AML™

REIMAGINING THE MAGNET TECHNOLOGY THAT DRIVES THE WORLD

Disruptive Technology for Decommoditizing the Magnet Supply Chain

Mine-to-Magnet-Workshop

Lockheed Martin Center for Leadership Excellence
Bethesda, MD

January 17, 2024

Company History

History

1995 – Founded with a focus on superconducting magnets for particle accelerators and colliders

2009-2014 – Funded by U.S. Department of Energy and NASA for development of superconducting electrical machines for offshore wind turbine generators and turbo-electric aero propulsion

2015 to Present – Focus on the development of PM-Wire™ permanent magnets, magnet manufacturing and electrical machine development

Corporate Headquarters & R&D

Manufacturing & Metal Alloy Development

Locations

Corporate Headquarters

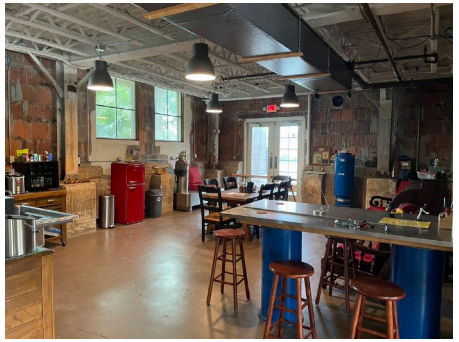
Melbourne, Florida

- ✓ Corporate, Operations
- ✓ Engineering, R&D
- ✓ Machine Shop, Prototyping

Manufacturing

Located 3 miles from Headquarters

- ✓ MITUS PM-Wire™ Pilot Manufacturing Line
- ✓ Metal Alloys Development Lab



Our Business

Vision

Create a new and stable magnet supply chain

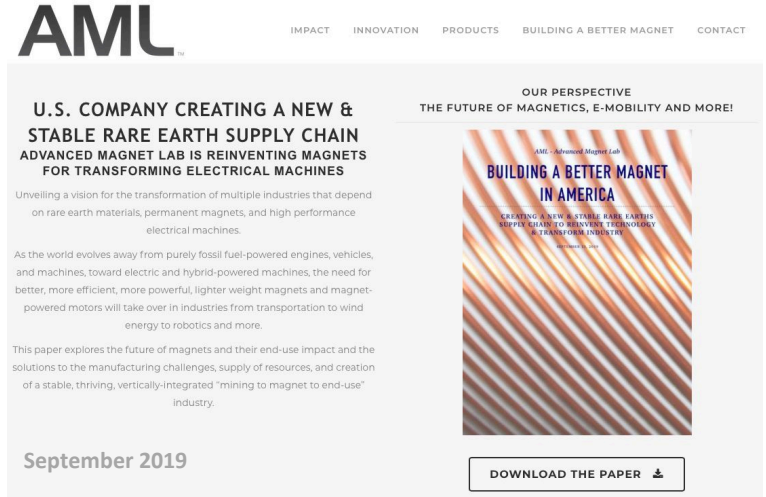
Mission

Magnet Innovation - “Building a Better Magnet in America”

Product

PM-Wire™ Technology Platform

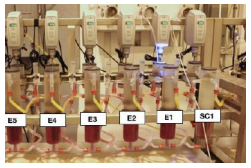
Innovative solution for the design, manufacture and application of magnets



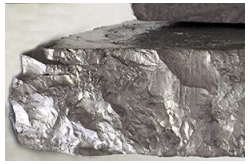
Value Proposition

Increased performance and lower cost end-use product

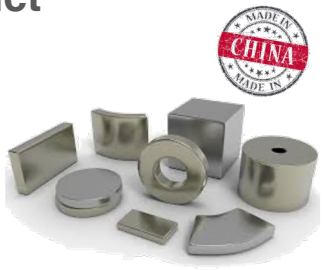
Mining / Recycling



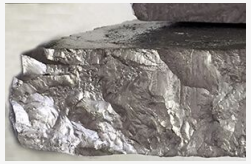
Oxide Extraction NdPr



Metal Alloys



Conventional Magnets



AML Metal Alloys

AML Magnets

AML is **REINVENTING** the Magnet Supply Chain

Magnets & Manufacturing Innovation

Reinventing the design and manufacturing of magnets

Our manufacturing is unique and state-of-art. Production is high-rate, high-yield, high-quality with a fraction of the labor and capital required for conventional manufacturing methods

Manufacturing Innovation

Materials Innovation

Reducing the cost of magnet alloys

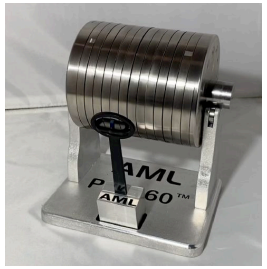
Our technology improves the application performance of all existing magnet materials and enables new, lower cost materials including non-rare earths

Lower Cost Metal Alloys

Magnet End-Use Product Innovation

Revolutionizing motors and generators

Our technology replaces conventional north-south topologies with optimized magnet shapes, magnetization and topologies which results in improved performance, reduced magnet count and ease of assembly



Magnet and Motor Innovation

We are Decommoditizing the Magnet Industry!

AML

Reimagining the Magnet Technology that Drives the World

Magnet Innovation

Reinventing the design and manufacturing of magnets

PM-Wire™ - A Technology Platform

Technology

PM-Wire™ - A unique process for the design, manufacturing and application of permanent magnets

Enabling Configurations – long-length, rings, helixes and more

Enabling Magnetization / Topologies – magnetic flux distribution optimized for the application

High-Rate Manufacturing – mass produced / high yield - >98%

Value Proposition

Improves performance and lowers the cost of end-use products (e.g., motors)

Performance – higher efficiency, lighter, smaller, higher temperature operation

Lower Cost Material Options – performance equivalent to higher cost materials

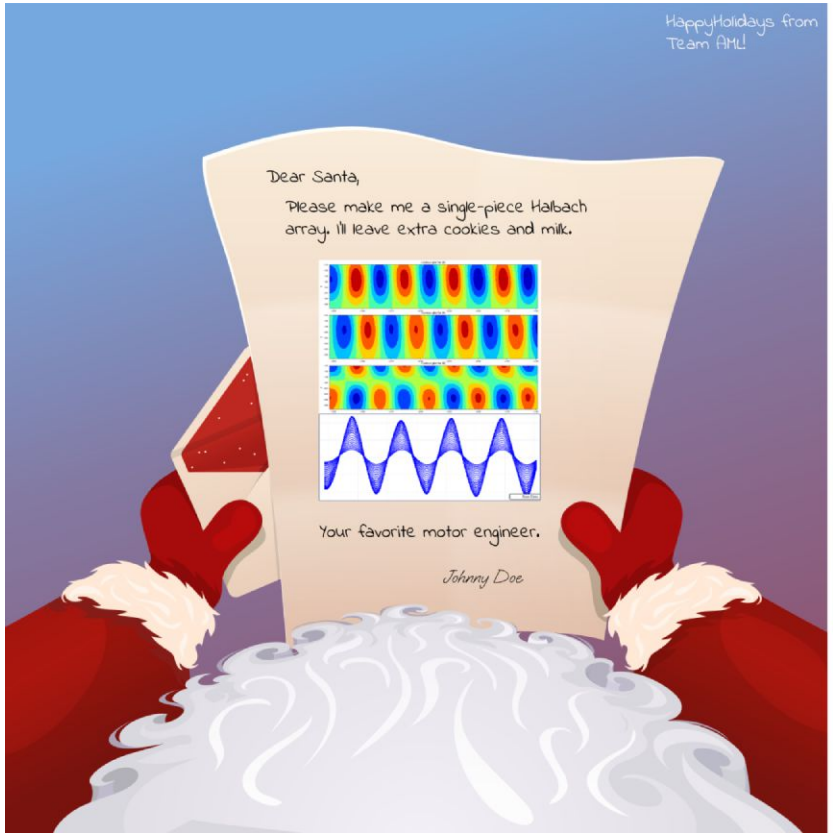
Manufacturing Ease and Safety – simplified assembly into end-use products

