is the total anisotropy energy (energy barrier) including magnetocrystalline, shape, and magnetoelastic anisotropies. In the case of iron and  $\text{Fe}_{50}\text{Ni}_{50}$ , large values of  $K$ , in excess of  $10^7$  erg/cm<sup>3</sup>, have been observed [96–98]. This enhancement of  $K$  in part accounts for the very large coercivities observed in magnetic particles [99], which can significantly increase the hysteresis loss and heat generation. The value of  $\tau_0$  was estimated to be  $10^{-11}$  s from neutron diffraction data [100] and  $10^{-13}$  s from Superconducting Quantum Interference Device (SQUID) magnetometer and Mössbauer spectroscopy [97].

Therefore, considering a magnetic particle of 10 nm at  $T = 300$  K, the relaxation rate ( $1/\tau$ ) is much smaller than the frequency of interest (0.1 to 100 MHz). Therefore, these moment rotations have no impact on induction heating.

Although the dimensional dependence of  $T_c$  in nanoparticles has not been studied, it has been found that finite-size scaling [101] can be used to explain phase transition behavior in reduced dimension structures. This theory predicts that the shift in the transition temperature from that of the bulk should depend on a dimension of the system in the following manner:

$$\frac{T_c(d) - T_c(\infty)}{T_c(\infty)} = (d/d_0)^{-\lambda}, \quad (5)$$

where  $d$  is the sample dimension, and  $d_0$  should be of the order of the characteristic microscope dimension of the system, such as the lattice parameter. The exponent  $\lambda$  is predicted to be related to the correlation length exponent by  $\lambda=1/\nu$ .

This behavior has been widely observed in the  $T_c$  of multilayer ferromagnetic systems [102] and spin freezing temperature ( $T_g$ ) in spin-glass systems [103, 104]. The spin freezing temperature in granular materials has also been found to follow the finite-size scaling rule [26]. The only study on  $T_c$  of nanoparticles was done using ferrites [105], where the value of  $T_c$  was found to increase with decreasing particle size. This observation was later argued to be due to the less-random cation distribution for large particles and not to finite size effects [106, 107].

An alternative and more reliable way to control the  $T_c$  is to use alloys. A wide selection of materials is available (e.g.,  $\text{Fe}_x\text{Cr}_{100-x}$  [ $0 < x < 70$ ,  $770^\circ\text{C} > T_c > 0^\circ\text{C}$ ],  $\text{Ni}_x\text{Cr}_{100-x}$  [ $0 < x < 8$ ,  $370^\circ\text{C} > T_c > 0^\circ\text{C}$ ], and  $\text{Ni}_x\text{Cu}_{100-x}$  [ $0 < x < 40$ ,  $370^\circ\text{C} > T_c > 0^\circ\text{C}$ ]). These alloys also have excellent corrosion and oxidation resistance. The disadvantage is the low magnetization compared to pure magnetic elements, which may reduce the heat generation capability. A study of  $T_c$  in magnetic nanoparticles should address the issues of dimensional dependence and alloy

composition and enable an investigation into the scaling relation in the zero dimension. To study the true  $T_c$ , particles can be embedded in a polymer or ceramic matrix to eliminate interparticle interactions.

### 3. Potential Applications

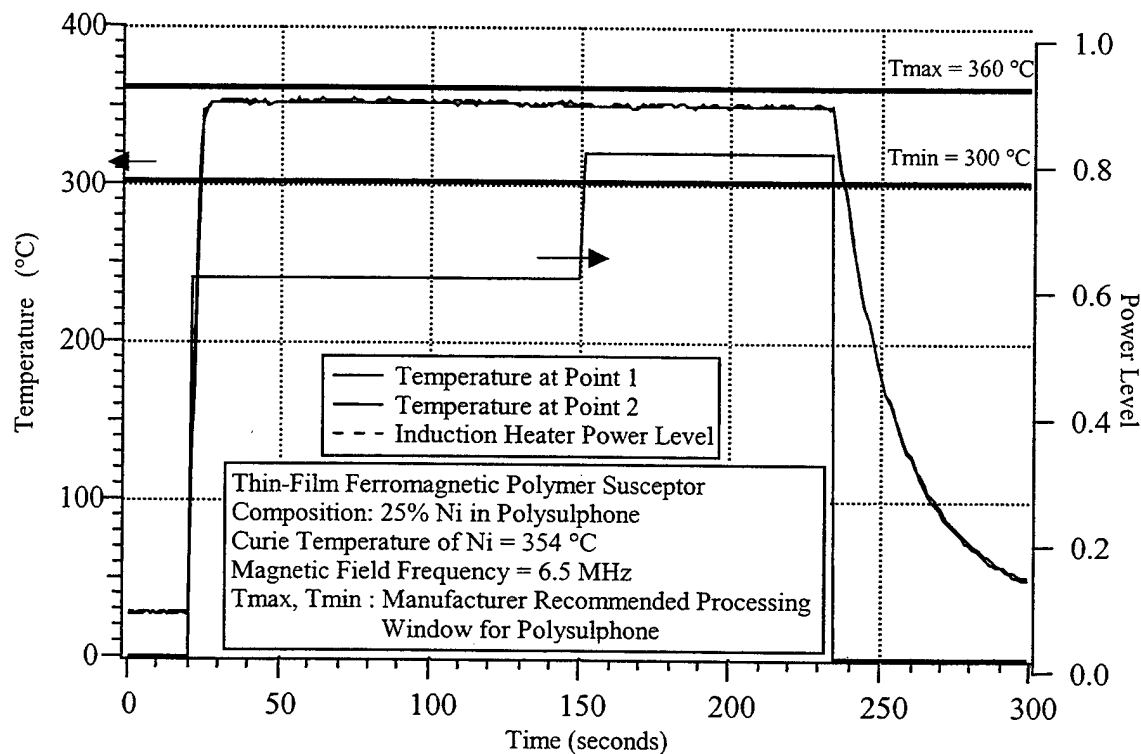
A number of fundamental issues in nanoparticle design—particle size, frequency, stoichiometry, and  $T_c$ —are common to the two applications that will be explored in this research program. The science base for design and synthesis of nanoparticles for hysteresis heating that will be developed as part of the proposed effort will provide a starting point for identifying nanoparticle systems that can be used in the two proposed applications.

**3.1 Polymer Processing.** Electromagnetic induction is a well-known and widely used heating technique for metals and alloys. More recently, significant research [108–116] has been undertaken to adapt induction-heating techniques to polymers for benefits such as reduced cost and processing times. Heat generation, in a material subjected to an alternating magnetic field, occurs due to joule-type losses [109, 112, 115] (using metal mesh susceptors) or hysteresis [117–119] (using magnetic particles). Both techniques can result in very rapid localized heating, which is ideal for polymer processing.

Existing polymer processing, bonding, and repair techniques require autoclaves, which have size restrictions and are quite costly. Rapid, noncontact, and localized heating will allow for accelerated cure of thermosetting polymers or the rapid interdiffusion of thermoplastic polymers by concentrating energy at the interphase of interest. The design and controlled multiaxis motion of the induction coil can also cure complex polymer composite parts. The advantages of induction-assisted processing include reduced cost and processing time per part, rapid manufacturing, and the potential for increased design complexity.

Of the two heat-generation techniques, hysteresis heating is the focus of this report. A significant advantage to this technique over joule-heating techniques is using the  $T_c$  of the

ferromagnetic material as a means of automatic or smart temperature control. By choosing materials such that  $T_c$  is within the processing temperature window of the polymer, one can automatically control the process temperature. However, one must also ensure that hysteresis heating is the sole heat-generation mechanism (no joule losses), and this can be achieved by using well-dispersed particles in the polymer. An example of this concept is shown in Figure 5. The nickel/polysulphone susceptor shows very rapid rise to steady-state temperature ( $\sim 350^\circ\text{C}$ ) once the induction coil is activated and then maintains the temperature regardless of any increase in input power. Polysulphone is a commercially used thermoplastic with a manufacturer-recommended processing window between  $300$  and  $360^\circ\text{C}$ , and nickel has a  $T_c$  of  $354^\circ\text{C}$ , resulting in an ideal combination.



**Figure 5. Self-Regulating Temperature Profile for Ferromagnetic Polymer Susceptor. The Two Horizontal Lines at  $300^\circ\text{C}$  and  $360^\circ\text{C}$  Represent the Lower and Upper Bounds on the Process, Respectively.**

By choosing ferromagnetic particle systems with  $T_c$  between 100 and 400 °C, it is possible to process any thermoset or thermoplastic with a built-in smart temperature control capability. In addition, by using the nanoparticles as additive fillers in the polymer, one can easily adapt existing processing techniques for hysteresis-heating-based processing of composites, with minimal loss in mechanical performance.

The science base for designing and synthesizing nanoparticles for hysteresis heating can provide a starting point in identifying ferromagnetic nanoparticle systems that can be used for polymer processing. Thermal requirements or cure cycles for the processing of polymers should be used to determine the optimal nanoparticle system, particle parameters and induction power, and frequency requirements. Ideally, it is desired that the power input, frequency and particle loading be as low as possible for sufficient heating to completely process the polymer.

Initial tests may focus on heat-transfer dynamics in nanoparticle/polymer systems. A calorimeter-type setup could be built into a hysteresis loop tracer to measure heat generation and correlated with ac hysteresis measurements of the particle system. Nanoparticles could be mixed with polymers for test samples, with particle size, particle composition, volume fraction, magnetic field, and frequency being the parameters. Particles could be mixed with polymers by either solvent casting techniques (e.g., dimethylacetamide and polysulphone) or milling particles with polymer powders and compression molding (e.g., milled nickel particles in polysulphone powder, molded at 350 °C). In both techniques, oxidation of nanoparticles could be minimized by reducing the exposure to air or using surface-treated particles. Effects of exposure to controlled environments (oxygen and air) on particle heating characteristics should also be quantified. Nanoparticle distribution in the polymer could be examined and quantified using SEM and TEM and then used as input for heat transfer simulations. Key results guiding the design of nanoparticles include actual polymer temperature, as compared to particle  $T_c$ , automatic temperature control capability, and heat generation.

Based on a finite element model for heat-transfer simulations in particle/polymer systems, nanoparticle systems that meet the thermal requirements for polymer processing could be

identified to ensure that particles are viable and optimized. Thin films could be fabricated using the polymer and nanoparticle system by solvent casting or compression molding and used in the polymer bonding and cure demonstrations. A new concept for curing polymers and composites using hybrid films consisting of different size particles could also be investigated. Typical polymer cure cycles involve multiple temperature steps and dwell times. For example, a typical 350 °F (177 °C) thermoset (TS) may be cured by heating to 250 °F (121 °C), dwelling for 1 hr, and then heating to 350 °F (177 °C) and dwelling for 2 hr. The same steps can be duplicated using a two-material hybrid nanoparticle system and induction heating, with one material having  $T_c$  near 250 °F (121 °C) and the other near 350 °F (177 °C) and different optimal frequencies (~700 kHz and ~4–5 MHz) for maximum heating.

