HIGH-SPEED HYBRID RELUCTANCE MOTOR WITH ANISOTROPIC MATERIALS

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General Motors
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Project ID#: ELT093

GENERAL MOTORS

OVERVIEW

Timeline

Start Date: October, 2016
End Date: December, 2019
Duration: 3 years

Completion: 70%

Barriers

- Implement lower cost HRE-free magnets with higher coercivity and designs protecting against demagnetization
- Design improved Cu-Al interfaces for improved conductivity and reduced cost
- Validate motor performance and endurance for vehicle reliability

Budget

Total funding for 3 years

$4.64M – DOE Share

$2.44M – GM Share

$7.08M – Total

FY2018 DOE Funds Rec'd: $666,719

FY2019 DOE Fund Forecast: $485,314

Project Lead

General Motors

Partner

- Oak Ridge National Lab

OBJECTIVE

Design and validate three motor variants with no heavy rare earth (HRE) content:

Heavy rare earth elements have limited sources and price volatility

- Variant 1: HRE-free permanent magnet (PM) motor
- Variant 2: Synchronous reluctance motor (SyRM) with HRE-free PM assist
- Variant 3: Hybrid induction motor with cast aluminum (Al) and insert copper (Cu) bars

Variants should be capable of meeting the following DoE year 2020 targets:

- Cost ($/kW) less than $4.7
- Specific Power (kW/kg) greater than 1.6
- Power density (kW/L) greater than 5.7

	Application	Primary Traction motor	Rear axle traction (AWD)
Variant 1	HRE-free PM motor	X	
Variant 2	SyRM with HRE-free PM assist		X
Variant 3	Hybrid Cu-Al Induction Motor	X	X

APPROACH TO BARRIERS

- HRE-free magnets provide less energy-product for motors, and experience permanent demagnetization at lower temperatures

  Completed: Identify capable materials and validate and test on a magnet level

- Cu-cast Al interfaces tend to be poor and fail rapidly under motor conditions

  Completed: Demonstrate improved Cu-Al interfaces on cast coupons

  Target: Optimize rotor casting parameters for best Cu-Al interfaces

- Many efforts to improve demagnetization resistance or power come at the expense of high speed mechanical strength

  Target: Validate novel designs compensating for mechanical strength while maintaining torque

MILESTONES

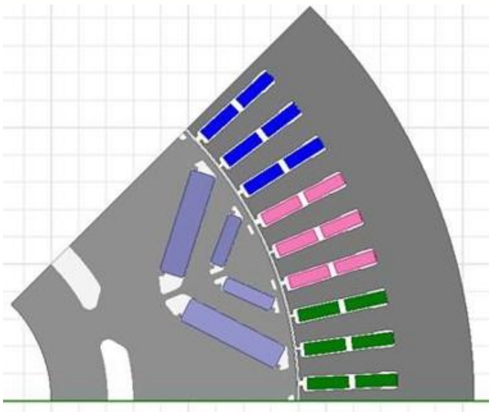
Milestone	Description	Planned Completion Date
Budget Period 2 (Jan 2018 – May 2019)		
Rotor and Stator Fabricated and Assembled	Rotor and Stator build complete and evaluate weight based on the active machine materials	5/10/19
Rotor High Speed Evaluation Complete	High Speed evaluation accomplished with report of burst test results	5/17/19
Production Process Developed	Production processes identified to achieve a cost production goal of $4.7/kW.	Complete
Motor cost in alignment with project targets	Motor cost assessment complete and used to construct test plan that aims to achieve a specific power of 1.6 kW/kg and power density of 5.7 kW/Liter	Complete
Budget Period 3 (May 2019 – Dec 2019)		
Initial Preparation for Motor Testing complete	Electric traction motors have been built and prepared for testing	5/30/2019
Motor Calibration Complete	Electric machine calibration completed for all motors	7/12/2019
Fatigue Tests Complete	Durability testing on two of the three motor types will be completed	10/31/2019
Performance Evaluation Complete	Performance Evaluation and Correlation – the results of performance testing will be compared to simulation results (Actual vs. Predicted).	12/31/2019

