Applications of Induction Heating Enabling Advancement in Materials Science

Presented at Colorado School of Mines
September 28, 2017

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www.fluxtrol.com

Overview

- What Is Induction Heating?
- Applications of Induction Heating
- Case Stories –
  – Additive Manufacturing
  – Cancer Treatment
  – Organ Transplantation
  – Deep Space Exploration
- Conclusions

What is Induction Heating?

Induction Heating is a Contactless Heating Method of bodies, which absorb energy from an **Alternating Magnetic Field**, generated by Induction Coil (Inductor)

There are two mechanisms of energy absorption:

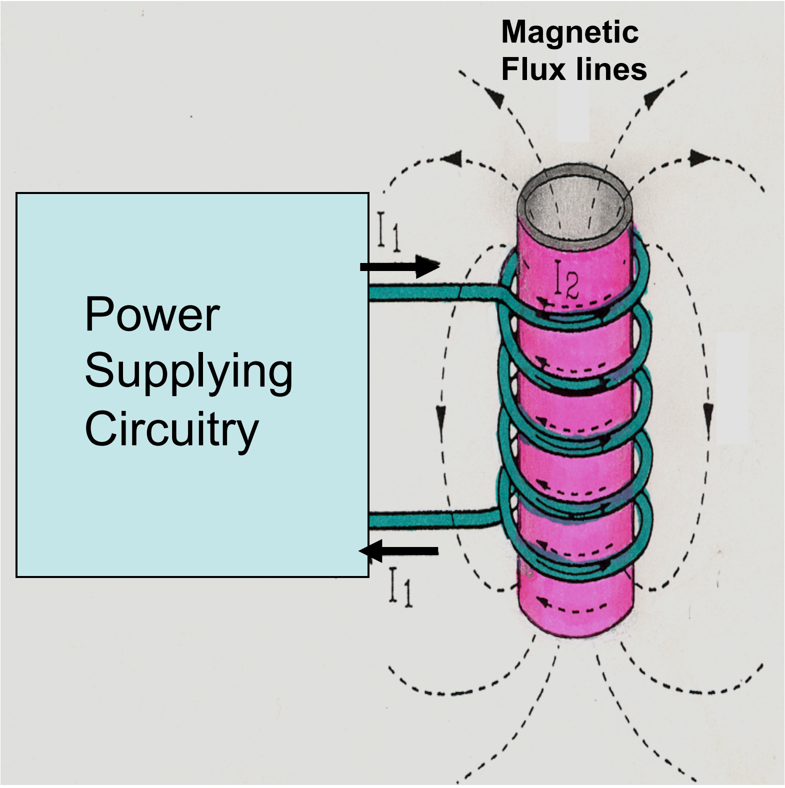
- generation of close-loop (eddy) currents inside the body which cause heating due to electrical resistance of the body material

- hysteresis heating (for magnetic materials ONLY!) due to a friction of magnetic micro volumes (domains), which rotate following orientation of external magnetic field

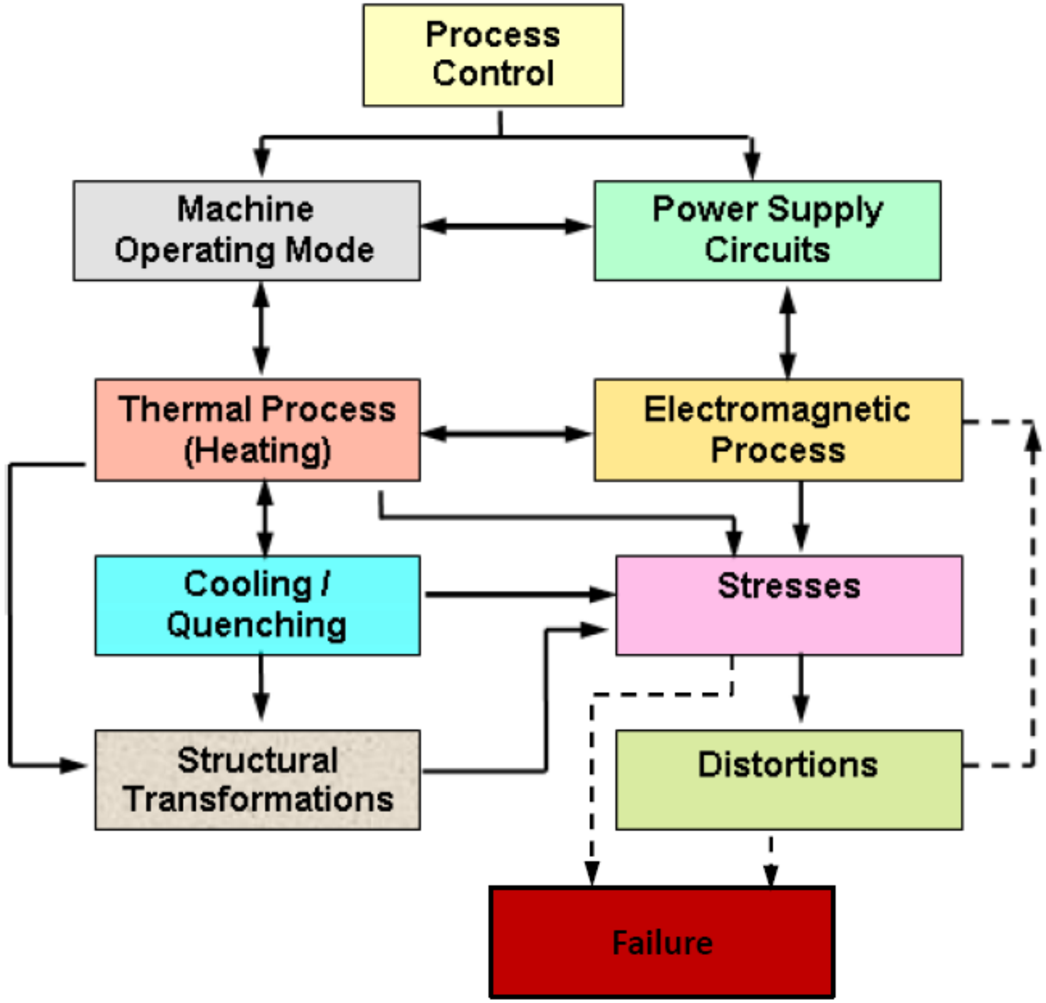
Principle of Induction Heating

Chain of phenomena:

1. Power supply delivers current (I1) to induction coil
2. Coil currents (ampere-turns) generate magnetic field. Lines of field are always closed (law of nature!) and each line goes around the current source – coil turns and workpiece
3. Alternating magnetic field flowing through the part cross-section (coupled to the part) **induces** voltage in the part
4. Induced voltage creates eddy currents (I2) in the part flowing in direction opposite to the coil current where possible
5. Eddy currents generate heat in the part



Mutually Coupled Phenomena in Induction Heating Process



Specific Features of Induction Heating

- Heat generation occurs inside the part
- Heating is contactless
- Method can provide very high power densities
- Heating may be highly selective in the depth and along the surface
- Any processing atmosphere (air, protective gas, vacuum)
- Very high temperatures may be created

Specific Features of Induction Heating Ctd.

- Stand-by losses of equipment are very low
- Fast start-up (instantaneous in most cases)
- Heating may be easily programmed and automated
- No contamination of treated material may be provided (important for medical material, semiconductors, ultrapure metals, etc.!)
- Environmentally friendly
  - If electricity is generated by renewable resources, zero greenhouse gas process!

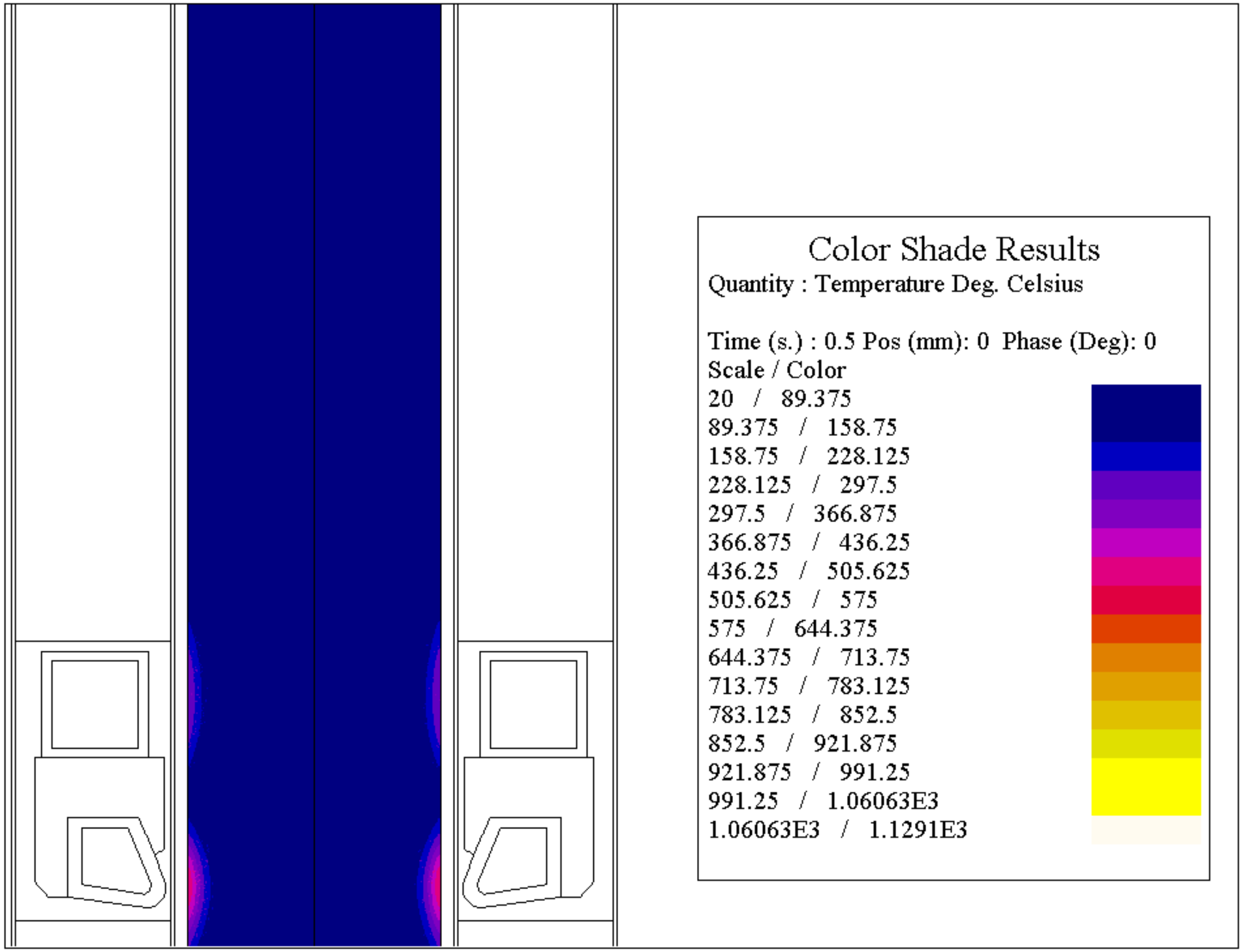
Where Is Induction Used?

