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Materials Innovation for Next-Generation T&D Grid Components: Workshop Summary Report

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Electrical and Electronics Systems Research Division

MATERIALS INNOVATION FOR NEXT-GENERATION T&D GRID COMPONENTS: WORKSHOP SUMMARY REPORT

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ABBREVIATED TERMS

AAC	all aluminum conductor
AC	alternating current
ACSR	aluminum core steel reinforced
AMO	Advanced Manufacturing Office
CEMI	Clean Energy Manufacturing Initiative
CNT	carbon nanotube
CTE	Coefficient of Thermal Expansion
CVD	chemical vapor deposition
DC	direct current
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
FACTS	flexible alternating current transmission systems
FPGA	field programmable gate array
FREEDM	the Future Renewable Electric Energy Delivery center
HDMMC	heavily deformed metal matrix composite
HF	high frequency
HTS	high temperature superconductivity
HVDC	high-voltage direct current
IGBT	insulated-gate bipolar transistor
K	Kelvin
kV	kilovolt
MOSFET	metal oxide semiconductor field effect transistor
MMC	metal matrix composite
NETL	National Energy Technology Laboratory
OE	Office of Electricity Delivery and Energy Reliability
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
PE	power electronics
R&D	research and development
SF_6	sulfur hexafluoride
SST	solid state transformers
T&D	transmission and distribution
TRAC	Transformer Resilience and Advanced Components
TRL	technology readiness level
XLPE	cross-linked polyethylene
WBG	wide bandgap

PREFACE

The *Materials Innovations for Next-Generation T&D Grid Components Workshop* was co-sponsored by the U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability and the Oak Ridge National Laboratory (ORNL) and held on August 26–27, 2015, at the ORNL campus in Oak Ridge, Tennessee. The workshop was planned and executed under the direction of workshop co-chair Dr. Kerry Cheung (DOE) and co-chair Dr. Dominic Lee (ORNL). The information contained herein is based on the results of the workshop, which was attended by nearly 50 experts from government, industry, and academia. The research needs and pathways described in this report reflect the expert opinions of workshop participants, but they are not intended to represent the views of the entire electric power community.

ACKNOWLEDGMENTS

Many thanks to everyone who participated in the *Materials Innovations for Next-Generation T&D Grid Components Workshop*, held on August 26–27, 2015, at the Oak Ridge National Laboratory campus in Oak Ridge, Tennessee. The plenary presentations and discussions that took place at the workshop provided the foundation for this report. Special thanks are extended to the plenary speakers (listed below) and to the many expert participants (a complete list is provided in Appendix A).

Plenary Speakers:
Joe Schatz (Southern Company)
Richard Ord (Electric Power Research Institute)
Alex Huang (North Carolina State University FREEDM Systems Center)
Debbie Haught (DOE)
Paul Ohodnicki (National Energy Technology Laboratory)
Jim Davidson (Vanderbilt University)
Mark Johnson (DOE)

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EXECUTIVE SUMMARY

Future economic growth, public health and safety, and environmental quality of the United States demands evolution and revolution in grid technologies to ensure reliable, affordable, secure, and clean electric power. Evolving capabilities, changing demands, and new technologies require greater flexibility and agility from the U.S. electric grid, including the ability to optimize grid operations dynamically. Current trends facing the electric power system include:

- *Changing demand* driven by population growth, adoption of energy-efficient technologies, dynamic economic conditions, broader electrification, and mass markets for electric vehicles

- *Changing supply mix* (e.g. renewable, nuclear, natural gas, coal) and location (centralized, distributed, off-shore) of the nation's generation portfolio driven by technology, market, and policy developments

- *Increasing variability of supply and demand patterns*, including the integration of variable renewable energy sources, more active consumer participation, and accommodating new technologies and techniques

- *Increasing threats to electric infrastructure*, such as more frequent and intense extreme weather events, cyber threats and attacks, and interdependencies with natural gas and water infrastructure

- *Aging electricity infrastructure* that requires new technologies to enable better failure detection, upgrade capabilities, and improve cybersecurity

These trends present opportunities to advance the capabilities of today's electricity delivery system. As the electric power system evolves to enable a more resilient and clean energy future, R&D can increase understanding of the physical impact these changes have on vital grid components, help to identify new technical requirements, and encourage adoption of new technologies and approaches. Applied R&D in advanced materials has the potential to improve the fundamental properties and capabilities of hardware for grid applications and support grid modernization efforts. During this period of transition, the deployment of new technologies will play a critical role in shaping the future grid.

With this context in mind, the U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability (OE), in collaboration with Oak Ridge National Laboratory (ORNL), organized and hosted a workshop to investigate the opportunities for materials innovation in the electric grid and their application to next-generation transmission and distribution (T&D) components. Experts in advanced materials and electric grid components lent their voices in exploring this opportunity space. Their leadership and participation in this process provided the appropriate expertise and experience needed to help ensure the results reflected the diverse needs of the stakeholder community.

