U.S. Department of Energy
Advanced Research Projects Agency – Energy (ARPA-E)

Request for Information (RFI)
DE-FOA-0002534
on
Enabling eLEctrical Conductor Technologies for Resistance ReductiON (ELECTRRON)

Introduction

The purpose of this RFI is to solicit input for potential future ARPA-E supported research efforts focused on novel, unconventional ideas, approaches, and **enabling technologies** to reduce electrical conductor resistivity.

This is a new "hybrid" RFI format where you may choose to (1) provide a written response, as with past ARPA-E RFI's, **and/or** (2) participate in a related online **"incubator" and "ask me anything" (AMA) discussion session hosted on a platform developed by Polyplexus, LLC**. Guidance for (1) is provided at the end of this document. For (2), please follow this weblink: https://polyplexus.com/incubator?idIncubator=606&initialTab=overview. The incubator and AMA, **which are scheduled from 6/11/2021 to 6/25/2021 and 6/18/2021 3:30pm-5:00pm, respectively,** are like an online chat forum that allows for dynamic, evidence-based discussions moderated by an ARPA-E Program Director, providing an opportunity for interested parties to actively influence the discussion and interact with the Program Director. The incubator discussions and AMA will be visible to any registered Polyplexus user; registration is free and available to anyone according to the terms available at the site linked above. Your participation in the incubator and AMA are not required in order to provide feedback on this potential future program, but encouraged.

Transporting electricity through conductors is among the most prevalent mechanisms for energy transfer today, and poised to grow significantly with increased electrification of the industrial, transportation, and building sectors. Reducing the energy losses in conductors improves the efficiency of electrical transport and reduces associated energy production emissions. Better conductors will also be critical for power transmission in a more distributed grid as renewable energies like solar and wind are integrated.[1,2,3]

There are two strategies to increase power transmission with minimal increase in losses:

(1) Employing higher voltages
(2) Moving electricity at higher current

For the first strategy, higher voltages pose material design challenges, particularly for high voltage

[1] Bird, L., Milligan, M. and Lew, D., 2013. *Integrating variable renewable energy: Challenges and solutions* (No. NREL/TP-6A20-60451). National Renewable Energy Lab.(NREL), Golden, CO (United States).
[2] Cochran, J., Denholm, P., Speer, B. and Miller, M., 2015. Grid integration and the carrying capacity of the US grid to incorporate variable renewable energy (No. NREL/TP-6A20-62607). National Renewable Energy Lab.(NREL), Golden, CO (United States).
[3] Mathis, Will, and Akshat Rathi. "Better Cables Could Halve U.S. Grid Emissions by 2030, Gates-Led Group Says." Bloomberg Green, Bloomberg, 2 Mar. 2021, https://www.bloomberg.com/news/articles/2021-03-02/bill-gates-led-group-shows-u-s-grid-emissions-can-fall-45.

insulating media that are used to prevent arcing or corona discharge in the lines and gas-insulated equipment (GIE). Recently, ARPA-E announced support for innovative methods for medium-voltage power distribution through the Connecting Aviation by Lighter Electric Systems (CABLES) program. Projects funded under the CABLES Program focus on development and identification of material systems with optimal gravimetric densities, insulating materials with high dielectric strength, high voltage connector designs and mechanisms that address partial discharge-related challenges.[4] As this strategy -- innovative methods for medium-voltage power distribution -- is covered by CABLES, it will not be a focus of this RFI.

For the second strategy, higher currents are impacted by resistance losses. As electrons pass through conductors, they collide and interact with atoms in the lattice, impurities, defects in the crystal structure of the material, and grain boundaries. These mechanisms hinder electron transport and result in Joule heating, with heat generated being proportional to the product of the square of the current and the resistance of the conductor. It is estimated that approximately 6%[5] of all electric power generated in the US is dissipated as heat as it is transmitted through the grid; expanding this number to include all electronics, the total energy losses due to Joule heating can amount to 15%[6].Reducing resistance losses can be accomplished by either increasing the cross-sectional area of the wire, or by developing enabling technologies for reducing the resistivity of the conductive material.