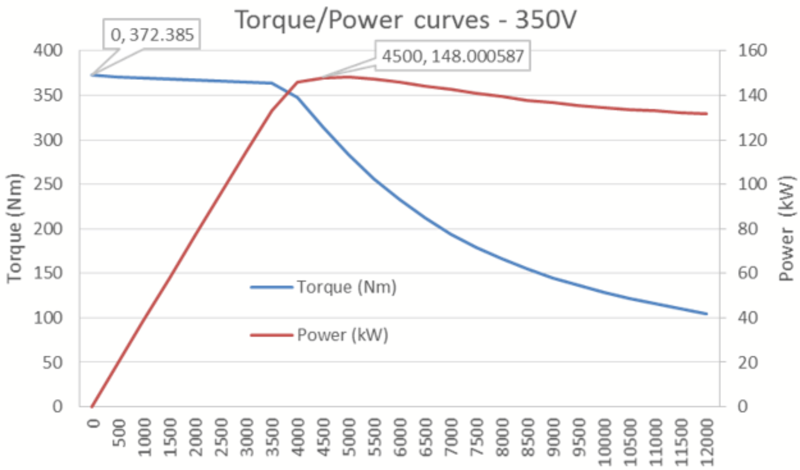
TECHNICAL ACCOMPLISHMENTS AND PROGRESS

- 3 Variant designs were designed to meet vehicle electromagnetic performance, mechanical, and thermal requirements

	HRE-free PM Motor	Synchronous Reluctance Motor with HRE-free PM Assist	Hybrid Induction Motor with Insert Cu Bars and Cast Al End-rings
Stator Outer Diameter (mm)	208	190	190
Rotor Outer Diameter (mm)	139.5	139.1	139.1
Stator Core Length (mm)	200	100	100
Power (kW)	148	86	84
Torque (N-m)	372	249	310
Max RPM	12000	16650	12950
Nominal Voltage (V)	350	350	350
Maximum Current (Arms)	400	450	450

