Materials Innovation Workshop at ORNL

Plenary: Materials Development Overview

ADVANCES IN NANOSCIENCE/NANOMATERIALS AND APPLICATION TO THE GRID

For example -

APPLICATION OF NANO-DIAMOND TO ENHANCE TRANSFORMER OIL

Jim Davidson
Dave Kerns

August 26, 2015

(Vanderbilt)

Advances in nanoscience / nanomaterials

"There's Plenty of Room at the Bottom" *

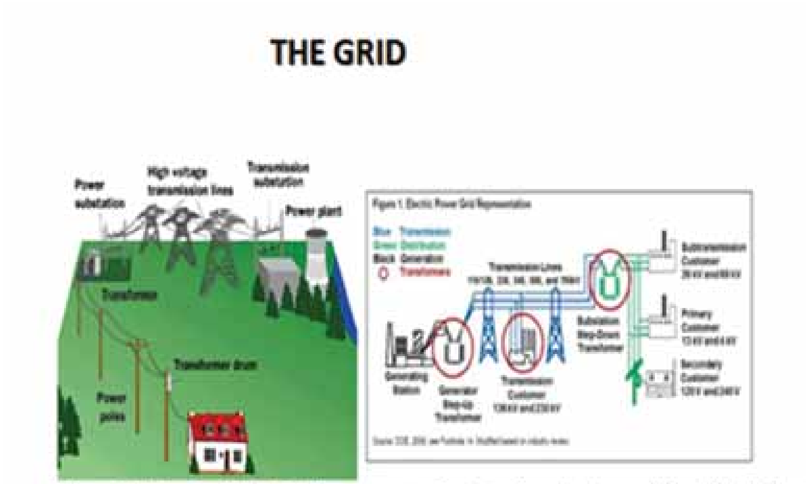
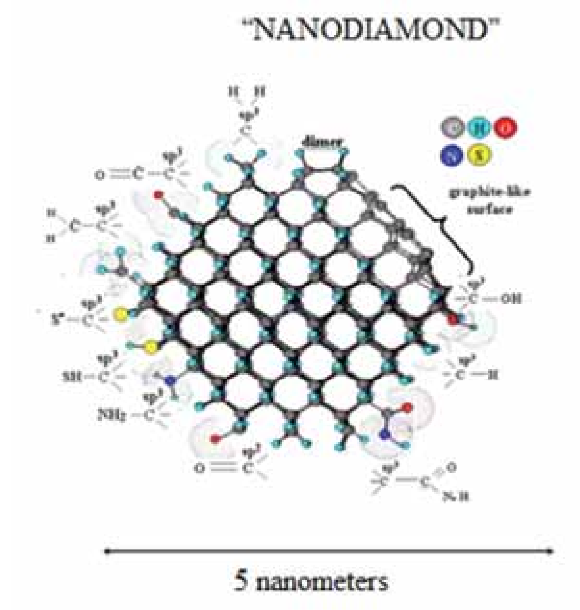
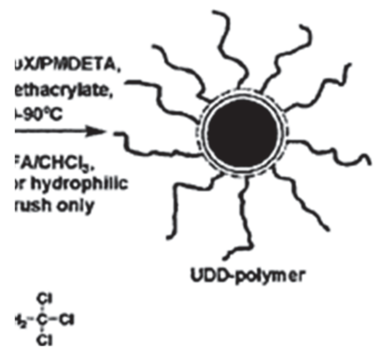


Figure 11. Showing the classical power generation, transforming, transmission-distribution pi elements, when taken in their entirety, make up "the grid".

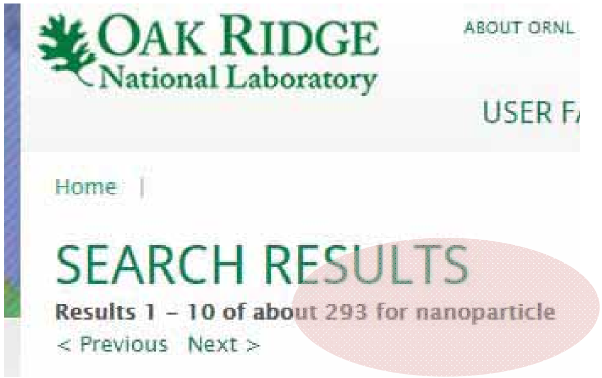




*was a lecture given by physicist Richard Feynman at an American Physical Societymeeting at Caltech on December 29, 1959.[1] Feynman considered the possibility of direct manipulation of individual atoms . In the 1990s it was rediscovered
https://en.wikipedia.org/wiki/There%27s_Plenty_of_Room_at_the_Bottom

NANOMATERIALS

NANOPARTICLES



ADDING B TO A TO IMPROVE A's PROPERTIES

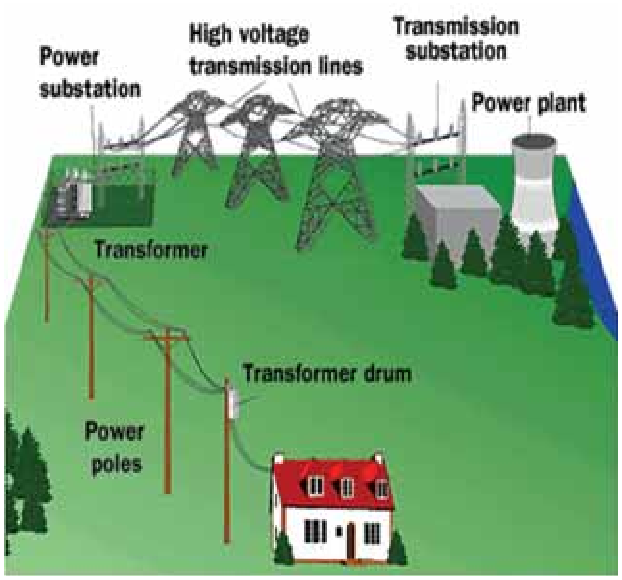
STRENGTH, THERMAL, ELECTRICAL, etc.

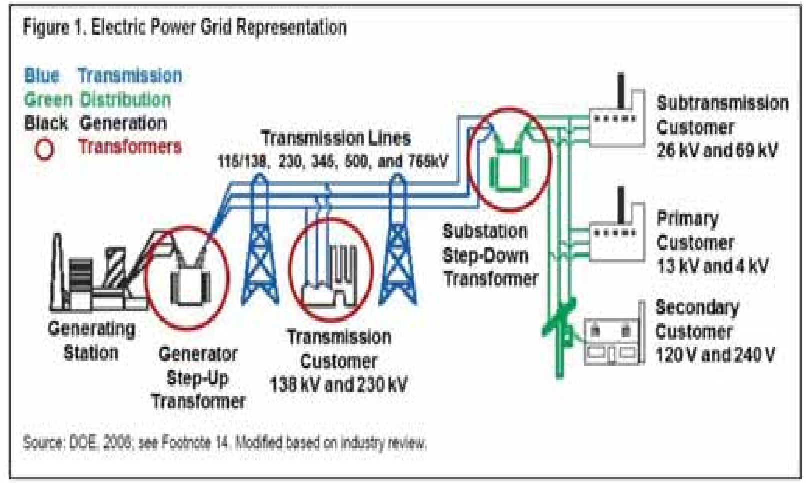
With the right particulate, at the nanoscale, can get enhanced effects that are well beyond simply additive

[ppm gets xx% improvement]

Understand this, develop this and can move existing materials:equipment:systems into new operational domains without 'overhauling' the entire macro-complex

Case in point





The classical power generation, *transforming*, transmission-distribution profile elements, when taken in their entirety, make up the power grid.

(whether generation is fossil, hydro or renewable, *transformers* are integral and essential)

OIL COOLED TRANSFORMERS

Diverse, very stratified

Pole mount

LPT

> 2 billion gallons

Background LONGEVITY CHALLENGES

“Aging Transformers: A Matter of Concern”
There is extensive evidence from the power technology community that transformers are crucial to the overall health and progress of the power system.
Challenge to utilities in the US: managing aging substation transformers installed in the 1960s and 1970s. (Approaching/beyond their original life expectancy.) Cost of replacement has forced many to keep transformers operating beyond their recommended life span.*

The main factors responsible for transformer aging are

- **Temperature**

  “Small (~1°C) reductions in winding temperatures can significantly extended transformer longevity”

  - Oxygen
  - Moisture

Controlling these variables can maximize the *life* of a transformer

[*according to EPRI, DOE, ABB, Siemens, etc.]

The case for improved transformer operation

assessments from experts:

"After transmission lines, distribution transformers are the second largest loss-making component in electricity networks. Transformers are relatively easy to replace, certainly in comparison with lines or cables, and their efficiency can fairly easily be classified, labeled and standardized. ..... Network losses represent a global economic loss of approximately US$ 61 billion [*], *"Network Efficiency Improvements", Sergio Ferreira, European Copper Institute Avenue de Tervueren, 168, 1150 Brussels*

* *World Energy Investment Outlook, International Energy Agency, 2003*

" The ubiquitous transformer could be the source of energy savings if a substantial number of installations included high-efficiency units.

***Coil loss is a function of the resistance of the winding materials and varies with the load on the transformer.* "**

"Transformer Efficiency - An overlooked energy conservation measure", John L. Fetters, CEM, CLEP, April 23, 2002 ; article developed with assistance from the Copper Development Association

Enhancing efficiency of a transformer

Transformer oil with better thermal conductivity will *significantly* increase its power out/reduce losses significantly *for the same energy in.*

Transformer power loses arise from two basic sources, :

1) No-Load Losses, independent of temperature and
2) **Load Losses**.

> Load Loss, *dominates* at transformer loads from 50% and above (normal operating conditions)

> Result of the *heating* of the transformer winding due to the *resistance* of the wire windings, either aluminum or copper. The current through the transformer windings *heat the core* as result of I^2R.

> Power is converted to heat and *wasted*.

Background RELIABILITY AND SAFETY

Failure of on line transformers can be catastrophic

"Fundamentally, there is the ever present concern as re. *public safety*. There are many instances we are all familiar with where the transformer failure, due to overheating or related load/lifetime situations, take on an entirely different level of concern than just efficiency."