Basic research on the behavior of materials in response to external stimuli is supported under the DOE Office of Science Physical Behavior of Materials research area[7], ARPA-E is interested to learn if some of the enabling technologies to support these superior electrical conductors should be researched and matured as well and what entitlement these conductors could achieve. In addition, ARPA-E would be interested to learn what applications could be first adopters of such new conductors, and what mechanical(density, strength), electrical(resistivity, AC performance, electromigration), cost and other metrics might be relevant for such applications.

The questions in this RFI are aligned along these areas; **(A) identification of application spaces for superior conductors** and **(B) identification of technology paths for reducing the resistivity of conductors and potentially required enabling technologies**.

[4] https://arpa-e-foa.energy.gov/Default.aspx?foaId=b2f61120-672c-4bfa-8552-d53cb687839c
[5] IEA Statistics © OECD/IEA 2018 https://data.worldbank.org/
[6] International Electrotechnical Commission, 2007. Efficient electrical energy transmission and distribution. Switzerland, IEC.
[7] https://science.osti.gov/bes/mse/Research-Areas/Physical-Behavior-of-Materials

Enabling technologies for potential technical paths of interest are depicted in Table 1, expressed in enhancement over International Annealed Copper Standard (IACS) [8] at particular application temperature ranges. These areas are designated as "Ultra conductors"[9] and "Hyper conductors"[10], referring to electrical conductors with superior conductivity properties at various temperature ranges and ultra-pure conductors at cryogenic temperatures, respectively. Note that ARPA-E's interest is not limited to these areas, and other innovative approaches that meet the objectives outlined in this RFI are welcome.

Area of interest	Designation	IACS enhancement target	Operational temperature range
i	Ultra conductors / advanced covetics	>125 %	20^{o}C to 150^{o}C
ii	High Temperature Ultra conductors	>125 %	150^{o}C to 400^{o}C
iii	Low Temperature Ultra conductors	>125 %	-80^{o}C to 20^o
iv	Ambient Temperature Super conductors	>> 125%	0^{o}C to 150^{o}C
v	Cryogenic Temperature Hyper conductors (not superconducting)	>> 125%	4^{o}K to 100^{o}K

Table 1 Potential interest areas and enhancement targets for enhanced electrical conductors

i. Ultra conductors / advanced covetics: Copper has been the conductor of choice for over a century. Although silver has lower intrinsic resistivity and aluminum is a better conductor on a per mass basis, cost and performance requirements have limited their use. More recently, alternative methods to enhance electrical conductivity in metals have been explored through development of carbon nanomaterial-metal composites, or covetics[11]. Some of the most well-known examples are layered copper composites integrating either carbon nanotube films or graphene sheets. These approaches have recently shown the potential for conductivity improvements up to 116% IACS, but have proven to be challenging to manufacture at scale (i.e. several feet in length and significant diameter).[12] The Department of Energy Advanced Manufacturing Office (DOE AMO) recently launched the CABLE Conductor Manufacturing Prize to support innovative approaches to overcome performance and manufacturing challenges associated with covetic materials[13].

   Several emerging research efforts and insights show promise for conduction enhancement beyond the AMO efforts already supported. As standalone structures, carbon, carbon nanotubes (CNTs) and other nanomaterials have advanced significantly over the past few decades and, in some cases, are exhibiting electrical, mechanical, and thermal material properties on par with their metal counterparts.[14] Furthermore, evidence of superior electrical conductivity in graphitic systems has been reported, potentially opening up entirely new avenues for carbon-based conductors.[15] There is sufficient evidence at lab scale to suggest that carbon-based conductors could play a significant role in future