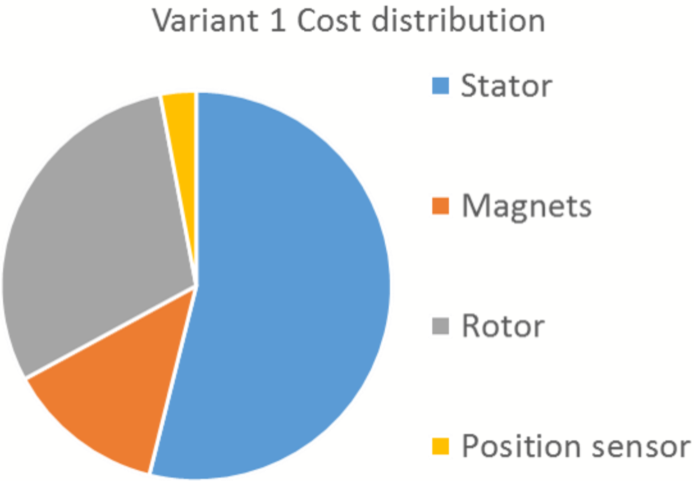
VARIANT 1 – HRE-FREE PM MOTOR



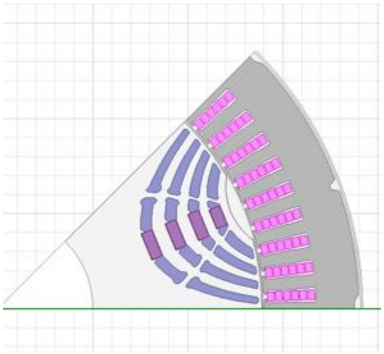


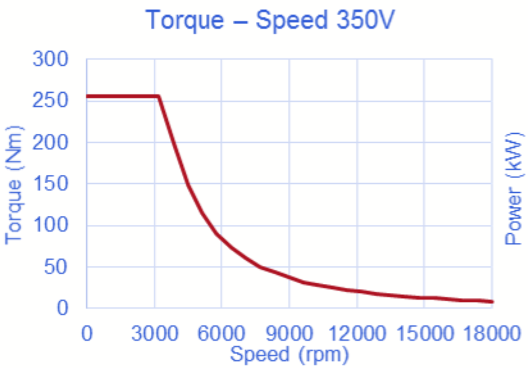
Performance						
	Mass	Volume	Power	Specific Power	Power Density	Cost
Target				≥1.6 kW/kilogram	≥5.7 kW/Liter	$4.7/kW
Variant 1	35.2 kg	6.6 L	148 kW	4.2 kW/kg	22.5 kW/L	Meets

VARIANT 1 – HRE-FREE PM MOTOR



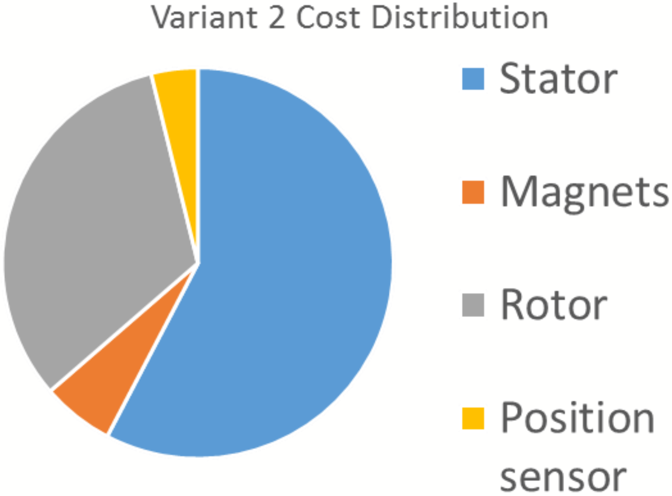
VARIANT 2 – SYRM WITH HRE-FREE PM ASSIST



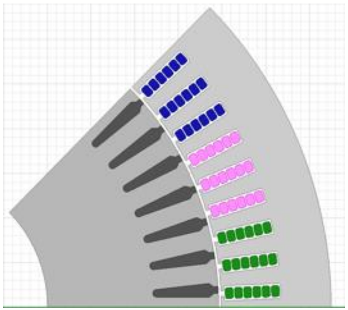


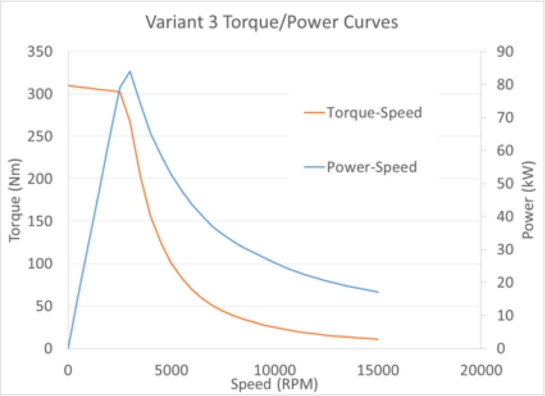
Performance						
	Mass	**Volume**	**Power**	**Specific Power**	**Power Density**	**Cost**
Target				≥1.6 kW/kilogram	≥5.7 kW/Liter	$4.7/kW
Variant 2	24.1 kg	5.4 L	86 kW	3.6 kW/kg	15.9 kW/L	Does not meet