Sustainable Business – does not compete in existing commoditized market

PM-Wire Impact Example

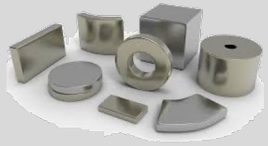
Electric Vehicle Motor

- ✓ Collaboration with the Oak Ridge National Laboratory
- ✓ Replace **~2,750** magnet Halbach array with **8** PM-360™ rings
- ✓ Eliminate need for active cooling of rotor
- ✓ Using a Non-sintered magnet alloy



- What motor engineers dream about -
"Single-piece Halbach array"

PM-Wire™ Products



Conventional Magnets

PM-UNIFORM™

Straight, curved, ring or helical magnets with Transverse or Radial magnetization

Single-Piece Magnets

Straight up to 1 m

Curved up 1 m arc

Rings up to 320 mm dia.

Helical (given by dia.)

Lower Cost Assemblies

Reduced part count

PM-360™ - "Better than a Halbach Array"

Straight, ring or helical magnets with "Continuously Changing Magnetization Direction"

Increased Performance

Halbach Array Performance

Reduced Weight

Iron Free

Lower Cost Assemblies

Reduced part count

Ease to assemble

PM-AXIAL™

Curved magnets with Axial magnetization allows rotor topologies having breakthrough benefits