Transformer Explodes in San Francisco

The burned awning and storefront of a Ralph Lauren store is seen Friday, Aug. 19, 2005, in San Francisco. A fiery explosion from an underground utility chamber in the downtown shopping district Friday burned a woman and shattered windows authorities said. Firefighters quickly doused a flaming awning and police evacuated several blocks around the store in the Crocker Galleria area, said fire spokesman Peter Howes. (AP Photo/Ben Margot)

Transformer Failure

Failure of on line transformers can be catastrophic

An outage in one area can lead to cascading outages in other areas. A cascade of failures that left 50 million people without power for two days across the United States and Canada *cost the economy an estimated $6 billion.*

Background SYNOPSIS

The main factors responsible for transformer aging are

- **Temperature**

“Small (~1°C) reductions in winding temperatures can significantly extended transformer longevity”

- Oxygen
- Moisture

Controlling these variables can maximize the *life* of a transformer

Cooler operation **of oil cooled transformers would offer benefits at several levels;**
Enhancing transformer longevity, performance, reliability and safety

Improved thermal conductivity **translates to better heat transfer, lower core temperature, which leads to better load handling and improved lifetime of a transformer.**

OVERVIEW – *Example of Liquid Cooling System*
ENHANCED *TRANSFORMER* COOLING

- **Background and Motivations**
  - Longevity Challenges
  - Performance Challenges (e.g., increase load limit)
  - Reliability and Safety Concerns

- **Performance Enhancements**
  - Explanation of Material Technology
  - Evidence of Thermal Property Enhancement

- **Compatibility with Present Systems**

Unique Properties of Nanoparticle Suspensions

- Wang et al. (1999)
  - 20 micron Al_2O_3 particles in ethylene glycol
  - "…the predicted thermal conductivities of nanoparticle-fluid mixtures are much lower than our measured data…. A more comprehensive theory is needed to fully explain the behavior of nanoparticle-fluid mixtures."
- Possible nanoscale effects
  - Enhanced Brownian motion (thermokinetic effects)
  - Nanofilaments

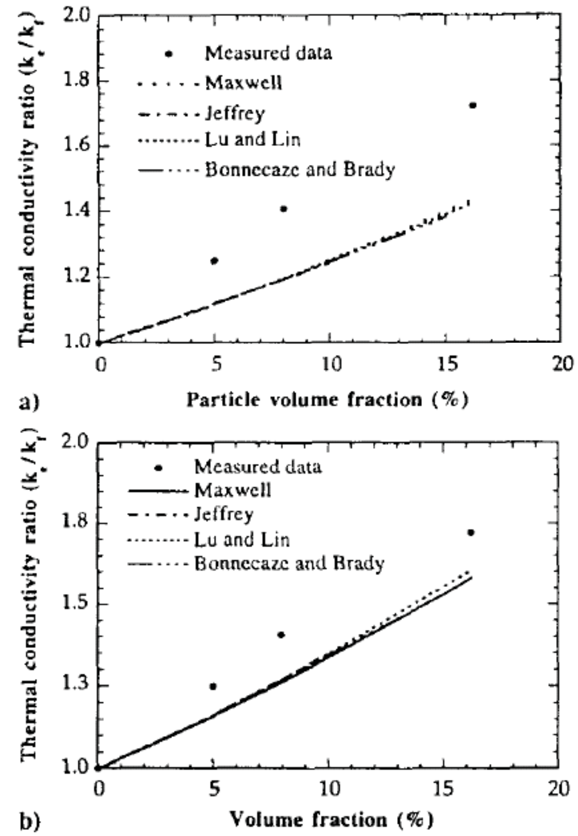


Fig. 5 Measured thermal conductivities of Al_2O_3–ethylene glycol mixtures vs effective thermal conductivities calculated from theories: a) $\alpha = 10$ and b) $\alpha = \infty$.

Rationale

- Dependence of temperature rise ΔT on thermo-fluid properties
  - Free convection

$$\Delta T \sim \frac{(\nu\alpha)^{\frac{1}{4} to \frac{1}{5}}}{k^{\frac{3}{4} to \frac{4}{5}}}$$

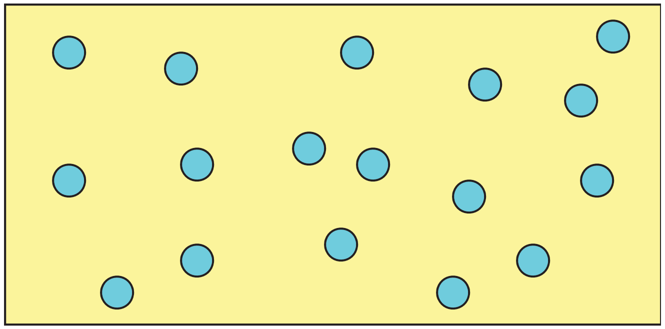
  - Forced convection

$$\Delta T \sim \frac{(\nu)^{\frac{1}{6} to \frac{7}{15}} (\alpha)^{\frac{1}{3}}}{k}$$

- Properties
  - ***k* = effective fluid thermal conductivity**
  - ν = effective fluid kinematic viscosity
  - α = effective fluid thermal diffusivity

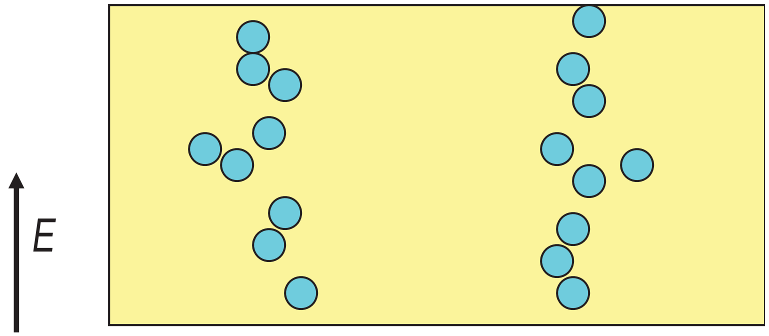
Effective Static Thermal Conductivity

- Random particulate dispersion (Jeffrey, 1973)
  - $\alpha = k_{particle} / k_{fluid}$
  - $\beta = (\alpha-1)/(\alpha-2)$
  - ϕ = particulate volume fraction



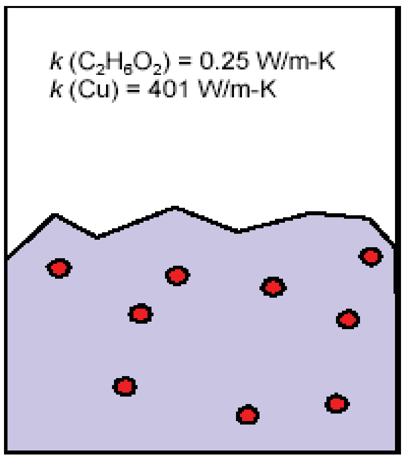
$$\frac{k_{eff}}{k_{fluid}} = 1 + 3\beta\phi + \phi^2\left(3\beta^2 + \frac{3\beta^2}{4} + \frac{9\beta^3}{16}\frac{\alpha+2}{2\alpha+3} + \frac{3\beta^4}{2^6} + \K\right)$$

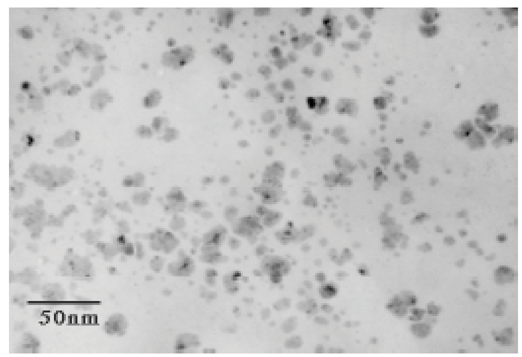
- Self-aligned nanoparticle filaments
  - Similar to above, but with enhanced volume fraction $\phi \Rightarrow \phi` = C\phi$, C >> 1

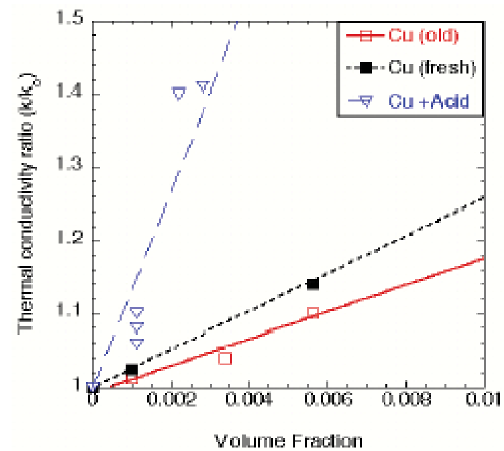


NANOPARTICLE PRINCIPLE WIDELY EXAMINED

Enhanced Thermal Transport in Nanofluids







- Our goal is to enhance the effective fluid thermal conductivity and heat transfer coefficient of liquids by dispersing solid nanoparticles.
- Condensation of copper vapor into ethylene glycol produces ~10 nm diameter copper nanoparticles; other techniques can also be used to produce nanofluids
- The thermal conductivity of ethylene glycol is significantly increased through the dispersion of copper nanoparticles; treating the particle surfaces with thioglycolic acid increases the enhancement

.A. Eastman, H.-S. Yang
..J. Thompson, S.R. Phillpot
Materials Science Division
Argonne National Laboratory
G. Skandan (*Nanopowder Enterprises, Inc.*)
S.U.S. Choi (*ANL/ET*)
P. Keblinski (*RPI*)