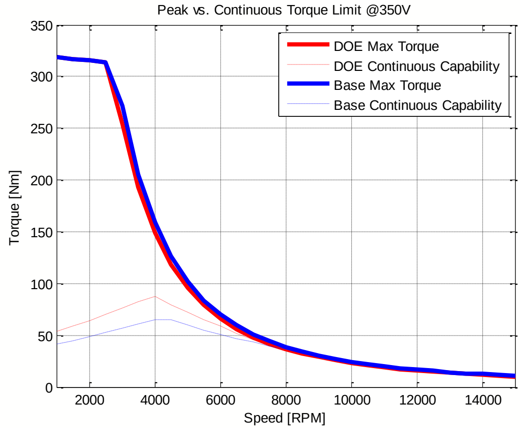
VARIANT 2 – SYRM WITH HRE-FREE PM ASSIST



VARIANT 3 – HYBRID CU-AL INDUCTION MOTOR

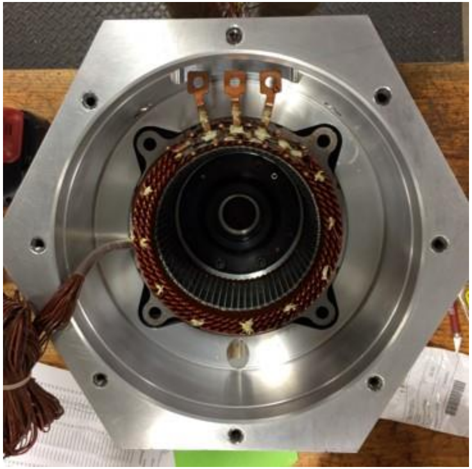


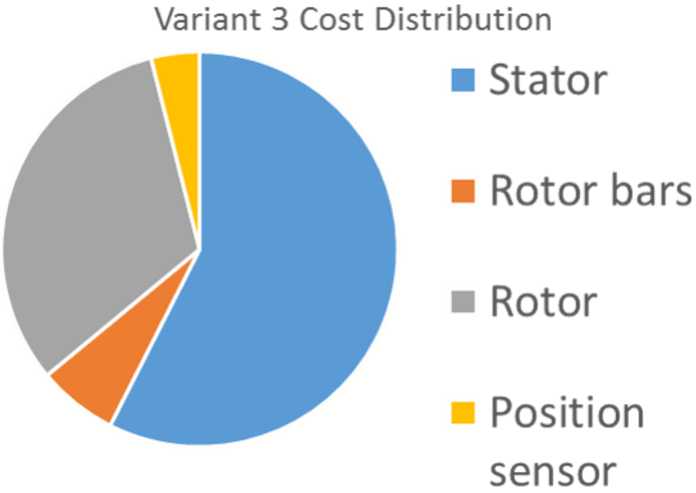




Performance						
	Mass	**Volume**	**Power**	**Specific Power**	**Power Density**	**Cost**
Target				≥1.6 kW/kilogram	≥5.7 kW/Liter	$4.7/kW
Variant 3	27.3 kg	5.4 L	84 kW	3.1 kW/kg	15.6 kW/L	Does not meet