Increased Performance

Halbach Array Performance

Higher Temperature

Reduced Overwrap

Reduced Weight

Iron Free

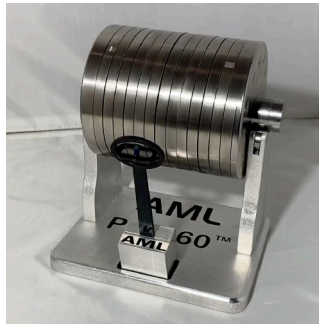
Lower Cost Assemblies

Reduced part count

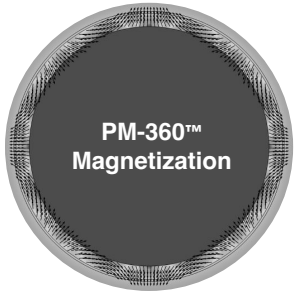
Ease to assemble

Lower grade metal alloys

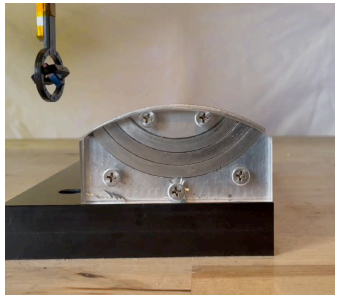
PM-UNIFORM™



PM-360™ - Helical



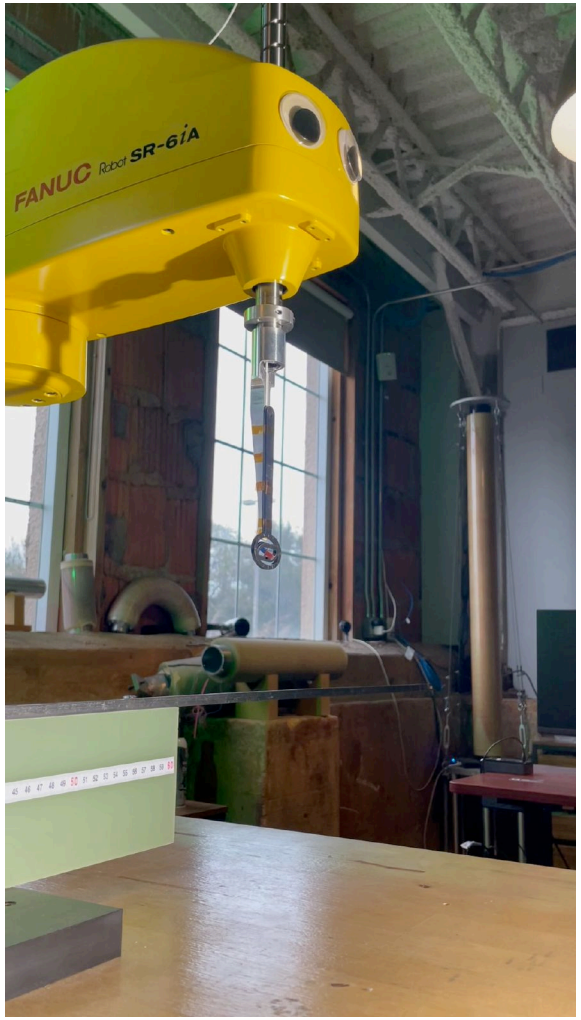
PM-360™ - Magnetization



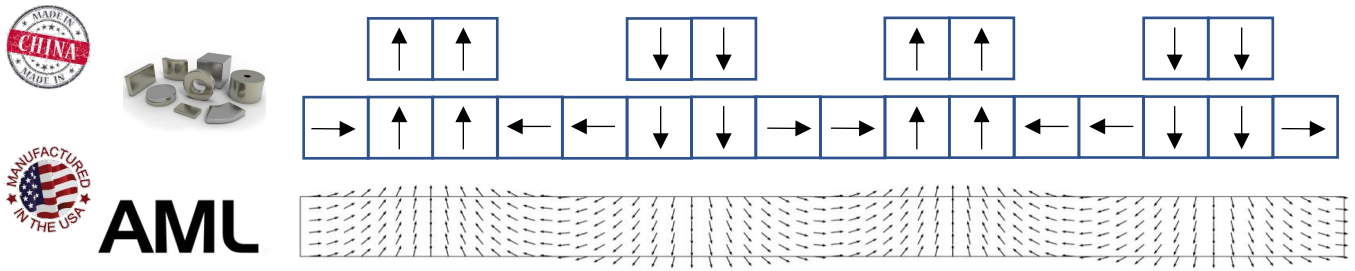
PM-AXIAL™

Straight PM-360™

Ideal magnetic field distribution, Single-piece “Halbach Array”, Long-lengths



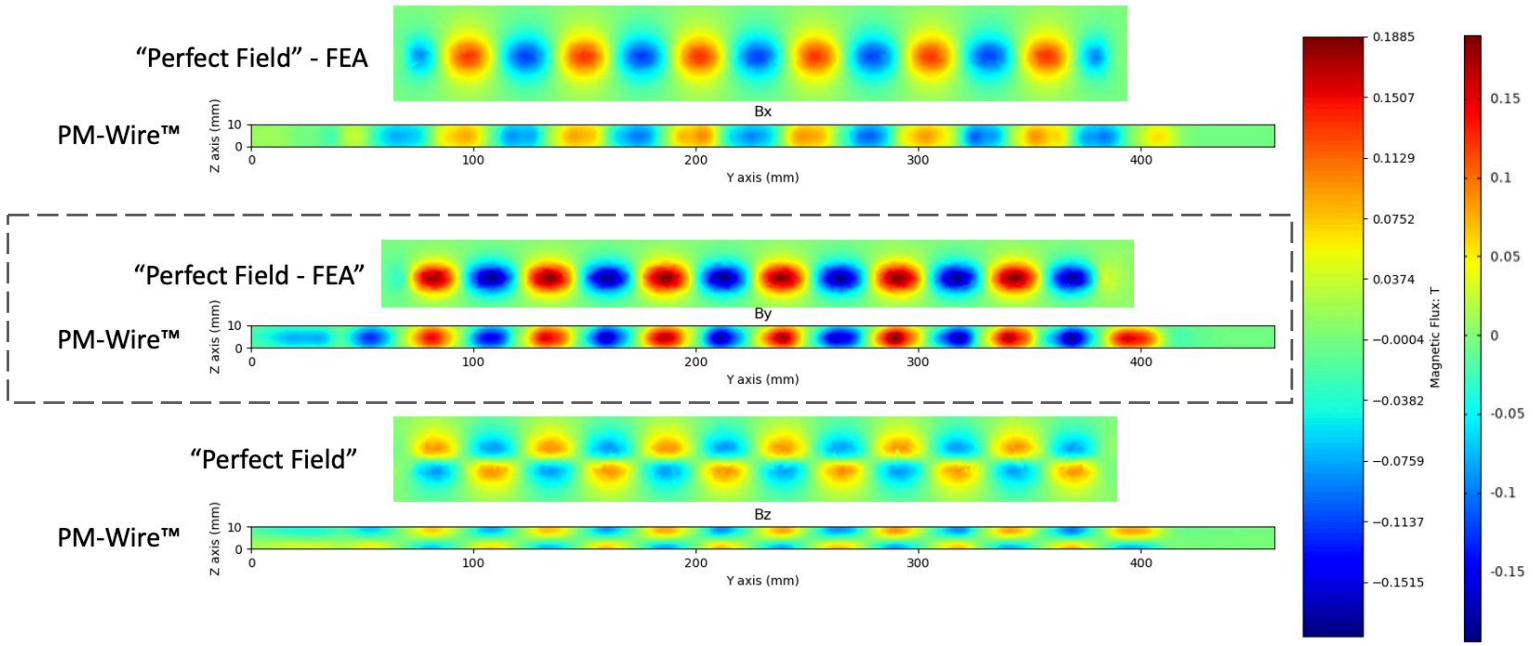
Video



North – South Magnetization

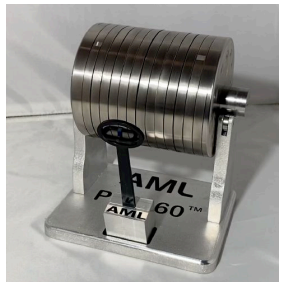
90 Degree Halbach Array

Continuously Changing Flux Direction

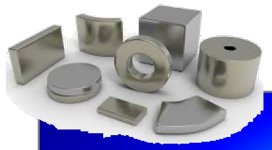


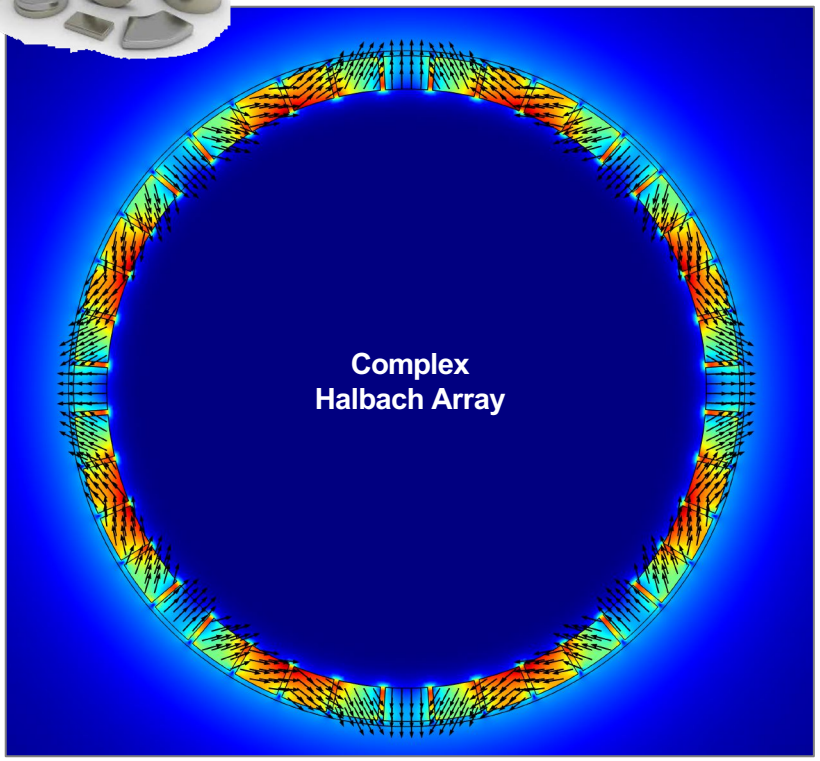
Circular PM-Wire™ - PM-360™

Single-piece, ring and helix “Halbach Array”