**3.2 Selective Cell Death.** The biological component described in this report is designed to directly test the ability of intracellular nanoparticles to cause selective cell death. These experiments would examine how varying parameters such as particle size, composition, and density, as well as induction frequency and power level, can be used to optimize hyperthermic damage. Hyperthermia is generally thought to cause immediate cell damage and necrosis through protein denaturing and loss of membrane integrity. However, more recent work has also demonstrated effects of moderate (43–46 °C) hyperthermia on DNA damage and apoptosis in various cells, both directly [120–123] and with lag periods requiring restoration of normal incubation temperatures [124]. Therefore, these experiments should examine both primary necrosis and apoptosis at varying times after hyperthermic treatment. Success in selective necrosis and apoptosis would allow the development of nanoparticle-based alternative treatments for cancer.

The general approach is to microinject magnetic nanoparticle suspensions of varying composition into individual cells, subject these cells to inductive heating of varying degree and time, and assay for cell death. Initial experiments could be performed on uninjected cells subjected to passive heating in a DSC to determine the sensitivity and onset of cell death or necrosis and apoptosis to such variables as rate of temperature change, maximum temperature exposure, and length of exposure. Optimal values of temperature rates, maximum temperature,

and duration of exposure would dictate the choice of magnetic nanoparticles and parameters for induction-heating experiments.

**3.2.1 Experimental Cell Bioassays.** Two types of cell systems are commonly used to study nanoparticle heating properties. The first is the amphibian (*Xenopus*) oocyte model, widely used in microinjection protocols for ribo-nucleic acid (RNA) expression studies or in-vitro fertilization studies [125–127]. To isolate individual oocytes, ovarian lobes are dissected from anesthetized frogs. A total of 10 to 50 stage V–VI oocytes are then removed and manually defolliculated by blunt dissection [125, 128]. Each cell is placed in a well, formed from the mesh of a piece of Nitex filter placed in a Petri dish. The cells are immersed in a modified Barth's solution (MBS). The oocytes can then be rapidly microinjected under a stereo microscope using a micromanipulator and an injection system (PicoPump, WPI, Inc.). Micropipettes are prepared from 1-mm glass capillaries with internal fiber, pulled on a Kopf pipette puller, and beveled to a final tip diameter of 5–10  $\mu\text{M}$ . Generally, injected volumes are 10–50 nl (2–10% of cell volume). Injected cells are then transferred to individual wells of a 96 well culture plate, containing MBS with 0.2% Trypan blue dye to screen for membrane integrity (dye exclusion assay). This model system allows for rapid screening of nanoparticle properties at the individual cell level.

The second assay system consists of cell cultures in various configurations. Both continuous cell lines, including 3T3 fibroblasts and MDCK kidney epithelial cells, and primary cell cultures of rat liver would be assayed. Cells lines are maintained at 37 °C in appropriate growth media (DMEM, RPMI 1640) with fetal bovine serum and subcultured at intervals of 7–14 days. For experiments, cells are plated onto 35-mm collagen-coated plastic Petri dishes. Rat hepatocyte cultures are generated using a collagenase dissociation method [129] and cultured on an artificial extracellular matrix (Matrigel, Becton Dickinson). Both the continuous and primary cell lines could be used in either subconfluent or confluent configurations to assess collateral damage at varying distances from the microinjected target cell. Single cells are microinjected as previously described, except using an inverted, compound microscope with phase contrast optics, micropipets with smaller tip diameters of approximately 1  $\mu\text{m}$ , and reduced injection volumes.

Following injection, the culture medium is replaced with physiological salt solution containing 0.2% Trypan blue. Induction-heating and cell death assays would be performed on the entire monolayer. Controls would include both oocytes and cultured cells injected with carrier solution alone, as well as nanoparticle-injected cells not subjected to the induction heating. The latter would provide information about the cytotoxicity of nanoparticles.

**3.2.2 Heating Tests.** Individual microinjected oocytes or cultured monolayers could be subjected to heating protocols of varying intensity and duration. Initial tests would use a DSC for passive heating under controlled conditions, with known heating rate, maximum temperature, and duration of heating. These tests will help determine the ideal heating conditions for cell death. Heating rates and maximum temperature would determine the composition, particle size, and  $T_c$  of the magnetic nanoparticle system, as well as the power and frequency of the induction heating system.

Individual cell and cell cultures would be microinjected with the selected nanoparticle system and inductively heated according to the heating conditions determined by DSC tests; cell death could then be assessed. It is expected that the induction-heating tests would duplicate the DSC test results and demonstrate the feasibility of this application. The final step would be to assess collateral damage and investigate means to mitigate it; this could be done by injecting selected cells with magnetic nanoparticles and assessing damage to surrounding cells after induction heating.

**3.2.3 Cell Death Assays.** Immediately after the thermal challenge, cells are examined under light microscopy for Trypan blue uptake. Positive staining indicates loss of membrane integrity and necrosis. Negative cells are then transferred back to an incubator set at normal growth temperature (37 °C) and monitored for an additional, variable period of 1–6 hr. At varying times during this period (1–6 hr post-treatment), some cells would also be assayed for apoptosis. The assay system is based on an in-situ fluorescence variation of the TUNEL (TdT-mediated dUTP-X nick end labeling) method (In Situ Cell Death Detection Kit, Boehringer Mannheim). Briefly, this method allows direct fluorescence visualization of apoptotic cells, based on the predictable

DNA fragmentation that accompanies apoptosis and the use of the enzyme terminal deoxynucleotidyl transferase to attach fluorescent derivatives to free 3'-OH groups on the DNA strands. This approach would allow for rapid screening of apoptosis in individual microinjected oocytes, as well as target and collateral cell death in cultured monolayers.

## 4. Summary

The goal of this multidisciplinary research would be to establish the science base for the design and synthesis of nanoparticles for hysteresis heating, with potential applications ranging from novel polymer processing techniques to alternative cancer treatments. This research plan would focus on *maximizing* hysteresis losses in magnetic particle systems, while research to date has focused on *minimizing* hysteresis.

**4.1 Particle Design.** The following are the primary barriers that need to be addressed.

- Magnetization dynamics in high-frequency magnetic fields.
- Effects of magnetic phase transition on hysteresis heating (energy loss).
- Identification of particle composition, size, microstructure, induction power, and frequency for maximum heat generation or power loss at a specified Curie temperature.

The research described in this report would establish the science base for design and synthesis of nanoparticles for hysteresis heating applications.

**4.2 Polymer Processing.** Magnetic particle systems with  $T_c$  between 100 and 400 °C would be chosen for polymer processing demonstrations. Heat-transfer simulations and experiments of nanoparticle/polymer systems will be performed to ensure that particles are viable and optimized for hysteresis heating applications.

**4.3 Selective Cell Death.** The biological component is designed to explore the ability of intracellular nanoparticles to cause selective cell death. These experiments would examine how varying parameters such as particle size, composition, and density, as well as induction frequency and power level, can be used to cause selective cell death with minimal collateral damage.

## 5. References

1. Edelstein, A. S., and R. C. Cammarata (editors). *Nanomaterials: Synthesis, Properties and Applications*. Bristol, PA: Institute of Physics Publishing, pp. 541–580, 1996.
2. Hadjipanayis, G. C., and R. W. Siegel (editors). *Nanophase Materials—Synthesis, Properties and Applications*. NATO ASI Series 260, pp. 729–800, 1994.
3. Siegel, R. W. “Cluster-Assembled Nanophase Materials.” *Annual Review of Materials Science*, vol. 21, pp. 559–578, 1991.
4. Matijevic, E. “Fine Particles: Science & Technology.” *MRS Bulletin*, vol. 14, no. 12, p. 18, 1989.
5. Ozaki, M. “Preparation and Properties of Well-Deferred Magnetic Particles.” *MRS Bulletin*, vol. 14, no. 12, p. 41, 1989.
6. Häfeli, U., W. Schütt, J. Teller, and M. Zborowski. *Scientific and Clinical Applications of Magnetic Carriers*. New York: Plenum Press, 1997.
7. Berkowitz, A. “Magnetic Recording Materials Present and Future.” *MRS Bulletin*, vol. 15, no. 3, p. 23–30, March 1990.
8. Prinz, G., and K. Hathaway. “Special Issue: Magnetoelectronics.” *Physics Today*, vol. 8, no. 4, p. 24, 1995.
9. Simonds, J. L. “Magnetoelectronics Today and Tomorrow.” *Physics Today*, vol. 8, no. 4, p. 26, 1995.
10. Dahlberg, E. D., and J. G. Zhu. “Micromagnetic Microscopy and Modeling.” *Physics Today*, vol. 8, no. 4, p. 34, 1995.
11. Awschalom, D. D., and D. P. DiVincenzo. “Complex Dynamics of Mesoscopic Magnets.” *Physics Today*, vol. 8, no. 4, p. 43, 1995.
12. White, R. M. “Opportunities in Magnetic Materials.” *Science*, vol. 229, pp. 11–15, 1985.
13. Freeman, J., and K. A. G. Schneider, Jr. *Magnetism in the Nineties*. North-Holland, Amsterdam, 1991.
14. Neel, L. “Magnetisme-Le Champ Coercitif Dune Poudre Ferromagnetique Cubique A Grains Anisotropes.” *Comptes Rendus Hebdomadaires Des Seances De L Academie Des Sciences*, vol. 224, no. 22, pp. 1550–1551, 1947.

15. Steinitz, R. "Magnetic Properties of Iron-Powder Compacts." *Transactions of the American Institute of Mining and Metallurgical*, vol. 175, pp. 834–847, 1948.
16. Kittle, C. "Physical Theory of Ferromagnetic Domains." *Reviews in Modern Physics*, vol. 21, no. 4, pp. 541–583, 1949.
17. Morrish, H. *The Physical Principle of Magnetism*. New York, NY: John Wiley, 1965.
18. Luborsky, F. E. "High Coercive Materials-Development of Elongated Particle Magnets." *Journal of Applied Physics*, vol. 32, no. 3, p. 1715, 1961.
19. Bean, C. P., J. D. Livingston, and D. S. Rodbell. "The Anisotropy of Very Small Cobalt Particles." *Journal of Applied Physics*, vol. 20, no. 2–3, p. 1205, 1959.
20. Tasaki, A., S. Tomiyana, and S. Iida. *Journal of Applied Physics*. Vol. 4, p. 708, 1986.
21. Hayashi, C. *Journal of Vacuum Science and Technology A*. Vol. 5, p. 1375, 1987.
22. Bertram, H. N., and J. G. Zhu. "Fundamental Magnetization Processes in Thin-Film Recording Media." *Solid State Physics*, vol. 46, p. 271, edited by H. Ehrenich and D. Thornbull, 1992.
23. Wernsdorfer, W., B. Doudin, D. Mailly, K. Hasselbach, A. Benoit, J. Meier, J. P. Ansermet, and B. Barbara. "Nucleation of Magnetization Reversal in Individual Nanosized Nickel Wires." *Physical Review Letters*, vol. 77, no. 9, pp. 1873–1876, 1996.
24. Wernsdorfer, W., E. B. Orozco, K. Hasselbach, A. Benoit, B. Barbara, N. Demoncey, A. Loiseau, H. Pascard, and D. Mailly. "Experimental Evidence of the Neel-Brown Model of Magnetization Reversal." *Physical Review Letters*, vol. 78, no. 9, pp. 1791–1794, 1997.
25. Coffey, W. T., et al. *Physical Review. B, Solid State*. Vol. 52, p. 12951, 1995.
26. Chien, C. L. *Science and Technology of Nanostructured Materials*. NATO Series 259, p. 477, edited by G. C. Hadjipanayis and G. Prinz, 1991.
27. Mørup, S., and E. Tronc. "Superparamagnetic Relaxation of Weakly Interacting Particles." *Physical Review Letters*, vol. 72, no. 20, pp. 3278–3281, 1994.
28. Fink, B. K, R. L. McCullough, and J. W. Gillespie, Jr. "Heating of Continuous Carbon Fiber Thermoplastic Composites by Magnetic Induction." *Proceedings of the Third DOD/NASA Repair Technology Workshop*, 1991.
29. Karamuk, E., E. D. Wetzel, and J. W. Gillespie, Jr. "Modeling and Design of Induction Bonding Process for Infrastructure Rehabilitation With Composite Materials." *Proceedings of ANTEC 95*, Society of Plastics Engineers, 1995.