- Automotive
- Off-Highway/Construction
- Aerospace
- Metallurgical Plants
- Oil & Gas Component Manufacturing
- Food/Drug Packaging
- High Tech Applications
  - Focus of today's talk

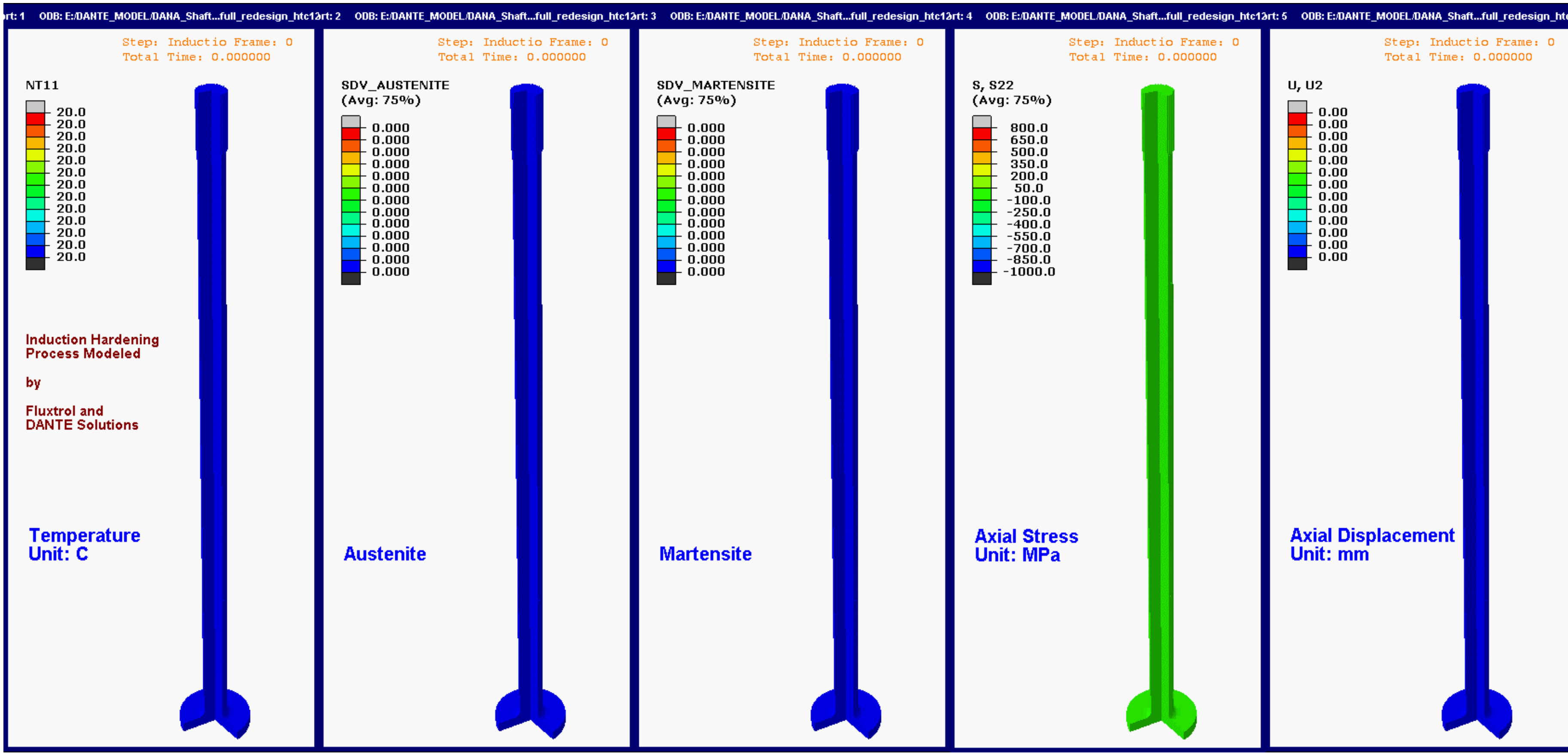
Major Applications of Induction Heating of Steel

- Melting
- Continuous casting
- Investment Casting
- Galvanizing
- Forging & Forming
- Preheating
- Welding
- Shrink-fitting
- Hard facing/ coating
- Bonding
- Brazing
- Heat Treatment

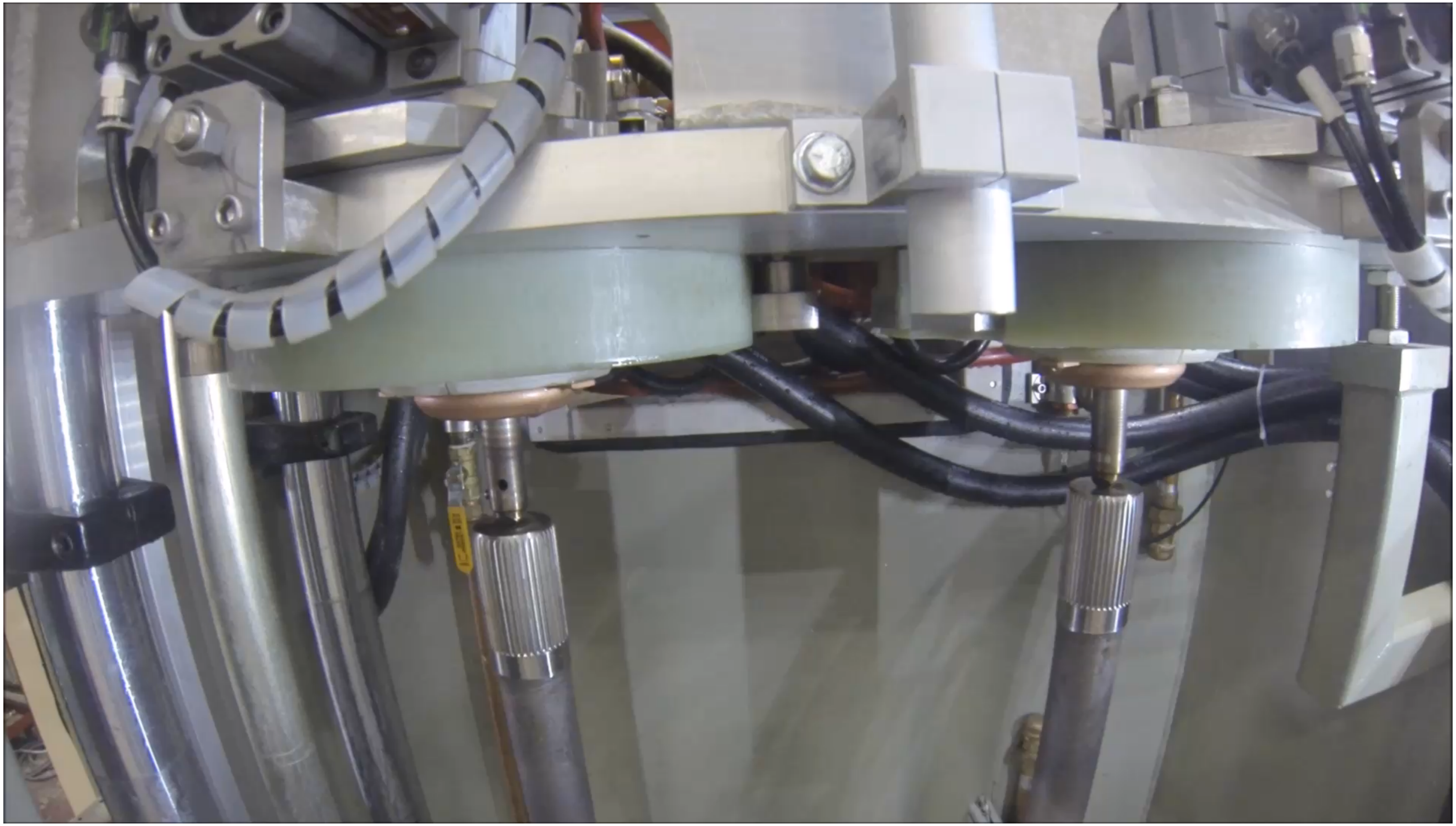
Axle Scan Hardening Model



More Advanced Model



Real Axle Scan Hardening Process



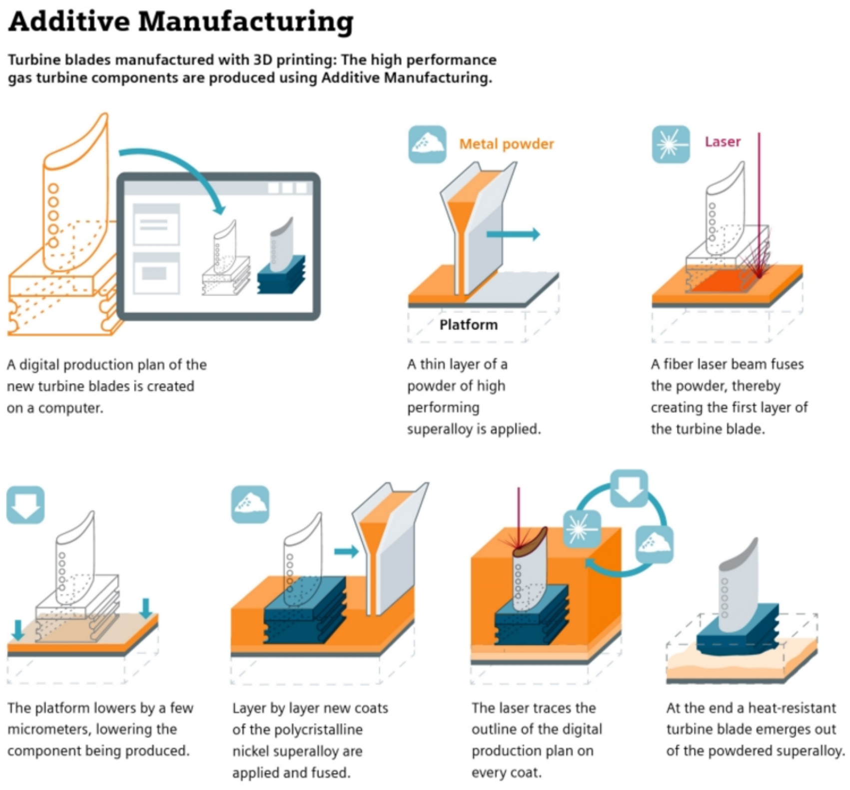
Video Courtesy of Inductoheat (www.inductoheat.com)

What is Additive Manufacturing?