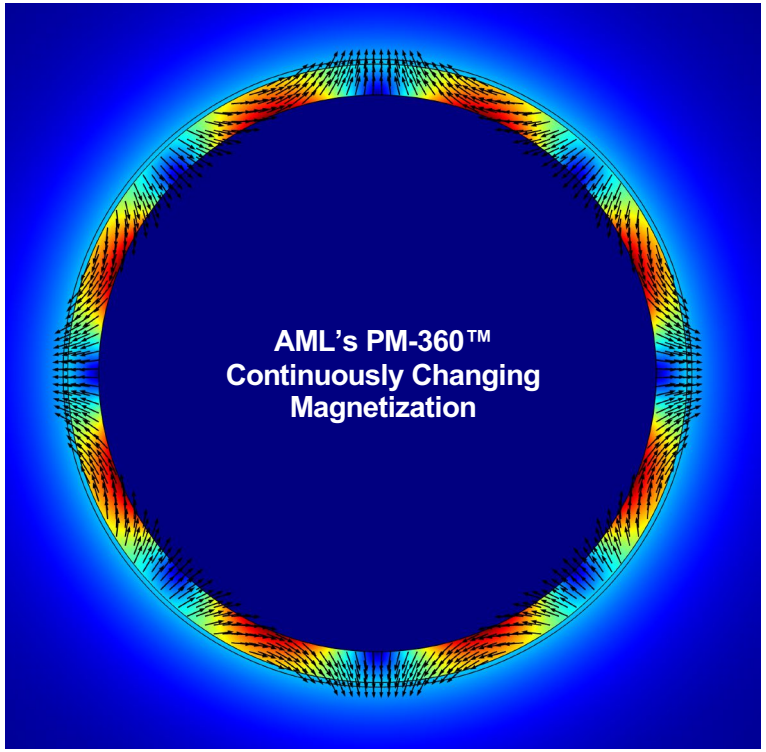


PM-360™ Rotor Prototype for
Heavy Industries Company





Conventional Magnets



PM-Wire™

PM-360™ Outrunner Rotor Prototype

PM-Wire™ Field Mapping & Pole Spacing Measurements

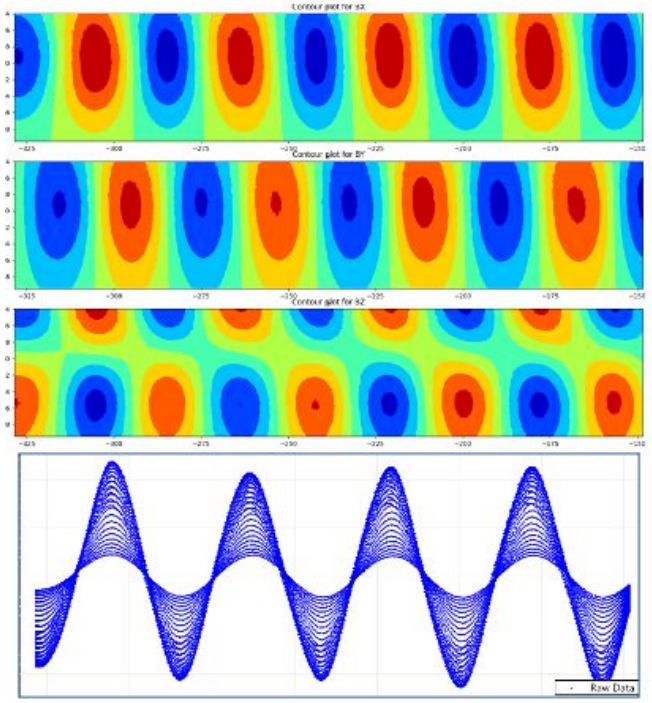
PM-360™ Sintered Magnet

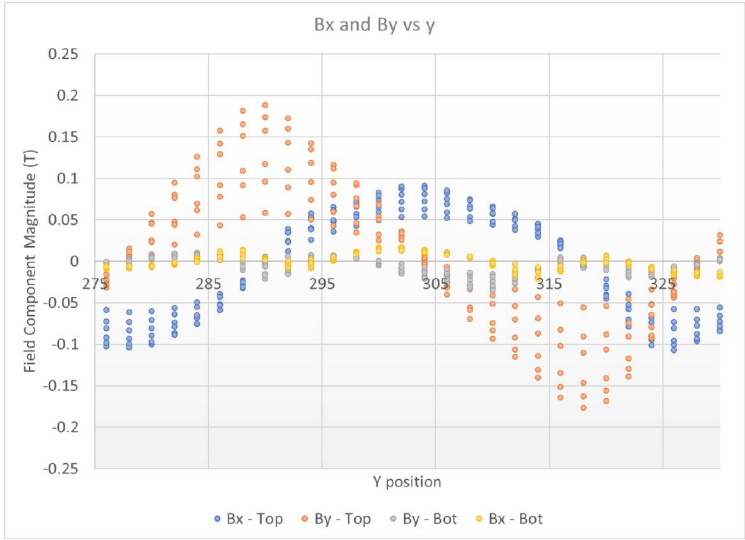
Single-piece Halbach array

Straight Sintered PM-360™

Curved Sintered PM-360™

AML Developed Magnetic Pole Detector





PM-360™ Field Map Plots

PM-Axial™ - Solution for Lower-Cost Alloys

PM-AXIAL™ Magnets

Improves the performance of existing alloys

Enables a motor topology which is well suited for low coercivity alloys

- ✓ Provides very low demagnetization field enabling the use of low coercivity alloys including non-rare earths

Additional Features and Benefits

Optimized Performance

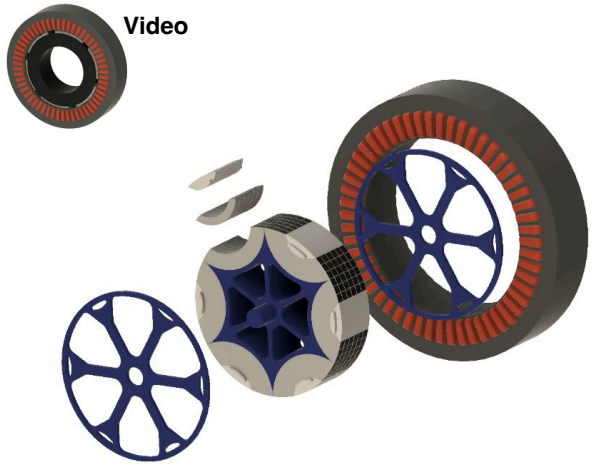
- ✓ Halbach Array like performance
- ✓ Higher Temperature Operation
- ✓ Enables lower grade / cost alloys with performance equal to higher grade alloys
- ✓ Significantly reduces or eliminates overwrap (magnet containment)

Reduced Weight

- ✓ No need for iron at the rotor

Ease of manufacturing and assembly

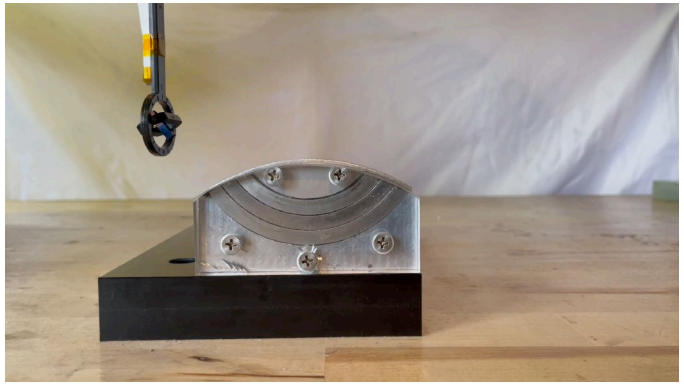
- ✓ All the segments can be mass-produced at low cost
- ✓ The magnetic flux is contained within the magnets making it easy and safe during assembly



Video

Example of PM-AXIAL™ rotor design

Video



Sample PM-AXIAL™ motor poles made with NdFeB alloy

Manufacturing Innovation

High-rate, high-yield, high-quality and low capex

PM-Wire™ High-Rate Manufacturing

AML

High Volume Manufacturing

3-6 meters / minute / production line

Capacity Potential Scenarios (magnet cross-section dependent)

Single Line Production Capacity - Straight PM-Wire™

High Volume (m/min)	Size by Cross Section	Daily Production (m)	Annual Production (m)	Daily Volume (mt)	Annual Volume (mt)	Capacity Per 6,000 mt of NdPr
4	2 cm x 2 cm	4,536	1,360,800	11	3,320	7 production lines
4	1.5 cm x 1.5 cm	4,536	1,360,800	6	1,868	11 production lines
4	1 cm x 1 cm	4,536	1,360,800	3	830	25 production lines

Production Parameters

Days Per Year	300
Hours Per Day	21
Line Utilization	90%

Production Capacity Comparison

NdPr Deposit	NdPr Supply	Potential Magnet Capacity (mtpa)	Planned Magnet Capacity (mt)
Mountan Pass Mine	6,000	20,000	1,000

AML capacity scenarios for producing 20,000 mt per year

Mount Pass Mine has an expected production capacity of 6,000 metric tons of NdPr rare earths which equates to ~20,000 metric tons of magnets

MP Material's 200,000 sq ft production facility will have the capacity to produce approximately 1,000 metric tons of magnets per year

MP Materials; Gabelli Funds 46th Annual Auto Symposium – October 31, 2022

Project MITUS - PM-Wire™ Pilot Line
Funded by the U.S. Department of Defense

Materials Innovation

Improving performance of existing and enabling new lower rare earth content alloys for electrical machines