[8] United States Department of Commerce, Circular of the Bureau of Standards. Copper Wire Cables. No. 31.(3d ed.)Oct. 1, 1914.
[9] Kakani, Shubhra., Kakani, S. L.. Superconductivity. United Kingdom: Anshan, 2009.
[10] Neelakanta, P. S.. Handbook of Electromagnetic Materials: Monolithic and Composite Versions and Their Applications. Italy: CRC-Press, 1995.
[11] Bakir, Mete, et al. "Novel metal-carbon nanomaterials: A review on covetics." Adv. Mater. Lett 8, no. 884 (2017): 10-5185.
[12] Adams, H.J. "Graphene-Copper Composite Structure and Manufacturing Method." U.S. Patent Application 15/697,114, 4/12, 2018.
[13] U.S. Department of Energy. n.d. "American-Made Challenges. CABLE Conductor Manufacturing Prize." Accessed March 2021. https://americanmadechallenges.org/cable/
[14] Taylor, Lauren W., Oliver S. Dewey, Robert J. Headrick, Natsumi Komatsu, Nicolas Marquez Peraca, Geoff Wehmeyer, Junichiro Kono, and Matteo Pasquali. "Improved properties, increased production, and the path to broad adoption of carbon nanotube fibers." Carbon 171 (2021): 689-694.
[15] Pezzini, Sergio, Vaidotas Miseikis, Giulia Piccinini, Stiven Forti, Simona Pace, Rebecca Engelke, Francesco Rossella et al. "30°-twisted bilayer graphene quasicrystals from chemical vapor deposition." Nano letters 20, no. 5 (2020): 3313-3319.

electrical conductors, though for now global production remains relatively small[16] and limited by quality challenges such as number of defects, number of layers, control over material morphology, etc. ARPA-E is interested in learning the state-of-the-art in producing high quality carbon structures and what projections can be made to lower cost in high-volume production of high-quality material.

ii. High Temperature Ultra Conductors: Some applications that could benefit from superior electrical conductors are those with higher operational temperature requirements (e.g. electric motors, conductors, and bus bars in power conversion electronics). The potential operational temperature range of these applications is important to consider as electrical conductor resistance changes with temperature. Due to the development of wide band gap semiconductors and the proliferation of electrified propulsion in transportation systems, electric propulsion systems that can operate at increasingly higher temperatures (>175ºC-250ºC) are being investigated. As the electrical resistance of a copper conductor at 175ºC is approximately 57% higher than at room temperature, it is apparent that higher temperature operation negatively impacts system efficiency. Materials whose conductivity exhibits a more favorable temperature-dependent behavior is important in such applications. New insights suggest that CNT-Cu and Cu-Carbon Nanodispersion (CND) metal matrix composites have a reduced temperature dependent resistivity gradient such that at higher temperatures, they could have the potential to outperform traditional conductors[17,18]. Such mechanisms might lead to a new material or composite material that might not be superior to copper at room temperature, but could lead to a significant electrical resistance reduction relative to standard conductors at high temperatures (150ºC to 400ºC), which is an area of interest for electrified transportation applications. ARPA-e would be interested to learn what enabling technologies are needed for superior conductors at higher temperatures.

iii. Low Temperature Ultra conductors: Operating at lower temperature is another route to reducing electrical resistance. For example, at -18ºC (typical home freezer temperature), copper electrical resistance is reduced by approximately 16% compared to room temperature and at -80°C, (laboratory ultra-low freezers), copper resistance drops by 40% compared to room temperature. If cooling can be delivered to the conductor at low cost and high efficiency, an inflection point can be envisioned where the added energy for cooling is compensated by the energy savings due to the lower resistance in the conductors. Low cost methods for modest cooling such as water evaporation[19,20] or enhanced radiative cooling[21] of transmission lines could potentially generate such a benefit if it can be employed cost effective and reliably.

iv. Ambient Temperature Super conductors: Beyond traditional metals, the search for room temperature superconductors has been an active area of research. Superconductivity enables lossless transmission of power by reducing resistance to zero. According to Bardeen–Cooper–Schrieffer (BCS) theory, superconductivity arises from a high degree of electron-phonon coupling, allowing the formation of coordinated electron pairs (Cooper pairs) that move efficiently through the lattice of the material. This effect can be maintained up to a critical temperature and critical current density; when these limits are exceeded, the state is quenched and resistance increases dramatically. Although some commercial

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[16] Zheng, Leiliang. “Advanced Materials Primer: Carbon Nanotubes”. February 8, 2021. BloombergNEF.

[17] Subramaniam, Chandramouli, Takeo Yamada, Kazufumi Kobashi, Atsuko Sekiguchi, Don N. Futaba, Motoo Yumura, and Kenji Hata. "One hundred fold increase in current carrying capacity in a carbon nanotube–copper composite." Nature communications 4, no. 1 (2013): 1-7.