Vanderbilt Diamond R&D Program

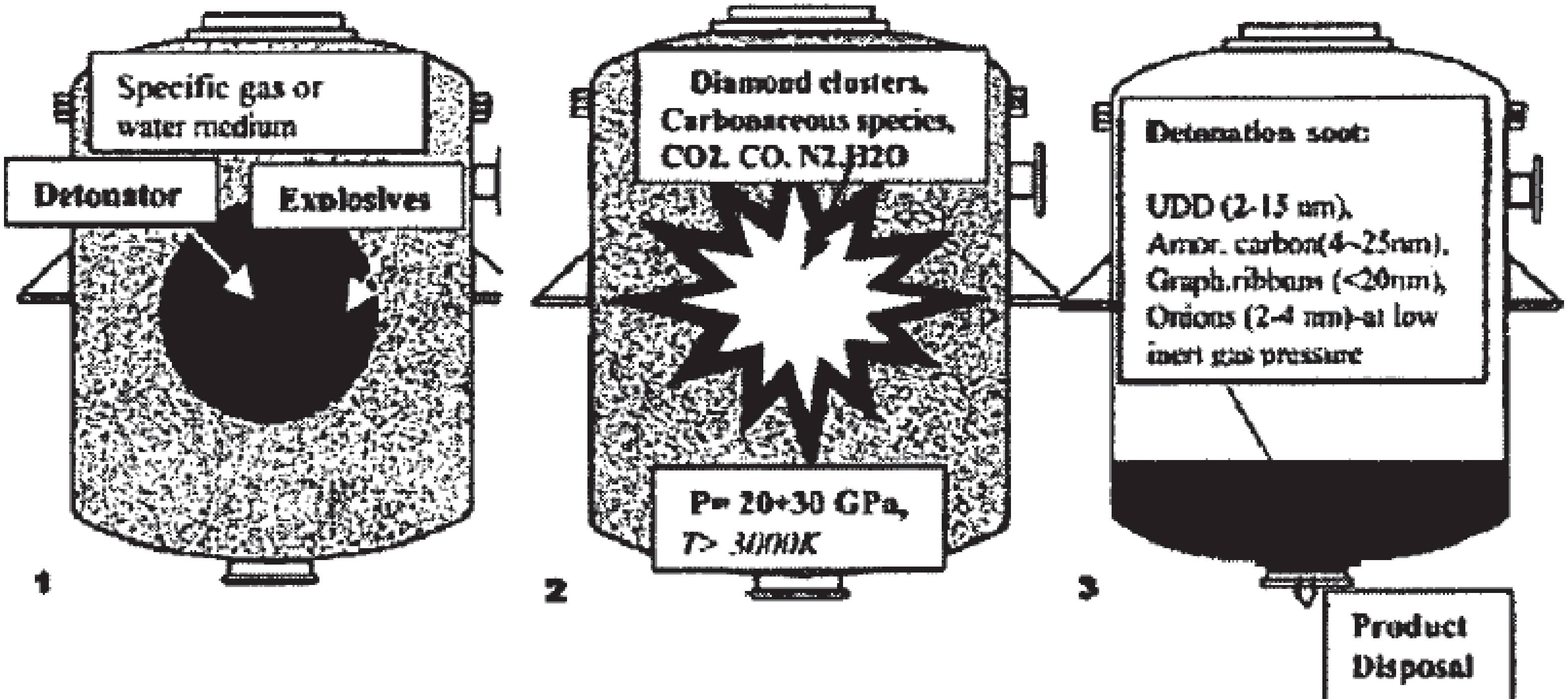
+

TVA T&D Systems Enhancement Interests

- ***CVD diamond devices for power***
- ***Could diamond cool transformers?***

DETONATION NANODIAMOND

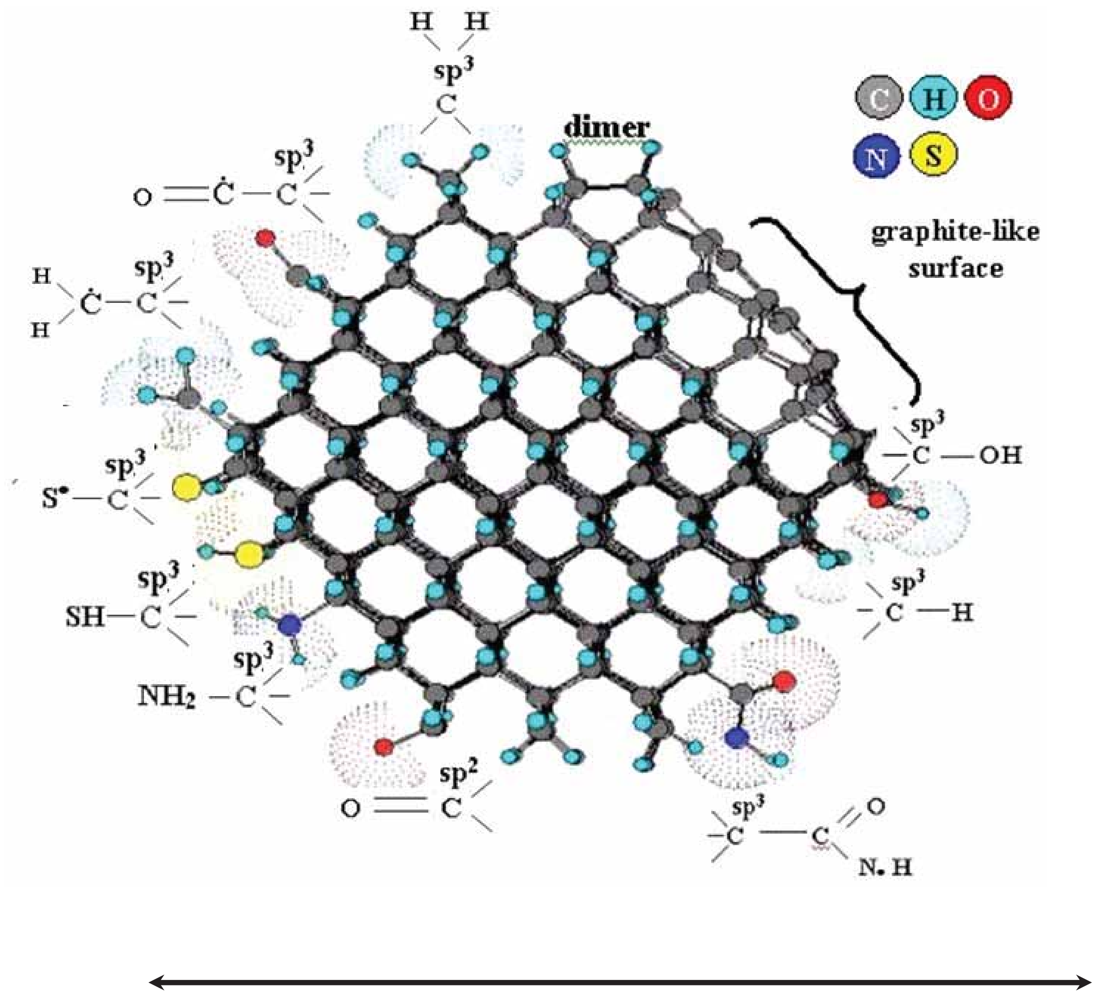
DETONATION NANODIAMOND



Shenderova, O. A. et al. Critical Reviews in Solid State and Materials Sciences 2002, 27,227-356.

“NANODIAMOND”

Schematic illustration of diamond particle with different surface groups and surface reconstructions. Structure was optimized using semiempirical quantum chemistry method PM3



5 nanometers

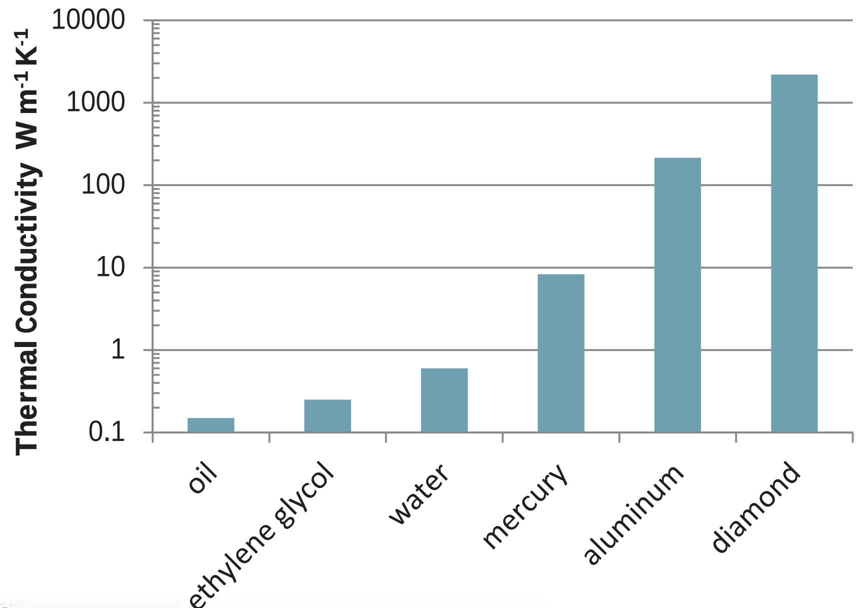
- Facts about nanodiamond:
  - Available in bulk
  - Inexpensive (~ 2% adder)
  - Currently in use :
    - *Polishing ; hard drive heads*

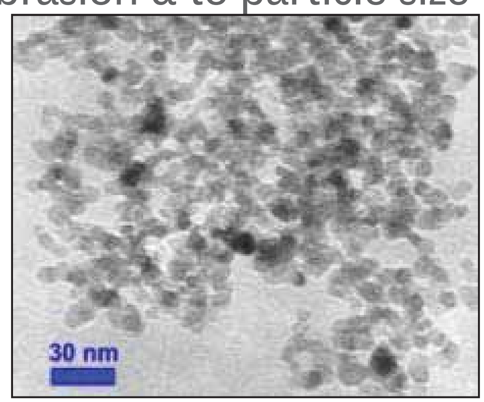
•Vanderbilt had 25,000 carats (~5 Kg) from two suppliers.