VARIANT 3 – HYBRID CU-AL INDUCTION MOTOR

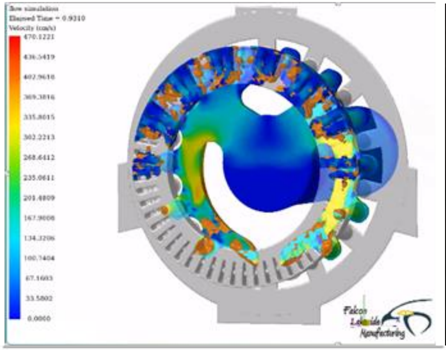


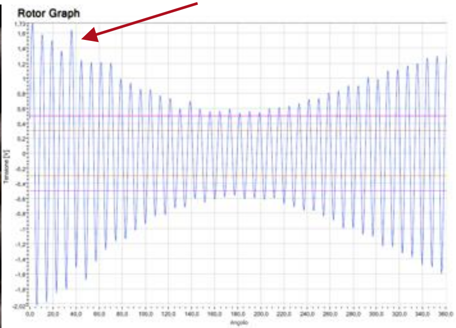


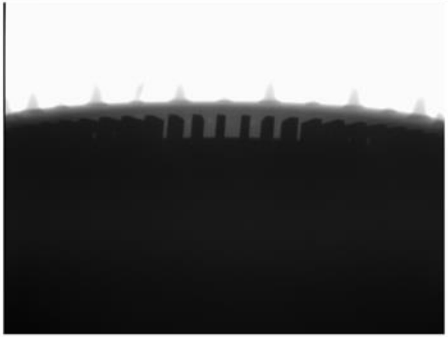
VARIANT 3 – HYBRID CU-AL INDUCTION MOTOR

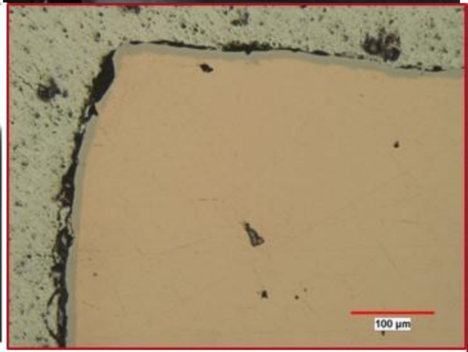
Focus is on improving casting parameters of Cu-Al cast rotors

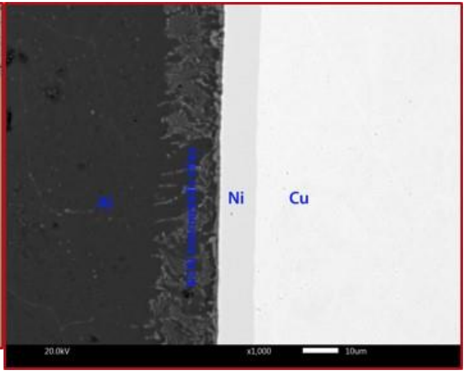
Reduce bar variation







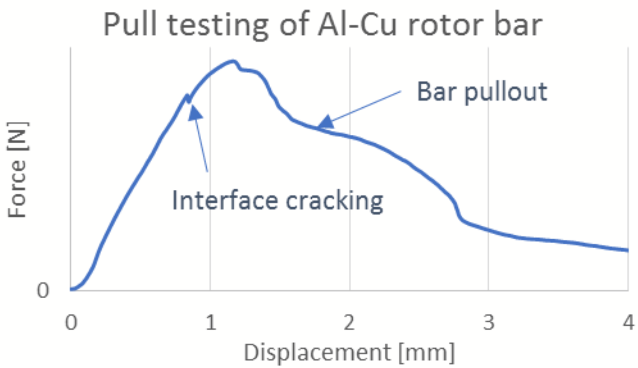


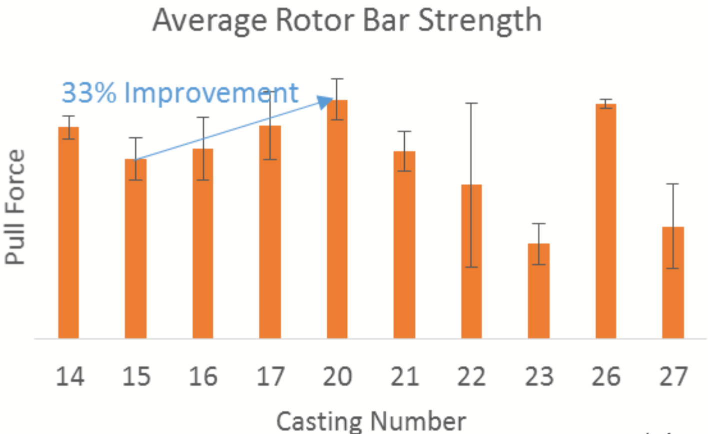


VARIANT 3 – HYBRID CU-AL INDUCTION MOTOR

Focus is on improving casting parameters of Cu-Al cast rotors

Parameters
Bar length into end ring
Shot temperature
Flux





RESPONSES TO PREVIOUS YEAR REVIEWERS' COMMENTS

Concerns expressed regarding exceeding the 2020 targets, suggested comparing to the 2025 targets