- "**A**dditive **M**anufacturing (**AM**) is an appropriate name to describe the technologies that build 3D objects by ***adding*** layer-upon-layer of material, whether the material is plastic, metal, concrete or one day…..human tissue."
  - Source – www.additivemanufacturing.com
- For today's talk, we will limit ourselves to metallic components used for high temperature, high performance applications
  - Layered Manufacturing
  - Additive Fabrication

Applications of Induction Heating in Additive Manufacturing

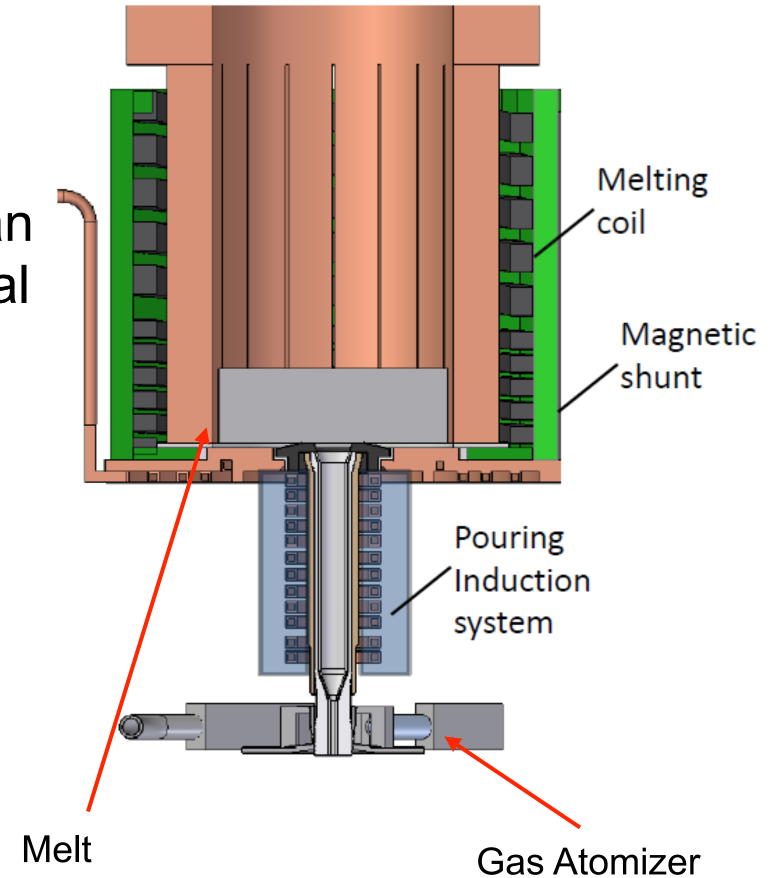
- High Quality Powder Production
- Primary Heat Source for Applications such as Hard Facing
- Heating for Control of Residual Stresses during AM Process
- Post-AM Heat Treatments



https://www.siemens.com/innovation/en/home/pictures-of-the-future/industry-and-automation/additive-manufacturing-3d-printed-gas-turbine-blades.html

High Quality Powder Production

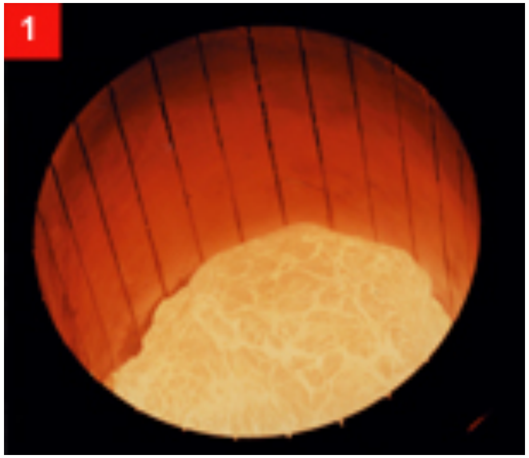
- Additive manufacturing requires precise particle size distributions with precise chemistries
- Small levels of impurities in the powder can have significant adverse effects on the final component properties
- Due to this, cold crucible melting is often used for titanium, titanium alloy and nickel based alloy powder production
- In cold crucible melting, a water cooled crucible is the only thing directly exposed to the metal, which forms a frozen skull with liquid metal inside preventing contamination of the melt allowing for precise chemistry
- Several other contactless inductive melting methods are use powder production



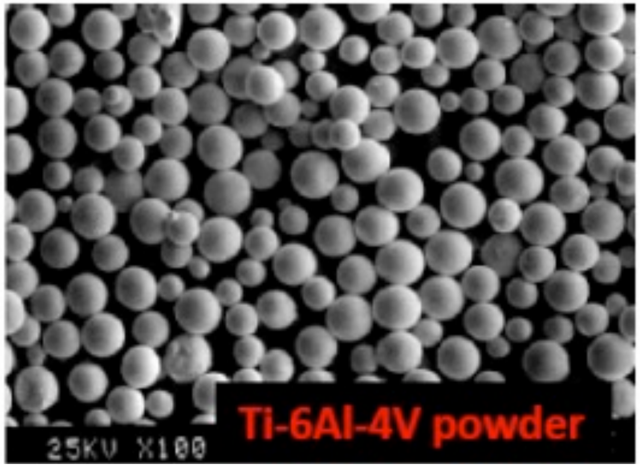
"Advances in Ti Alloy Powder Production by Close-Coupled Gas Atomization" – Heidloff, et. al. PowderMet 2011

Process Images

http://web.ald-vt.de/cms/vakuum-technologie/anlagen/cold-crucible-vim/



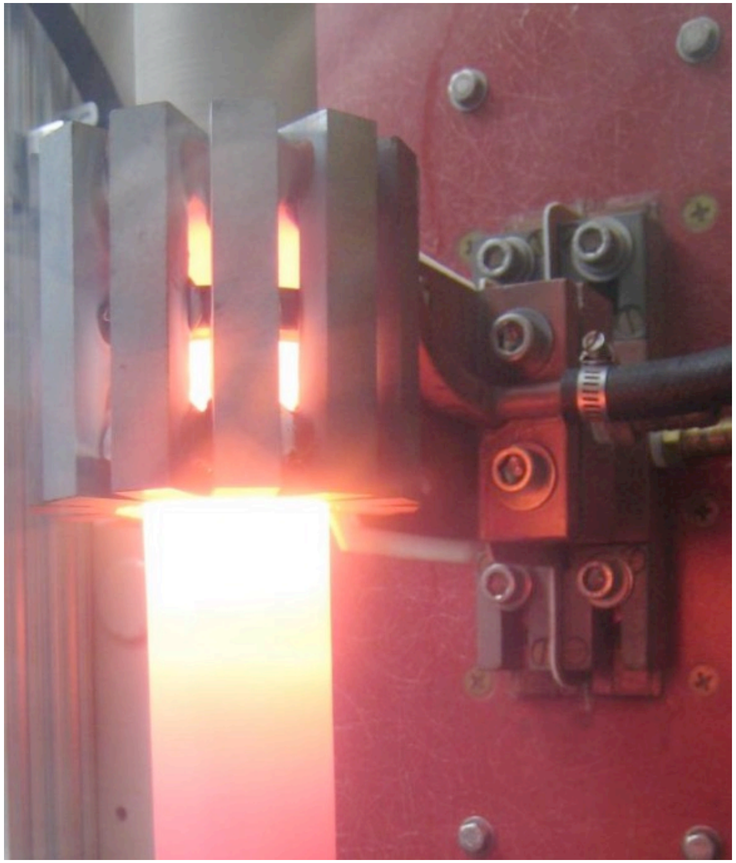
Fluxtrol Photo of Titanium Skull after Bottom Pouring



“Advances in Ti Alloy Powder Production by Close-Coupled Gas Atomization” – Heidloff, et. al. PowderMet 2011

Induction Hard Facing

- Often used to simultaneously improve corrosion and wear resistance of massive components
- A powder made of a high value material is applied to the surface of a large component made of less expensive material or material with desired bulk properties
- The surface of the less expensive material is heated using induction heating, melting the powder applied to the surface
- Melting from the base metal out significantly improves the product quality and consistency compared to surface energy deposition and enables formation of thicker layers protective layers



Progressive melting of corrosion resistant layer on the surface of a steel component for the oil and gas industry

Cancer Treatment

- Proper delivery of elevated temperatures (hyperthermia) has been proven to have beneficial effect in the treatment of cancer, especially when combined with radiation and/or chemotherapy
- Coupling of Radio Frequency (RF) energy into the body for medical hyperthermia is common
- High frequencies (microwave range) are good for focused heating of superficial/near surface tumors due to high absorption in tissue and short wavelength
- Mid-range radio frequencies (70-150MHz) penetrate to body core if used in multi-antenna phased arrays, but heat large regions (whole pelvis) due to long wavelength
- Low radio frequencies (induction heating) have good potential for treating deep seated tumors, especially using a susceptor inserted in the region where heating is desired (tumor)
- The challenge is to heat the tumor region in a controlled manner to a sufficient temperature for therapeutic effect without exposing too much healthy tissue to toxic levels of heat

Induction Heating for Cancer Treatment using Interstitial Rods

- First human trials in the 1970's thru early 1990's were conducted using an array of interstitial metal needle or seed implants in the tumor for heat delivery

System designed in 1970's by Paul Stauffer at University of Arizona

Clinical Trial Results

● *Phase I/II Clinical Trials*

INTERSTITIAL IRRADIATION VERSUS INTERSTITIAL THERMORADIOTHERAPY FOR SUPRATENTORIAL MALIGNANT GLIOMAS: A COMPARATIVE SURVIVAL ANALYSIS

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Purpose: To compare the survival of two groups of patients with supratentorial malignant gliomas who were treated on two sequential protocols with either interstitial thermoradiotherapy or with interstitial irradiation without hyperthermia.

Methods and Materials: Between 1988–1992, patients with anaplastic astrocytoma or glioblastoma multiforme were treated at the University of Arizona on a Phase I/II protocol of interstitial thermoradiotherapy with ferromagnetic seeds. The treatment protocol consisted of debulking surgery, a course of external beam radiotherapy and hyperthermia given immediately before and after brachytherapy. The survival of patients so treated was compared with that of a similar group of patients treated with interstitial brachytherapy alone at the Barrows Neurological Institute between 1982–1990.

Results: Twenty-five patients with primary tumors treated at the time of initial presentation with thermoradiotherapy were compared with a control group of 37 patients treated with interstitial brachytherapy alone. All primary patients were followed for a minimum of 34 months post implant. Multivariate analysis based on proportional hazards models showed that hyperthermia ($p = 0.027$), patient age ($p \leq 0.00001$) and histology (anaplastic astrocytoma vs. glioblastoma multiforme, $p = 0.0017$) were the only factors significantly associated with survival in this data set. From the fitted model, the hazard of dying when treated with hyperthermia was .53 times (95% confidence intervals 0.29–0.94) than that of the control group. In addition, we treated a small group of patients with recurrent tumors (13 with brachytherapy alone, and eight with thermoradiotherapy) and found no survival difference ($p = 0.62$).

Conclusion: Within the constraints of the selection factors and the different treatment parameters used in these studies, we conclude that an interstitial thermoradiotherapy boost confers a statistically significant survival benefit to patients with primary high grade gliomas when compared to interstitial brachytherapy alone.