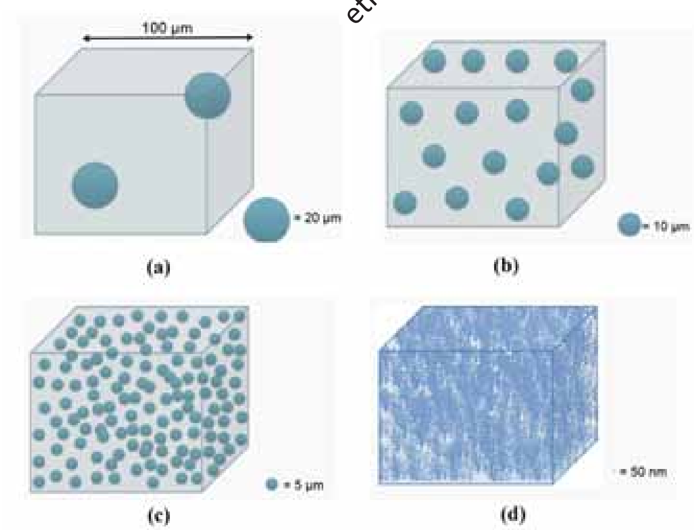
Nanodiamond as
a
commodity

NANODIAMOND BASED ADDITIVES ENHANCE THERMAL CONDUCTIVITY

- Diamond is Ideal Material
  - Highest Thermal Conductivity
  - Good Dielectric Properties
  - Biologically and Environmentally Friendly
- Nanoscale nanodiamond additives are so small:
  - Filters/small channels won't clog
  - Settling time α^{-1} to particle size
  - Abrasion α to particle size

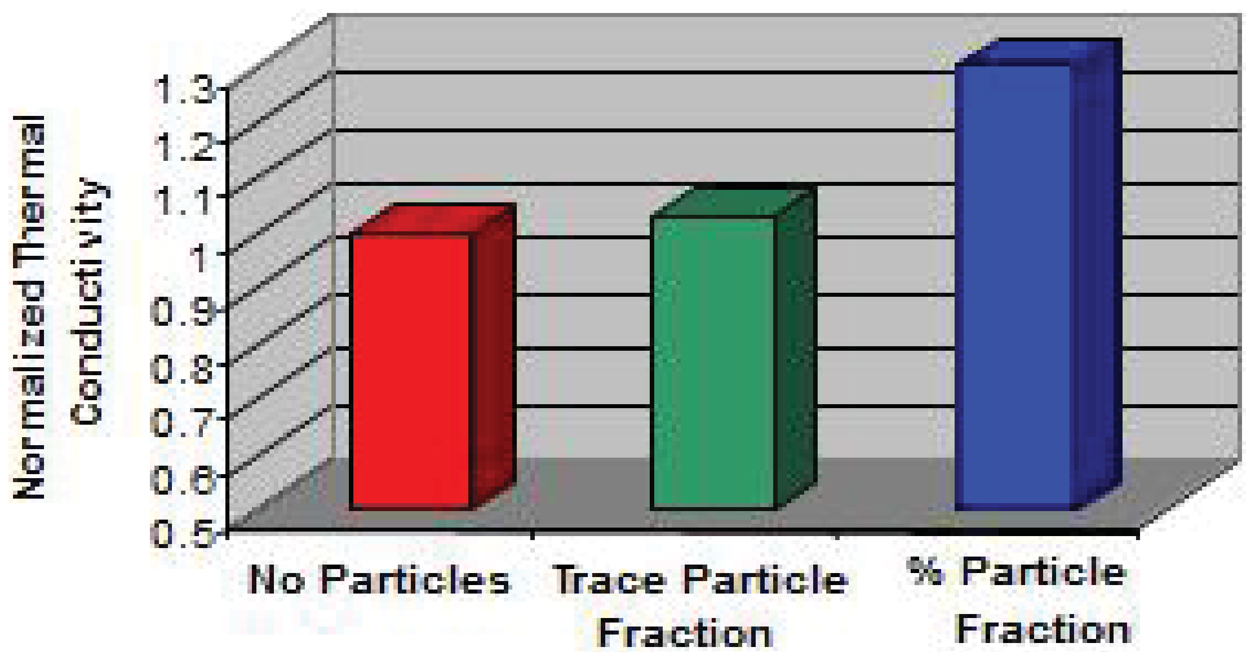






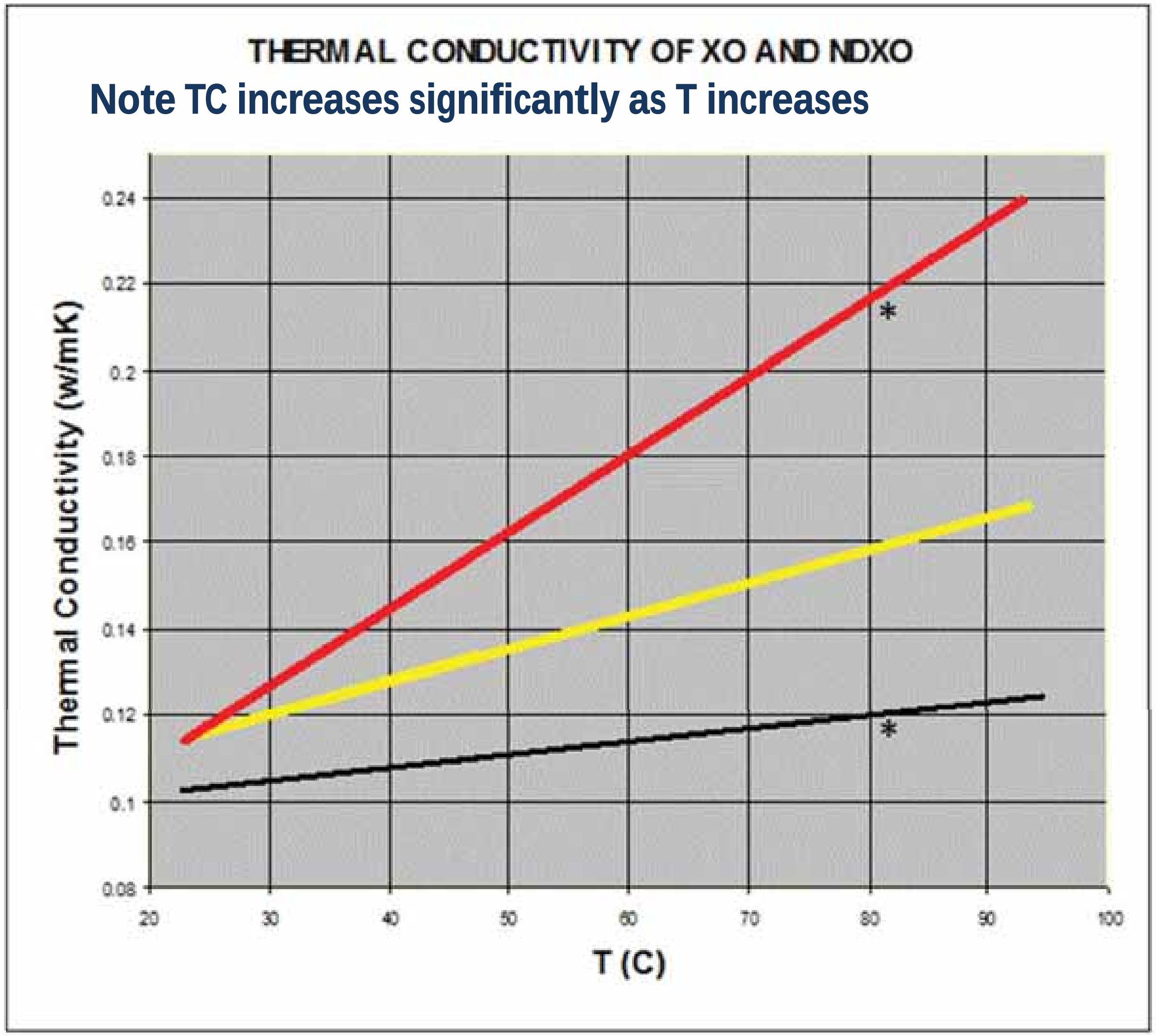
NANODIAMOND THERMAL CONDUCTIVITY

- Have seen increased thermal conductivity up to 25% for NDXO suspensions
- Established in-situ substation testing capabilities
- Study effects in real system



Development program with TVA – nanodiamond *in* Transformers

The thermal conductivity ***improves*** *as the system gets hotter*



NDXO 2

NDXO 1

XO

(different additive formulations)

Slope

S1:S2:S3

3e-4:8e-4:18e-4

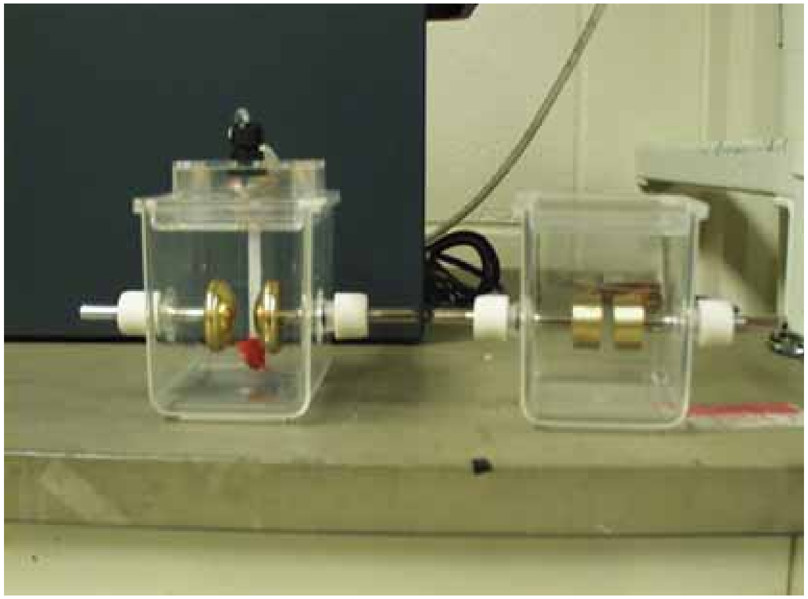
The rate of increase in TC as f(T) of NDXO 2 is *6X* that of plain XO

Performance improves as load increases

* ~80% higher TC

Dielectric Breakdown
Device and Measurement Standards

- Method
- Measurement Standards (ASTM D1816 & D877)



XO sample	*Trials*	*Breakdown Voltage (KV)*
11/21/2004	1	19.6
Room Temp = 23 C	2	27.6
D1816 Standard	3	24.4
	4	22.1
	5	24.1
	6	20.8
	7	22.3
	8	23.5
	9	21.2
	10	22
Average BV m		**22.76**
Stdev s		**2.259400117**
s/m		**0.099270655**

NDXO sample	*Trials*	*Breakdown Voltage (KV)*
11/21/2004	1	29.9
Room Temp = 23 C	2	31.6
D1816 Standard	3	34.6
	4	32.8
	5	31.5
	6	31.3
	7	33.4
	8	32.4
	9	33.3
	10	30.6
Average BV m		**32.14**
Stdev s		**1.425326473**
s/m		**0.044347432**

- ASTM D1816 standard shows that NDXO has a higher breakdown voltage than XO

Development program with TVA
Nanodiamond in transformers

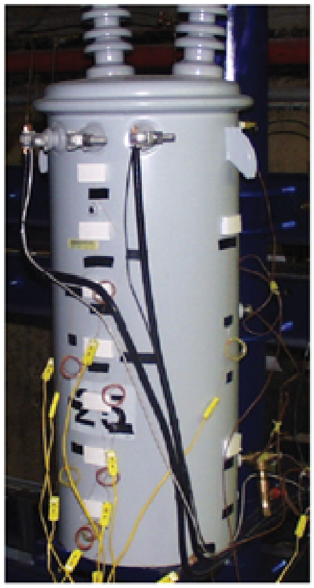
"A Novel Transformer Oil Additive to Extend Transformer Rating and/or Life"

Using nanometer sized, low cost sp^3 carbon (diamond) particles, i.e., particulate functionalized nanodiamond (ND), as an additive to transformer oil (XO), "NDXO", to enhance the TC and dielectric properties of the oil.