The Materials Innovation for Next-Generation Transmission and Distribution Grid Components Workshop, held August 26–27, 2015, at ORNL, investigated various advanced materials and their potential application to next-generation transmission and distribution (T&D) components.

Figure 1 illustrates the relationship between functional materials that form the basis of transmission and distribution components and their role in an evolving electric power system. Materials innovation can enhance grid components to address emerging system trends; simultaneously, system trends change grid component requirements that may require new material innovations.

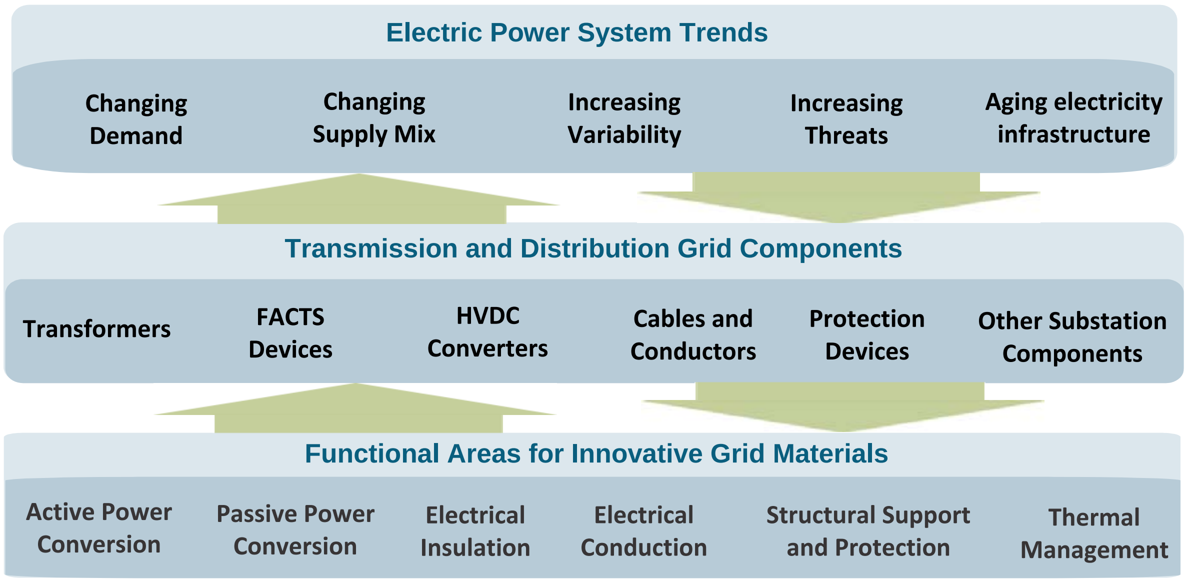

Fig. 1. Connection between functional areas for innovative grid materials, T&D grid components and electric power system trends.

TECHNICAL CHALLENGES

During the workshop, a voting process among the workshop participants was used to determine the areas with technical challenges that may warrant further investigation. Figure 2 graphically depicts the results of the voting process from more than 40 people, in the form of a *heat map*, showing the number of votes cast by participants in each individual cell. Material functionalities are listed in the left column. Grid component classifications are listed across the top row. Each cell represents material functionalities that are potentially applicable to a specific grid component. The green cells indicate areas receiving large number of votes for containing technical challenges with the greatest impact if overcome. The darker green cells represent component-specific functional issues that were most often classified by participants as areas requiring further investigation.

	A. Transformers	B. FACTS Devices	C. HVDC Converters	D. Cables and Conductors	E. Protection Devices	F. Other Substation Components	G. Other
1. Active Power Conversion	11	8	9	0	12	0	1
2. Passive Power Conversion	11	9	11	0	1	0	0
3. Electrical Insulation	14	0	0	12	5	0	0
4. Electrical Conduction	2	1	0	23	3	0	0
5. Structural Support & Protection	2	0	0	4	2	1	0
6. Thermal Management	19	8	6	4	5	0	6
7. Other	4	0	0	0	3	1	8

Fig. 2. Technical challenges affecting the performance and development of grid components

As reflected in the above heat map, in aggregate, the workshop participants identified the following technical challenge areas as most pressing:

- ***Electrical conduction and insulation for cables and conductors***: Electric power is routed through a long network of transmission and distribution wire, cable, transformers, and additional components, before reaching its destination in a consumer load. Throughout this process, an estimated 6% of the available electricity is lost.[1] Novel materials can be developed to enhance the electrical conduction of overhead conductors and underground cables, while adding other beneficial properties. For instance, next generation cables and conductors could benefit from greater mechanical strength, improved thermal conductivity, superior insulating capabilities, and a resistance to the accumulation of ice and debris.