[18] Medeliene, V. and Stankevic, V. "The Influence of Particles of Carbon Nanoderivative on the Properties of the Electrodeposited Copper Nanocomposite Coating." Galvanotechnik 103, no. 5 (2012): 942-946.

[19] Rabinowitz, Mario, et al. "Evaporation-cooled transmission line system." U.S. Pat. 4,091,230, issued May 23, 1978.

[20] Ramakrishna Prabhu, G. G., and Vidhya, K., and Thamilselvan, R. "Power Transmission Lines Cooling in Underground Cables and Overhead Lines." International Journal of Advanced Science and Technology 29. No. 12s (2020): 1982-1990.

[21] Li, Xiangyu, Joseph Peoples, Peiyan Yao, and Xiulin Ruan. "Ultrawhite $BaSO_4$ Paints and Films for Remarkable Daytime Subambient Radiative Cooling." ACS Applied Materials & Interfaces (2021).

deployment of superconducting systems occurs, system costs for maintaining temperatures below the critical temperature (typically in the cryogenic range), materials cost for low temperature superconductor (LTS) and high temperature superconductor (HTS) wires, and risks for system quenching have limited further large-scale commercial deployment of cryogenic supercondcutors. However, research efforts continue for cryogenic superconductors in areas including grid transmission cables, aviation propulsion, and wind turbine power generation. [22,23,24]

Ideally a superconductor would work at ambient temperature conditions. Recent findings have demonstrated the potential for ambient temperature superconducting behavior, though only at extremely high pressures.[25] By compressing a mixture of carbon, sulfur, and hydrogen to ~267 GPa in a diamond anvil, a sharp transition to a superconducting state was observed at 288 K. Although the exact structure of the material has not yet been determined, it is hypothesized that electrons couple to the high frequency phonon modes of a “metallic hydrogen” analogue (high T superconductivity has been similarly observed in other metal hydride and covalent metal systems). These developments open up the intriguing possibility of superconductivity without the need for refrigeration. The National Science Foundation(NSF) has supported a number of projects on superconductivity through the Condensed Matter and Materials Theory (CMMT) program[26] and recently published a letter inviting the research community to establish pathway towards light-element superconductivity at normal temperature and pressure.[27] Another approach to solve this challenge could be to identify mechanisms to develop transmission systems that are internally under high compression. ARPA-E is interested in learning what enabling technologies are required to mature this kind of technology for future use.

v. Cryogenic Temperature Hyper conductors (not superconducting): Controlling the purity in metals is another route towards lower-resistance wires. Enhancing the purity in copper conductors can potentially reduce the electrical resistance by a factor of two to three at cryogenic temperatures. The residual resistance ratio (RRR) describes the ratio of the resistance of a material at 0 K compared to room temperature and can be used as an approximate surrogate for purity. It is reported that at RRR 30,000, a copper resistance reduction of several orders of magnitude below standard 99.95% purity copper[28] could potentially be achieved. Although such a conductor would not have zero resistance, as would be expected in a superconductor, it might have sufficiently low resistance for highly efficient systems. Such “hyper conductors” would not have the traditional superconductor challenges of potential quenching, sensitivity to magnetic fields, and limited AC operations[29]. Although increased conductivity may contribute to higher alternating current (AC) losses due to ‘skin effect’, that may be prevented by the well-known Litz wiring technique. Production methods for high-purity germanium and silicon have been developed for the semiconductor industry; Enabling technologies for production of high-purity copper, aluminum and other metals to achieve low cost, highly pure electrical

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[22] https://www.powerengineeringint.com/smart-grid-td/td-infrastructure/high-temperature-superconductors-could-solve-future-transmission-challenges/

[23] Madavan, Nateri, J. Heidmann, C. Bowman, P. Kascak, A. Jankovsky, and R. Jansen. "A NASA perspective on electric propulsion technologies for commercial aviation." In Proceedings of the Workshop on Technology Roadmap for Large Electric Machines, Urbana-Champaign, IL, USA, pp. 5-6. 2016.