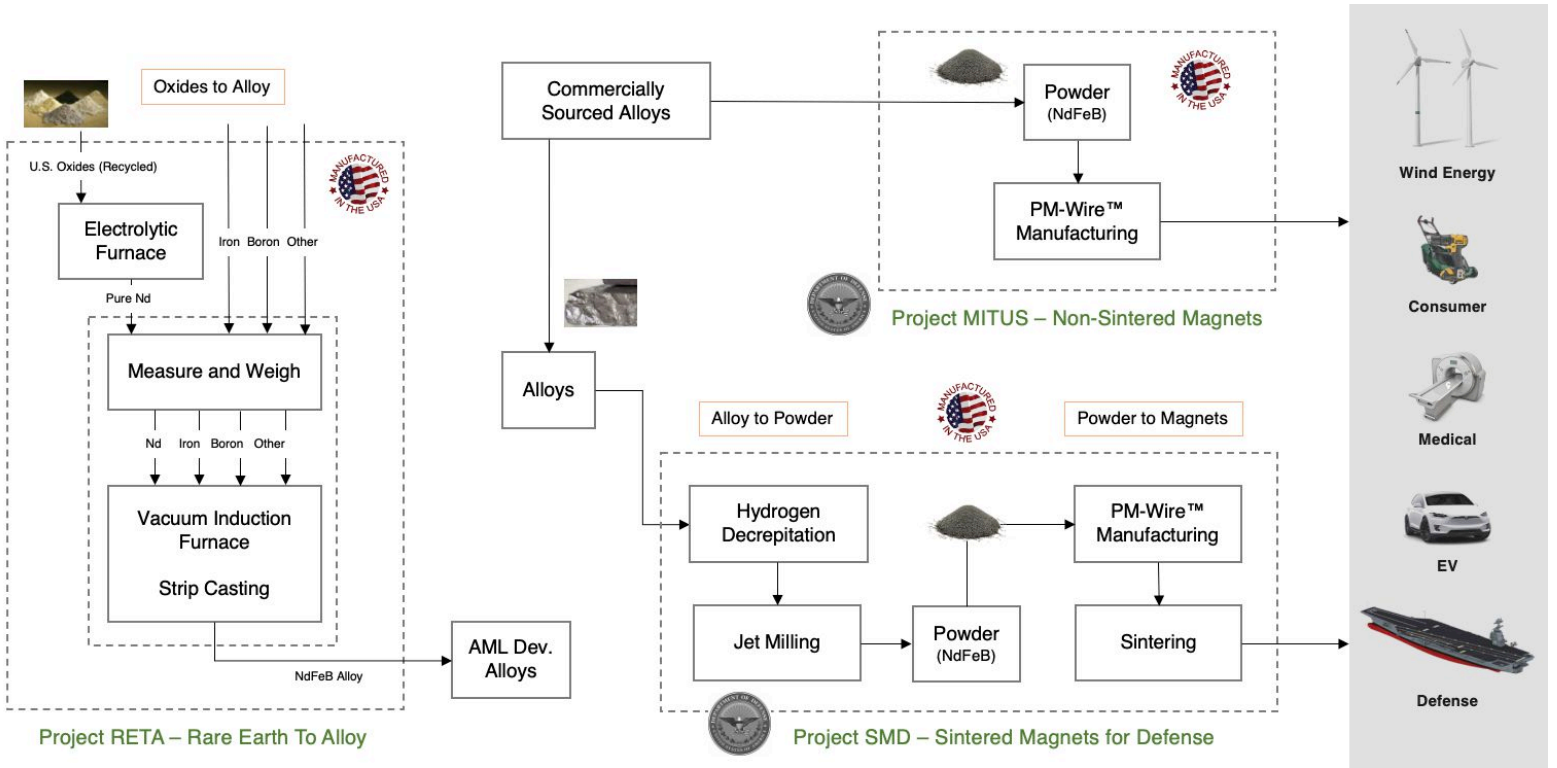
PM-Wire™ – A Materials Enabler

Improved end-use product performance of existing sintered alloy compositions

Enable non-sintered alloys

Enable lower critical rare earth alloys

Enable non-rare earth alloys



AML

Reimagining the Magnet Technology that Drives the World

Electrical Machine Innovation

Increased performance and lower cost electrical machines

PM-Wire™ Impact

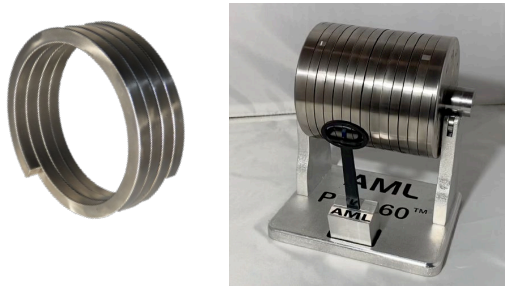
Value Proposition

Improving the performance and lowering the cost of the end-use product like electrical machines

How this is possible?

PM-Wire magnets can replace conventional north-south rotor topologies

- ✓ Unique magnet shapes
- ✓ Unique magnetization
- ✓ Unique motor topologies

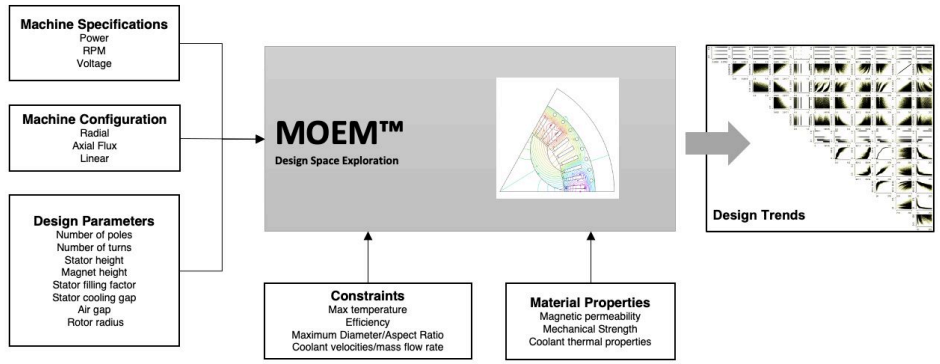


PM-360™ - Helical

PM-360™ - Magnetization

Impact Examples

- ✓ PM-AXIAL™ - Industrial Motor With Significant Improvement In Performance (NdFeB)
- ✓ PM-360™ - Industrial Motor Using Non-Sintered Alloy (NdFeB)
- ✓ PM-AXIAL™ - Industrial Motor Using Reduced Critical Rare Earth Alloy (Mischmetal NdFeB)
- ✓ PM-360™ - Electric Vehicle Motor Using Using Non-Sintered Alloy (NdFeB)
- ✓ PM-360™ - Electric Vehicle Motor Using Non-Sintered and Non-Rare Earth Alloy (MnBi)
- ✓ PM-AXIAL™ - Electric Vehicle Motor Using Non-Rare Earth Alloy (FeN)



AML Application Development

Proprietary software and unique experience used for electrical machine optimization

Process flow: 1st Order Design Study (no charge) → Preliminary Design → Detailed Design → Prototyping → Optimized Product