- ***Enhancing the performance of transformers***: Transformers are an essential part of the structure and operation of the electric power system. Thermal management and electrical insulation significantly affects the service lifetime and reliability of conventional transformers. Transformer heating is a result of power losses (inefficiency) in the transformer core and windings that can degrade the performance of its insulation. Therefore, materials with lower losses or improved electrical insulation at elevated temperatures could enhance transformer lifetime and reliability.

- ***Active and passive power conversion for HVDC Converters, FACTS Devices, and transformers***: Many technical challenges were common to high-voltage direct current (HVDC) converters, flexible alternating current transmission systems (FACTS) devices, and solid state transformers (SST). As a cluster of technical challenge areas, power electronics proved to be a topic with high potential for improving the grid. Technical challenges associated with power electronic systems include limitations of active switching devices and passive devices, like capacitors and magnetic elements. High frequency magnetic materials with optimized magnetic properties and improved ductility could enable improvements in the power density of power electronic systems. Wide bandgap (WBG)

[1] "How much electricity is lost in transmission and distribution in the United States?", US Energy Information Agency, http://www.eia.gov/tools/faqs/faq.cfm?id=105&t=3, July 10, 2015

semiconductor devices could enhance efficiencies by reducing switching and conduction losses, and enabling converter operation at higher frequencies and temperatures.

- ***Thermal management, protection devices, and other:*** Aside from the specific component challenges discussed above, there are several other key outcomes identified. Thermal management, while critical for transformers, is a technical challenge area that spans across all grid components. In addition to FACTS devices, HVDC converters, and SST, semiconductors could be utilized to enhance protection devices. Finally, there are several impactful technical challenge areas associated with components and functional materials not reflected in Figure 2, such as lightning arrestors and distribution equipment.

INNOVATIVE MATERIALS

After identifying the challenges impacting the grid, participants also identified innovative materials that may show promise to enhance T&D components, including materials for active power conversion (i.e., semiconductors), passive power conversion (i.e., magnetics), electrical insulation, electrical conduction, structural support and protection, and thermal management. Some high-impact materials identified include:

- *Diamond-based semiconductors:* Diamond-based power electronic circuits may provide superior thermal management and system performance, compared to other technologies.

- *Nanocomposite soft magnetic materials:* These materials offer low-loss operation when utilized at high frequencies, and have the potential to create a disruptive impact in the field of passive power conversion for electrical transformers.

- *Metal hydride alloys:* Metal hydride alloys demonstrate enhanced heat dissipation, compared to standard metals used in transformer construction. Materials with a specific heat in the range of 1200 to 3000 kJ/kg could find broad application in thermal management.

- *Self-healing ceramics and polymers:* Self-healing ceramics and polymers could address technical challenges with electrical insulation in transformers. Ceramics or polymers, like perovskites, are an example of a material that could quickly recover if damaged. In addition, polymers with high thermal conductivity but low electrical conductivity may be explored for thermal management applications like heat sinks.

- *Soft magnetic materials adapted for additive manufacturing:* Magnetics that are carefully "3D-printed" may exhibit lower parasitics, among other benefits. The manufacturing of soft-magnetic materials has been a hindrance to their widespread adoption to date. Three dimensional printing can address this issue if it enables the creation of finely tuned geometries and magnetic microstructures to reduce eddy current losses.

- *Materials with decoupled electrical and thermal properties:* An isotropic material could be developed that orients electrical conduction and thermal conduction in different directions.

- *Room temperature superconductors:* Developing room temperature superconductors would greatly enhance power density, system capacity, and operating effectiveness.

- *Ballistic carbon nanotubes and graphene:* Utilizing ballistic conductivity exhibited by carbon nanotubes for electrical conductors would produce power lines and cables with performance that exceeds copper and could offer the same operating performance as room temperature superconducting materials.

- *Heat pipes:* Creating heat pipes from non-conducting composites as opposed to aluminum, which is typical, could result in a device that exhibits high heat transfer, with no electrical conductivity.

- *Superhydrophobic Materials and Coatings:* Super hydrophobic materials can enhance reliability by preventing the buildup of ice and particulate on conductors. Anti-fouling and self-cleaning coatings have the potential to be developed.

- *'Smart' Fault Current Limiting Devices:* Materials that alter their intrinsic properties when exposed to fault conditions can enhance the performance of protection systems.

- *Structural Composites:* Lightweight, high strength, failure proof structural materials can reduce weight and installation costs, while enhancing reliability.

- *Oil-Improving Additives for Thermal Management:* Additives, used as suspensions in transformer oil, have the ability to increase the thermal conductivity of the oil, enhancing the lifetime and reliability of transformers.