Tested in 25KW transformers

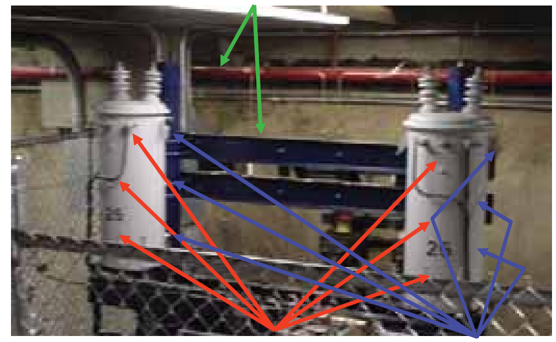
Development program with TVA
Nanodiamond in transformers

Pole-pig measurements



- nine external thermocouples measuring skin temperature
- three internal thermocouples measuring oil temperature near canister wall
- two identical 25kVA transformers (other than the oil) "feeding" off each other
- tests performed at 5kVA, 15kVA
- tests last for several days at each power level
- achieved some "anomalous" readings

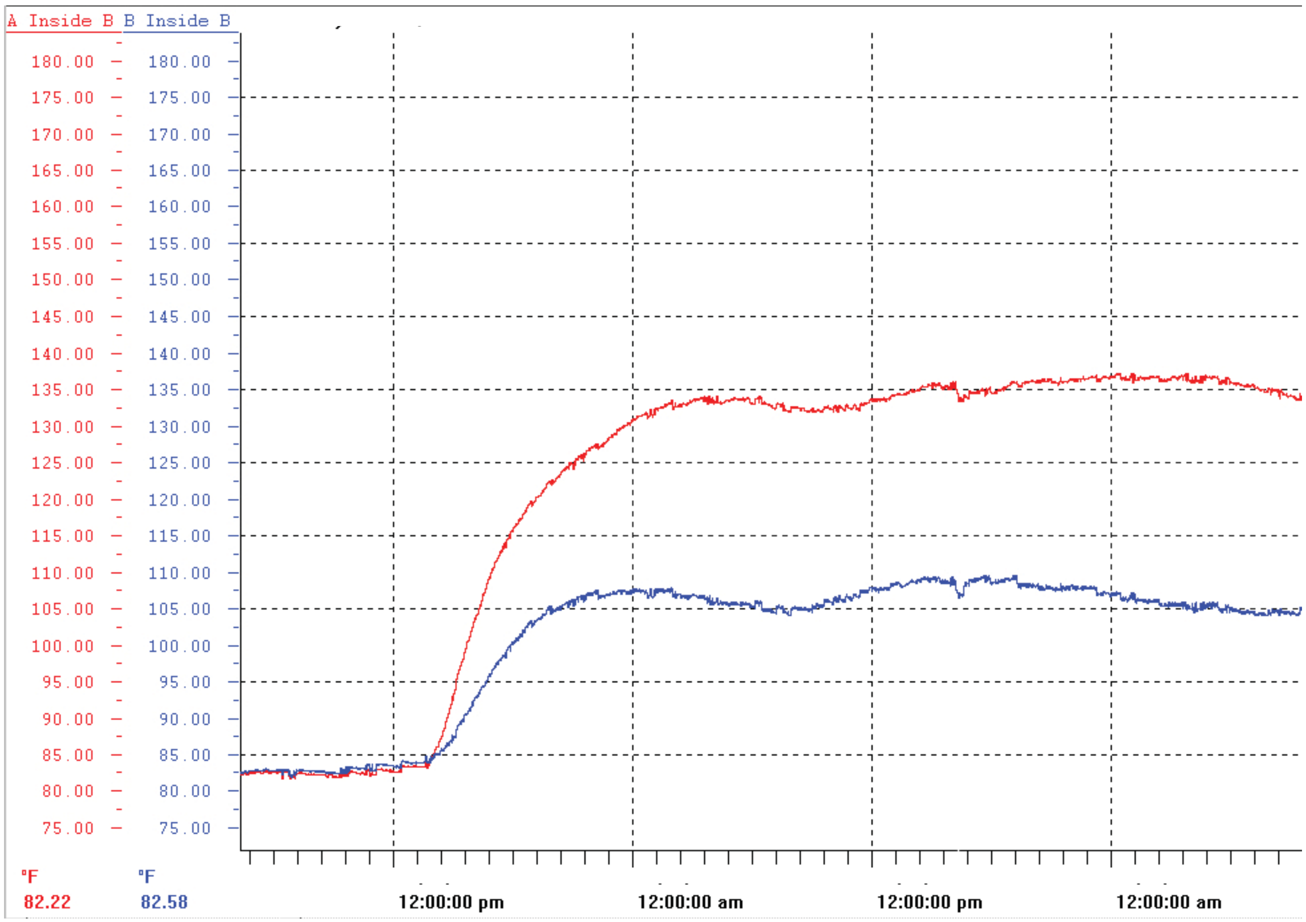
TVA **Thermocouple Distribution and Layout**



NDXO Thermal Testing

Bottom Internal Thermocouples

Transformers α & β



Test Power Level: 15 KW

Development program with TVA
Nanodiamond in transformers

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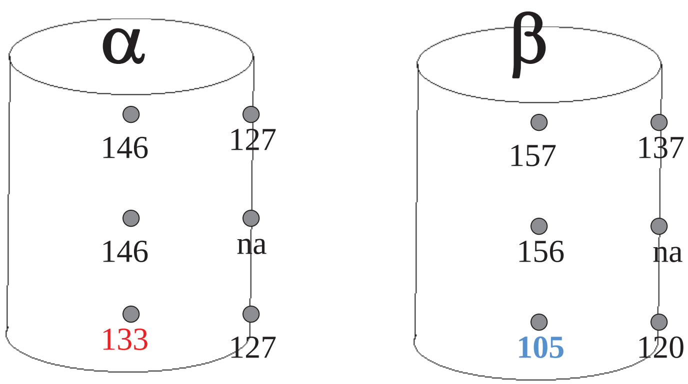
Tested in 25KW transformers

observed ~30^{o}F reduction at core

Transformer NDXO Thermal Testing

COMPARISON OF TEMPERATURES

Nominal temperatures; stabilized,energized > 24 hours



α – standard   β – NDXO

<u>Observations -</u>

Bottom β much cooler than bottom α

Bottom inside β cooler than skin b

(opposite in α)

Upper of β hotter than α

Differences in rise time

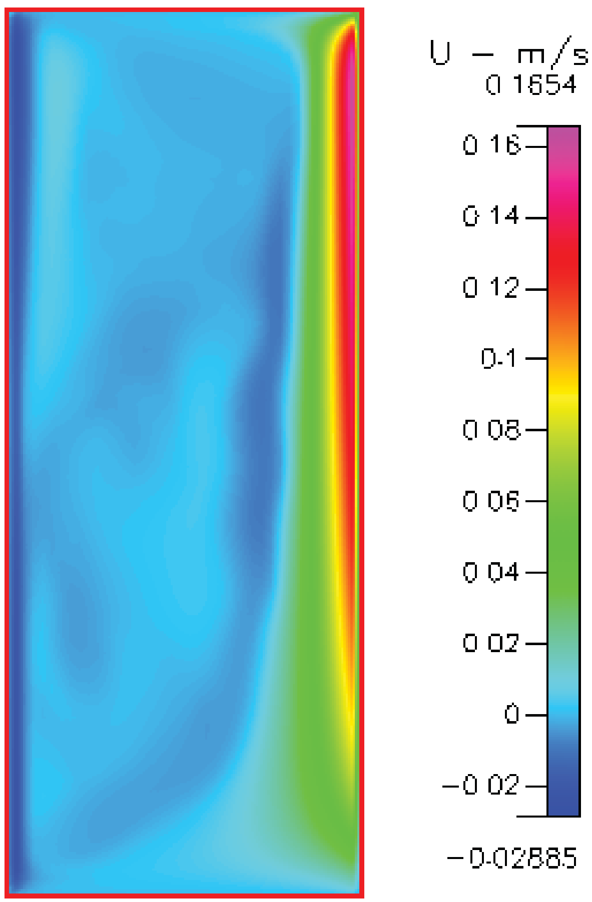
<u>Possible effects in play -</u>

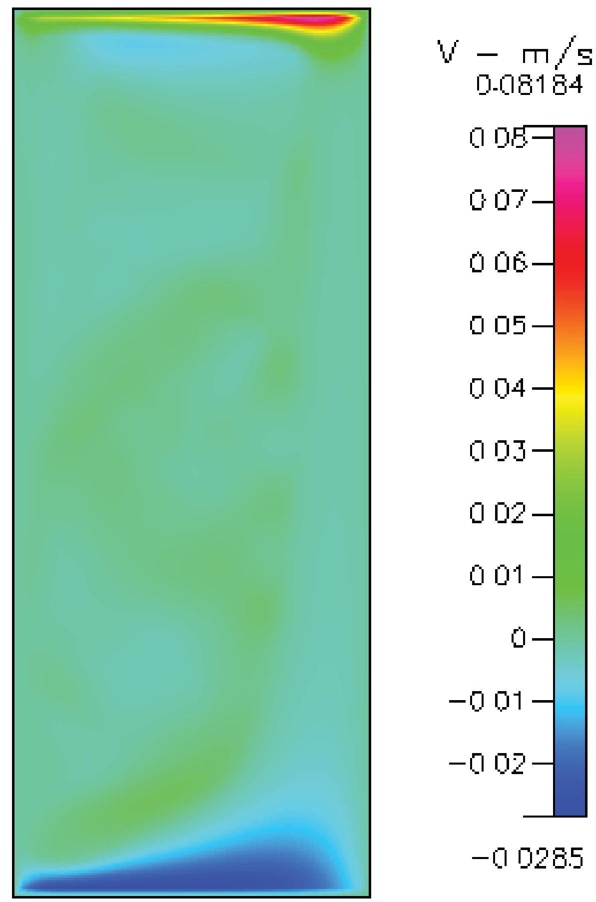
Convection

MODELING Heat Transfer Effects

- **Bulk fluid motion changes**
  - **Internal natural convection**
    - **Governs internal temperature distribution**
    - **Affected by property characterization**
  - **External natural convection**
    - **Affected by internal temperature distribution**
- **Property characterization changes**
  - **XO thermal conductivity and diffusivity**
  - **XO viscosity**