Industrial Motor

Baseline Design - Large, global electrical machine manufacturer

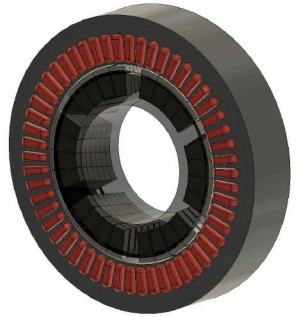
Torque - 311 Nm; Efficiency - 98.6%; Power - 375 kW; RPM - 11,500 RPM

Magnet Material: N48SH

Operating Temperature: 100 C

Critical Rare Earth Mass: 1.74 kg

- ✓ **NdPr = 1.49 kg**
- ✓ **Dysprosium = 0.25 kg**



Example 1

PM-AXIAL™ - Industrial Motor With Significant Improvement In Performance (NdFeB)

Solution

- ✓ Retrofit solution replaced north-south rotor pole topology with PM-AXIAL™
- ✓ No change to motor stator
- ✓ Same magnet N48SH NdFeB alloy

AML Performance Improvement

- ✓ Halbach array performance
- ✓ 150 C - 50% increase in operating temperature
- ✓ 50% reduction in rotor overwrap thickness
- ✓ Reduction in mass by removing the iron
- ✓ Modification of motor stator would result in additional increase in performance

Industrial Motor

Example 2

PM-360™ - Industrial Motor Using Non-Sintered Alloy (NdFeB)

Specifications: 375 kW / 11,000 RPM

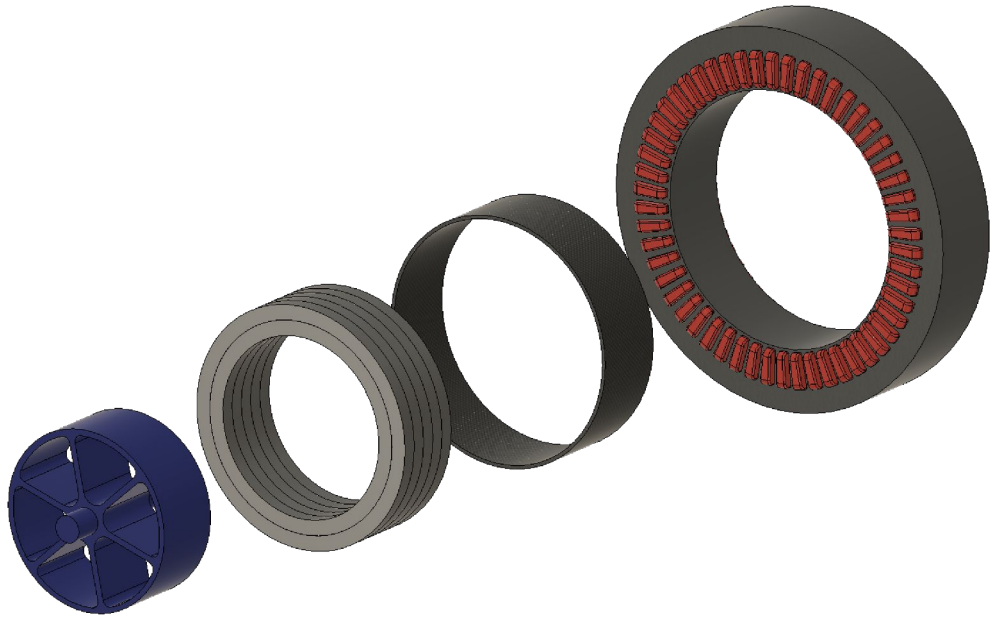
Solution

- ✓ Retrofit solution replaced north-south rotor pole topology with PM-360™
- ✓ No change to motor stator
- ✓ **Non-Sintered MF18P** alloy
  - Br and Hci (@ 120 C) = 0.89 T and 9.2 kGauss
- ✓ Replace 168 sintered N48SH magnets with **10 PM-360™ rings**

AML Performance

- ✓ Equivalent torque and efficiency
- ✓ 10% reduction in active mass

Video



Industrial Motor

Example 3

PM-AXIAL™ - Industrial Motor With Significant Improvement In Performance (NdFeB)

Specifications: 375 kW / 11,000 RPM

Solution

- ✓ Retrofit solution replaced north-south rotor pole topology with PM-AXIAL™
- ✓ No change to motor stator
- ✓ **Mischmetal (40%) / NdPr (60%)** FeB alloy
  - [Br and Hci (@ 120 C) = 1.01 T and 1.850 kGauss]

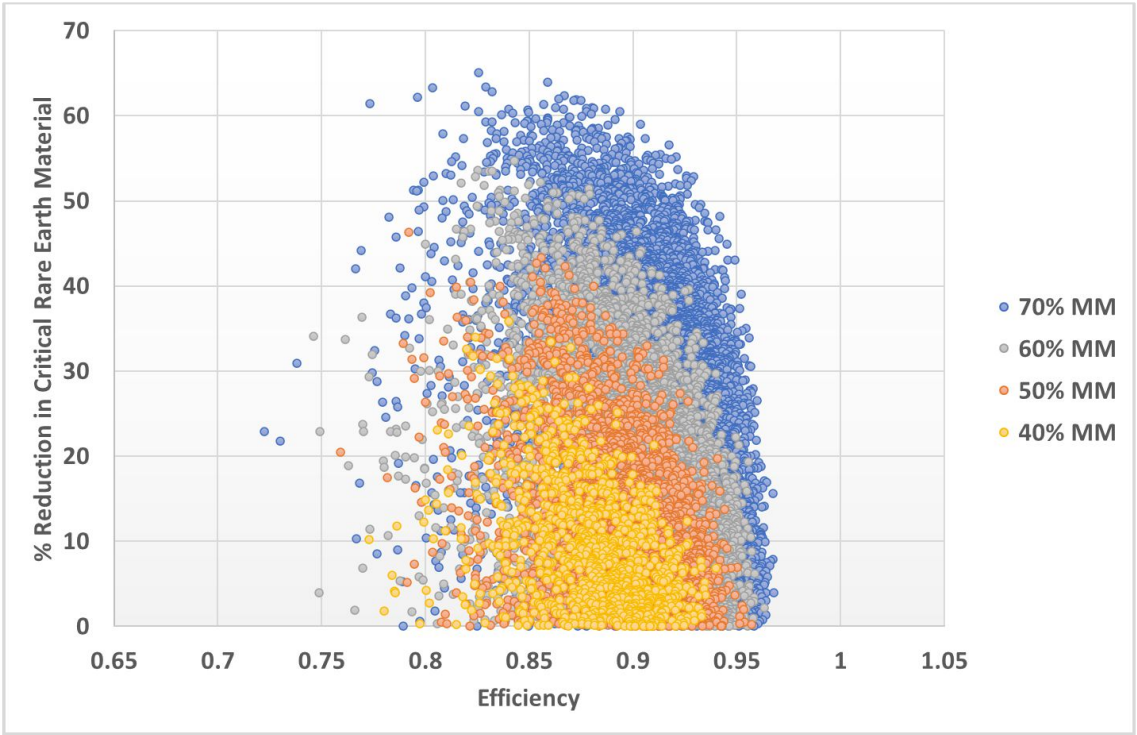
AML Performance

- ✓ Equivalent torque and efficiency
- ✓ 37% reduction in critical rare earths (**NdPr**) and no **dysprosium**
- ✓ 11% reduction in active mass

Cost Comparison

NdPr - ~ $90 per kilogram

Mischmetal - $1-$5 per kilogram
(55% Cerium, 25% Lanthanum, 18%Neodymium, %2 Praseodymium)