30. Fink, B. K., R. L. McCullough, and J. W. Gillespie, Jr. "A Local Theory of Heating in Cross-ply Carbon Fiber Thermoplastic Composites by Magnetic Induction." *Polymer Engineering and Science*, vol. 32, no. 5, pp. 357-369, 1992.
31. McKnight, S. H., B. K. Fink, S. Wells, S. Yarlagadda, and J. W. Gillespie, Jr. "Accelerated Curing of Epoxy Paste Adhesives for Repair of Composites Using Induction Heating." *Proceedings of ANTEC 98*, Society of Plastics Engineers, Atlanta, GA, 26 April-1 May, 1998.
32. Fink, B. K., J. Q. Xiao, J. W. Gillespie, Jr., and S. Yarlagadda. "Self-Regulating Optimized Ferromagnetic Susceptors for Multi-Step Induction Heating." Patent disclosure completed April 1997.
33. Jordan, A., P. Wust, R. Scholz, H. Faehling, J. Krause, and R. Felix. "Magnetic Fluid Hyperthermia." *Scientific and Clinical Applications of Magnetic Carriers*, edited by U. Häfeli et al., New York, NY: Plenum Press, 1997.
34. Streffer, C., and D. van Beuningen. "The Biological Basis for Tumor Therapy by Hyperthermia and Radiation." *Hyperthermia and the Therapy of Malignant Tumors*, pp. 24-70, edited by J. Streffer, Berlin: Springer, 1987.
35. Burgman, P., A. Nussenzweig, and G. C. Li. "Thermotolerance." *Thermoradiotherapy and Thermochemotherapy, Vol 1: Biology, Physiology, Physics*, pp. 75-87, edited by M. H. Seegenschmiedt, P. Fessenden, and C. C. Vernon, Berlin: Springer, 1995.
36. Sellins, K. S., and J. J. Cohen. "Hyperthermia Induces Apoptosis in Thymocytes." *Radiation Research*, vol. 126, no. 1, pp. 88-95, 1991.
37. Harmon, B. V., Y. S. Takano, C. M. Winterford, and G. C. Gobe. "The Role of Apoptosis in the Response of Cells and Tumors to Mild Hyperthermia." *International Journal of Radiation Biology*, vol. 59, no. 2, pp. 489-501, 1991.
38. Takano, Y. S., B. V. Harmon, and J. F. R. Kerr. "Apoptosis Induced by Mild Hyperthermia in Human and Murine Tumor-Cell Lines-A Study Using Electron-Microscopy and DNA Gel-Electrophoreses." *Journal of Pathology*, vol. 163, no. 4, pp. 329-336, 1991.
39. Fairbairn, J. J., M. W. Khan, K. J. Ward, B. W. Loveridge, D. W. Fairbairn, and K. L. O'Neill. "Induction of Apoptotic Cell-DNA Fragmentation in Human-Cells After Treatment With Hyperthermia." *Cancer Letters*, vol. 89, no. 2, pp. 183-188, 1995.
40. Bulte, J. W. M., and R. A. Brooks. "Magnetic Nanoparticles as Contrast Agents for MR Imaging. An Overview." *Scientific and Clinical Applications of Magnetic Carriers*, edited by U. Häfeli, W. Schütt, J. Teller, and M. Zborowski, New York, NY: Plenum Press, pp. 527-543, 1997.

41. Grüttner, C., J. Teller, W. Schütt, F. Westphal, C. Schüichen, and B. R. Paulke. "Preparation and Characterization of Magnetic Nanospheres for in Vivo Application." *Scientific and Clinical Applications of Magnetic Carriers*, pp. 53–67, edited by U. Häfeli, W. Schütt, J. Teller, and M. Zborowski, New York, NY: Plenum Press, 1997.
42. Borelli, N. F., A. A. Luderer and J. N. Panzarino. "Hysteresis Heating for the Treatment of Tumors." *Physics in Medicine and Biology*, vol. 29, pp. 484–494, 1984.
43. Chen, J. S, D. R. Poirier, M. A. Damento, L. J. Demer, F. Biancaniello, and T. C. Cetas. "Development of Ni-4 wt.% Si Thermoseeds for Hyperthermia Cancer Treatment." *Journal of Biomedical Materials Research*, vol. 22, pp. 303–319, 1988.
44. Jones, S. K, B. N. Gray, M. A. Burton, J. P. Codde and R. Street. "Evaluation of Ferromagnetic Materials for Low-Frequency Hysteresis Heating of Tumours." *Physics in Medicine and Biology*, vol. 37, pp. 293–299, 1992.
45. Gordon, R. T. "Use of Magnetic Susceptibility Probes in the Treatment of Cancer." U.S. Patent 4,662,359, 1987.
46. Suzuki, M., M. Shinkai, M. Kamihira, and T. Kobayashi. "Preparation and Characteristics of Magnetite-Labeled Antibody With the Use of Poly (Ethylene Glycol) Derivatives." *Biotechnology and Applied Biochemistry*, vol. 21, pp. 335–345, 1995.
47. Luborsky, E. "High Coercive Materials-Development of Elongated Particle Magnets." *Journal of Applied Physics*, vol. 32, no. 3, p. 1715, 1961.
48. Chow, G. M., T. Ambrose, J. Q. Xiao, M. E. Twigg, S. Baral, A. M. Ervin, S. B. Qadri, and C. R. Feng. "Chemical Precipitation and Properties of Nanocrystalline Fe-Cu Alloy and Composite Powders." *NanoStructured Materials*, vol. 1, no. 5, p. 361, 1992.
49. Yiping, L., G. C. Hadjipanayis, C. M. Sorensen, and K. J. Klabunde. "Magnetic and Structural Properties of Ultrafine Co-B Particles." *Journal of Magnetism and Magnetic Materials*, vol. 79, no. 3, pp. 321–326, 1989.
50. Chow, G. M., T. Ambrose, J. Q. Xiao, F. Kaatz, and A. Ervin. "Nanostructured Co-Cu Powders Via a Chemical Route." *NanoStructured Materials*, vol. 2, no. 2, p. 131, 1993.
51. Watanabe, A., T. Uehori, S. Saitoh, and Y. Immaoka. "Fine Metal Particles Having Super High Coercivity." *IEEE Transactions on Magnetics*, vol. 17, p. 1455, 1983.
52. Klein, L. C. *Nanomaterials: Synthesis, Properties and Applications*. Edited by A. S. Edelstein and R. C. Cammarata, Bristol, PA: Institute of Physics Publishing, 1996.

53. Slade, S. B, A. E. Berkowitz, and F. T. Parker. "Preparation and Properties of Noninteracting Spherical Magnetic Particles." *Journal of Applied Physics*, vol. 69, no. 8, Part 2A, pp. 5127–5129, 1991.
54. Berkowitz, E., J. L. Walter, and K. F. Wall. "Magnetic-Properties of Amorphous Particles Produced by Spark Erosion." *Physical Review Letters*, vol. 46, no. 22, pp. 1484–1487, 1981.
55. Kodama, R. H, A. E. Nash, F. E. Spada, and A. E. Berkowitz. *Nanophase Materials—Synthesis, Properties, Applications*. Edited by G. C. Hadjipanayi and R. W. Siegel, NATO ASI Series 260, p. 101, 1994.
56. Gilman, P. S., and J. S. Benjamin. "Mechanical Alloying." *Annual Reviews in Material Science*, vol. 13, p. 279, 1983.
57. Gangopadhyay, S., G. C. Hadjipanayis, B. Dale, C. M. Sorensen, K. J. Klabunde, V. Papaefthymiou, and A. Kostikas. "Magnetic-Properties of Ultrafine Iron Particles." *Physical Review B, Condensed Matter*, vol. 45, no. 17, pp. 9778–9787, 1992.
58. Xiao, J. Q., J. S. Jiang, and C. L. Chien. "Giant Magnetoresistance in Nonmultilayer Magnetic Systems." *Physical Review Letters*, vol. 68, no. 25, pp. 3749–3752, 1992.
59. German, R. M. *Powder Metallurgy Science*. Metal Powder Industries Federation, NJ, 1994.
60. Pileni, M. P. "Reverse Micelles as Microreactors." *Journal of Physical Chemistry*, vol. 97, no. 27, pp. 6961–6973, 1993.
61. Pilai, V., P. Kumar, M. J. Hou, P. Ayyub, and D. O. Shah. "Preparation of Nanoparticles of Silver Halides, Superconductors and Magnetic Materials Using Water-In-Oil Microemulsions as Nano-Reactors." *Advances in Colloid and Interface Science*, vol. 55, pp. 241–269, 1995.
62. Petit, C., and M. P. Pileni. "Nanosize Cobalt Boride Particles: Control of the Size and Properties." *Journal of Magnetism and Magnetic Materials*, vol. 166, pp. 82–90, 1997.
63. Chen, J. P, C. M. Sorensen, K. J. Zklabunde, and G. C, Hadjipanayis. "Enhanced Magnetization of Nanoscale Colloidal Cobalt Particles." *Physical Review B-Condensed*, vol. 51, no. 17, pp. 11527–11532, 1995.
64. Fecht, J. *Nanophase Materials*. Edited by G. C. Hadjipanayis and R. W. Siegel, The Netherlands: Kluwer Academic Publishers, p. 125, 1994.
65. Fecht, J. "Nanostructure Formation by Mechanical Attrition." *Nanostructured Materials*, vol. 6, pp. 33–42, 1995.