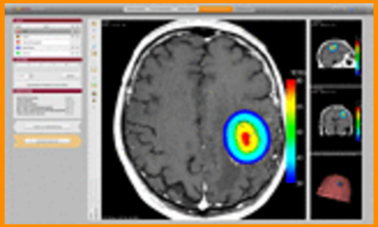
Table 2. Estimated survival (and 95% confidence interval) in primary patients

Time point (months)	Interstitial brachytherapy	Interstitial thermoradiotherapy
12	0.53 (0.36, 0.70)	0.80 (0.64, 0.96)
24	0.18 (0.048, 0.30)	0.48 (0.28, 0.68)
36	0.12 (0.0093, 0.23)	0.36 (0.17, 0.54)
48	0.12 (0.0093, 0.23)	0.27 (0.089, 0.44)
60	0.12 (0.0093, 0.23)	0.13 (0.00, 0.34)
Median survival (months)	13.3	23.5

- Median survival significantly better than today's treatments for GBM in USA
- Treatment did not gain FDA approval due to some acute toxicities during the trials and high surgical effort required to implant catheter arrays

Magforce AG Magnetic Nanoparticle Hyperthermia System

- Has EU approval for treatment of GBM
- Currently available at 6 centers in Germany
- 1 System currently installed in US (Seattle, WA) with a goal of conducting a clinical trial for prostate cancer
- System produces lower survivability results compared to Ferroseed trials, but with fewer acute toxicities
  - Some differences in radiation protocols and patient populations, not 100% apples to apples comparison



NanoPlan®

NanoActivator®

http://www.magforce.de/en/produkte/nanotherm.html

Comparison of Hyperthermia Trials for Brain Cancer

Sneed Trials

Int. J. Radiation Oncology Biol. Phys., Vol. 40, No. 2, pp. 287–295, 1998

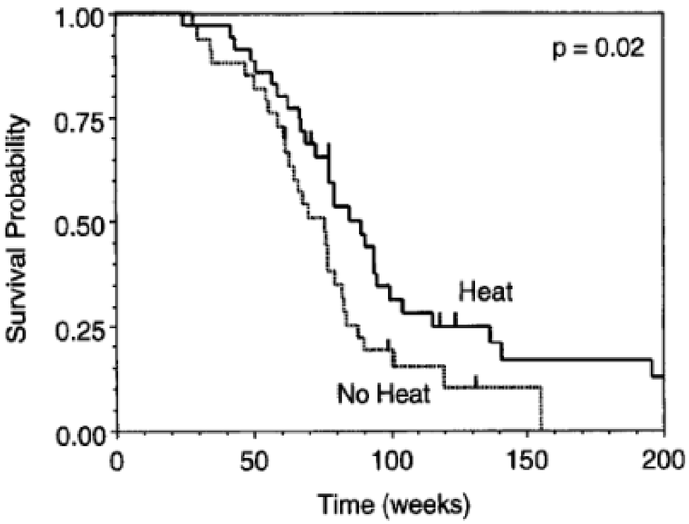


Fig. 2. Kaplan–Meier survival curves for evaluable patients who actually had brachytherapy boost, comparing 33 ''no heat'' patients to 35 ''heat'' patients (log rank $p = 0.02$). The median survival was 76 weeks for ''no heat'' patients vs. 85 weeks for ''heat'' patients with 2-year survival probabilities of 15% vs. 31%, respectively.

Magforce Trials

J Neurooncol (2011) 103:317–324

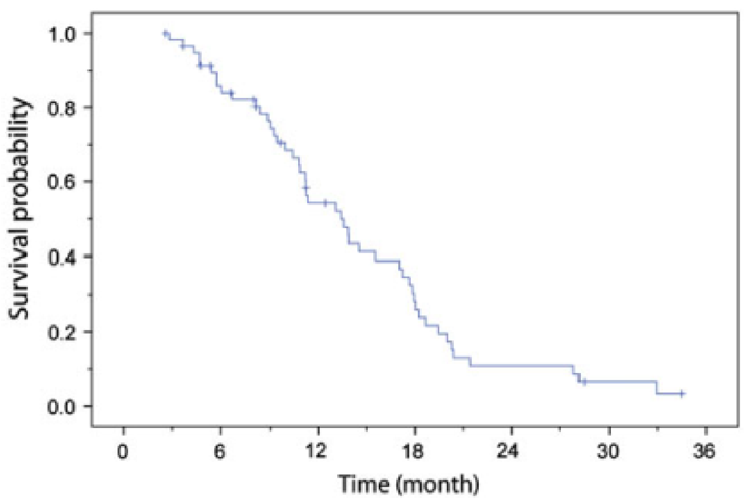


Fig. 2 Overall survival after diagnosis of first tumor recurrence/progression (OS-2) of 59 glioblastoma patients treated with combined thermo-/radiotherapy for reintervention

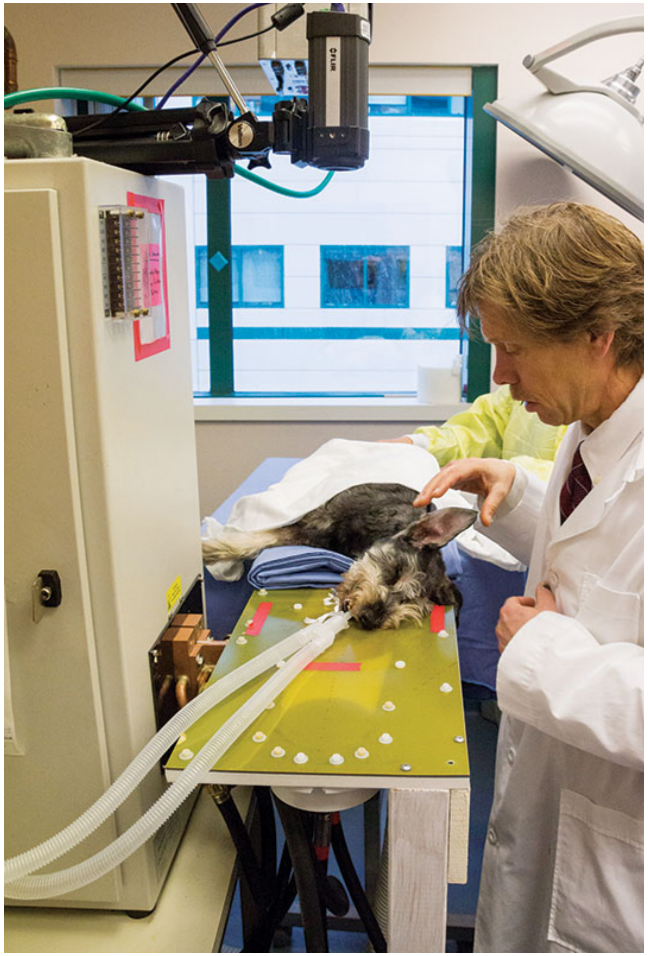
Some differences in radiation protocols and patient populations, not 100% apples to apples comparison

Background on Fluxtrol/AMF Lifesystems Activities in the Medical Field

- Fluxtrol, Inc. is a company founded in 1981 specializing in the control of alternating magnetic fields from DC to the low MHz frequency range
  - Materials for magnetic flux control
  - Process and Induction Coil Optimization
  - Cooperative development of new technologies
- Fluxtrol began working on applications for magnetic hyperthermia in the late 1990’s.
  - Heating of Interstitial Self-regulating Thermal Rods for prostate cancer with Ablation Technologies
- In 2001, Fluxtrol began working in the area of magnetic nanoparticle hyperthermia with the Triton Systems group (through several evolutions, became the technology being utilized at Dartmouth for magnetic hyperthermia)
- As activity and potential for the market increased, AMF Lifesystems (AMF) was founded as a stand alone company in 2008 to develop systems for medical therapies utilizing alternating magnetic fields

AMF Systems already Built for Cancer Research

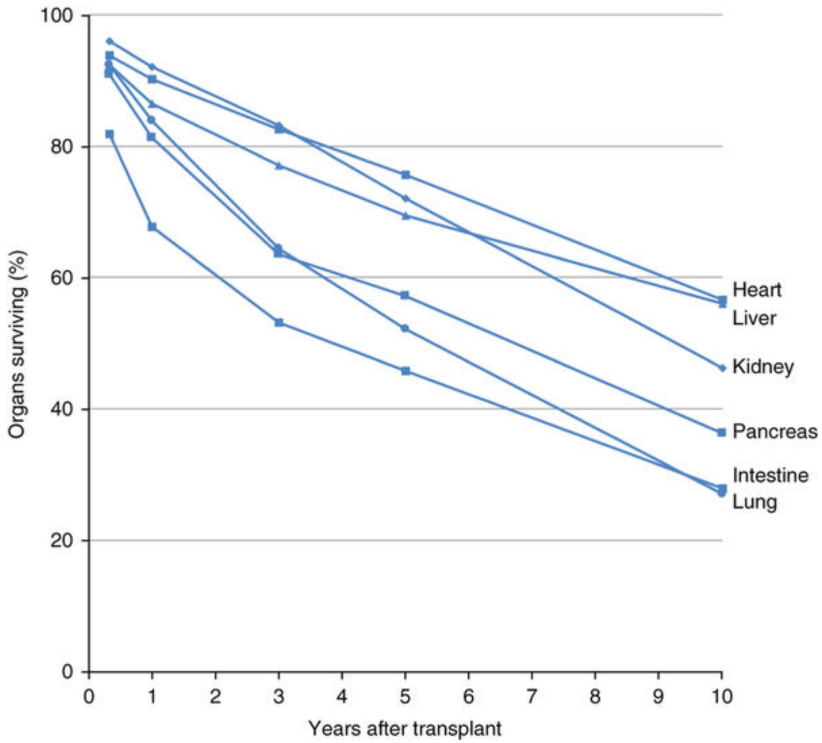
- Magnetic field measurement at levels of clinical relevance
- SAR measurement of magnetic nanoparticles
- High Field In-Vitro testing
- High Field Small Animal In-Vivo testing
- High Field Medium Sized Animal testing
- Surface Heating Equipment Currently being Used in for treatment of naturally occurring oral melanoma in human companion animals (family dogs)



Power Supply, Induction Coil and Treatment Table in Dartmouth Animal Laboratory – Manufactured by AMF Lifesystems (http://dartmed.dartmouth.edu/winter13/html/nanotech/)

Organ Transplantation

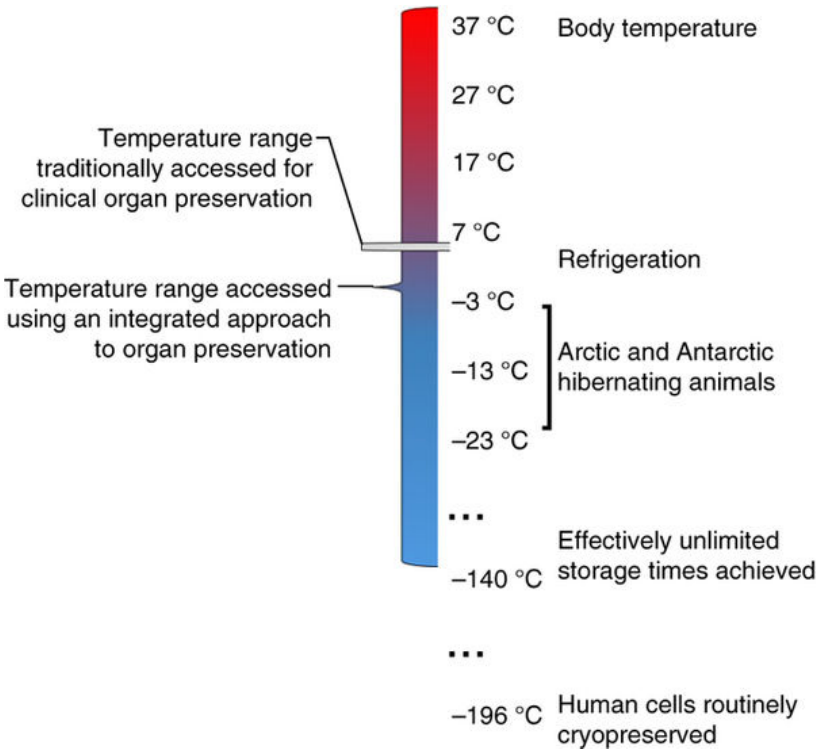
- One of the main challenges with organ transplantation is that as soon as an organ is no longer supported by a living organism, the organ begins to rapidly degrade
- The organ can remain suitable for transplantation outside of its living biological host for a period of hours (hearts, livers, etc.) to up to around 2 days (kidneys) with standard preservation methods (placing on ice, etc.)
- This makes for significant logistical challenges, which limit the ability to find "good" matches and also drives up the cost of the process significantly
- The worse condition the organ is in upon transplantation or the lower the quality of the match, the more likely the organ recipient is to have additional complications and the shorter the lifetime of the transplant organ