Reduction in Critical Rare Earth Materials vs. Efficiency for an example AML Retrofit Design

Electric Vehicle Motor

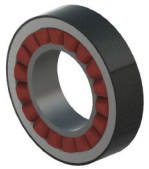
Motor Specifications

Collaboration with the Oak Ridge National Laboratory

Outrunner Configuration

Power: 58 kW

RPM: 20,000



Video

Example 4

PM-360™ - Electric Vehicle Motor Using Using Non-Sintered Alloy (NdFeB)

Solution

- ✓ Retrofit solution replacing Halbach rotor topology with PM-360™
- ✓ Replacing ~**2,750** NdFeB sintered magnets with **8 PM-360™ rings**
- ✓ Anisotropic Bonded (MQA-36-19) alloy
  - Br and Hci (@ 80 C) = 0.9 T and 19 kGauss

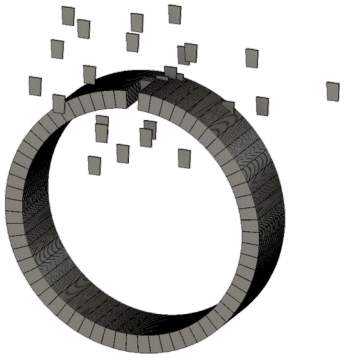
AML Performance

- ✓ Equivalent torque and efficiency
- ✓ Eliminate the need to actively cool the motor rotor
- ✓ Significantly reduce part count and complexity of assembly
- ✓ A fraction of the cost compared to sintered complex Halbach array design

AML

PM-360™

OAK RIDGE National Laboratory



Halbach Array

Vs.

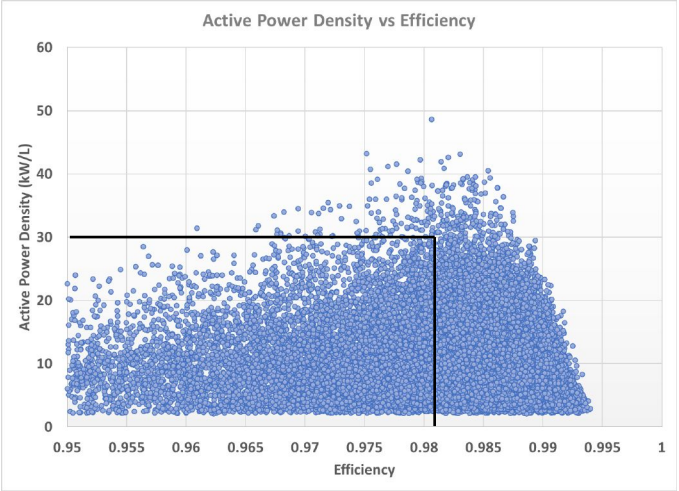
Electric Vehicle Motor

Motor Specifications

Power Density: > 30 kW/L

Power: 300 kW

RPM: 12,000



Example 5

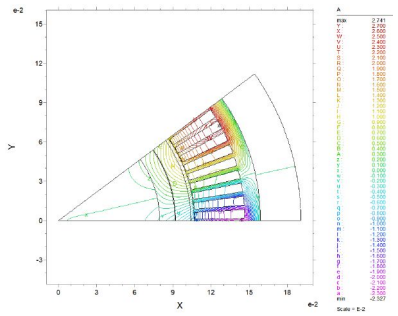
PM-360™ - Electric Vehicle Motor Using Non-Sintered and Non-Rare Earth Alloy (MnBi)

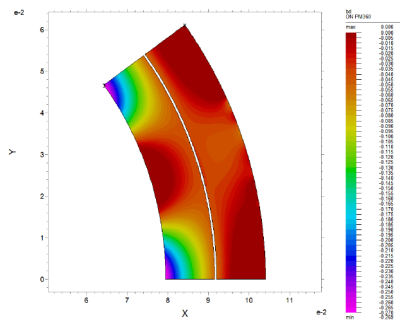
Solution

- ✓ New Design (re-design of stator and rotor)
- ✓ **Manganese Bismuth (MnBi)** alloy
  - MnBi @ 120 C, Br = 0.235 T and Hci = 15 kG

AML Performance

- ✓ Design Space Exploration shows the full design space opportunity for >30 kW/L power densities





Electric Vehicle Motor

Motor Specifications

2022 U.S. Department of Energy Power Density Goal: > 50 kW/L

Power: 300 kW

RPM: 12,000

Example 6

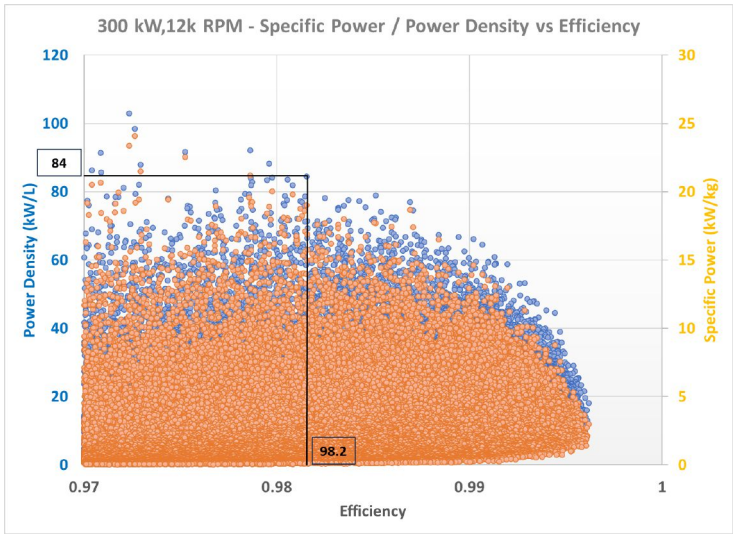
PM-AXIAL™ - Electric Vehicle Motor Using Non-Rare Earth Alloy (FeN)

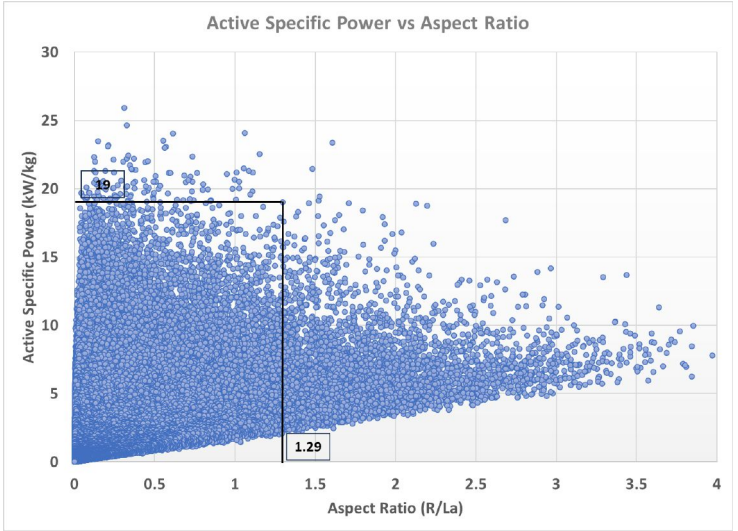
Solution

- ✓ New Design (re-design of stator and rotor)
- ✓ **Non-Rare Earth - Iron Nitride (FeN)** alloy
  - NRE magnet material – Iron Nitride (FeN) with Br = 0.88T, Hci = 3 kGauss