66. Koch, C. C. "Synthesis of Nanostructured Materials by Mechanical Milling: Problems and Opportunities." *Nanostructured Materials*, vol. 9, no. 1-8, pp. 13-22, 1997.
67. Majetich, S. A., J. H. Scott, E. M. Kirkpatrick, K. Chowdary, K. Gallagher and M. E. McHenry. "Magnetic Nanoparticles and Magnetocrystalline Anisotropy." *Nanostructured Materials*, vol. 9, no. 1-8, pp. 291-300, 1997.
68. Ranlinski, P., A. Calka, B. W. Ninham, and W. A. Kaczmarek. "Application of Surface Active Substances in Mechanical Alloying." *Materials Science & Engineering A: Structural Materials: Properties, Microstructure and Processing*, vol. A134, pp. 1346-1349, 1991.
69. Kaczmark, W. A., and B. W. Ninham. "Magnetic Properties of Ba-Ferrite Powders Prepared by Surfactant Assisted Ball Milling." *IEEE Transactions on Magnetics*, vol. 30, no. 2, pp. 717-719, 1994.
70. Gilman, P. S., and W. D. Nix. "Structure and Properties of Aluminum Alloys Produced by Mechanical Alloying-Powder Processing and Resultant Powder Structures." *Metallurgical Transactions A (Physical Metallurgy and Materials Science)*, vol. 12A, no. 5, pp. 813-824, 1981.
71. Hellstern, E., H. J. Fecht, C. Garland, and W. L. Johnson. "Structural and Thermodynamic Properties of Heavily Mechanically Deformed Ru and Airu." *Journal of Applied Physics*, vol. 65, no. 1, pp. 305-310, 1989.
72. Trudeau, M. L., R. Schultz, L. Zaluski, S. Hosatte, D. H. Ryan, C. B. Doner, P. Tessier, J. D. Strom-Olsen, and A. Van Neste. *Materials Science Forum*. Vol. 88-90, p. 537, 1992.
73. Oleszak, D., and P. H. Shingu. "Nanocrystalline Metals Prepared by Low Energy Ball Milling." *Journal of Applied Physics*, vol. 79, no. 6, p. 2975, 1996.
74. Eckert, J., J. C. Holzer, C. E. Krill, III, and W. L. Johnson. "Structural and Thermodynamic Properties of Nanocrystalline FCC Metals Prepared by Mechanical Attrition." *Journal of Materials Research*, vol. 7, no. 7, pp. 1751-1761, 1992.
75. Hellstern, E., H. J. Fecht, C. Garland, and W. L. Johnson. *Journal of Materials Research Society-Symposium Proceedings*. Vol. 132, p. 137, 1989.
76. Suryanarayana, C., G. E. Korth, and F. H. Froes. *Processing and Properties of Nanocrystalline Materials*. Edited by C. Suryanarayana, J. Singh, and F. H. Froes, Warrendale, PA: TMS, p. 291, 1996.

77. Awschalom, D. D., M. A. McCord, and G. Grinstein. "Observation of Macroscopic Spin Phenomena in Nanometer-Scale Magnets." *Physical Review Letters*, vol. 65, no. 6, p. 783–786, 1990.
78. Awschalom, D. D., J. F. Smyth, G. Grinstein, D. P. DiVincenzo, and D. Loss. "Macroscopic Quantum Tunneling in Magnetic Proteins." *Physical Review Letters*, vol. 68, no. 20, pp. 3092–3095, 1992.
79. Bishop, J. E. L. "Magnetic Domain Structure Eddy Currents and Permeability Spectra." *British Journal of Applied Physics*, vol. 17, no. 11, p. 1451, 1966.
80. Valenzuela, R. *Magnetic Ceramics*. Cambridge: Cambridge University Press, p. 175, 1994.
81. Polivanov, M. *IZV Akad. Nauk SSSR, Ser. Fiz*, vol. 16, p. 446, 1952.
82. Pry, R. H., and C. P. Bean. "Calculation of the Energy Loss in Magnetic Sheet Materials Using a Domain Model." *Journal of Applied Physics*, vol. 29, no. 3, pp. 532–533, 1958.
83. Yu, R. H., S. Basu, and J. Q. Xiao. "Pinning Effect of the Grain Boundaries on Magnetic Domain Wall in FeCo-Based Magnetic Alloys." *Journal of Applied Physics*, vol. 85, no. 9, p. 6655, 1999.
84. Wang, H., and S. T. Chui. Personal communication, 1998.
85. Chui, S. T. "Spin Reversal in Bilayer Ultrathin Magnetic Films." *Physical Review B, Solid State*, vol. B55, no. 6, p. 3688, 1997.
86. Chui, S. T., and De-Cheng Tian. "Switching in Single Domain Nanostructures at Finite Temperatures." *Journal of Applied Physics*, vol. 78, no. 6, p. 3965, 1995.
87. Morrish, H. *Physical Principles of Magnetism*. New York, NY: Wiley, 1965.
88. Callan, E., Y. J. Liu, and J. R. Cullen. "Initial Magnetization, Remanence, and Coercivity of Random Anisotropy Amorphous Ferromagnet." *Physical Review B-Condensed Matter*, vol. 16, no. 1, pp. 263–270, 1977.
89. Alben, R., J. Becker, and M. C. Chi. "Random Anisotropy in Amorphous Ferromagnets." *Journal of Applied Physics*, vol. 49, no. 3, pp. 1653–1658, 1978.
90. Herzer, G. "Grain-Structure and Magnetism of Nanocrystalline Ferromagnets." *IEEE Transactions on Magnetism*, vol. 25, no. 5, pp. 3327–3329, 1989.
91. Herzer, G. "Grain Size Dependence of Coercivity and Permeability in Nanocrystalline Ferromagnets." *IEEE Transactions on Magnetism*, vol. 26, no. 5, pp. 1397–1402, 1990.

92. Abeles, B. *Applied Solid State Science: Advances in Materials and Device Research*. Edited by R. Wolfe, New York, NY: Academic Press, p. 1, 1976.
93. Abeles, B., P. Sheng, M. D. Coutts, and Y. Arie. "Structural and Electrical Properties of Granular Metal-Films." *Advances in Physics*, vol. 24, no. 3, pp. 407-461, 1975.
94. Chien, C. L. "Antigranulocytes Magnetic Solids." *Journal of Applied Physics*, vol. 69, no. 8, pp. 5267-5272, 1991.
95. Zhu, J., M. T. Clavaguera-Mora, and N. Clavaguera. "Relaxation Process of Fe(CuNb)SiB Amorphous Alloys Investigated by Dynamical Calorimetry." *Applied Physics Letters*, vol. 70, no. 13, p. 1709, 1997.
96. Gavrin, A., and C. L. Chien. "Fabrication and Magnetic-Properties of Granular Alloys." *Journal of Applied Physics*, vol. 67, no. 2, pp. 938-942, 1990.
97. Gang, X. O., S. H. Liou, A. Levy, J. N. Taylor, and C. L. Chien. "Magnetic-Relaxation in FE-(S102) Antigranulocytes Films." *Physical Review B-Condensed Matter*, vol. 34, no. 11, pp. 7573-7577, 1986.
98. Morup, S., T. Topsoe, and B. C. Clausen. "Magnetic-Properties of Micro-Crystals Studied By Mossbauer-Spectroscopy." *Physica Scripta*, vol. 25, no. 6, pp. 713-719, 1982.
99. Chien, C. L. "Magnetism and Giant Magnetotransport Properties in Granular Solids." *Annual Review of Materials Science*, vol. 25, pp. 129-160, 1995.
100. Logothetis, E. M., W. J. Kaiser, H. K. Plummer, and S. S. Shinozak. "Tandem Deposition of Small Metal-Particle Composites." *Journal of Applied Physics*, vol. 60, no. 7, pp. 2548-2552, 1986.
101. Barber, M. N. *Phase Transition and Critical Phenomena*. Vol. 8, p. 145, edited by C. Domb and J. L. Lebowitz, New York, NY: Academic Press, 1983.
102. Falicov, M. et al. "Surface, Interface, and Thin-Film Magnetism." *Journal of Materials Research*, vol. 5, no. 6, pp. 1299-1340, 1990.
103. Kenning, G. G., J. M. Slaughter, and J. A. Cowen. "Finite-Size Effects in a Cumn Spin-Glass." *Physical Review Letters*, vol. 59, no. 22, pp. 2596-2599, 1987.
104. Gavrin, A., J. R. Childress, C. L. Chien, B. Martinez, and M. B. Salamon. "Evidence of Dimensional Crossover of the Spin-Glass Transition in Thin Cumn Multilayers." *Physical Review Letters*, vol. 64, no. 20, pp. 2438-2441, 1990.

105. Tang, Z. X., C. M. Sorensen, K. J. Klabunde, and G. C. Hadjipanayis. "Size-Dependent Curie-Temperature in Nanoscale MNFE204 Particles." *Physical Review Letters*, vol. 67, no. 25, pp. 3602-3605, 1991.
106. Van der Zaag, P. J., A. Noordermeer, M. T. Johnson, and P. F. Bongers. "Size-Dependent Curie-Temperature in Nanoscale MNFE204 Particles-Comment." *Physical Review Letters*, vol. 68, no. 20, p. 3112, 1992.
107. Barbers, V. A. M. *Physical Review Letters*. Vol. 68, p. 3113, 1992.
108. Weider, S. M., H. J. Lause, and R. Fountain. "Structural Repair Systems for Thermoplastic Composites." *Composite Repairs: SAMPE Monograph No. 1*, edited by Brown, Covina, CA: SAMPE, 1985.
109. Benatar, A., and T. G. Gutowski. "Methods for Fusion Bonding Thermoplastic Composites." *SAMPE Quarterly*, October 1986.
110. Border, J., and R. Salas. "Induction Heated Joining of Thermoplastic Composites Without Metal Susceptors." *34th SAMPE Symposium*, 1989.
111. Nagumo, T., H. Makamura, Y. Yoshida, and K. Hiraoka. "Evaluation of PEEK Matrix Composites." *32nd International Symposium*, SAMPE, 1987.
112. Buckley, J. D., R. L. Fox, and J. R. Tyeryar. "Seam Bonding of Graphite Reinforced Composite Panels." *NASA Advanced Composites Conference*, 1986.
113. Lewis, C. F. "Materials Keep a Low Profile." *Materials Engineering*, vol. 105, 1988.
114. Buckley, J. D., and R. L. Fox. "Rapid Electromagnetic Induction Bonding of Composites, Plastics and Metals." *Materials Research Society Symposium*, vol. 124, 1988.
115. Lawless, G. W., and T. J. Reinhart. "Study of the Induction Heating of Organic Composites." *International SAMPE Conference*, Toronto, Canada, October 1992.
116. Wedgewood, A. R., and P. E. Hardy. "Induction Welding of Thermoset Composite Adherends Using Thermoplastic Interlayers and Susceptors." *International SAMPE Conference*, vol. 28, Seattle, WA, November, 1996.
117. Derbyshire, R. T. "Connector Containing Fusible Material and Having Intrinsic Temperature Control." U.S. Patent 4,914,267, 1987.
118. McGaffigan, T. H. "Method, System and Composition for Soldering by Induction Heating." U.S. Patent 5,093,545, 1992.