Performance						
	Mass	Volume	Power	Specific Power	Power Density	Cost
Target 2020				≥1.6 kW/kilogram	≥5.7 kW/L	≥$4.7/kW
Target 2025				≥5 kW/kg	≥50 kW/L	≥$3.3/kW
Variant 1	35.2 kg	6.6 L	148 kW	4.2 kW/kg	22.5 kW/L	Meets 2020 Does not meet 2025
Variant 2	24.1 kg	5.4 L	86 kW	3.6 kW/kg	15.9 kW/L	Does not meet 2020 Does not meet 2025
Variant 3	27.3 kg	5.4 L	84 kW	3.1 kW/kg	15.6 kW/L	Does not meet 2020 Does not meet 2025

Parameters per FOA-0001384

- Calculate cost based on 2015 equivalent dollars
- Calculate power based on peak power capability for a duration of at least 2 seconds
- Calculate weight based on active machine materials including rotor shaft and bearings. Weight does not need to include the machine case, connections, or connectors.
- Calculate volume based on overall stator outside diameter (or maximum diameter) and overall length. Volume does not need to include case, connections, or connectors.

RESPONSES TO PREVIOUS YEAR REVIEWERS' COMMENTS

Several reviewers expressed concerns regarding the novelty of the three motor variants

Vehicle	Vehicle Type	Model Year	Power/(magnet mass)	HRE-containing (benchmarking)
1	EV	2014	57 kW/kg	Yes
2	EV	2014	50 kW/kg	Yes
3	EV	2018	52 kW/kg	Yes
4	EV	2018	112 kW/kg	Yes
5	HEV	2018	101 kW/kg	Yes
6	HEV	2018	105 kW/kg	No
7	HEV	2016	98 kW/kg	Yes
Variant 1	EV		86 kW/kg	No
Variant 2	HEV		172 kW/kg	No

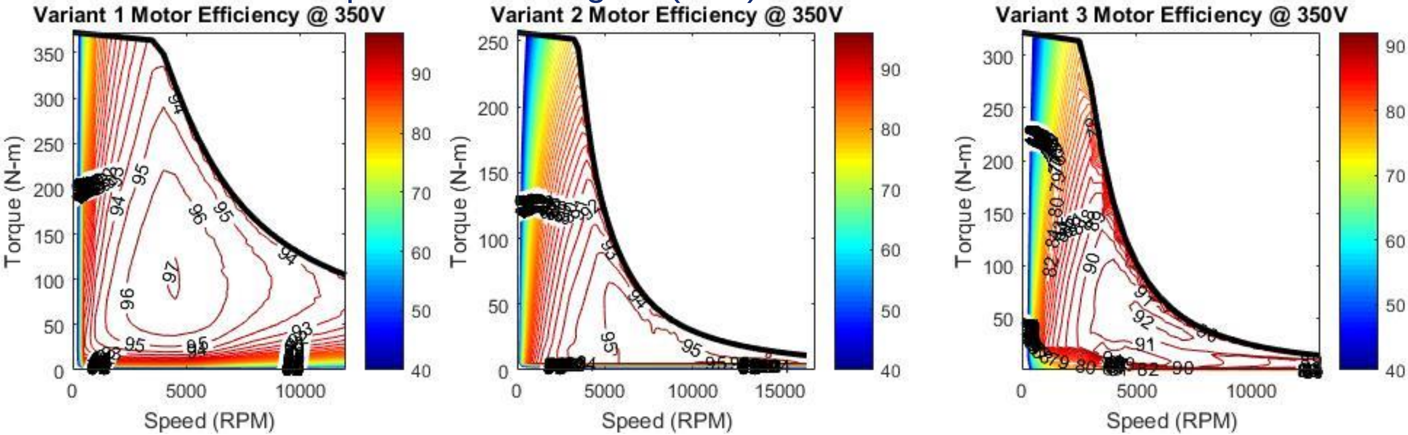
RESPONSES TO PREVIOUS YEAR REVIEWERS' COMMENTS