Velocity magnitude – convection issue





Nanodiamond process improvement

> *Deaggregation*

Disassociate clusters to *completely* seperate 5nm nanodiamonds

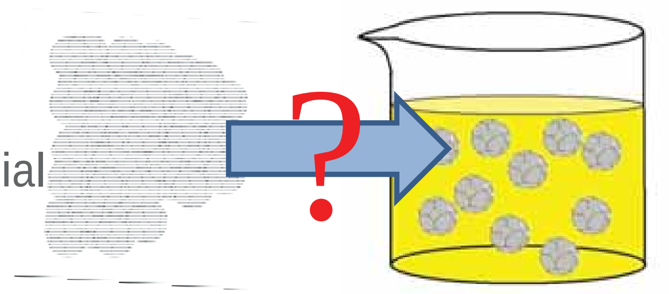
> *Functionalize*

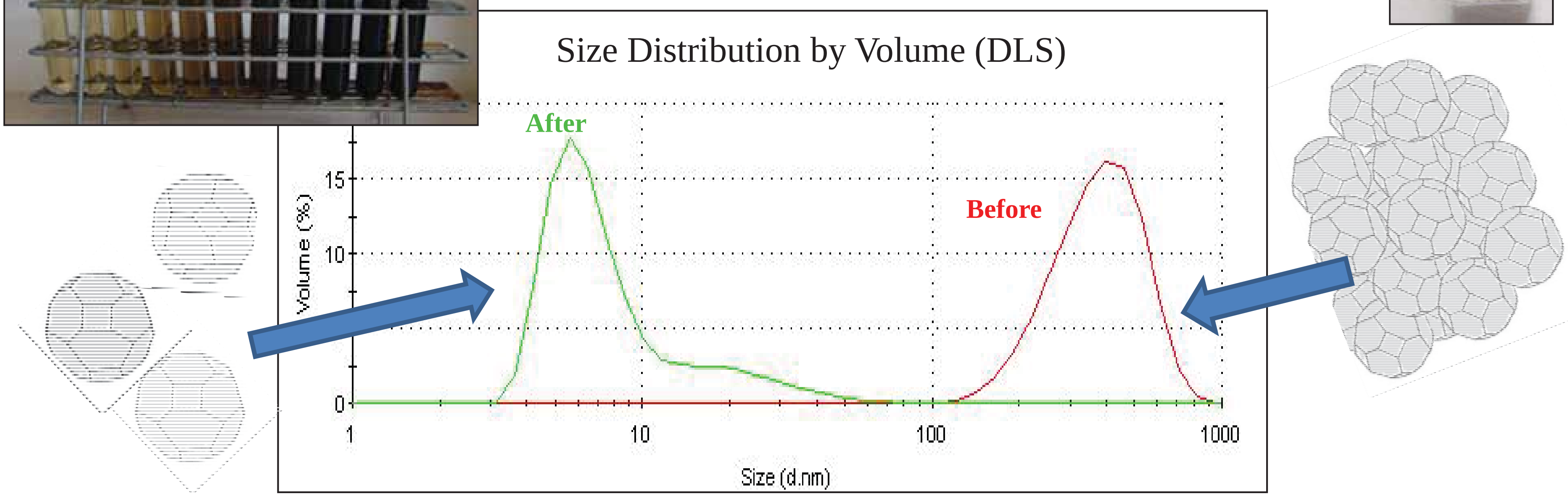
Chemically attach functional groups to the 5nm particles *compatible* with the host liquid

"Nanodiamond Nanofluids For Enhanced Thermal Conductivity: Stable, Static Nanodiamond Dispersions in Ethylene Glycol or Mineral Oil", ACS Nano (ID nn-2012-05664x), **Branson, Blake**; Beauchamp, Paul; Lukehart, Charles; Davidson, Jimmy

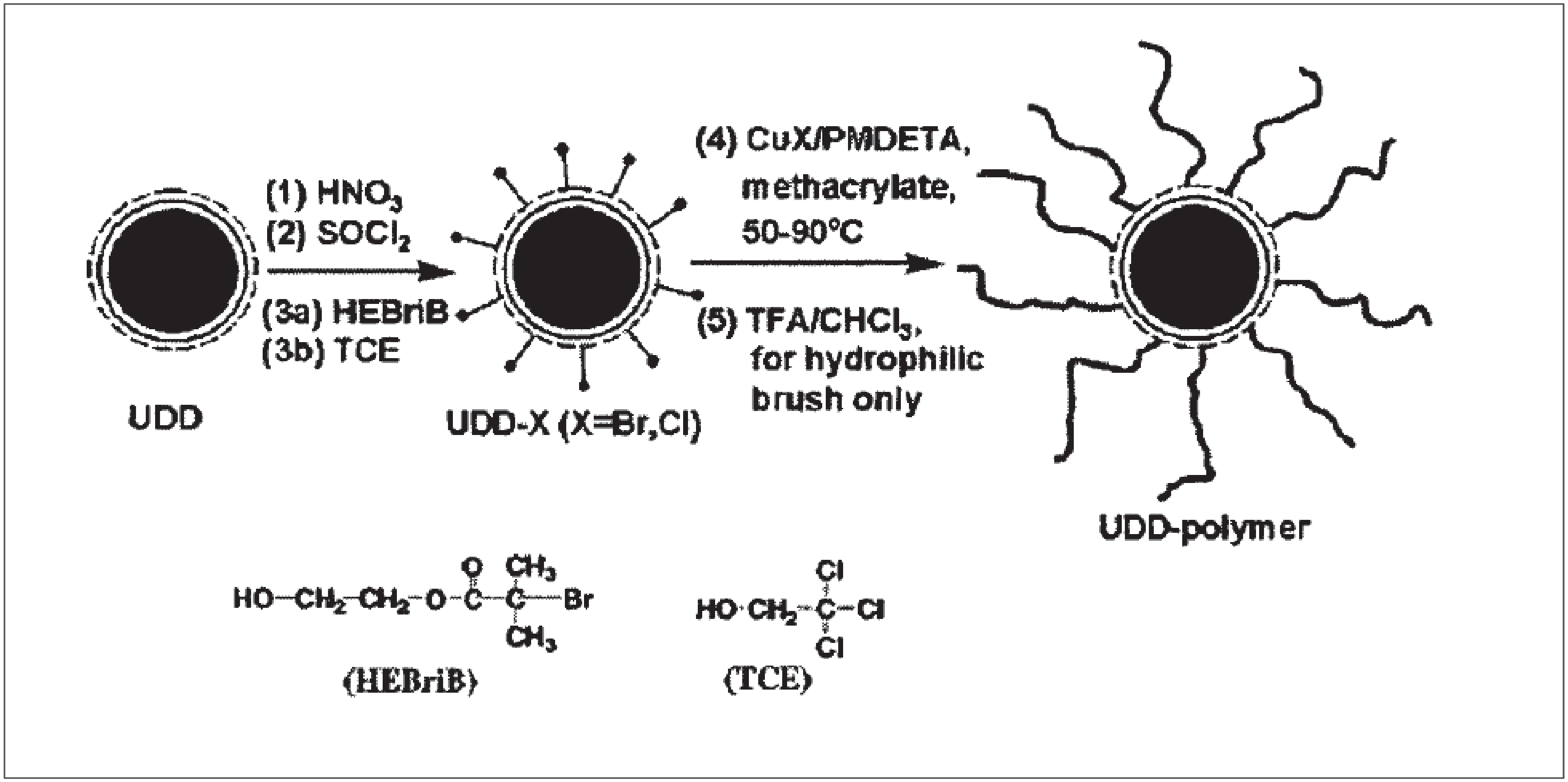
DE-AGGREGATION PROCESS ESTABLISHED

- Technology Platform
  - Well-dispersed suspensions
  - Highly Stable
  - Highly-compatible With host material