119. Matsen, et al. "Retort for Achieving Thermal Uniformity in Induction Processing of Organic Matrix Composites of Metals." U.S. Patent 5,645,744, 1997.
120. Harmon, B. V., Y. S. Takano, C. M. Winterford, and G. C. Gobe. "The Role of Apoptosis in the Response of Cells and Tumors to Mild Hyperthermia." *International Journal of Radiation Biology*, vol. 59, pp. 489-501, 1991.
121. Jorritsma, J. B. M., and A. W. T. Konings. "The Occurrence of DNA Strand Breaks After Hyperthermic Treatments of Mammalian Cells With and Without Radiation." *Radiation Research*, vol. 98, pp. 198-204, 1984.
122. Jorritsma, J. B. M., and A. W. T. Konings. "DNA Lesions in Hyperthermic Cell Killing: Effects of Thermotolerance, Procaine, and Erythritol." *Radiation Research*, vol. 106, pp. 89-97, 1986.
123. Warters, R. L., L. M. Brizgys, and J. Axtell-Bartlett. "DNA Damage Production in CHO Cells at Elevated Temperatures." *Journal of Cell Physiology*, vol. 124, pp. 481-486, 1985.
124. Sellins, K. S., and J. J. Cohen. "Hyperthermia Induces Apoptosis in Thymocytes." *Radiation Research*, vol. 126, pp. 88-95, 1991.
125. Seidman, S., and H. Soreq. *Transgenic Xenopus. Microinjection Methods and Developmental Neurobiology*. New Jersey, NJ: Humana Press, 1997.
126. Sigel, E. "Use Of Xenopus Oocytes For The Functional Expression of Plasma Membrane Proteins." *Journal of Membrane Biology*, vol. 117, pp. 201-221, 1990.
127. Wormington, M. "Preparation of Synthetic mRNAs and Analyses of Translational Efficiency in Microinjected Xenopus Oocytes." *Methods in Cell Biology*, vol. 36, pp. 167-183, edited by B. K. Kay and H. B. Peng, New York, NY: Academic Press, 1991.
128. Smith, L. D., W. Xu, and R. L. Varnold. "Oogenesis and Oocyte Isolation." *Methods in Cell Biology*, vol. 36, pp. 45-60, edited by B. K. Kay and H. B. Peng, New York, NY: Academic Press, 1991.
129. Guguen-Guillouzo, C. *Culture of Epithelial Cells*. Vol. 1, pp. 197-223, edited by A. R. Liss and R. I. Freshney, Glasgow, 1992.

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	DEFENSE TECHNICAL INFORMATION CENTER DTIC DDA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218	1	DIRECTOR US ARMY RESEARCH LAB AMSRL D D R SMITH 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	HQDA DAMO FDT 400 ARMY PENTAGON WASHINGTON DC 20310-0460	1	DIRECTOR US ARMY RESEARCH LAB AMSRL DD 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	OSD OUSD(A&T)/ODDDR&E(R) R J TREW THE PENTAGON WASHINGTON DC 20301-7100	1	DIRECTOR US ARMY RESEARCH LAB AMSRL CI AI R (RECORDS MGMT) 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	DPTY CG FOR RDA US ARMY MATERIEL CMD AMCRDA 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001	3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN PO BOX 202797 AUSTIN TX 78720-2797	1	DIRECTOR US ARMY RESEARCH LAB AMSRL CI AP 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DARPA B KASPAR 3701 N FAIRFAX DR ARLINGTON VA 22203-1714		<u>ABERDEEN PROVING GROUND</u>
1	NAVAL SURFACE WARFARE CTR CODE B07 J PENNELLA 17320 DAHLGREN RD BLDG 1470 RM 1101 DAHLGREN VA 22448-5100	4	DIR USARL AMSRL CI LP (BLDG 305)
1	US MILITARY ACADEMY MATH SCI CTR OF EXCELLENCE MADN MATH MAJ HUBER THAYER HALL WEST POINT NY 10996-1786		

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CP CA D SNIDER 2800 POWDER MILL RD ADELPHI MD 20783-1145	2	COMMANDER US ARMY ARDEC AMSTA AR AE WW E BAKER J PEARSON PICATINNY ARSENAL NJ 07806-5000
1	DIRECTOR US ARMY RESEARCH LAB AMSRL OP SD TA 2800 POWDER MILL RD ADELPHI MD 20783-1145	1	COMMANDER US ARMY ARDEC AMSTA AR TD C SPINELLI PICATINNY ARSENAL NJ 07806-5000
3	DIRECTOR US ARMY RESEARCH LAB AMSRL OP SD TL 2800 POWDER MILL RD ADELPHI MD 20783-1145	1	COMMANDER US ARMY ARDEC AMSTA AR FSE PICATINNY ARSENAL NJ 07806-5000
1	DIRECTOR US ARMY RESEARCH LAB AMSRL OP SD TP 2800 POWDER MILL RD ADELPHI MD 20783-1145	6	COMMANDER US ARMY ARDEC AMSTA AR CCH A W ANDREWS S MUSALLI R CARR M LUCIANO E LOGSDEN T LOUZEIRO PICATINNY ARSENAL NJ 07806-5000
1	HQDA DAMI FIT NOLAN BLDG WASHINGTON DC 20310-1025	4	COMMANDER US ARMY ARDEC AMSTA AR CC G PAYNE J GEHBAUER C BAULIEU H OPAT PICATINNY ARSENAL NJ 07806-5000
1	DIRECTOR DA OASARDA SARD SO 103 ARMY PENTAGON WASHINGTON DC 20310-0103	1	COMMANDER US ARMY ARDEC AMSTA AR CCH P J LUTZ PICATINNY ARSENAL NJ 07806-5000
1	DPTY ASST SECY FOR R&T SARD TT THE PENTAGON RM 3EA79 WASHINGTON DC 20301-7100		
1	COMMANDER US ARMY MATERIEL CMD AMXMI INT 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001		

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	COMMANDER US ARMY ARDEC AMSTA AR FSF T C LIVECCHIA PICATINNY ARSENAL NJ 07806-5000	9	COMMANDER US ARMY ARDEC AMSTA AR CCH B P DONADIA F DONLON P VALENTI C KNUTSON G EUSTICE S PATEL G WAGNECZ R SAYER F CHANG PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR QAC T C C PATEL PICATINNY ARSENAL NJ 07806-5000		
2	COMMANDER US ARMY ARDEC AMSTA AR M D DEMELLA F DIORIO PICATINNY ARSENAL NJ 07806-5000	2	COMMANDER US ARMY ARDEC AMSTA AR CCH C H CHANIN S CHICO PICATINNY ARSENAL NJ 07806-5000
3	COMMANDER US ARMY ARDEC AMSTA AR FSA A WARNASH B MACHAK M CHIEFA PICATINNY ARSENAL NJ 07806-5000	6	COMMANDER US ARMY ARDEC AMSTA AR CCL F PUZYCKI R MCHUGH D CONWAY E JAROSZEWSKI R SCHLENNER M CLUNE PICATINNY ARSENAL NJ 07806-5000
2	COMMANDER US ARMY ARDEC AMSTA AR FSP G M SCHIKSNIS D CARLUCCI PICATINNY ARSENAL NJ 07806-5000	1	COMMANDER US ARMY ARDEC AMSTA AR QAC T D RIGOGLIOSO PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR FSP A P KISATSKY PICATINNY ARSENAL NJ 07806-5000	1	COMMANDER US ARMY ARDEC AMSTA AR SRE D YEE PICATINNY ARSENAL NJ 07806-5000

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	COMMANDER US ARMY ARDEC AMSTA AR WET T SACHAR BLDG 172 PICATINNY ARSENAL NJ 07806-5000	6	PM SADARM SFAE GCSS SD COL B ELLIS M DEVINE R KOWALSKI W DEMASSI J PRITCHARD S HROWNAK PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA ASF PICATINNY ARSENAL NJ 07806-5000	1	COMMANDER US ARMY ARDEC PRODUCTION BASE MODERN ACTY AMSMC PBM K PICATINNY ARSENAL NJ 07806-5000
1	US ARMY ARDEC INTELLIGENCE SPECIALIST AMSTA AR WEL F M GUERRIERE PICATINNY ARSENAL NJ 07806-5000	3	COMMANDER US ARMY TACOM PM TACTICAL VEHICLES SFAE TVL SFAE TVM SFAE TVH 6501 ELEVEN MILE RD WARREN MI 48397-5000
11	PM TMAS SFAE GSSC TMA R MORRIS C KIMKER D GUZOWICZ E KOPACZ R ROESER R DARCY R MCDANOLDS L D ULISSE C ROLLER J MCGREEN B PATTEN PICATINNY ARSENAL NJ 07806-5000	1	COMMANDER US ARMY TACOM PM BFVS SFAE ASM BV 6501 ELEVEN MILE RD WARREN MI 48397-5000
2	PEO FIELD ARTILLERY SYS SFAE FAS PM H GOLDMAN T MCWILLIAMS PICATINNY ARSENAL NJ 07806-5000	1	COMMANDER US ARMY TACOM PM AFAS SFAE ASM AF 6501 ELEVEN MILE RD WARREN MI 48397-5000
1	COMMANDER US ARMY TACOM PM ABRAMS SFAE ASM AB 6501 ELEVEN MILE RD WARREN MI 48397-5000	1	COMMANDER US ARMY TACOM PM RDT&E SFAE GCSS W AB J GODELL 6501 ELEVEN MILE RD WARREN MI 48397-5000

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	COMMANDER US ARMY TACOM PM SURV SYS SFAE ASM SS T DEAN SFAE GCSS W GSI M D COCHRAN 6501 ELEVEN MILE RD WARREN MI 48397-5000	14	COMMANDER US ARMY TACOM AMSTA TR R J CHAPIN R MCCLELLAND D THOMAS J BENNETT D HANSEN AMSTA JSK S GOODMAN J FLORENCE K IYER J THOMSON AMSTA TR D D OSTBERG L HINOJOSA B RAJU AMSTA CS SF H HUTCHINSON F SCHWARZ WARREN MI 48397-5000
1	COMMANDER US ARMY TACOM PM SURVIVABLE SYSTEMS SFAE GCSS W GSI H M RYZYI 6501 ELEVEN MILE RD WARREN MI 48397-5000	1	COMMANDER US ARMY TACOM AMSTA SF WARREN MI 48397-5000
1	COMMANDER US ARMY TACOM PM BFV SFAE GCSS W BV S DAVIS 6501 ELEVEN MILE RD WARREN MI 48397-5000	1	COMMANDER WATERVLIET ARSENAL SMCWV QAE Q B VANINA BLDG 44 WATERVLIET NY 12189-4050
1	COMMANDER US ARMY TACOM PM LIGHT TACTICAL VHCLS AMSTA TR S A J MILLS MS 209 6501 ELEVEN MILE RD WARREN MI 48397-5000	1	COMMANDER WATERVLIET ARSENAL SMCWV SPM T MCCLOSKEY BLDG 253 WATERVLIET NY 12189-4050
1	COMMANDER US ARMY TACOM PM GROUND SYSTEMS INTEGRATION SFAE GCSS W GSI R LABATILLE 6501 ELEVEN MILE RD WARREN MI 48397-5000	2	TSM ABRAMS ATZK TS S JABURG W MEINSHAUSEN FT KNOX KY 40121
1	COMMANDER US ARMY TACOM CHIEF ABRAMS TESTING SFAE GCSS W AB QT T KRASKIEWICZ 6501 ELEVEN MILE RD WARREN MI 48397-5000		