NEXT STEPS

This workshop served as the initial step in an on-going effort to investigate the opportunity space for materials innovation in next-generation T&D grid components. DOE will use the outputs of this workshop to inform future activities and research programs. DOE will continue to engage and convene the material science and grid component communities across levels of government, academia, and industry to further explore this critical topic.

Potential future activities include:

- Focused workshops on gap areas identified (e.g., cables and conductors, thermal management)
- Refinement of R&D pathways for grid components (e.g., technical specifications, milestones)
- Development of technical roadmaps to coordinate and align stakeholder efforts

1. INTRODUCTION

1.1 OVERVIEW

Reliable, affordable, secure, and clean electric power underpins national priorities such as economic growth, public health and safety, and environmental quality. However, the electric grid is being operated in ways for which it was not originally designed, which has the potential to impact these priorities. Current trends facing the electric power system include the following:

- *Changing demand* driven by population growth, adoption of energy-efficient technologies, dynamic economic conditions, broader electrification, and mass markets for electric vehicles

- *Changing supply mix* (e.g. renewable, nuclear, natural gas, coal) and location (centralized, distributed, off-shore) of the nation's generation portfolio driven by technology, market, and policy developments

- *Increasing variability of supply and demand patterns*, including the integration of variable renewable energy sources, more active consumer participation, and accommodating new technologies and techniques

- *Increasing threats to electric infrastructure*, such as more frequent and intense extreme weather events, cyber threats and attacks, and interdependencies with natural gas and water infrastructure

- *Aging electricity infrastructure* that requires new technologies to enable better failure detection, upgrade capabilities, and improve cybersecurity

The result of these trends is a system that is under increasing stress and requires much greater flexibility, agility, and ability to dynamically optimize grid operations. These trends present challenges as well as opportunities to advance the capabilities of today's electricity delivery system. During this period of transition, the deployment of new technologies will play a critical role in shaping the future grid.

As the electric power system evolves to enable a more resilient and clean energy future, research and development (R&D) will be needed to understand the physical impact these changes have on vital grid components, identify new technical requirements, and encourage adoption of new technologies and approaches. Applied R&D in advanced materials has the potential to improve the fundamental properties and capabilities of hardware for grid applications and to support grid modernization efforts.

The U.S. Department of Energy (DOE) Office of Electricity Delivery and Energy Reliability (OE), in collaboration with Oak Ridge National Laboratory (ORNL), organized and hosted a workshop on August 26-27, 2015 to investigate the opportunities for materials innovation in the electric grid and their application to next-generation transmission and distribution (T&D) components.

Experts in advanced materials and electric grid components were invited to attend this important event, lending their voices in exploring this opportunity space. Their leadership and participation in this process provided the expertise needed to ensure the results reflect the diverse needs of the stakeholder community.

1.2 WORKSHOP SCOPE AND PROCESS

Unlike meetings consisting only of presentations, this workshop encouraged participants to actively probe the role that materials innovation can play in developing next-generation T&D components. Professional facilitators were present to guide discussions, allowing participants to concentrate on identifying the performance barriers of current grid components and the high-impact material innovations that have the greatest potential to enable advanced grid capabilities.

1.2.1 Prior to the Meeting

Participants were supplied with background information, including a scoping document, which provided a situational analysis of the T&D components landscape. Participants were encouraged to begin thinking about the long-term vision of the U.S. electric grid and the role innovative materials will play in enabling this future grid. Participants were asked to reflect on their personal experiences, considering the major technical barriers they have encountered in their work, and potential relevant and innovative material solutions. It was suggested that participants discuss these issues with colleagues within their organization to gain additional thoughts, insights, and perspectives.

1.2.2 During the Meeting

Participants actively shared ideas through facilitated discussions. Structured brainstorming and critical analysis were used to draw out participants' best thinking and identify key insights. The workshop was divided into three breakout sessions, which were focused on 1) identifying technical challenges, 2) identifying innovative materials, and 3) developing R&D pathways. Three facilitators led each group which worked independently to address focus questions for each of the breakout sessions. The responses from all three groups were collected, recorded, and tabulated during each session. The matrix, provided in Table 1-1 below, and definition of terms were used to guide group discussions and frame the conversation.

Table 1-1: Matrix of Technical Challenges and Application Areas

	A Transformers	B FACTS Devices	C HVDC Converters	D Cables and Conductors	E Protection Devices (e.g., breakers)	F Other Substation Components	G Other
1. Active Power Conversion (e.g., semiconductors)							
2. Passive Power Conversion (e.g., magnetics)							
3. Electrical Insulation							
4. Electrical Conduction							
5. Structural Support and Protection							
6. Thermal Management							
7. Other							

The following definitions were used to clarify the meaning of each item listed in the matrix.