[24] U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. January 20, 2021. "Department of Energy Selects Projects to Develop High-Efficiency, Lightweight Wind Turbine Generators for Tall Wind and Offshore Applications." Accessed March 2021. https://www.energy.gov/eere/articles/department-energy-selects-projects-develop-high-efficiency-lightweight-wind-turbine

[25] Snider, Elliot, Nathan Dasenbrock-Gammon, Raymond McBride, Mathew Debessai, Hiranya Vindana, Kevin Vencatasamy, Keith V. Lawler, Ashkan Salamat, and Ranga P. Dias. "Room-temperature superconductivity in a carbonaceous sulfur hydride." Nature 586, no. 7829 (2020): 373-377.

[26] https://www.nsf.gov/pubs/2020/nsf20582/nsf20582.htm

[27] https://www.nsf.gov/pubs/2021/nsf21039/nsf21039.jsp

[28] Matula, R.A., 1979. Electrical resistivity of copper, gold, palladium, and silver. J. Physical and Chemical Reference Data, 8(4), pp.1147-1298.

[29] Sumption, M.D., Murphy, J., Susner, M. and Haugan, T., 2020. Performance metrics of electrical conductors for aerospace cryogenic motors, generators, and transmission cables. Cryogenics, 111, p.103171.

conductors is of potential interest to ARPA-E.

Applying transport concepts from other fields may also yield new insights in electrical conductivities. As an example, how might mechanisms that support high efficiency thermal transport in heat pipes and vapor chambers be replicated or translated to electronic systems? Heat pipes and vapor chambers use a liquid-to-vapor phase change in a working fluid at the evaporator to absorb energy and release this energy through condensation at the heat rejection or condenser side. Working fluids for heat pipes and vapor chambers range from water, ammonia, salts and low melting point alloys. This "bucket-brigade" mechanism allows for heat pipes and vapor chambers to realize effective thermal conductivities far superior to their intrinsic material capabilities.[30,31,32] ARPA-E would be interested to learn if similar mechanisms could be explored for efficient electron transfer.

Other recent advances in topological materials and Weyl metals have also challenged the traditional views related to electrical conductors and insulators. Topological materials are a class of materials with robust, fixed electronic states and electromagnetic responses. The electronic states are fully protected and remain unchanged, even with changes in the physical structure of the materials or changes in temperature.[33] As a result, entirely new material properties are being observed. For example, $Bi_{0.96}Sb_{0.04}$ exhibited a nonlinear voltage-current relationship under a longitudinal magnetic field, a clear violation of Ohm's law.[34] In another study, the topological metal, MoP, was found to have half the electrical resistivity of copper at low temperatures (6 nΩ cm at 2K) due to a triple point in the metal's Fermi surface.[35] In addition, some topological insulators feature superconductive transport along the surface of the material, in contrast to their insulating properties in the bulk of the material.[36] ARPA-E would be interested to learn about the potential of these approaches and needs for enabling supporting technologies.

[30] "Heat Pipes – A basics demonstration", Advanced Cooling Technologies, 1-act.com, https://youtu.be/51bwzEO8XCw
[31] Chi, S. W. "Heat pipe theory and practice." Washington (1976).
[32] Faghri, A., 1995. Heat pipe science and technology. Global Digital Press.
[33] Savage, Neil. 2018. "Topological Materials Move from the World of Theoretical Physics to Experimental Chemistry." C&EN, June 23, 2018. https://cen.acs.org/articles/96/i26/Topological-materials-move-world-theoretical.html.
[34] Shin, Dongwoo, Yongwoo Lee, M. Sasaki, Yoon Hee Jeong, Franziska Weickert, Jon B. Betts, Heon-Jung Kim, Ki-Seok Kim, and Jeehoon Kim. "Violation of Ohm's law in a Weyl metal." Nature materials 16, no. 11 (2017): 1096-1099.
[35] Kumar, Nitesh, Yan Sun, Michael Nicklas, Sarah J. Watzman, Olga Young, Inge Leermakers, Jacob Hornung et al. "Extremely high conductivity observed in the triple point topological metal MoP." Nature communications 10, no. 1 (2019): 1-7.
[36] Kononov, Artem, Gulibusitan Abulizi, Kejian Qu, Jiaqiang Yan, David Mandrus, Kenji Watanabe, Takashi Taniguchi, and Christian Schönenberger. "One-dimensional edge transport in few-layer WTe2." Nano letters 20, no. 6 (2020): 4228-4233.