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
10	BENET LABORATORIES AMSTA AR CCB R FISCELLA G D ANDREA M SCAVULO G SPENCER P WHEELER K MINER J VASILAKIS G FRIAR R HASENBEIN AMSTA CCB R S SOPOK WATERVLIET NY 12189-4050	4	DIRECTOR US ARMY CECOM NIGHT VISION & ELECTRONIC SENSORS DIR AMSEL RD NV CM CCD R ADAMS R MCLEAN A YINGST AMSEL RD NV VISP E JACOBS 10221 BURBECK RD FT BELVOIR VA 22060-5806
3	ARMOR SCHOOL ATZK TD R BAUEN J BERG A POMEY FT KNOX KY 40121	2	US ARMY CORPS OF ENGINEERS CERD C T LIU CEW ET T TAN 20 MASS AVE NW WASHINGTON DC 20314
2	HQ IOC TANK AMMUNITION TEAM AMSIO SMT R CRAWFORD W HARRIS ROCK ISLAND IL 61299-6000	1	US ARMY COLD REGIONS RSCH & ENGRNG LAB P DUTTA 72 LYME RD HANOVER NH 03755
1	DIRECTOR US ARMY AMCOM SFAE AV RAM TV D CALDWELL BLDG 5300 REDSTONE ARSENAL AL 35898	1	SYSTEM MANAGER ABRAMS ATZK TS LTC J H NUNN BLDG 1002 RM 110 FT KNOX KY 40121
2	COMMANDER US ARMY AMCOM AVIATION APPLIED TECH DIR J SCHUCK FT EUSTIS VA 23604-5577	1	COMMANDANT US ARMY FIELD ARTILLERY CENTER AT FT SILL ATFS CD LTC BUMGARNER FT SILL OK 73503-5600
1	US ARMY CERL R LAMPO 2902 NEWMARK DR CHAMPAIGN IL 61822	1	CHIEF USAIC ATZB COM LTC T J CUMMINGS FT BENNING GA 31905-5800
		1	NAVAL AIR SYSTEMS CMD J THOMPSON 48142 SHAW RD UNIT 5 PATUXENT RIVER MD 20670

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
8	DIRECTOR US ARMY NATIONAL GROUND INTELLIGENCE CTR D LEITER M HOLTUS M WOLFE S MINGLEDORF J GASTON W GSTATTENBAUER R WARNER J CRIDER 220 SEVENTH ST NE CHARLOTTESVILLE VA 22091	1	NAVAL SURFACE WARFARE CTR TECH LIBRARY CODE 323 17320 DAHLGREN RD DAHLGREN VA 22448
		3	NAVAL RESEARCH LAB I WOLOCK CODE 6383 R BADALIANCE CODE 6304 L GAUSE WASHINGTON DC 20375
		1	NAVAL SURFACE WARFARE CTR CRANE DIVISION M JOHNSON CODE 20H4 LOUISVILLE KY 40214-5245
6	US ARMY SBCCOM SOLDIER SYSTEMS CENTER BALLISTICS TEAM J WARD MARINE CORPS TEAM J MACKIEWICZ BUS AREA ADVOCACY TEAM W HASKELL SSCNC WST W NYKVIST T MERRILL S BEAUDOIN KANSAS ST NATICK MA 01760-5019	2	COMMANDER NAVAL SURFACE WARFARE CTR CARDEROCK DIVISION R PETERSON CODE 2020 M CRITCHFIELD CODE 1730 BETHESDA MD 20084
		2	NAVAL SURFACE WARFARE CTR U SORATHIA C WILLIAMS CD 6551 9500 MACARTHUR BLVD WEST BETHESDA MD 20817
9	US ARMY RESEARCH OFC A CROWSON J CHANDRA H EVERETT J PRATER R SINGLETON G ANDERSON D STEPP D KISEROW J CHANG PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709-2211	1	DAVID TAYLOR RESEARCH CTR SHIP STRUCTURES & PROTECTION DEPT CODE 1702 BETHESDA MD 20084
		2	DAVID TAYLOR RESEARCH CTR R ROCKWELL W PHYLLAIER BETHESDA MD 20054-5000
		1	OFC OF NAVAL RESEARCH D SIEGEL CODE 351 800 N QUINCY ST ARLINGTON VA 22217-5660
1	NAVAL SURFACE WARFARE CTR DAHLGREN DIV CODE G06 DAHLGREN VA 22448		

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
8	NAVAL SURFACE WARFARE CTR J FRANCIS CODE G30 D WILSON CODE G32 R D COOPER CODE G32 J FRAYSSE CODE G33 E ROWE CODE G33 T DURAN CODE G33 L DE SIMONE CODE G33 R HUBBARD CODE G33 DAHLGREN VA 22448	2	AFRL F ABRAMS J BROWN BLDG 653 2977 P ST STE 6 WRIGHT PATTERSON AFB OH 45433-7739
1	NAVAL SEA SYSTEMS CMD D LIESE 2531 JEFFERSON DAVIS HWY ARLINGTON VA 22242-5160	1	AFRL MLS OL L COULTER 7278 4TH ST BLDG 100 BAY D HILL AFB UT 84056-5205
1	NAVAL SURFACE WARFARE CTR M LACY CODE B02 17320 DAHLGREN RD DAHLGREN VA 22448	1	OSD JOINT CCD TEST FORCE OSD JCCD R WILLIAMS 3909 HALLS FERRY RD VICKSBURG MS 29180-6199
1	OFC OF NAVAL RES J KELLY 800 NORTH QUINCEY ST ARLINGTON VA 22217-5000	1	DEFENSE NUCLEAR AGENCY INNOVATIVE CONCEPTS DIV 6801 TELEGRAPH RD ALEXANDRIA VA 22310-3398
2	NAVAL SURFACE WARFARE CTR CARDEROCK DIVISION R CRANE CODE 2802 C WILLIAMS CODE 6553 3A LEGGETT CIR BETHESDA MD 20054-5000	1	WATERWAYS EXPERIMENT D SCOTT 3909 HALLS FERRY RD SC C VICKSBURG MS 39180
1	EXPEDITIONARY WARFARE DIV N85 F SHOUP 2000 NAVY PENTAGON WASHINGTON DC 20350-2000	3	DARPA M VANFOSSEN S WAX L CHRISTODOULOU 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
1	AFRL MLBC 2941 P ST RM 136 WRIGHT PATTERSON AFB OH 45433-7750	2	FAA TECH CENTER D OPLINGER AAR 431 P SHYPRYKEVICH AAR 431 ATLANTIC CITY NJ 08405
1	AFRL MLSS R THOMSON 2179 12TH ST RM 122 WRIGHT PATTERSON AFB OH 45433-7718	2	SERDP PROGRAM OFC PM P2 C PELLERIN B SMITH 901 N STUART ST STE 303 ARLINGTON VA 22203

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	FAA MIL HDBK 17 CHAIR L ILCEWICZ 1601 LIND AVE SW ANM 115N RESTON VA 98055	7	NIST R PARNAS J DUNKERS M VANLANDINGHAM MS 8621 J CHIN MS 8621 D HUNSTON MS 8543 J MARTIN MS 8621 D DUTHINH MS 8611 100 BUREAU DR GAITHERSBURG MD 20899
1	US DEPT OF ENERGY OFC OF ENVIRONMENTAL MANAGEMENT P RITZCOVAN 19901 GERMANTOWN RD GERMANTOWN MD 20874-1928	1	LOCKHEED MARTIN MISSILES & FIRE CONTROL R TAYLOR PO BOX 650003 M S WT 93 DALLAS TX 75265-0003
1	DIRECTOR LLNL F ADDESSIO MS B216 PO BOX 1633 LOS ALAMOS NM 87545	1	HYDROGEOLOGIC INC SERDP ESTCP SPT OFC S WALSH 1155 HERNDON PKWY STE 900 HERNDON VA 20170
5	DIRECTOR LLNL R CHRISTENSEN S DETERESA F MAGNESS M FINGER MS 313 M MURPHY L 282 PO BOX 808 LIVERMORE CA 94550	3	DIRECTOR SANDIA NATIONAL LABS APPLIED MECHANICS DEPT DIV 8241 J HANDROCK Y R KAN J LAUFFER PO BOX 969 LIVERMORE CA 94550-0096
1	OAK RIDGE NATIONAL LABORATORY R M DAVIS PO BOX 2008 OAK RIDGE TN 37831-6195	3	NASA LANGLEY RSCH CTR AMSRL VS W ELBER MS 266 F BARTLETT JR MS 266 G FARLEY MS 266 HAMPTON VA 23681-0001
1	OAK RIDGE NATIONAL LABORATORY C EBERLE MS 8048 PO BOX 2009 OAK RIDGE TN 37831	1	NASA LANGLEY RSCH CTR T GATES MS 188E HAMPTON VA 23661-3400
1	OAK RIDGE NATIONAL LABORATORY C D WARREN MS 8039 PO BOX 2009 OAK RIDGE TN 37922	1	USDOT FEDERAL RAILRD M FATEH RDV 31 WASHINGTON DC 20590

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	FHWA E MUNLEY 6300 GEORGETOWN PIKE MCLEAN VA 22101	1	COMPOSITE MATERIALS INC C RILEY 14530 S ANSON AVE SANTA FE SPRINGS CA 90670
1	CENTRAL INTLLGNC AGNCY OTI WDAG GT W L WALTMAN PO BOX 1925 WASHINGTON DC 20505	2	COMPOSIX D BLAKE L DIXON 120 O NEILL DR HEBRUN OHIO 43025
1	MARINE CORPS INTLLGNC ACTVTY D KOSITZKE 3300 RUSSELL RD STE 250 QUANTICO VA 22134-5011	4	CYTEC FIBERITE R DUNNE D KOHLI M GILLIO R MAYHEW 1300 REVOLUTION ST HAVRE DE GRACE MD 21078
1	DIRECTOR NATIONAL GRND INTLLGNC CTR LANG TMT 220 SEVENTH ST NE CHARLOTTESVILLE VA 22902-5396	2	SIMULA J COLTMAN R HUYETT 10016 S 51ST ST PHOENIX AZ 85044
1	DIRECTOR DEFENSE INTLLGNC AGNCY TA 5 K CRELLING WASHINGTON DC 20310	1	SIOUX MFG B KRIEL PO BOX 400 FT TOTTEN ND 58335
1	GRAPHITE MASTERS INC J WILLIS 3815 MEDFORD ST LOS ANGELES CA 90063-1900	2	PROTECTION MATERIALS INC M MILLER F CRILLEY 14000 NW 58 CT MIAMI LAKES FL 33014
1	ADVANCED GLASS FIBER YARNS T COLLINS 281 SPRING RUN LANE STE A DOWNINGTON PA 19335	3	FOSTER MILLER J J GASSNER M ROYLANCE W ZUKAS 195 BEAR HILL RD WALTHAM MA 02354-1196
1	COMPOSITE MATERIALS INC D SHORTT 19105 63 AVE NE PO BOX 25 ARLINGTON WA 98223	1	ROM DEVELOPMENT CORP R O MEARA 136 SWINEBURNE ROW BRICK MARKET PLACE NEWPORT RI 02840
1	COMPOSITE MATERIALS INC R HOLLAND 11 JEWEL CT ORINDA CA 94563		