Transmission and Distribution Components:

A. **Transformers** – equipment that transforms voltage levels, stepping them up for long-distance transmission from a power plant, and stepping them down for distribution to consumers

B. **FACTS (Flexible AC Transmission Systems)** – a family of power electronics-based devices able to enhance alternating current (AC) system controllability and stability and to increase power transfer capability. FACTS are combinations of solid state switches and computerized automation that enable nearly instantaneous customized control of AC power flows, far faster than traditional, electromechanical AC switches.

C. **High Voltage Direct Current (HVDC) Converters** – connect two systems with different operating frequencies or frequency controls usually deployed as a back-to-back station or a point-to-point connection where a large amount of power has to be transmitted. HVDC is used to transmit electricity over long distances by overhead transmission lines or submarine cables when it becomes economically attractive over conventional AC transmission lines.

D. **Cables and Conductors**– These components form the backbone of the grid, carrying power generated from centralized and distributed sources, along designated rights-of-way and distribution feeders, to customers.

E. **Protection Devices** – System devices such as circuit breakers, surge arresters, fault current limiters, protective relays, and lightning arrestors that help protect critical substation and electric power equipment. Circuit breakers are automatically-operated electrical switches designed to protect an electrical circuit from damage caused by overload or short circuit. Surge arresters discharge the over voltages that can occur due to lightning strikes and switching surges. Current limiting reactors are a well-known fault current limiting technology which is more economical compared to many other short circuit reduction methods.

F. **Other Substation Components –** Components such as bus bars, isolator switches, switch gear, concrete foundations, control housing, voltage regulators, capacitor banks, and shunt reactors that can be found inside a substation other than the components described above.

Materials Innovations:

1. **Active Power Conversion Materials (e.g., semiconductors) -** Materials that can be used to fabricate devices such as transistors and diodes that enable functions such as high power control, conversion, switching, etc. e.g., wide bandgap (WBG) materials in various stages of development: silicon carbide (SiC), gallium nitride (GaN), diamond, aluminum nitride (AlN), zinc oxide (ZnO), and gallium (III) oxide (Ga_2O_3), etc.
2. **Passive Power Conversion Materials (e.g., magnetics) -** Materials used to fabricate passive electronic components such as inductors and capacitors. e.g., magnetic steel, soft ferrite, soft iron, silicon steel laminates, high performance soft magnetics materials, dual phase magnetic materials, nanostructured soft magnetic materials for high frequency inductors and transformers, etc.
3. **Electrical Insulation Materials -** Materials used to prevent electrical breakdown under high voltages. Dielectrics and insulating solids and fluids (including gases) include polymers (e.g., cross-linked polyethylene), ceramics (e.g., alumina, steatite), insulating fluids (e.g., transformer oil, liquid nitrogen for superconductors), insulating gases (e.g., sulfur hexafluoride (SF_6), air, halogens), nanofluids (NFs), compatible high temperature superconductor (HTS) insulators, high temperature and high voltage insulation, replacement for SF_6 insulation, low cost HVDC cable insulation, stress grading materials for high voltage apparatus, etc.

4. **Electrical Conduction Materials -** Materials to enable the transmission and distribution of electricity, including interconnections. e.g., copper, aluminum (e.g., all-aluminum conductor, aluminum conductor steel-reinforced), high temperature superconductors, high temperature solders and metals/conductors with increased conductivity, high ampacity and lightweight metal/CNT hybrid conductors for wires and cables, increased strength to permit core-less cables, high temperature tolerance, etc.
5. **Structural Support and Protection Materials -** Materials that can be used to protect or support grid devices and components, such as transformer housing, power electronics packaging, transmission towers, cable structural support, etc. e.g., steel, alloys, aluminum-steel hybrids, composites, ceramics, synthetic packaging, 3D woven composites, fiber reinforced plastic foams, nano stitched functional composites, etc.
6. **Thermal Management Materials -** Materials that can be used to provide cooling and other thermal management for grid hardware components such as transformers, power electronics, etc. e.g., copper, aluminum, metal matrix composites (MMCs) e.g., Al/SiC, polymer matrix composites (PMCs), working fluid, phase change materials (PCMs), liquid coolants with nanoparticle suspensions, graphene, ultra-high molecular weight polyethylene (UHMWPE) fibers, etc.

In order to keep the discussion focused, there were several areas that were not included in the scope of the workshop. These areas included advanced materials for energy storage devices and sensors.

1.2.3 After the Meeting

The results generated from the workshop participant discussion was compiled and analyzed into this summary report. This report describes the high impact technical challenges associated with grid components looking into 2030 and advanced materials with high potential for developing next-generation grid components that participants identified during the workshop.

1.3 STRUCTURE OF THIS REPORT

This summary report captures and organizes the remarks made by all participants in every breakout session. Chapter 3 summarizes the technical challenges that limit T&D grid component performance and capabilities (e.g., efficiency, reliability, resilience) of the grid. It also highlights the key areas that participants felt contained the most important technical challenges for various grid components. Chapter 4 covers innovative materials that can be used to enhance performance and overcome technical challenges for T&D grid components. It also highlights top innovative materials that have the greatest potential and feasibility to improve grid components. Chapter 5 presents potential R&D pathways proposed by workshop participants to integrate innovative materials into next-generation T&D components.