"The Promise of Organ and Tissue Preservation to Transform Medicine" – Giwa, et. al. Nature Biotechnology

Cryopreservation of Organs

- How quickly an organ degrades is strongly dependent upon temperature
- If organs could be vitrified (T< - 140 C) successfully, they could be stored more or less indefinitely



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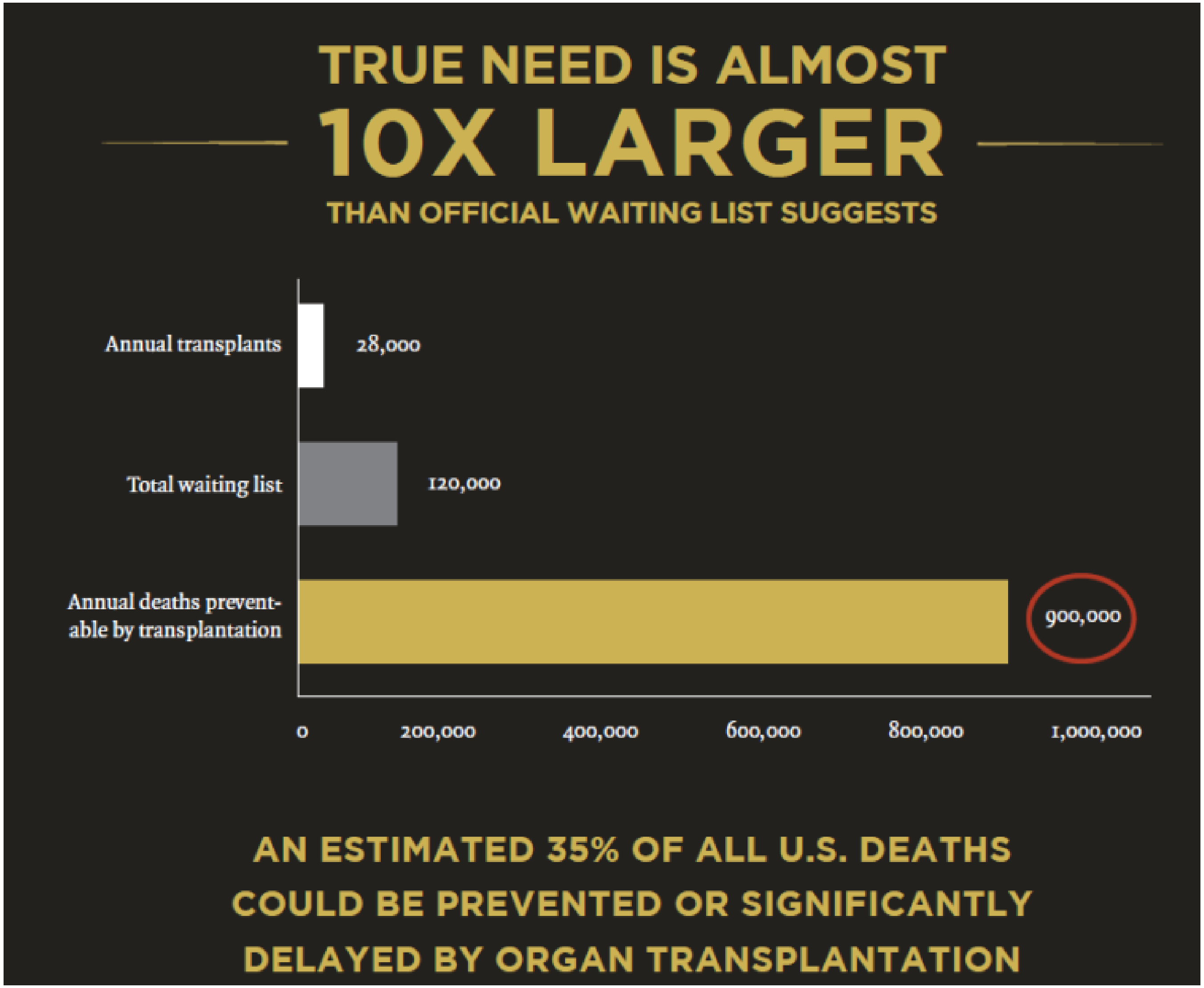
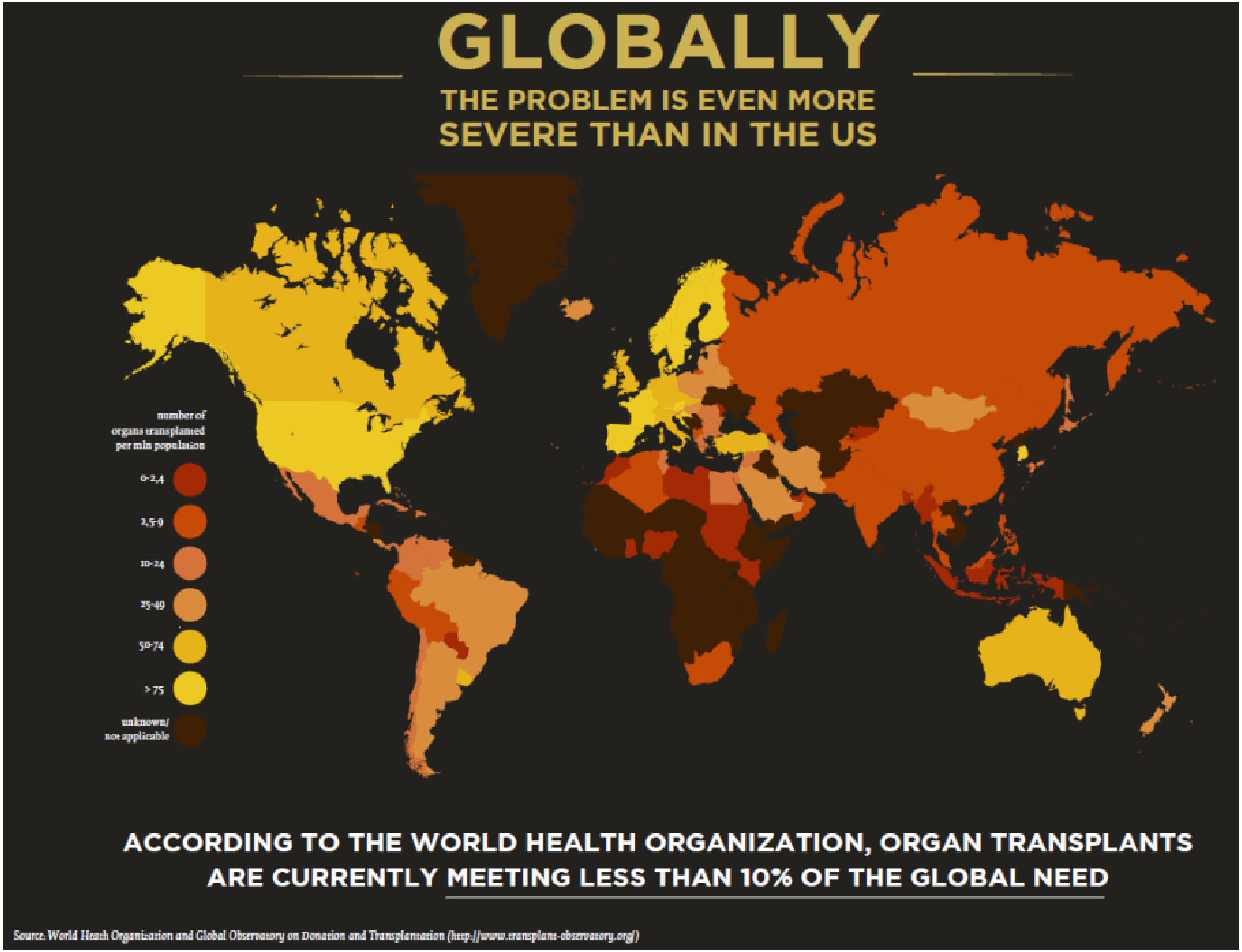


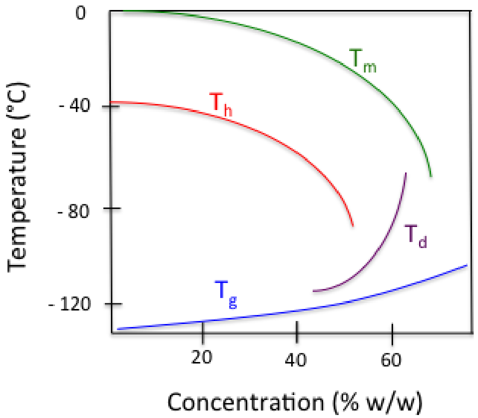
"Enabling Breakthroughs in Organ Transplantation Medicine" – Organ Preservation Alliance



“Enabling Breakthroughs in Organ Transplantation Medicine” – Organ Preservation Alliance

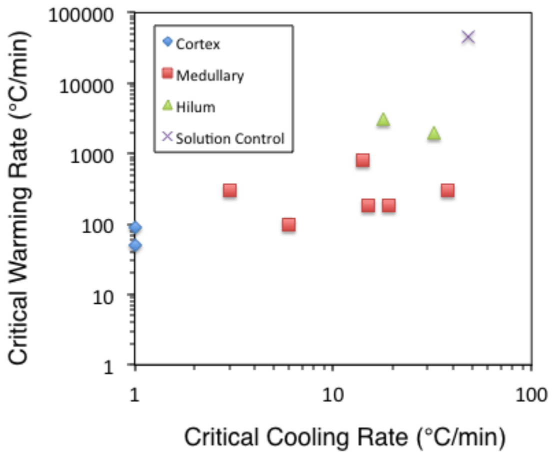
Preservation in Glass: Regenerative Medicine

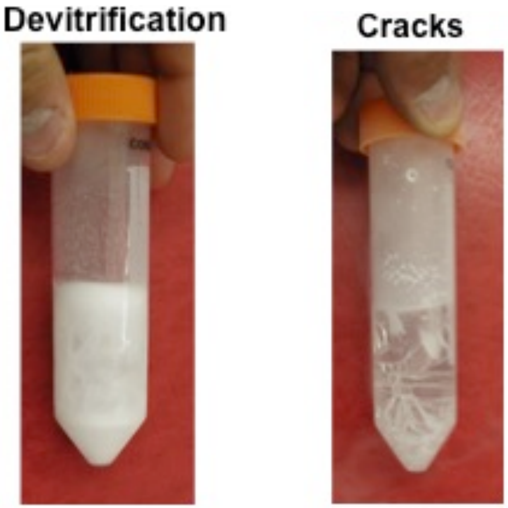
Cooling to glass works…but warming back remains a challenge

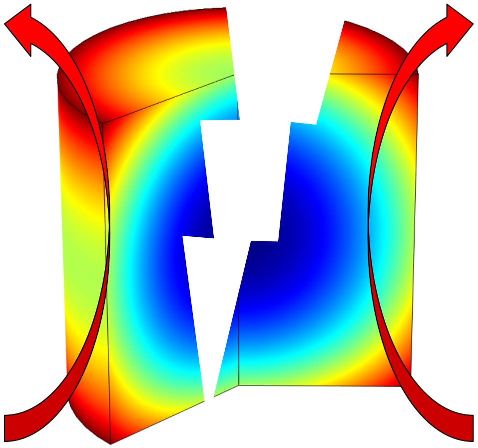


Need Speed - avoid devitrification

Need Uniformity - avoid cracks





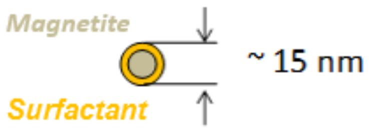


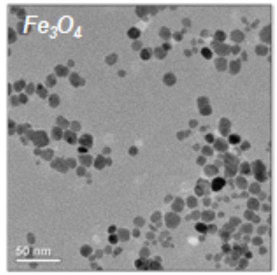
Etheridge *Technology 2014b,* Fahy Cryobiology 1984, Peyrideu *Cryobiology 1986*