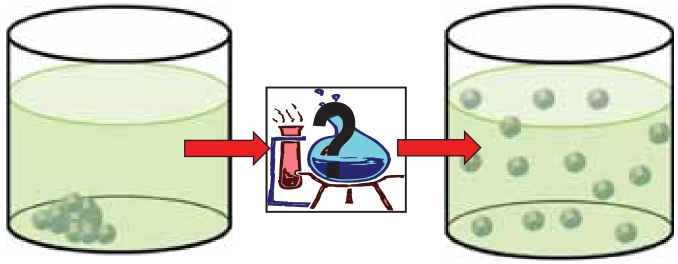
FUNCTIONALIZATION PROCESSES ESTABLISHED

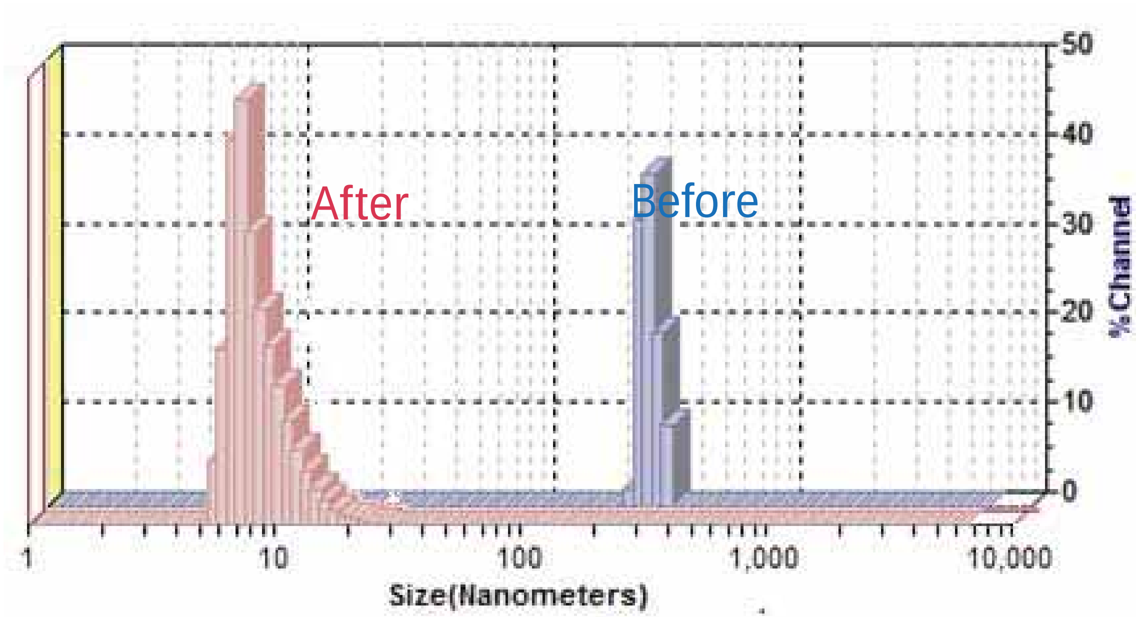


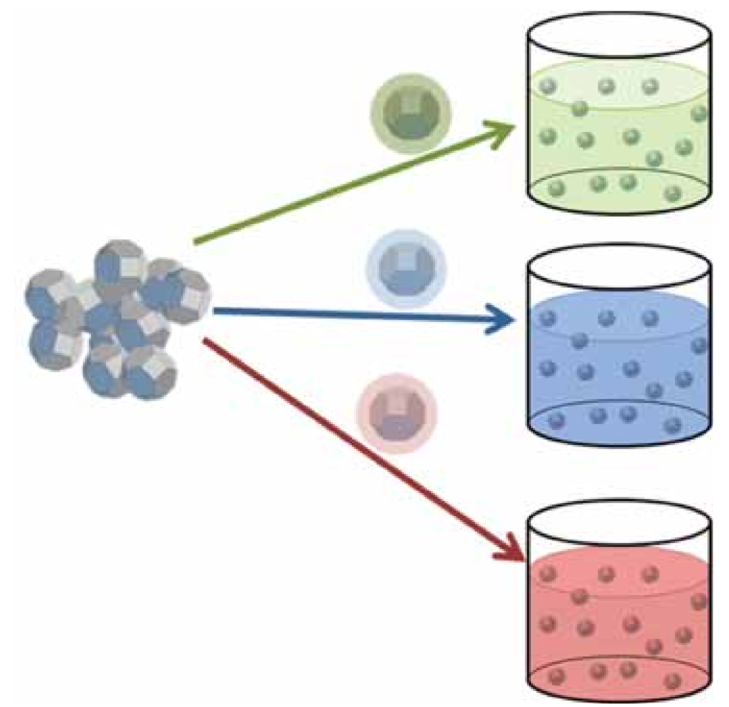
fDDN : functionalized Deaggregated Diamond Nanoparticles

PROCESSING UNLOCKS POTENTIAL

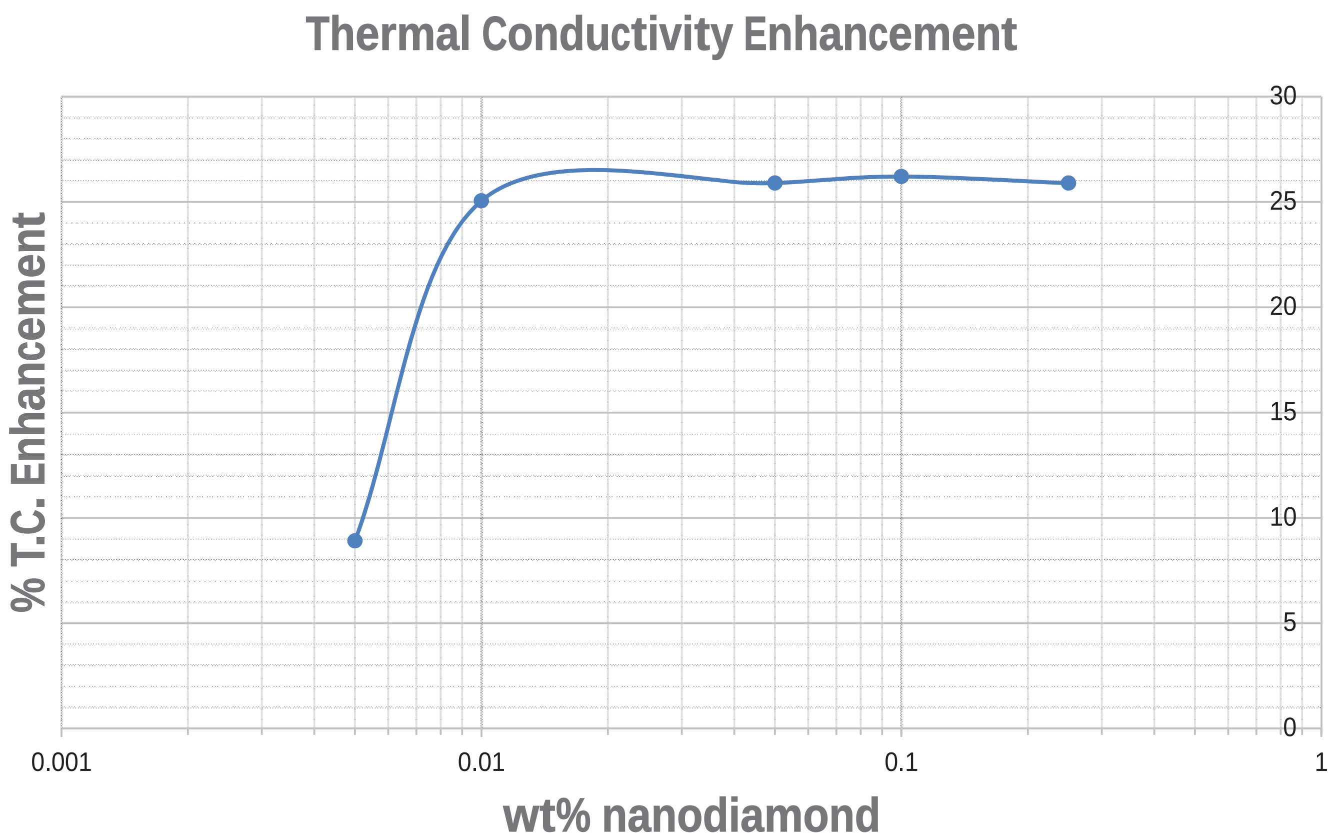
- Disaggregation & Chemical Modification
  - Reduces Micron-sized Clusters To Single Nanocrystals
  - Changes Surface Chemistry For Compatibility







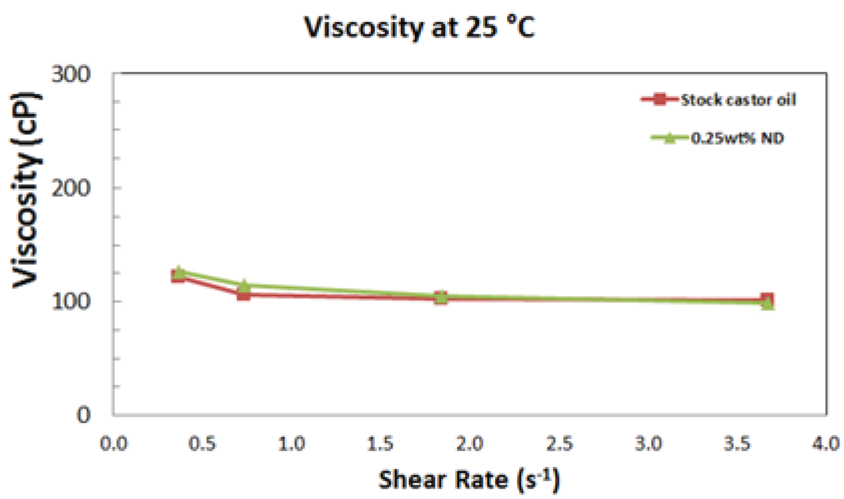
PERFORMANCE ENHANCEMENT : **fDDN** IN SOY OIL



- Strong Enhancement at Low Concentrations
- ***25% at 100 ppm***

Compatibility with Present Systems (in situ)

- **fDDN** Does Not Change Viscosity



- **fDDN** Will Not Clog Filters
  - Easily Passes Through Fine Filters (<1µm)
- **fDDN** Will Not Damage Fluid Handling Systems
- **fDDN** is Not Toxic and Not Abrasive

Compatibility with Present Systems (monitoring)

fDDN

- Will Not Affect Dissolved Gas Analysis
- Will Not Affect Karl Fischer Test
- Traditional Oil Analysis Tests (UOA) Do Not Detect Particles
- Particles Will Not Change Oil's Dielectric Properties

fDDN

Functionalized Deaggregated Diamond Nanoparticles

Nanodiamond

diamond particles ~ 5nm in size

dis-aggregated

dispersed

functionalized

“SO NOW”

?

A Practical Additive for Enhancing Properties of Materials*

We have a product derived from *nanodiamond* (diamond particles ~ 5nm in size, *dis-aggregated*, *dispersed* and *functionalized* for compatibility with host material) which, in small quantities, can be *added* directly to and significantly improve the thermal, strength, and dielectric properties without adverse effects on the host material.

* **fDDN** (Functionalized Deaggregated Diamond Nanoparticles) for High-Performance Fluid Additives

Example of Liquid Cooling System – Increasing Thermal Conductivity of ***Transformer Oil***

Jim Davidson, Ph.D
David Kerns, Ph.D.
Blake Branson, Ph.D
International FemtoScience, Inc.

FemtoSci℠
International FemtoScience, Inc.