2. PLENARY PRESENTATIONS

Leading experts in grid applications and materials science provided presentations to set the stage for subsequent discussions in the workshop breakout sessions. Summaries of the presentations are as follows:

- **Dr. Kerry Cheung (DOE)** initiated the workshop with an overview presentation addressing key topics. He provided background on DOE and its recent release of the Quadrennial Energy Review (QER).[2] He spoke specifically about OE and its vision for a modernized grid. Dr. Cheung highlighted DOE's past efforts related to grid modernization, including those supported through the American Recovery and Reinvestment Act and the Smart Grid Investment Grant program. Given the service age and expected lifetime of many grid components, Dr. Cheung stressed the need for next-generation transformers and other grid components to meet the reliability needs of the future grid and its customers. Dr. Cheung introduced the Transformer Resilience and Advanced Components (TRAC) program by describing its goals and activities. He then discussed matters related to the remainder of the event, namely introductions of the other speakers and the purpose and scope of the workshop.

- **Mr. Joe Schatz (Southern Company)** provided an overview of T&D components commonly found on the electric grid. He then provided a "wish list" of materials and characteristics that could address existing grid component issues. Mr. Schatz presented visual examples of different equipment classes, including transformers, structural supports systems, conductors, flexible alternating current transmission systems (FACTS) devices, controllers, and sensors.

- **Mr. Richard Ord (Electric Power Research Institute)** represented the Electric Power Research Institute (EPRI), introducing its mission, research approach, and action plans. Mr. Ord provided examples from EPRI's asset management action plan, as well as an example related to research for new components and materials. More specifically, Mr. Ord described advanced coatings for conductors and insulators, as well as their potential applications in self-cleaning and ice-phobic systems. Mr. Ord described EPRI's tiered testing system for analyzing new technologies.

- **Dr. Alex Huang (North Carolina State University FREEDM Systems Center)** delivered a presentation on ultra-high-voltage SiC power devices. Dr. Huang addressed issues that currently prevent high penetrations of renewable and distributed energy resources. Dr. Huang compared the future of the grid to the Internet, stating that the next-generation grid will allow for consumer-to-consumer commerce and change the role of the traditional utility. Dr. Huang also presented a vision for an all-direct-current (DC) electric grid and described key enabling technologies. These include solid-state transformers, 50 kilovolt (kV) thyristors, and hybrid solid-state circuit breakers, among others.

- **Ms. Debbie Haught (DOE)** outlined the history of successes from DOE's support of high-temperature superconductivity (HTS) research. She discussed the benefits and applications of HTS, as well as the history and achievements of the DOE HTS program. Ms. Haught presented a timeline of HTS technology development and related federal government funding and research activities. She described many example projects that use HTS cable. She also discussed factors contributing to the success of the HTS program and proposed that the program could serve as a model for other programs geared at developing new technologies.

- **Dr. Paul Ohodnicki (National Energy Technology Laboratory)** delivered a presentation expounding the benefits of wide bandgap (WBG) semiconductor devices and high-frequency (HF)

[2] http://energy.gov/epsa/downloads/quadrennial-energy-review-full-report

magnetic devices. He reviewed the progress made in developing commercial WBG devices, discussed the system-level needs that hinder wide-scale deployment of WBG devices, and identified needs and opportunities for research in HF magnetics. Dr. Ohodnicki described the technical advances of WBG devices and the major governmental programs that have supported their development. Dr. Ohodnicki described the key research priorities and system-level challenges that need to be addressed to create WBG power electronic systems from WBG devices, such as design, layout, and modeling; packaging and thermal management; and advanced passive devices. Dr. Ohodnicki then described suitable materials that are classified as soft magnetics and presented research conducted at the National Energy Technology Laboratory on soft magnetic materials manufacturing for a variety of applications.

- **Dr. Jim Davidson (Vanderbilt University)** discussed advances in the nanoscience that have applications in improving grid components. Building on the famous 1959 "There's Plenty of Room at the Bottom" lecture, Dr. Davidson described the relationship between the grid and nanomaterials, focusing on the role that nanoparticles could play in enhancing the lifetime and reliability of components. Dr. Davidson described the process by which nanoparticle suspensions could enhance transformer efficiency by serving as an additive, increasing the thermal conductivity of the transformer oil. Dr. Davidson provided background and motivations for using nanoparticle suspensions and detailed the benefits of detonation nanodiamond—a particular nanoparticle with demonstrated performance enhancements, verified through testing at Vanderbilt University. Dr. Davidson also discussed processes to improve nanodiamond quality and its compatibility with present systems for transformer cooling.