Slide Courtesy of Prof. John Bischof, University of Minnesota

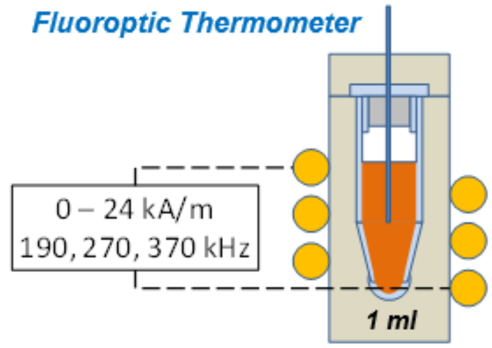
IONP Heating in RF (Alternating Magnetic) Fields

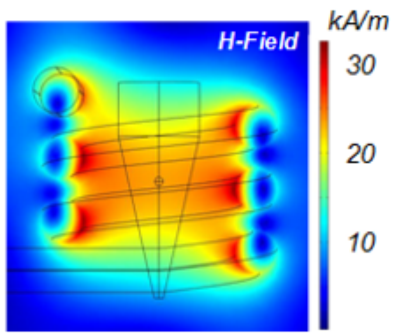
Ferrotec EMG-308:



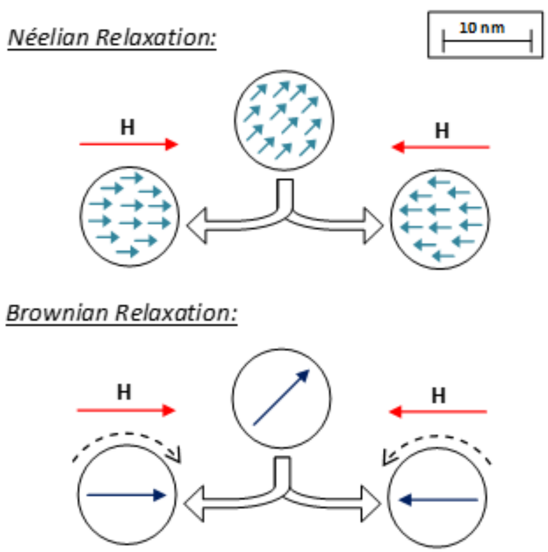


TEM Courtesy: **Katie Hurley**

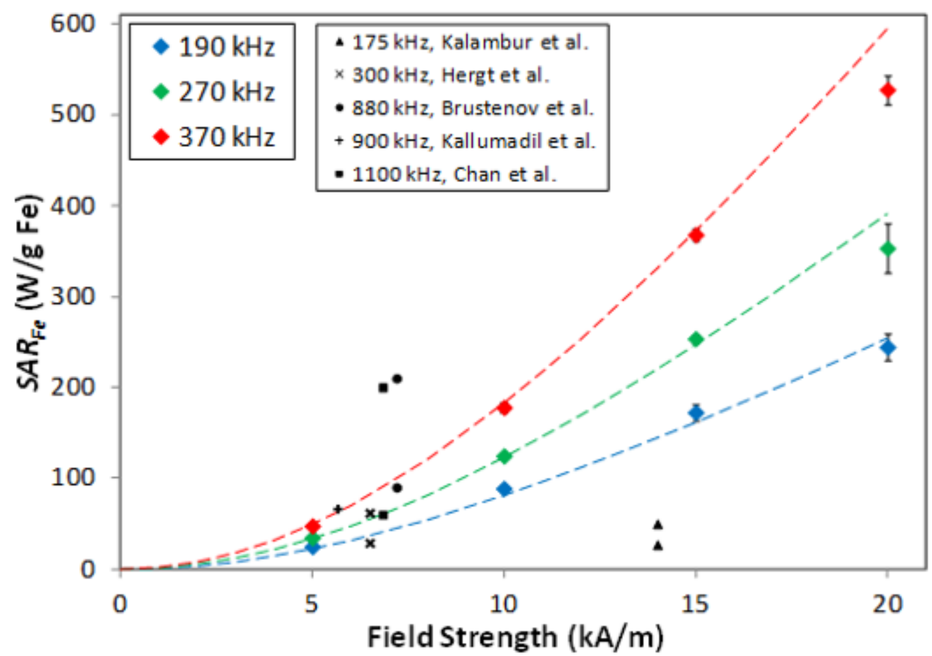




Mechanisms of Heating:



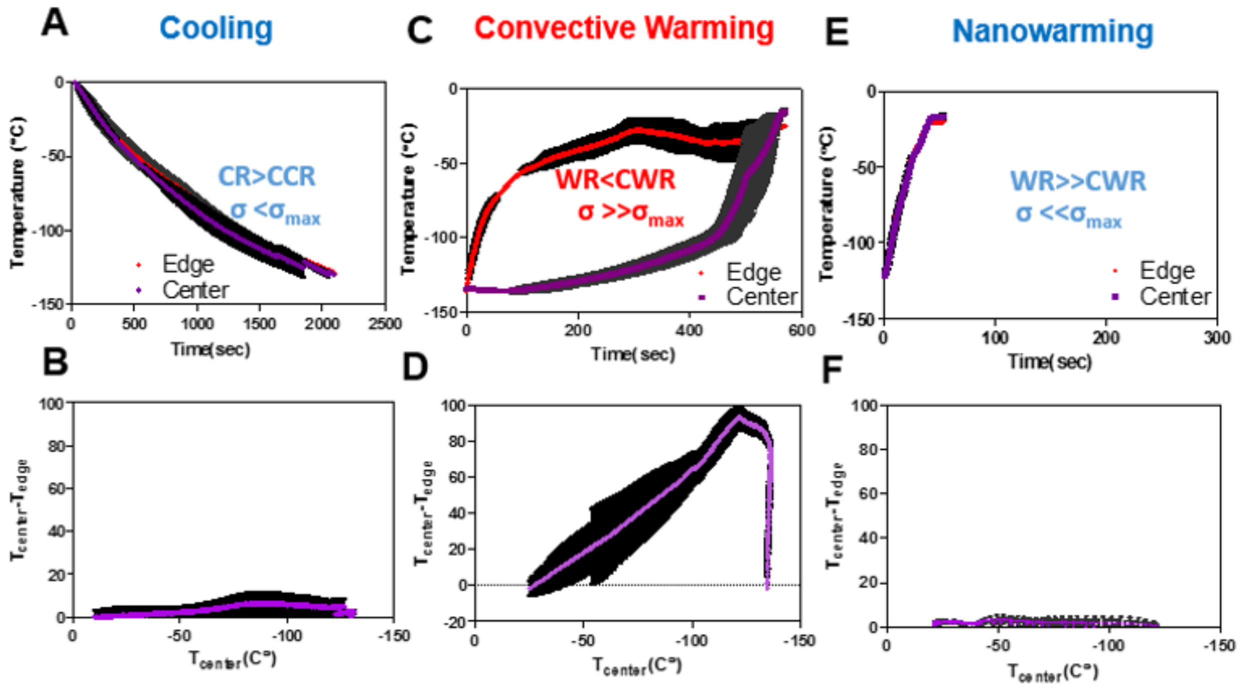
3 mg Fe/ml (0.08% v/v), ***185 kHz and 20 kA/m***

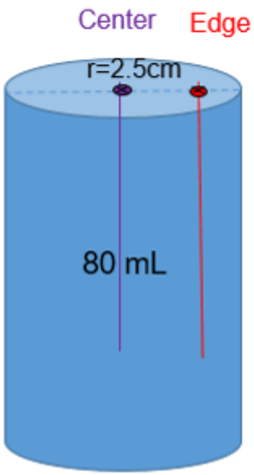


Rosensweig. JMMM 2002.
Etheridge et al. CRC Press 2013.
Etheridge and Bischof. ABME 2013.

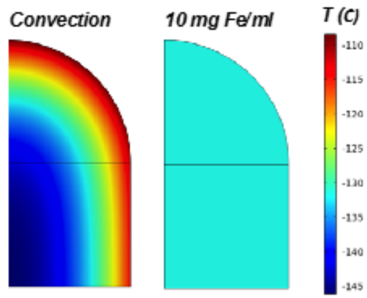
Slide Courtesy of Prof. John Bischof, University of Minnesota

Nanowarming Scale Up

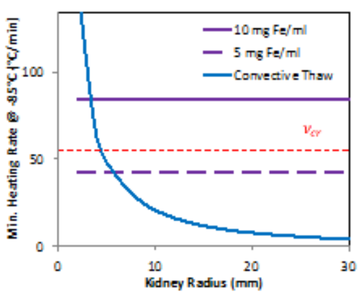




First organ goal: Rabbit Kidneys



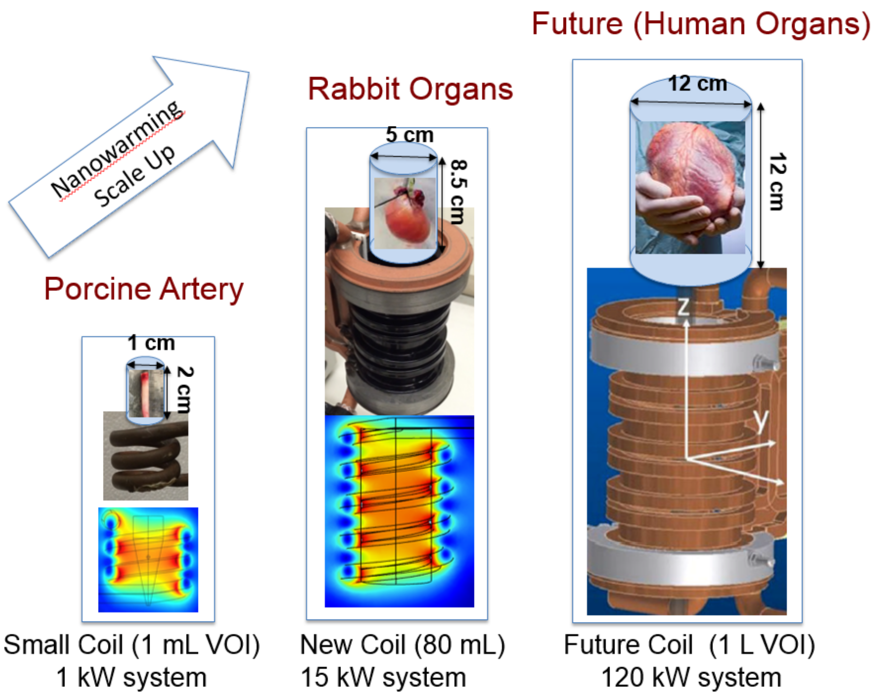
r = 5mm, after 10 sec of heating



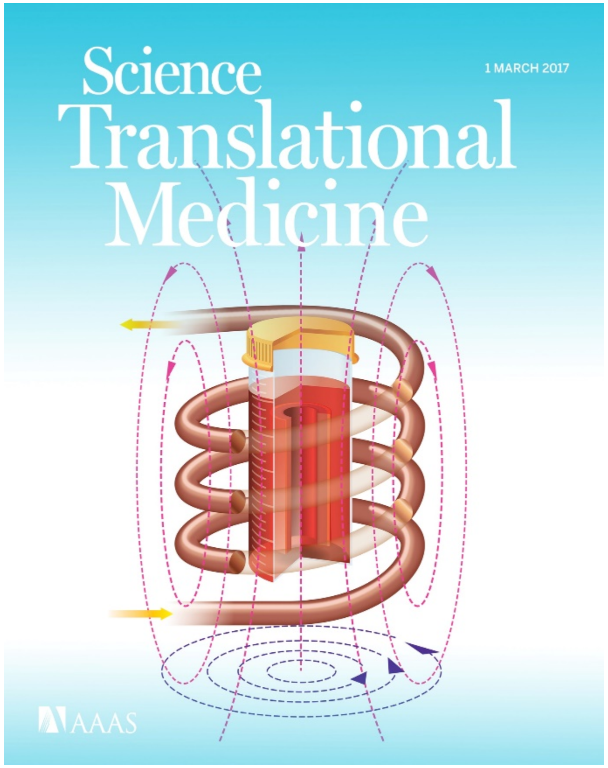
Manucherhabadi, et al *Science Trans. Med.* 2017
Etheridge et al. *Technology* 2014b

Slide Courtesy of Prof. John Bischof, University of Minnesota

Successful Nanowarming of 50 mL Samples represents > 10X increase in volume compared to previous record!