Intellectual Property

- **FemtoSci™ has licensed the 2 original nanodiamond additive patents from Vanderbilt University**

- **FemtoSci™ has licensed the relevant patent related to functionalization aspects in liquid systems from Vanderbilt University**

- **FemtoSci™ with Vanderbilt has a patent pending on fDDN *in solids***

- **FemtoSci™ has a patent pending on fDDN to delay aging of transformer insulative paper**

Transformer Paper Concerns

Transformer paper plays a pivotal role in the insulating and filtering mechanisms of a transformer coil. As it ages:

CORE & COIL

- **Loss of dielectric isolation in terminals**
- **Infiltration of core and windings with harmful/dangerous contaminants**
- **Aggregate clogging and subsequent diminishment of convective oil flow**

Use of nanoparticle-based additives to the oil for extending the life of power transformers and related high power equipment that utilize oil-paper systems. The present invention pertains to the use of nanoparticle-based additives to the oil that may decrease the temperature by increasing the thermal conductivity. More particularly, the present invention pertains to **the use of nanoparticles to reduce the moisture content of the transformer paper (or other hydrophilic elements in the system), and perhaps that of the oil, thereby extending the useful life of the system.**

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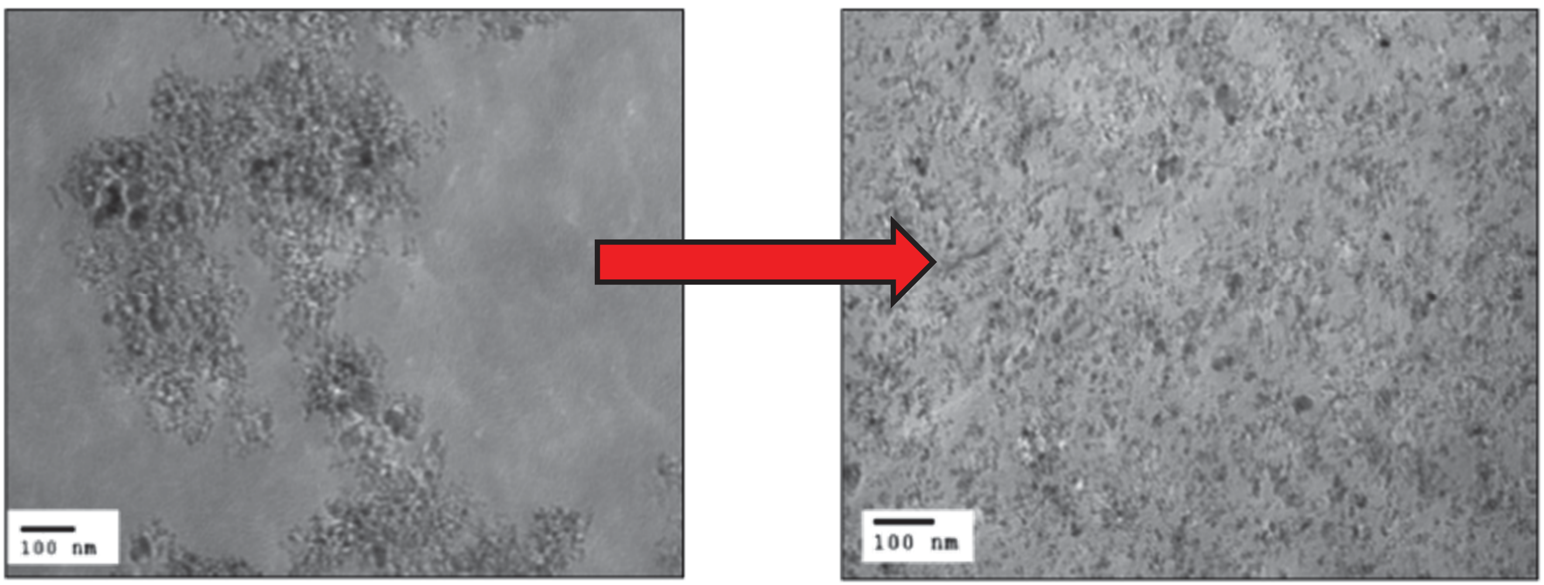
TITLE OF THE INVENTION-MATERIALS AND METHODS FOR REMOVING CONTAMINANTS FROM OIL-BASED SYSTEMS

NANOCOMPOSITES

- Demonstrated Good Dispersion of Modified Nanodiamond In:
  - Thermoplastics (PAN, PMMA, etc)
  - Thermosets (epoxies, vinyl ester resins)
  - Well-dispersed Products
  - Highly Stable



PERFORMANCE ENHANCEMENT

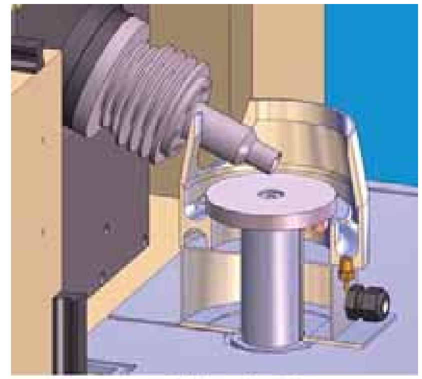
Functionalization of diamond nano particles mixed in plastic, find that <<0.1% diamond increases thermal conductivity by ~ > 10% without compromising electrical or mechanical properties.

Specifically, observed increase in TC from 0.200 W/mK in one commercial polymer system to 0.212 (6%) with addition of 0.01% fDDN

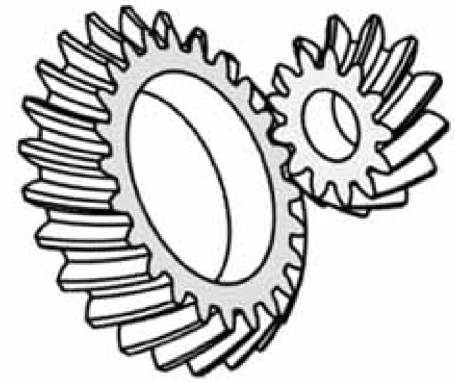
fDDN ADDITIVE DEPLOYED IN *LUBRICANTS*

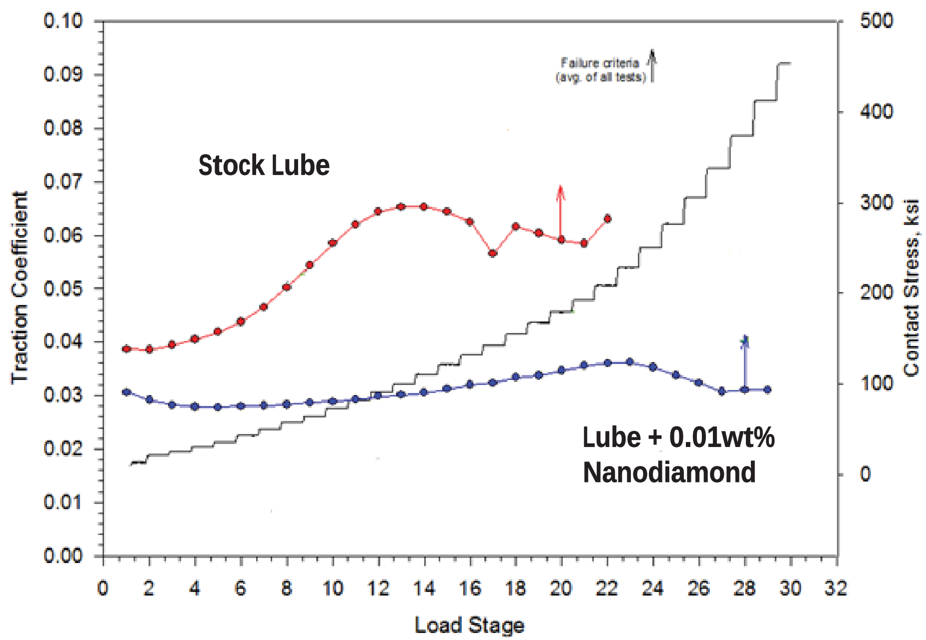
APPLICATION – GEARBOX LUBRICANT

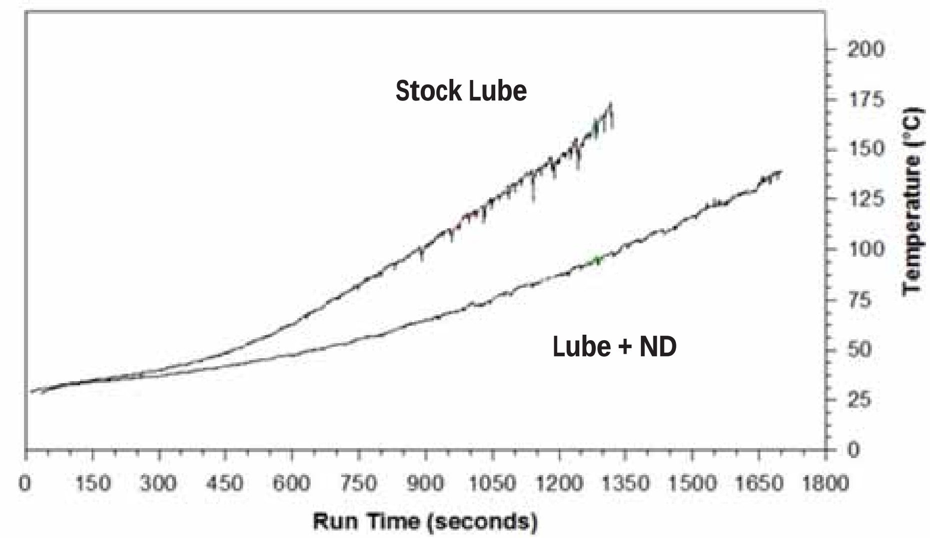
- Gearbox lube (DOD-PRF-85734)
- WAM Tests:
  - > 50% Reduction in Friction
  - > 70°C Lower Surface Temperatures
  - >100% Increase in Scuffing Stress



Source: Wedeven Associates







APPLICATION – GEARBOX LUBRICANT

Operational experience reveals that the gearboxes of modern electrical utility wind turbines at the MW level of rated power are their weakest-link-in-the-chain component. Small wind turbines at the kW level of rated power do not need the use of gearboxes since their rotors rotate at a speed that is significantly larger than utility level turbines and can be directly coupled to their electrical generators.

The typical design lifetime of a utility wind turbine is 20 years, but the gearboxes, which convert the rotor blades rotational speed of between 5 and 22 rpm to the generator-required rotational speed of around 1,000 to 1,600 rpm, commonly fail within an operational period of 5 years, and have to be replaced. That 20 year lifetime goal is itself a reduction from an earlier 30 year lifetime design goal.

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ADVANCES IN NANOSCIENCE/NANOMATERIALS AND APPLICATION TO THE GRID

NANOMATERIALS

NANOPARTICLES

ADDING B TO A TO IMPROVE A's PROPERTIES

STRENGTH, THERMAL, ELECTRICAL, etc.

With the right particulate, at the nanoscale, can get enhanced effects that are well beyond simply additive

[ppm gets xx% improvement]

Understand this, develop this and can move existing materials:equipment:systems into new operational domains without 'overhauling' the entire macro-complex

Materials Innovation Workshop at ORNL

Plenary: Materials Development Overview

ADVANCES IN NANOSCIENCE/NANOMATERIALS AND APPLICATION TO THE GRID

For example -

APPLICATION OF NANO-DIAMOND TO ENHANCE TRANSFORMER OIL

Jim Davidson
Dave Kerns

(Vanderbilt)

THANK YOU

Q & A