- **Dr. Mark Johnson (DOE)** discussed enabling materials and processes for clean energy and electric power. Dr. Johnson described the intersection of economics, security, and the environment, noting how it presents opportunities for clean energy solutions. Dr. Johnson discussed U.S. energy consumption trends and the industries that consume large amounts of electricity. He stated that many clean energy technologies are dependent on these industries and their manufacturing processes. Dr. Johnson provided background on the DOE Clean Energy Manufacturing Initiative (CEMI) and described the strategic inputs that inform the approach taken within the program. Dr. Johnson also highlighted the topical priorities of the Advanced Manufacturing Office (AMO). He outlined the manufacturing technology maturation process and described the three mechanisms through which AMO makes an impact: providing technical assistance to the manufacturing industry, supporting R&D projects, and providing access to shared R&D facilities. Dr. Johnson provided examples of research projects and described a subset of the shared facilities, which include the Critical Materials Institute, the Manufacturing Demonstration Facility, and PowerAmerica.

3. TECHNICAL CHALLENGES

3.1 OVERVIEW OF BREAKOUT SESSION ONE

Breakout session one focused on the following topic area and focus question:

- *Topic area:* Key technical challenges limiting grid component performance and capabilities

- *Focus question:* For the various grid components highlighted, what are the key technical challenges across the functional areas that limit their performance and capabilities (e.g., efficiency, reliability, resilience) through 2035?

During the breakout session, each group identified technical challenges that currently affect the performance of grid components. Participants then used the matrix introduced in the Workshop Scope and Process section of this report to identify the application areas that were most affected by the particular technical challenge.

The following sections capture additional details provided by the groups on the highest-ranking items identified. Highest ranking items were identified by taking the top vote getting cell, dividing that number in half and then adding one. For example, the highest vote getting cell in the matrix for Group One was electrical conduction in cables and conductors with 11 votes. Using the "half max + one" criteria, all the cells with six votes and above are expanded on below. The "half max + one" criterion was used throughout this report for displaying voting results.

3.2 RESULTS FROM GROUP ONE

During breakout session one, Group One was asked to respond to the focus question presented. The group identified key technical challenges limiting grid component performance and capabilities. Participants then ranked the components in terms of their potential. Group One's results from session one are shown in Fig. 3.

Group One - Breakout Session One	A. Transformers	B. FACTS Devices	C. HVDC Converters	D. Cables and Conductors	E. Protection Devices	F. Other Substation Components	G. Other
1. Active Power Conversion	9	6	7	0	5	0	0
2. Passive Power Conversion	1	4	3	0	0	0	0
3. Electrical Insulation	5	0	0	1	0	0	0
4. Electrical Conduction	0	0	0	11	0	0	0
5. Structural Support & Protection	0	0	0	1	0	0	0
6. Thermal Management	8	3	1	1	0	0	0
7. Other	0	0	0	0	0	0	4

Fig. 3. Results for Group One, session one.

Electrical Conduction in Cables and Conductors: The performance of conductors tends to decrease as the conductors age, and, simultaneously, corrosion develops. The next generation of conductors would benefit from having the following characteristics: light weight, durability, thermal stability, high power capacity, and economic practicality.

Two opportunity areas include subsea cables using high-voltage direct current (HVDC) systems and underground T&D cables. Subsea cables require improvements in handling high pressure, thinner and lighter designs, and reduced costs. Underground cables are more difficult to diagnose problems and maintain than overhead lines; there is an opportunity to improve reliability by developing new cables with more robust insulation and current carrying capacity.

Active Power Conversion for Transformers: Solid-state transformers (SST) can offer benefits of increased functionality and reduced size compared to conventional transformers. Because SST rely on a combination of HF magnetic devices and high-switching-frequency semiconductors, realizing the benefits of SST requires improvements in WBG semiconductor technology and passive devices. Specifically, there is a need for high-voltage and high-current devices with acceptable performance at high switching frequencies, as well as low parasitics packaging. Since a SST is much smaller than a conventional transformer with the same power rating, an effective means must be developed for removing heat due to the higher power density.

Thermal Management for Transformers: To enhance the reliability of conventional transformers, it is important to address limitations in the design of current thermal management systems. The next generation of transformers will require electrical insulation with a higher withstand temperature and consistent insulating performance over its service lifetime. Cellulosic insulators used in present-day transformers exhibit degradation with excess heating exacerbated by aging, leading to diminished reliability.

The overall size, mass, and volume of thermal management systems need to be decreased. This applies to all components, including motors, fans, pumps, heat exchangers, and insulation. The development of effective passive-cooling techniques that do not require mechanical systems such as pumps and fans would greatly enhance system reliability. The development of forced convection with no moving parts would be a significant contribution to thermal management.