Slide Courtesy of Prof. John Bischof, University of Minnesota



Cover story for March issue of Science Translational Medicine

Clinical Sized AMF System

- Pilot Machine in Operation at Johns Hopkins University for Cancer Research
- Modular Remote Heat Station and Coil
- Patent Pending
- IP Behind this System Basis for System Capable of Nanowarming Large Tissues/Organs

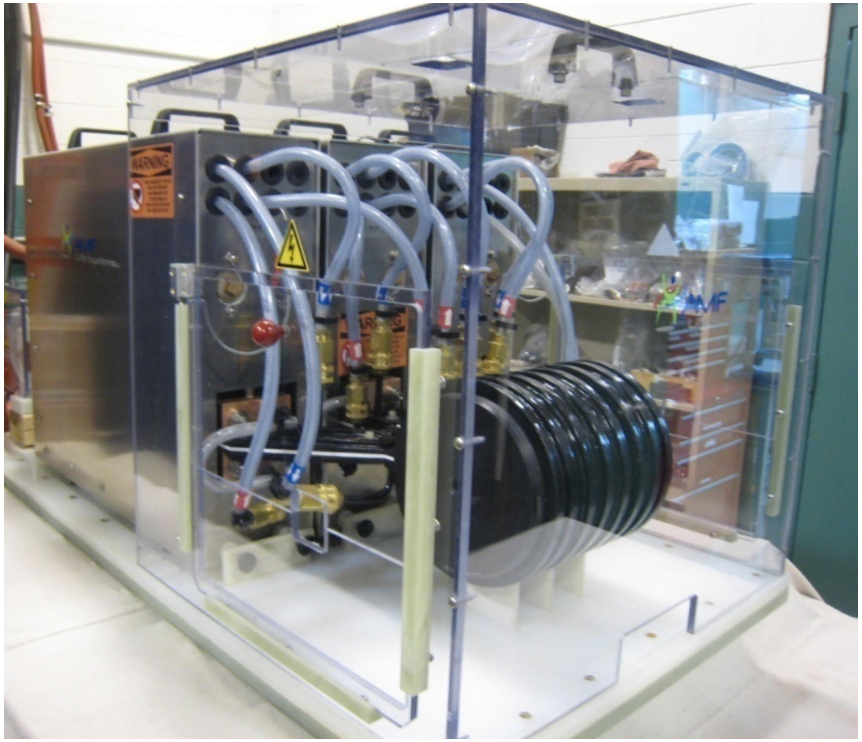
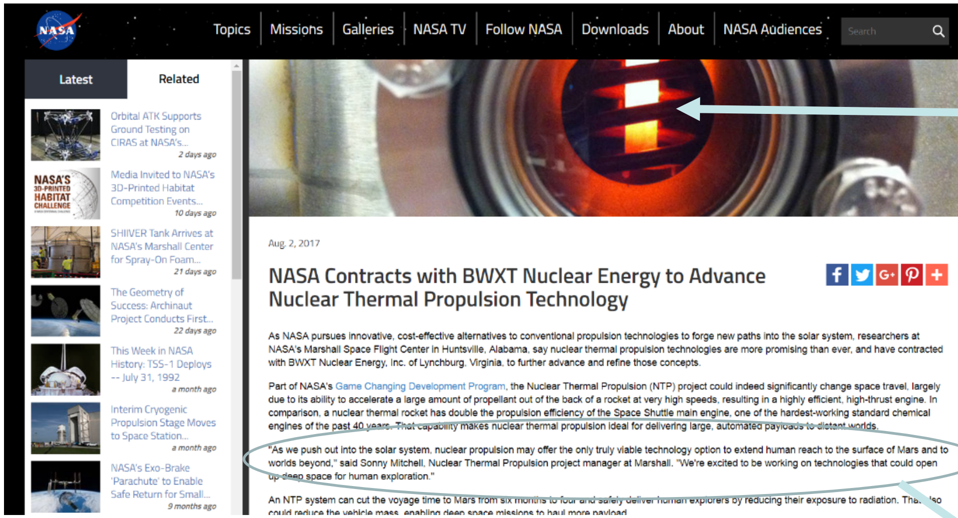


Photo taken in Fluxtrol lab during system run-off

Deep Space Exploration



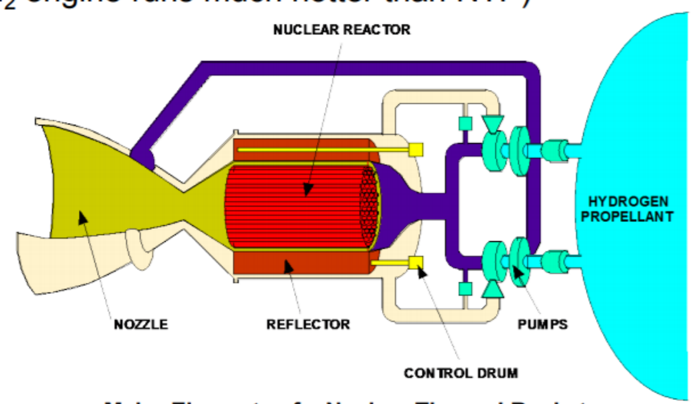
Induction Heating!

Source - Nasa.gov

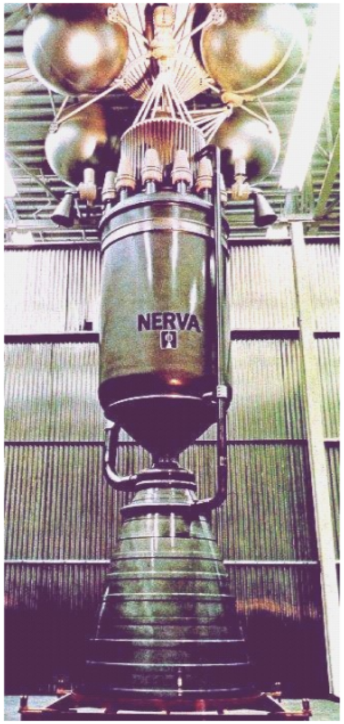
- "As we push out into the solar system, nuclear propulsion may offer the only truly viable technology option to extend human reach to the surface of Mars and to worlds beyond," said Sonny Mitchell, Nuclear Thermal Propulsion project manager at Marshall. "We're excited to be working on technologies that could open up deep space for human exploration."
- An NTP system can cut the voyage time to Mars from six months to four and safely deliver human explorers by reducing their exposure to radiation. That also could reduce the vehicle mass, enabling deep space missions to haul more payload.

How Does Nuclear Thermal Propulsion (NTP) Work?

- Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle
- Low molecular weight propellant – typically Hydrogen
- Thrust directly related to thermal power of reactor: 100,000 N ≈ 450 MW_{th} at 900 sec
- Specific Impulse directly related to exhaust temperature: 830 - 1000 sec (2300 - 3100K)
- Specific Impulse improvement over chemical rockets due to lower molecular weight of propellant (exhaust stream of O_2/H_2 engine runs much hotter than NTP)



Major Elements of a Nuclear Thermal Rocket



NERVA Nuclear Thermal Rocket Prototype

2

- 20 NTP engines built and tested in 1970's.
- Testing was halted due program termination
- CFEET and NTREES systems developed to test survivability of fuel elements under operating conditions without radiation lowering test costs to around $25 k
- **Induction Heating is Used to simulate power densities generated by nuclear reactor**

Slide from "NASA's Nuclear Thermal Propulsion (NTP) Project", Houts, et. al. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170003378.pdf

Nuclear Thermal Propulsion

Project Manager: Sonny Mitchell

Objective:

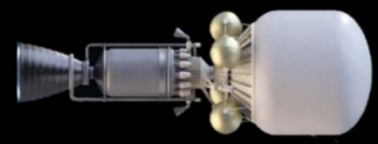
The overall goal of this three-year GCD technology project is to determine the feasibility and affordability of a Low Enriched Uranium (LEU)-based NTP engine with solid cost and schedule confidence.

Approach:

Leverages government, industry and academic expertise to achieve project objectives.

Success Criteria:

1. Demonstrate the ability to purify tungsten to 90 percent purity and determine the cost to produce a kilogram at that level of purity.
2. Determine the technical and programmatic feasibility of an NTP engine in the thrust range of interest for a human Mars mission.
3. Determine the program cost of a LEU NTP system and the confidence level of each major cost element.