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	TEXTRON SYSTEMS T FOLTZ M TREASURE 201 LOWELL ST WILMINGTON MA 08870-2941	3	PACIFIC NORTHWEST LAB M SMITH G VAN ARSDALE R SHIPPELL PO BOX 999 RICHLAND WA 99352
1	JPS GLASS L CARTER PO BOX 260 SLATER RD SLATER SC 29683	2	AMOCO PERFORMANCE PRODUCTS M MICHNO JR J BANISAUKAS 4500 MCGINNIS FERRY RD ALPHARETTA GA 30202-3944
1	O GARA HESS & EISENHARDT M GILLESPIE 9113 LESAINT DR FAIRFIELD OH 45014	1	SAIC M PALMER 2109 AIR PARK RD S E ALBUQUERQUE NM 87106
2	MILLIKEN RSCH CORP H KUHN M MACLEOD PO BOX 1926 SPARTANBURG SC 29303	1	SAIC G CHRYSSOMALLIS 3800 W 80TH ST STE 1090 BLOOMINGTON MN 55431
1	CONNEAUGHT INDUSTRIES INC J SANTOS PO BOX 1425 COVENTRY RI 02816	1	AAI CORPORATION T G STASTNY PO BOX 126 HUNT VALLEY MD 21030-0126
2	BATTELLE NATICK OPNS J CONNORS B HALPIN 209 W CENTRAL ST STE 302 NATICK MA 01760	1	APPLIED COMPOSITES W GRISCH 333 NORTH SIXTH ST ST CHARLES IL 60174
1	BATTELLE NW DOE PNNL T HALL MS K231 BATTELLE BLVD RICHLAND WA 99352	3	ALLIANT TECHSYSTEMS INC J CONDON E LYNAM J GERHARD WV01 16 STATE RT 956 PO BOX 210 ROCKET CENTER WV 26726-0210
1	ARMTEC DEFENSE PRODUCTS S DYER 85 901 AVE 53 PO BOX 848 COACHELLA CA 92236	1	CUSTOM ANALYTICAL ENG SYS INC A ALEXANDER 13000 TENSOR LANE NE FLINTSTONE MD 21530
2	GLCC INC J RAY M BRADLEY 103 TRADE ZONE DR STE 26C WEST COLUMBIA SC 29170		

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
8	ALLIANT TECHSYSTEMS INC C CANDLAND MN11 2830 C AAKHUS MN11 2830 B SEE MN11 2439 N VLAHAKUS MN11 2145 R DOHRN MN11 2830 S HAGLUND MN11 2439 M HISSONG MN11 2830 D KAMDAR MN11 2830 600 SECOND ST NE HOPKINS MN 55343-8367	1	ZERNOW TECHNICAL SERVICES L ZERNOW 425 W BONITA AVE STE 208 SAN DIMAS CA 91773
		2	OLIN CORPORATION FLINCHBAUGH DIV E STEINER B STEWART PO BOX 127 RED LION PA 17356
1	PROJECTILE TECHNOLOGY INC 515 GILES ST HAVRE DE GRACE MD 21078	1	OLIN CORPORATION L WHITMORE 10101 NINTH ST NORTH ST PETERSBURG FL 33702
2	LORAL VOUGHT SYSTEMS G JACKSON K COOK 1701 W MARSHALL DR GRAND PRAIRIE TX 75051	1	GKN AEROSPACE D OLDS 15 STERLING DR WALLINGFORD CT 06492
5	AEROJET GEN CORP D PILLASCH T COULTER C FLYNN D RUBAREZUL M GREINER 1100 WEST HOLLYVALE ST AZUSA CA 91702-0296	5	SIKORSKY AIRCRAFT G JACARUSO T CARSTENSAN B KAY S GARBO MS S330A J ADELMANN 6900 MAIN ST PO BOX 9729 STRATFORD CT 06497-9729
3	HEXCEL INC R BOE F POLICELLI J POESCH PO BOX 98 MAGNA UT 84044	1	PRATT & WHITNEY D HAMBRICK 400 MAIN ST MS 114 37 EAST HARTFORD CT 06108
1	HERCULES INC HERCULES PLAZA WILMINGTON DE 19894	1	AEROSPACE CORP G HAWKINS M4 945 2350 E EL SEGUNDO BLVD EL SEGUNDO CA 90245
1	BRIGS COMPANY J BACKOFEN 2668 PETERBOROUGH ST HERNDON VA 22071-2443	2	CYTEC FIBERITE M LIN W WEB 1440 N KRAEMER BLVD ANAHEIM CA 92806

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	HEXCEL T BITZER 11711 DUBLIN BLVD DUBLIN CA 94568	1	NORTHROP GRUMMAN CORP ELECTRONIC SENSORS & SYSTEMS DIV E SCHOCH MS V 16 1745A W NURSERY RD LINTHICUM MD 21090
1	BOEING R BOHLMANN PO BOX 516 MC 5021322 ST LOUIS MO 63166-0516	2	NORTHROP GRUMMAN ENVIRONMENTAL PROGRAMS R OSTERMAN A YEN 8900 E WASHINGTON BLVD PICO RIVERA CA 90660
2	BOEING DFNSE & SPACE GP W HAMMOND S 4X55 J RUSSELL S 4X55 PO BOX 3707 SEATTLE WA 98124-2207	1	UDLP D MARTIN PO BOX 359 SANTA CLARA CA 95052
2	BOEING ROTORCRAFT P MINGURT P HANDEL 800 B PUTNAM BLVD WALLINGFORD PA 19086	1	UDLP G THOMAS PO BOX 58123 SANTA CLARA CA 95052
1	BOEING DOUGLAS PRODUCTS DIV L J HART SMITH 3855 LAKEWOOD BLVD D800 0019 LONG BEACH CA 90846-0001	2	UDLP R BARRETT MAIL DROP M53 V HORVATICH MAIL DROP M53 328 W BROKAW RD SANTA CLARA CA 95052-0359
1	LOCKHEED MARTIN S REEVE 8650 COBB DR D 73 62 MZ 0648 MARIETTA GA 30063-0648	3	UDLP GROUND SYSTEMS DIVISION M PEDRAZZI MAIL DROP N09 A LEE MAIL DROP N11 M MACLEAN MAIL DROP N06 1205 COLEMAN AVE SANTA CLARA CA 95052
1	LOCKHEED MARTIN SKUNK WORKS D FORTNEY 1011 LOCKHEED WAY PALMDALE CA 93599-2502	4	UDLP R BRYNSVOLD P JANKE MS 170 T GIOVANETTI MS 236 B VAN WYK MS 389 4800 EAST RIVER RD MINNEAPOLIS MN 55421-1498
1	LOCKHEED MARTIN R FIELDS 1195 IRWIN CT WINTER SPRINGS FL 32708	1	GDLS DIVISION D BARTLE PO BOX 1901 WARREN MI 48090
1	MATERIALS SCIENCES CORP B W ROSEN 500 OFC CENTER DR STE 250 FT WASHINGTON PA 19034		

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
2	GDLS D REES M PASIK PO BOX 2074 WARREN MI 48090-2074	2	UNIV OF DAYTON RESEARCH INST R Y KIM A K ROY 300 COLLEGE PARK AVE DAYTON OH 45469-0168
1	GDLS MUSKEGON OPERATIONS W SOMMERS JR 76 GETTY ST MUSKEGON MI 49442	1	MIT P LAGACE 77 MASS AVE CAMBRIDGE MA 01887
1	GENERAL DYNAMICS AMPHIBIOUS SYS SURVIVABILITY LEAD G WALKER 991 ANNAPOLIS WAY WOODBRIDGE VA 22191	1	IIT RESEARCH CENTER D ROSE 201 MILL ST ROME NY 13440-6916
5	INST FOR ADVANCED TECH T KIEHNE H FAIR P SULLIVAN W REINECKE I MCNAB 4030 2 W BRAKER LN AUSTIN TX 78759	1	GA TECH RSCH INST GA INST OF TCHNLGY P FRIEDERICH ATLANTA GA 30392
2	CIVIL ENGR RSCH FOUNDATION PRESIDENT H BERNSTEIN R BELLE 1015 15TH ST NW STE 600 WASHINGTON DC 20005	1	MICHIGAN ST UNIV MSM DEPT R AVERILL 3515 EB EAST LANSING MI 48824-1226
1	ARROW TECH ASSO 1233 SHELBURNE RD STE D 8 SOUTH BURLINGTON VT 05403-7700	1	UNIV OF KENTUCKY L PENN 763 ANDERSON HALL LEXINGTON KY 40506-0046
1	R EICHELBERGER CONSULTANT 409 W CATHERINE ST BEL AIR MD 21014-3613	1	UNIV OF WYOMING D ADAMS PO BOX 3295 LARAMIE WY 82071
1	UCLA MANE DEPT ENGR IV H T HAHN LOS ANGELES CA 90024-1597	1	UNIV OF UTAH DEPT OF MECH & INDUSTRIAL ENGR S SWANSON SALT LAKE CITY UT 84112
		2	PENN STATE UNIV R MCNITT C BAKIS 212 EARTH ENGR SCIENCES BLDG UNIVERSITY PARK PA 16802

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	PENN STATE UNIV R S ENGEL 245 HAMMOND BLDG UNIVERSITY PARK PA 16801	3	THE UNIV OF TEXAS AT AUSTIN CTR FOR ELECTROMECHANICS J PRICE A WALLS J KITZMILLER 10100 BURNET RD AUSTIN TX 78758-4497
1	PURDUE UNIV SCHOOL OF AERO & ASTRO C T SUN W LAFAYETTE IN 47907-1282	3	VA POLYTECHNICAL INST & STATE UNIV DEPT OF ESM M W HYER K REIFSNIDER R JONES BLACKSBURG VA 24061-0219
1	STANFORD UNIV DEPT OF AERONAUTICS & AEROBALLISTICS S TSAI DURANT BLDG STANFORD CA 94305	1	UNIV OF MARYLAND DEPT OF AEROSPACE ENGNRNG A J VIZZINI COLLEGE PARK MD 20742
1	UNIV OF DAYTON J M WHITNEY COLLEGE PARK AVE DAYTON OH 45469-0240	1	DREXEL UNIV A S D WANG 32ND & CHESTNUT ST PHILADELPHIA PA 19104
7	UNIV OF DELAWARE CTR FOR COMPOSITE MTRLS J GILLESPIE M SANTARE G PALMESE S YARLAGADDA S ADVANI D HEIDER D KUKICH 201 SPENCER LABORATORY NEWARK DE 19716	1	SOUTHWEST RSCH INST ENGR & MATL SCIENCES DIV J RIEGEL 6220 CULEBRA RD PO DRAWER 28510 SAN ANTONIO TX 78228-0510
1	UNIV OF ILLINOIS AT URBANA CHAMPAIGN NATIONAL CENTER FOR COMPOSITE MATERIALS RESEARCH J ECONOMY 216 TALBOT LABORATORY 104 S WRIGHT ST URBANA IL 61801		<u>ABERDEEN PROVING GROUND</u>
1	NORTH CAROLINA STATE UNIV CIVIL ENGINEERING DEPT W RASDORF PO BOX 7908 RALEIGH NC 27696-7908	1	US ARMY MATERIEL SYSTEMS ANALYSIS P DIETZ 392 HOPKINS RD AMXSY TD APG MD 21005-5071
		1	DIRECTOR US ARMY RESEARCH LAB AMSRL OP AP L APG MD 21005-5066