Several reviewers expressed concerns regarding the novelty of the three motor variants

Vehicle	Vehicle Type	Model Year	Rotor type (benchmarking)
8	EV	2015	Cu
9	EV	2015	Cu
10	HEV	2018	Al
11	EV	2019	Al
12 (GM)	HEV	2016	Al
Variant 3	HEV / EV		Hybrid Cu/Al

RESPONSES TO PREVIOUS YEAR REVIEWERS' COMMENTS

One reviewer requested information on efficiency and comparisons to a baseline internal permanent magnet (IPM) motor



	Max Efficiency	Torque density (N-m/L)	Power density (kW/L)
Variant 1	97%	56	22.5
Variant 2	95%	46	15.9
Variant 3	92%	57	15.6
GM IPM		56	22.5

COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

ORNL collaboration (Partner)

Prepared with assistance from Tim Burress, Ercan Cakmak, Yanli Wang

Motor steel sample analysis

- Edge analysis – optical analysis of sheared edge from stamping operation
- Microhardness – harness in various locations in cross-section
- Compositional analysis – to determine composition of material
- Coating thickness – important for stacking factor and resistance between laminations
- Coating composition – same as above
- Density
- Electromagnetic properties – permeability, loss, and exciting power vs flux density and frequency
- Tensile and fatigue

Induction motor bar analysis

- Porosity of casting
- Tensile and fatigue testing of copper/cast aluminum interface

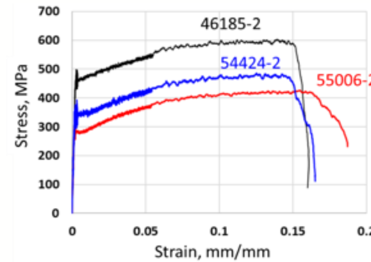
COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

Comparison of properties for 3 types of material

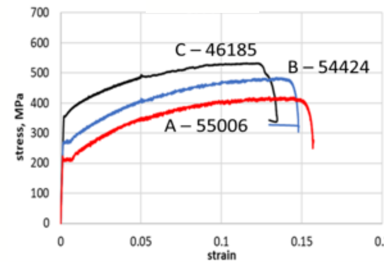
Both room temperature and high temperature testing being performed

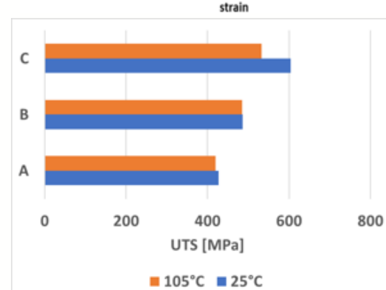
Extensive fatigue testing underway

25°C



150°C

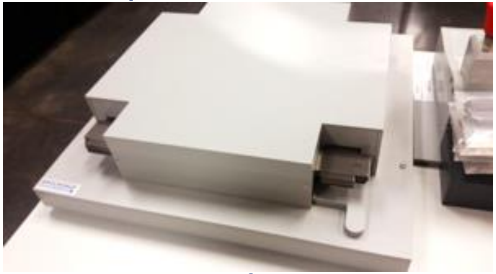




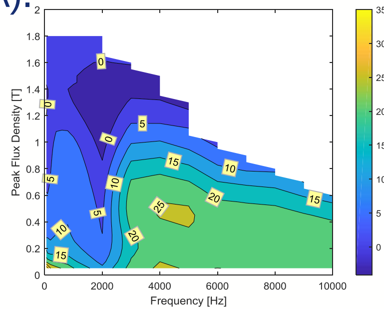
Ultimate tensile strength for room temperature and 105°C

COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

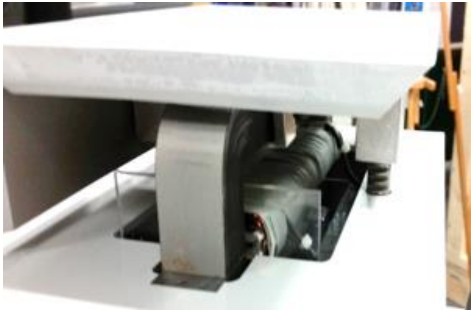
Epstein strips and single sheet tester (SST) strips tested for permeability and core loss at various flux densities and frequencies.
Additional SST tests underway to investigate impact of residual stresses and subsequent stress relief annealing (SRA).



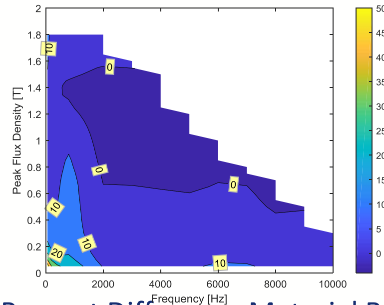
Epstein test frame



Core loss result: Material C: SRA-NSRA



SST test frame



SST Core Loss Percent Difference Material B: SRA - NSRA

COLLABORATION AND COORDINATION WITH OTHER INSTITUTIONS

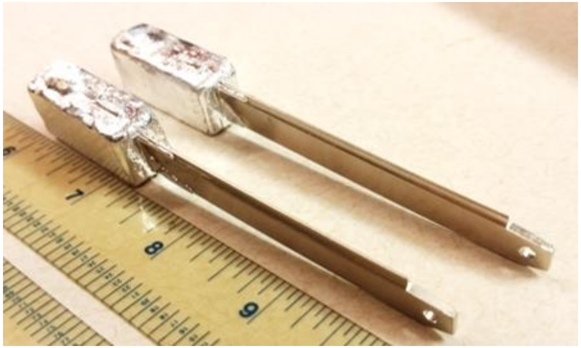
3D Scanning of Rotor Bars

- Pores near the copper and cast aluminum interface can have significant impacts on mechanical strength and electrical conductivity.
- Although pores were observed in a different part of the sample, very few were observed near the copper and aluminum interface.

3D Reconstruction of Pore Geometry

Material Opacity Increased to Show Sample Orientation

X-ray CT Scanning – Same Scan and Angle



REMAINING CHALLENGES AND BARRIERS

- Support supplier base through rotor manufacturing process
- Validate rotor mechanical strength through burst testing
- Validating design performance and endurance through hardware testing

Any proposed future work is subject to change based on funding levels

PROPOSED FUTURE RESEARCH

- Motor hardware to be tested to confirm analytical results

Induction Motor	Motor Calibration
	Spin Loss (UM)
	Performance & Efficiency
	Rotor Endurance
SyRM w/ HRE-Free PM Assist	Motor Calibration
	Spin Loss (M & UM)
	Performance & Efficiency
	Demagnetization Test
	Rotor Endurance
HRE-Free PM Motor	Motor Calibration
	Performance & Efficiency
	Demagnetization Test

- Cost and material robustness alternatives to the HRE-free PM and hybrid induction motor studied through alternative motor variants

Any proposed future work is subject to change based on funding levels

SUMMARY

- All three designs meet DoE performance targets and address initial design barriers on a materials level.
- Cost analysis completed showing cost meeting target on Variant 1, but not Variant 2 or 3
- Motor hardware builds to be completed in Q2 2019
- Motors to be validated and performance to be compared to analytical results

Performance						
	Mass	Volume	Power	Specific Power	Power Density	Cost
Target 2020				≥1.6 kW/kilogram	≥5.7 kW/L	≥$4.7/kW
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