System Feasibility Analysis

Fuel Element Development and Testing

Exhaust Capture Analysis and Testing

Project Status

Team:
MSFC (Lead), GRC, SSC, DoE, industry partners, academia

Milestones:
Tungsten purified to 50%; 70%; and 90%
Testing of Surrogate Cermet FE in CFEET (SEP17)
Testing of the DU Cermet FE in NTREES/CFEET (SEP18)

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Slide from "NASA's Nuclear Thermal Propulsion (NTP) Project", Houts, et. al.
https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170003378.pdf

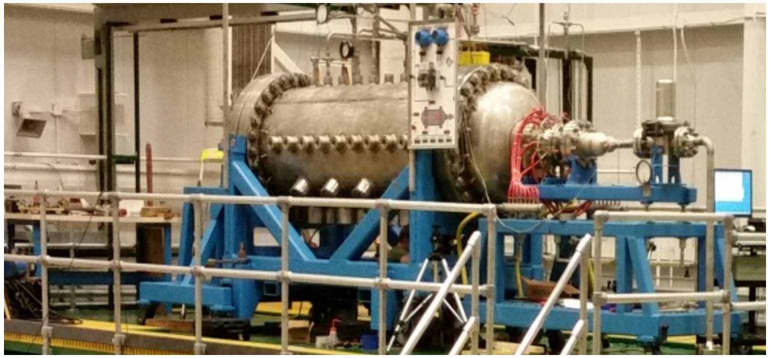
ER24/Nuclear Systems Branch

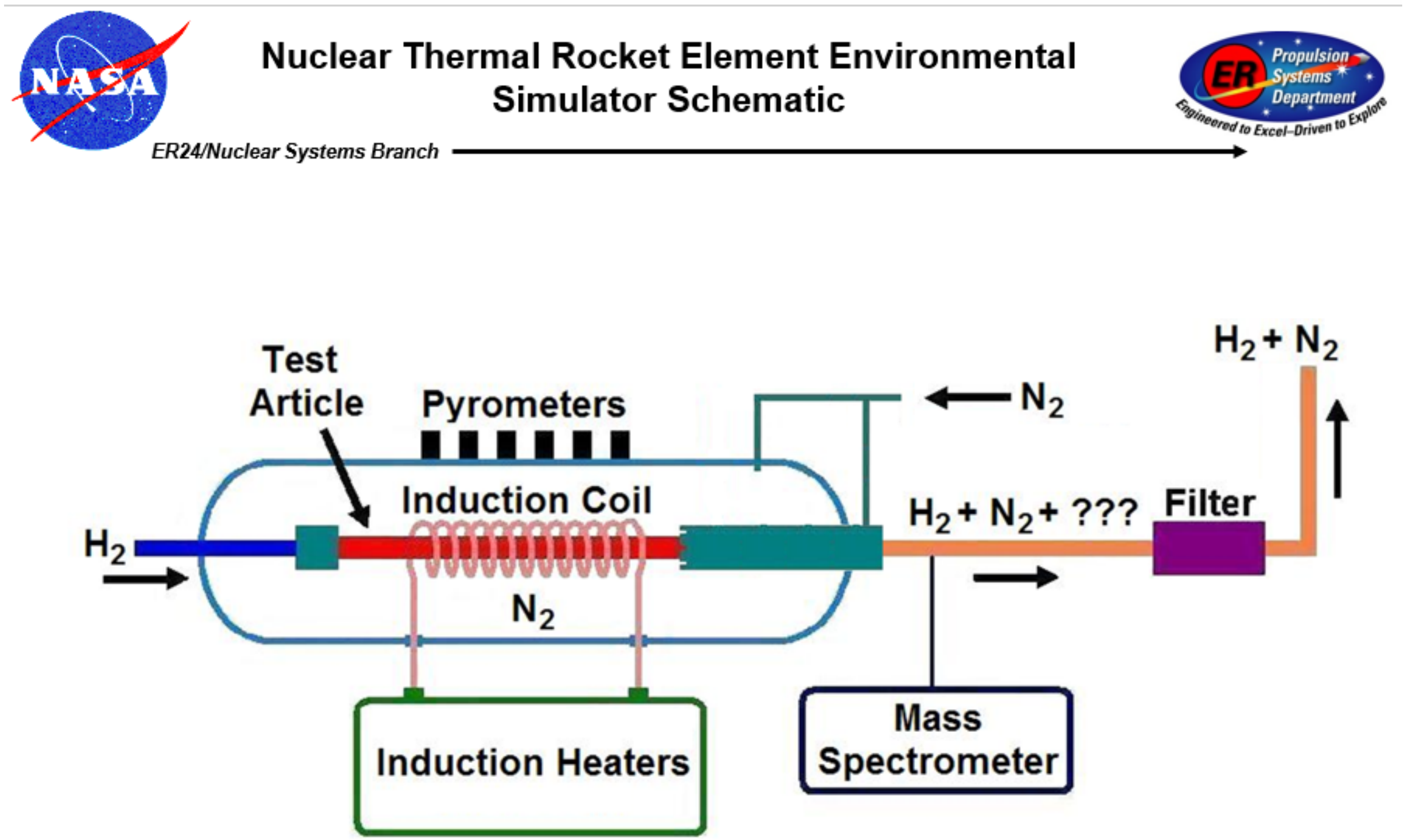
NTREES Overview

- The NTREES is designed to reproduce the conditions (minus the radiation) to which nuclear rocket fuel elements and other components would be subjected to during reactor operation.
- The NTREES consists of a water cooled ASME code stamped pressure vessel and its associated control hardware and instrumentation coupled with inductive heaters to simulate the heat provided by the fission process.
- The current NTREES induction heating capacity is 1.2 MW
- Capable of testing prototypical nuclear fuel elements to over 3000 K at pressures of up to 7 MPa (1000 psi) with flowing hydrogen
- Licensed by the Nuclear Regulatory Commission to test uranium bearing fuel elements

Goal is to increase to 5 -10 MW over next several years

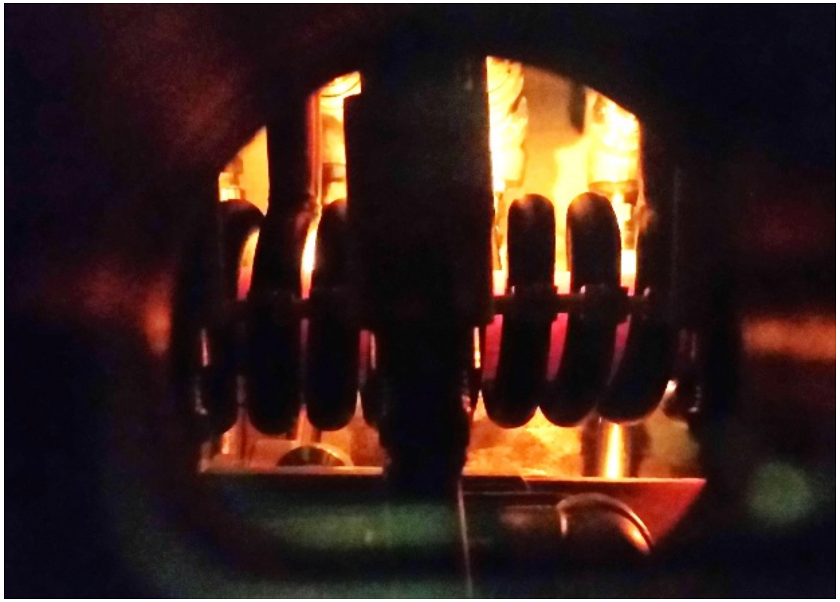
Slide and image from "Nuclear Cryogenic Propulsion Stage (NCPS) Fuel Element Testing in the Nuclear Thermal Rocket Element Environmental Simulator (NTREES)", Bill Emrich





Slide from “Nuclear Cryogenic Propulsion Stage (NCPS) Fuel Element Testing in the Nuclear Thermal Rocket Element Environmental Simulator (NTREES)”, Bill Emrich

“Low” Power Testing of Fuel Element

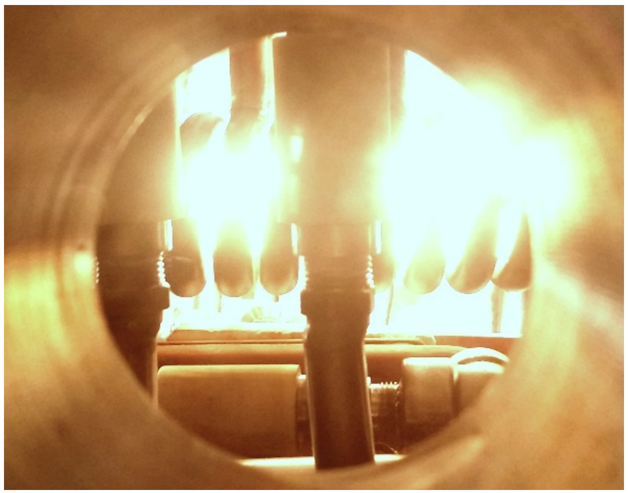


Element at 2000 K

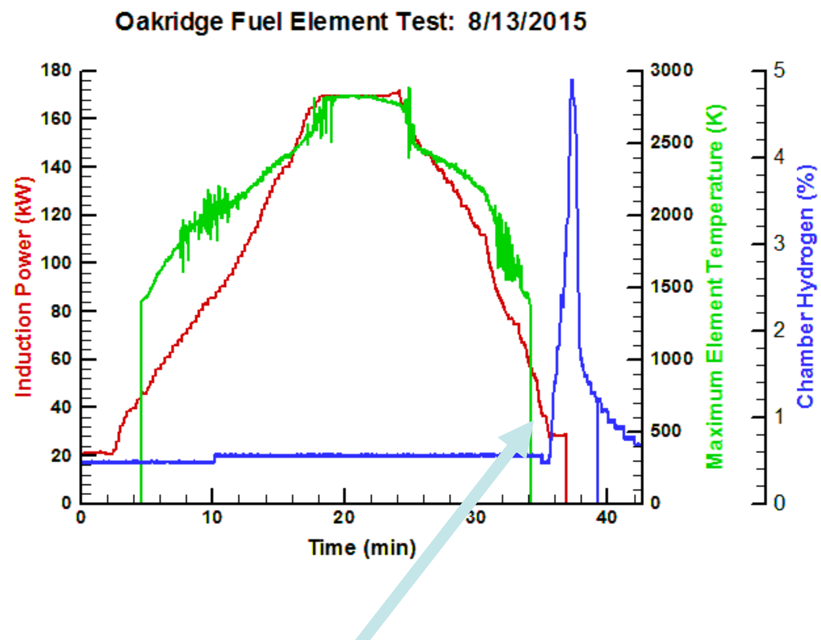
Element shows no sign of degradation after test

Images taken from “Nuclear Cryogenic Propulsion Stage (NCPS) Fuel Element Testing in the Nuclear Thermal Rocket Element Environmental Simulator (NTREES)”, Bill Emrich

“Medium” Power Testing



2825 K!

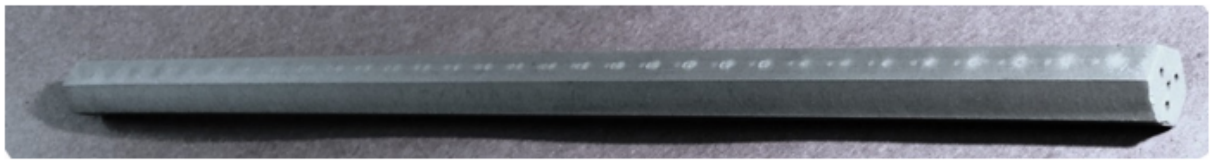


Images taken from “Nuclear Cryogenic Propulsion Stage (NCPS) Fuel Element Testing in the Nuclear Thermal Rocket Element Environmental Simulator (NTREES)”, Bill Emrich

H2 spike is a sign of potential element failure (pyrometer drop due to range of pyrometer – notice step function at beginning of cycle)

Post Test Condition of Oakridge Test Element after Aggressive Testing Sequence

Before Test



After Test

Slide taken from "Nuclear Cryogenic Propulsion Stage (NCPS) Fuel Element Testing in the Nuclear Thermal Rocket Element Environmental Simulator (NTREES)", Bill Emrich

Summary

- Induction heating is a unique, environmentally friendly technology that is being utilized in a wide variety of manufacturing industries
- Induction heating is also being utilized in the development of new medical technologies that have the potential to save many lives
  - Hyperthermia technology for treatment of cancer
  - Nanowarming for thawing of cryopreserved organs
- Induction heating is often used for Accelerated Lifetime Testing to verify performance of components in high power density applications
  - NTREES system for ensuring safe deep space exploration

Acknowledgements

- Many of the slides in this presentation were taken from the "Basics of Induction Heating Parts I & II" prepared by Dr. Valentin Nemkov (www.fluxtrol.com)
- Thanks to Prof. John Bischof for permission to use many of his slides on the nanowarming technology
- Thanks to Dr. Bill Emrich for providing the slides and videos on the NTREES system

Thanks for Your Attention