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
	<u>ABERDEEN PROVING GROUND (CONT)</u>
106	DIR USARL
	AMSRL CI
	AMSRL CI H
	W STUREK
	AMSRL CI S
	A MARK
	AMSRL CS IO FI
	M ADAMSON
	AMSRL SL B
	J SMITH
	AMSRL SL BA
	AMSRL SL BL
	D BELY
	R HENRY
	AMSRL SL BG
	AMSRL SL I
	AMSRL WM B
	A HORST
	E SCHMIDT
	AMSRL WM BA
	F BRANDON
	AMSRL WM BC
	P PLOSTINS
	D LYON
	J NEWILL
	S WILKERSON
	A ZIELINSKI
	AMSRL WM BD
	B FORCH
	R FIFER
	R PESCE RODRIGUEZ
	B RICE
	AMSRL WM BE
	C LEVERITT
	D KOOKER
	AMSRL WM BR
	C SHOEMAKER
	J BORNSTEIN
	AMSRL WM M
	D VIECHNICKI
	G HAGNAUER
	J MCCAULEY
	B TANNER
	AMSRL WM MA
	R SHUFORD
	P TOUCHET
	N BECK TAN

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
	<u>ABERDEEN PROVING GROUND (CONT)</u>
	AMSRL WM MA
	D FLANAGAN
	L GHIORSE
	D HARRIS
	S MCKNIGHT
	P MOY
	P PATTERSON
	G RODRIGUEZ
	A TEETS
	R YIN
	AMSRL WM MB
	B FINK
	J BENDER
	T BLANAS
	T BOGETTI
	R BOSSOLI
	L BURTON
	K BOYD
	S CORNELISON
	P DEHMER
	R DOOLEY
	W DRYSDALE
	G GAZONAS
	S GHIORSE
	D GRANVILLE
	D HOPKINS
	C HOPPEL
	D HENRY
	R KASTE
	M KLUSEWITZ
	M LEADORE
	R LIEB
	E RIGAS
	J SANDS
	D SPAGNUOLO
	W SPURGEON
	J TZENG
	E WETZEL
	AMSRL WM MB ALC
	A FRYDMAN
	AMRSL WM MC
	J BEATTY
	E CHIN
	J MONTGOMERY
	A WERECZCAK
	J LASALVIA
	J WELLS

NO. OF  
COPIES      ORGANIZATION

ABERDEEN PROVING GROUND (CONT)

AMSRL WM MD  
W ROY  
S WALSH  
AMSRL WM T  
B BURNS  
AMSRL WM TA  
W GILLICH  
T HAVEL  
J RUNYEON  
M BURKINS  
E HORWATH  
B GOOCH  
W BRUCHEY  
AMSRL WM TC  
R COATES  
AMSRL WM TD  
A DAS GUPTA  
T HADUCH  
T MOYNIHAN  
F GREGORY  
A RAJENDRAN  
M RAFTENBERG  
M BOTELER  
T WEERASOORIYA  
D DANDEKAR  
A DIETRICH  
AMSRL WM TE  
A NIILER  
J POWELL  
AMSRL SS SD  
H WALLACE  
AMSRL SS SE R  
R CHASE  
AMSRL SS SE DS  
R REYZER  
R ATKINSON  
AMSRL SE L  
R WEINRAUB  
J DESMOND  
D WOODBURY

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	LTD R MARTIN MERL TAMWORTH RD HERTFORD SG13 7DG UK	2	ROYAL MILITARY COLLEGE OF SCIENCE SHRIVENHAM D BULMAN B LAWTON SWINDON WILTS SN6 8LA UK
1	SMC SCOTLAND P W LAY DERA ROSYTH ROSYTH ROYAL DOCKYARD DUNFERMLINE FIFE KY 11 2XR UK	1	SWISS FEDERAL ARMAMENTS WKS W LANZ ALLMENDSTRASSE 86 3602 THUN SWITZERLAND
1	CIVIL AVIATION ADMINSTRATION T GOTTESMAN PO BOX 8 BEN GURION INTERNL AIRPORT LOD 70150 ISRAEL	1	ISRAEL INST OF TECHNOLOGY S BODNER FACULTY OF MECHANICAL ENGR HAIFA 3200 ISRAEL
1	AEROSPATIALE S ANDRE A BTE CC RTE MD132 316 ROUTE DE BAYONNE TOULOUSE 31060 FRANCE	1	DSTO MATERIALS RESEARCH LAB NAVAL PLATFORM VULNERABILITY SHIP STRUCTURES & MTRLS DIV N BURMAN PO BOX 50 ASCOT VALE VICTORIA AUSTRALIA 3032
1	DAIMLER BENZ AEROSPACE J BAUER D 81663 MUNCHEN MUNICH GERMANY	1	ECOLE ROYAL MILITAIRE E CELENS AVE DE LA RENAISSANCE 30 1040 BRUXELLE BELGIQUE
3	DRA FORT HALSTEAD P N JONES D SCOTT M HINTON SEVEN OAKS KENT TN 147BP UK	1	DEF RES ESTABLISHMENT VALCARTIER A DUPUIS 2459 BOULEVARD PIE XI NORTH VALCARTIER QUEBEC CANADA PO BOX 8800 COURCELETTE GOA IRO QUEBEC CANADA
1	DEFENSE RESEARCH ESTAB VALCARTIER F LESAGE COURCELETTE QUEBEC COA IRO CANADA	1	INSTITUT FRANCO ALLEMAND DE RECHERCHES DE SAINT LOUIS DE M GIRAUD 5 RUE DU GENERAL CASSAGNOU BOITE POSTALE 34 F 68301 SAINT LOUIS CEDEX FRANCE

<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>	<u>NO. OF COPIES</u>	<u>ORGANIZATION</u>
1	ECOLE POLYTECH J MANSON DMX LTC CH 1015 LAUSANNE SWITZERLAND	1	TNO DEFENSE RESEARCH I H PASMAN POSTBUS 6006 2600 JA DELFT THE NETHERLANDS
1	TNO PRINS MAURITS LABORATORY R IJSSELSTEIN LANGE KLEIWEG 137 PO BOX 45 2280 AA RIJSWIJK THE NETHERLANDS	1	B HIRSCH TACHKEMONY ST 6 NETAMUA 42611 ISRAEL
2	FOA NATL DEFENSE RESEARCH ESTAB DIR DEPT OF WEAPONS & PROTECTION B JANZON R HOLMLIN S 172 90 STOCKHOLM SWEDEN	1	DEUTSCHE AEROSPACE AG DYNAMICS SYSTEMS M HELD PO BOX 1340 D 86523 SCHROBENHAUSEN GERMANY
2	DEFENSE TECH & PROC AGENCY GROUND I CREWTHERR GENERAL HERZOG HAUS 3602 THUN SWITZERLAND		
1	MINISTRY OF DEFENCE RAFAEL ARMAMENT DEVELOPMENT AUTH M MAYSELESS PO BOX 2250 HAIFA 31021 ISRAEL		
1	DYNAMEC RESEARCH AB A PERSSON BOX 201 S 151 36 SODERTALJE SWEDEN		
1	ERNST MACH INSTITUT EMI A STILP ECKERSTRASSE 4 7800 FREIBURG GERMANY		

INTENTIONALLY LEFT BLANK.

<b>REPORT DOCUMENTATION PAGE</b>			<i>Form Approved</i> OMB No. 0704-0188	
<small>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project(0704-0188), Washington, DC 20503.</small>				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE November 2000	3. REPORT TYPE AND DATES COVERED Final, Aug 98 - Jan 99	
4. TITLE AND SUBTITLE Functional Nanostructures for Induction Heating: A Review of Literature and Recommendations for Research			5. FUNDING NUMBERS AH42	
6. AUTHOR(S) Bruce K. Fink, Shridhar Yarlagadda, John Q. Xiao, Gary H. Laverty, and John W. Gillespie, Jr.				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: AMSRL-WM-MB Aberdeen Proving Ground, MD 21005-5069			8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-2365	
9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT( <i>Maximum 200 words</i> ) <p>This report presents the concept for a multidisciplinary research program aimed at establishing the science base for the design and synthesis of magnetic nanoparticles for hysteresis heating, with potential applications ranging from novel composites processing techniques to alternative cancer treatments. Magnetic materials are used in a wide range of applications and designed for maximum efficiency or minimized hysteresis loss. The uniqueness of this project is that, while considerable work has been aimed at reducing hysteresis losses, the converse effect (i.e., increasing hysteresis losses and therefore heat generation) has not been fully studied. Hysteresis-based heating has several advantages over conventional heating techniques, including the fact that it is a very rapid and noncontact process. In addition, the Curie temperature of magnetic materials can also be used as a means of "smart" thermal control. Exploratory basic research through ongoing programs at the U.S. Army Research Laboratory (ARL) has established the feasibility of Curie temperature control and demonstrated the effects of particle size, frequency, and stoichiometry on hysteresis losses. The following scientific barriers are addressed in this report: magnetization dynamics in high-frequency magnetic fields, the effects of magnetic phase transition on hysteresis heating, and the dimensional dependence of Curie temperature in nanoparticles. If carried out, the research program outlined in this report would establish the science base for the design and synthesis of nanoparticles for hysteresis heating applications.</p>				
14. SUBJECT TERMS fiber optics sensors, composite materials, integral armor, resin transfer molding			15. NUMBER OF PAGES 59	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-2365 (Fink) Date of Report November 2000

2. Date Report Received \_\_\_\_\_

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) \_\_\_\_\_  
\_\_\_\_\_  
\_\_\_\_\_

CURRENT ADDRESS  
Organization \_\_\_\_\_  
Name \_\_\_\_\_ E-mail Name \_\_\_\_\_  
Street or P.O. Box No. \_\_\_\_\_  
City, State, Zip Code \_\_\_\_\_

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD ADDRESS  
Organization \_\_\_\_\_  
Name \_\_\_\_\_  
Street or P.O. Box No. \_\_\_\_\_  
City, State, Zip Code \_\_\_\_\_

(Remove this sheet, fold as indicated, tape closed, and mail.)  
(DO NOT STAPLE)