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below. Please note, in particular, that the information you provide will be used by ARPA-E solely for program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME.**

Purpose and Need for Information

The purpose of this RFI is solely to solicit input for ARPA-E consideration to inform the possible formulation of future research programs. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI without any attribution to the source. This RFI provides the broad research community with an opportunity to contribute views and opinions.

REQUEST FOR INFORMATION GUIDELINES

No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E may contact respondents to request clarification or seek additional information relevant to this RFI. All responses provided will be considered, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents shall not include any information in the response to this RFI that could be considered proprietary or confidential.**

Responses to this RFI should be submitted in PDF format to the email address **ARPA-E-RFI@hq.doe.gov** by **5:00 PM Eastern Time on 7/31/2021**. Emails should conform to the following guidelines:

- Please insert "Response to RFI on Enabling eLEctrical Conductor Technologies for Resistance ReductiON (ELECTRRON)- <your organization name>" in the subject line of your email
- In the body of your email, include your name, title, organization, type of organization (e.g. university, non-governmental organization, small business, large business, federally funded research and development center (FFRDC), government-owned/government-operated (GOGO), etc.), email address, telephone number, and area of expertise.
- Responses to this RFI are limited to no more than 10 pages in length (12-point font size).
- Responders are strongly encouraged to include preliminary results, data, and figures that describe their potential innovations.

Targeted Questions Seeking Specific Feedback

Please provide responses and information about any of the following. ARPA-E does not expect any one respondent to answer all, or even many, of these prompts. Simply indicate the question number in your response. Citations are encouraged as appropriate. When possible please be as quantitative as possible, in particular with potential energy savings and carbon footprint reduction, economics and technological advancements, and other areas of direct significance to ARPAE mission. Respondents are also welcome to address other relevant avenues/technologies that are not outlined below.

A. **Identification of application spaces for superior conductors, Impact and technical metrics**

i. What applications would benefit the most from a superior electrical conductor? What are the most promising first market applications? For any applications identified, what performance targets would enhanced conductors need to achieve to be commercially viable?
   - IACS conductivity enhancement % (and at what temperature range)
   - AC conductivity target (frequency vs skin depth)
   - Other electrical properties (Ampacity, electromigration)
   - Twist and bendability of the conductors (minimum twist pitch and bend radius)
   - Thermal conductivity (W/m/K)
   - Specific weight- Mechanical properties
   - Minimum length of the developed conductors (mm, cm, or meters)
   - Cost targets ($/kg or $/kA-m)
   - Others?

B. **Technical approaches and enabling technologies to enhance electrical conductivity**

i. Ultra conductors / advanced covetics: Covetics and carbon nano-enhanced conductors have been studied extensively over the past decade. What has been the key bottleneck that has prohibited their ability to achieve significant >125% enhancement in IACS conductivity at significant scale? What is the maximum IACS enhancement potential of these approaches?

ii. High Temperature Ultra Conductors: Are there new ideas for electrical conductors that outperform IACS at higher temperatures 150-400^{o}C and/or exhibit differentiated beneficial temperature dependent performance gradients?

iii. Low Temperature Ultra conductors: Are there cooling methods that can be made at such low cost and high efficiency to take advantage of the lower resistance of conductors in the -80^{o}C to 20^{o}C temperature range? Where would the inflection point be at which the energy savings from reducing electrical conduction losses outpace the energy cost of cooling?

iv. Ambient Temperature Super conductors: What are enabling technologies required to bring high pressure ambient super conductors to maturity? What methods could be envisioned to reach high levels of compression in conductors (i.e. cables) and what levels could be reached? Are there other approaches to reach ambient super conductivity? What is the timeframe anticipated for these technologies to have meaningful maturation and energy impact?

v. Cryogenic Temperature Hyper conductors (not superconducting): Could high purity, high RRR conductors be a complement to LTS/HTS? Will their AC and non-quenching abilities provide meaningful benefits or are these insufficient to yield new technology concepts? Are there low-cost approaches to develop such high purity conductors?

vi. Other: Are there other electrical conductor technologies that have the potential to reach commercial maturity in the next 10-15 years? Are there adjacent “enabling” technology developments from multi-disciplinary teams needed to bring some of these new electrical conductors to maturity?