AML Performance

- ✓ Motor Efficiency ~ 98%
- ✓ Motor Power Density ~ **70 kW/L**





AML Differentiation – Enable New Material Markets

Market Pathways

Pathways are based on magnet material (alloy) type

Non-Sintered Magnets

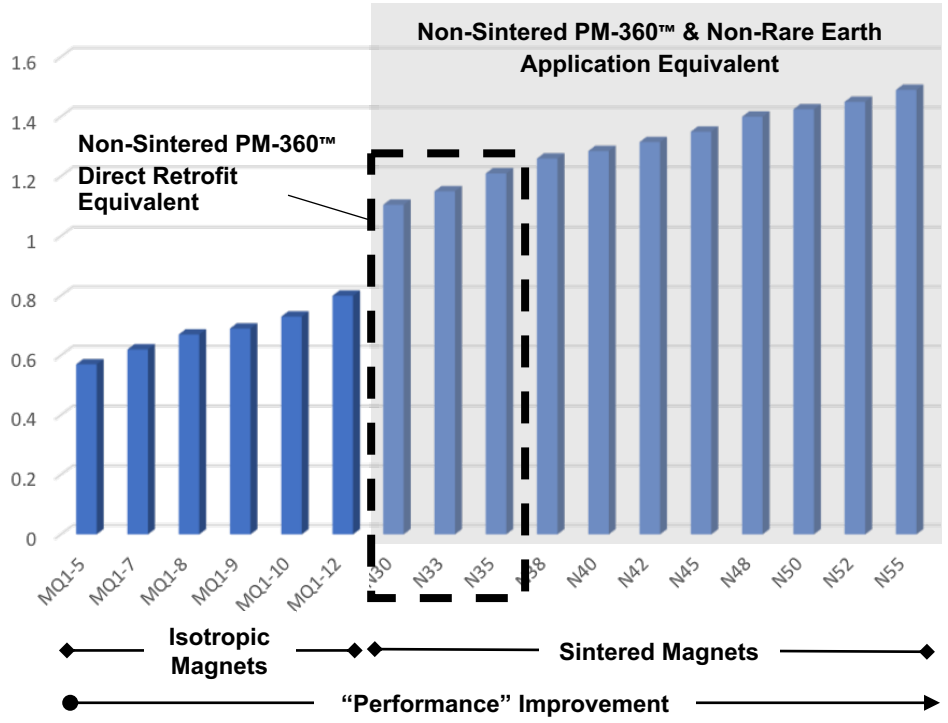
- ✓ PM-Wire™ manufacturing process validated for producing non-sintered NdFeB magnets
- ✓ Ideal for densifying and containing material and eliminates need for a bonding agent
- ✓ Configured as a PM-360™ or PM-AXIAL™ magnets can replace sintered magnets
- ✓ **MITUS Manufacturing Line is ready for Full-Rate Manufacturing**

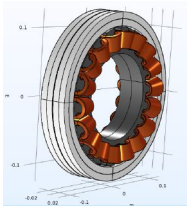
Sintered Magnes

- ✓ PM-Wire™ manufacturing process validated for producing conventional magnets
- ✓ Requires engineering and commissioning Full-Rate Manufacturing automation
- ✓ **Low-rate manufacturing with a focus on defense applications in 2024**

Non-Rare Earth Magnets

- ✓ PM-Wire™ manufacturing process validated for producing non-rare earth magnets
- ✓ Ideal for densifying and containing material and eliminates need for a bonding agent
- ✓ PM-AXIAL™ non-rare earth magnets can replace sintered magnets in motors and generators
- ✓ MITUS Manufacturing Line is ready for Full-Rate Manufacturing
- ✓ **Once materials are commercialization**

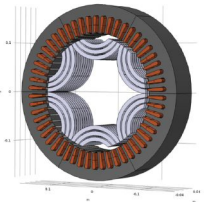




Non-Sintered Validation

OAK RIDGE National Laboratory

EV

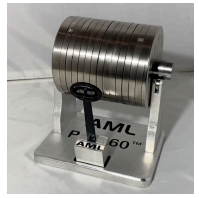


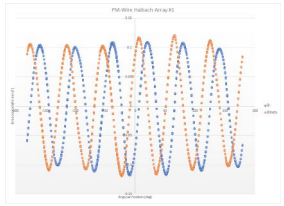
Non-Rare Earth Validation

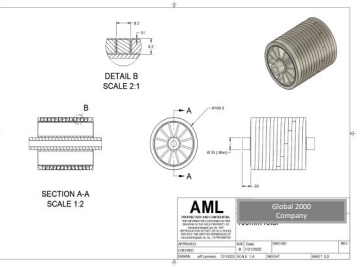
PM-Wire™ Commercialization Activities

Current PM-Wire™ Magnet Production Programs

Branch of the U.S. Department of Defense







Heavy Industries Company

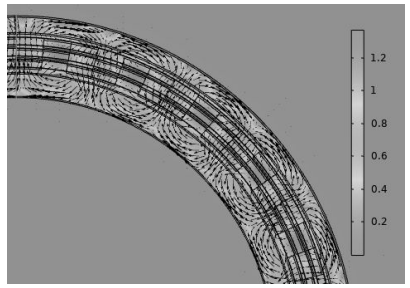
PM-Wire™ products in a variety of motor and generator products

Current PM-Wire™ Based Application Developments

U.S. Aerospace and Defense Company

High-power density aero propulsion motors and generators

Funded by the U.S. Department of Energy / ARPA-E



U.S. Defense Contractor

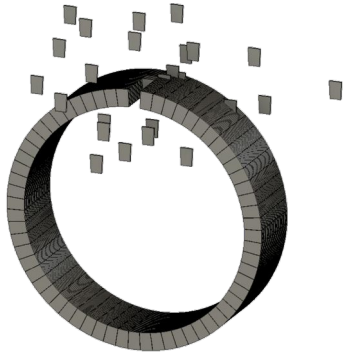
Development of several electrical machines

Oak Ridge National Laboratory

Electric Vehicles

PM-360™

Vs.



Halbach Array

AML Materials / Alloy Development

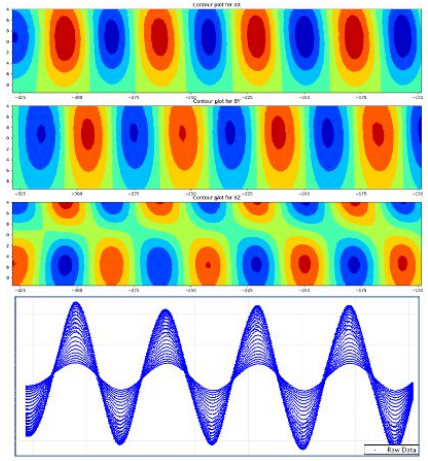
Lab Scale Development

Collaborations

- ✓ U.S Supply Chain Partner
- ✓ Ames National Laboratory / Critical Materials Institute
- ✓ Argonne National Laboratory

Takeaway

Imagine a Magnet Industry Without Limitations



Materials

Enabling less critical rare earth and non rare earth alloys

Magnets & Manufacturing

High-rate, high-yield, high-quality, low CapEx

Magnet End-Use Product

Improving the performance and lowering the cost of the end-use product

Along with our supply chain, governmental and end-use partners,

We are Decommoditizing the Magnet Industry!

AML

Reimagining the Magnet Technology that Drives the World

THANK YOU!

AML-Enabled.com

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PM-Wire™