Another potential method for enhancing transformer thermal management involves the use of additive materials in transformer oil to enhance the thermal conductivity. Nanomaterials such as nanodiamond, which exhibits low electrical conductivity, would make effective additives when dispersed in cooling oil.

Active Power Conversion for HVDC Converters and FACTS Devices: Given the similarities that exist between the technical topologies, the technical challenges with FACTS and HVDC devices are nearly identical. Developments in HVDC and FACTS technology are limited by the current generation of power electronic switching devices. State of the art semiconductor switches are considered high voltage at ratings above 6.5 kV, and are considered ultra-high at ratings above 15 kV. An increase in a FACTS/HVDC system operating voltage translates proportionally into an increase in the number of semiconductor devices required. It also has a proportional impact on the required cooling capacity and other auxiliary equipment. Using cost-effective devices with higher breakdown voltages and lower losses can reduce system costs. Devices with breakdown voltages greater than 15 kV are required. These devices must also have current ratings greater than 1000 A. To enable this, current densities need to increase without creating new issues in device packaging, parasitics, or thermal management.

Historical tradeoffs between device characteristics must also be overcome. For instance, devices must be simultaneously rated for high voltage and high current. They must also enable high frequency switching without reducing their voltage ratings. Performance improvements cannot come at the cost of decreased reliability. Research is needed to uncover the factors that drive failure mechanisms in new and emerging semiconductor technologies.

A full listing of the ideas discussed by Group One during session one is provided in Appendix B.

3.3 RESULTS FROM GROUP TWO

During breakout session one, Group Two was asked to respond to the focus question presented. The group identified key technical challenges limiting grid component performance and capabilities. Participants then ranked the components in terms of their potential. Group Two’s results from breakout session one are shown in Fig. 4.

Group Two - Breakout Session One	A. Transformers	B. FACTS Devices	C. HVDC Converters	D. Cables and Conductors	E. Protection Devices	F. Other Substation Components	G. Other
1. Active Power Conversion	2	0	1	0	4	0	0
2. Passive Power Conversion	4	3	5	0	0	0	0
3. Electrical Insulation	2	0	0	5	0	0	0
4. Electrical Conduction	0	0	0	8	2	0	0
5. Structural Support & Protection	1	0	0	3	2	0	0
6. Thermal Management	3	0	2	2	5	0	0
7. Other	4	0	0	0	2	1	0

Fig. 4. Results for Group Two, session one.

The following captures additional details provided by Group Two on the highest-ranking items identified by the group.

Electrical Conduction for Conductors and Cables: Conductors and cables are a top priority in addressing technical challenges for grid equipment. Increasing conduction can provide significant benefits, but electrical conduction is a property that is tied to many other physical properties of materials. For example, purer metals tend to exhibit better electrical conductivity but possess lower mechanical strength. Hence, improvement in conductivity must be accomplished without degradation in other essential properties. The discussion on conductors focused on the need to achieve high conductivity while maintaining equipment operation at ambient temperatures. Next-generation cables will need to demonstrate high thermal ratings while decreasing in weight.

Conductor-connectors are integral part of a cable system that electrically and mechanically joins adjacent cable segments together to form a continuous power line. Typical compression-type connectors suffer from surface corrosion as a result of joule heating at the cable-connector interface, leading to increased resistance and lowered mechanical integrity of the joint. There is a need to optimize the surface contact resistance of the conductor-connector systems, possibility through doping that exhibits joint compound and other safety characteristics.

Electrical Insulation for Cables and Conductors: There is a need for broad dielectric improvement to enhance the effectiveness of electrical insulation for cables and conductors. For instance, the dielectric properties of insulation need to be high performance and cost-effective. The dielectric strength and thermal conductivity of the fluid or solid cable insulation should be improved.

Passive Power Conversion for HVDC Converters: There is a clear and distinct need for high-voltage capacitors for HVDC systems (and FACTS devices). These capacitors must be ultra-compact and have a long service lifetime. There is also a need for high-performance magnetic devices that can be supplied in large quantities. These needs necessitate research in high-performance, low-cost materials.

Thermal Management for Protection Devices: Thermal management does not only apply to conductors and transformers; it also affects protection devices, which play a direct role in maintaining the reliability of the grid. Many protection devices experience high-temperature degradation, providing an opportunity for enhancement through materials research.

A full listing of the ideas discussed by Group Two during session one is provided in Appendix B.

3.4 RESULTS FROM GROUP THREE

During breakout session one, Group Three was asked to respond to the focus question presented. The group identified key technical challenges limiting grid component performance and capabilities. Participants then ranked the components in terms of their potential. Group Three's results from session one are shown in Fig. 5.

Group Three - Breakout Session One	A. Transformers	B. FACTS Devices	C. HVDC Converters	D. Cables and Conductors	E. Protection Devices	F. Other Substation Components	G. Other
1. Active Power Conversion	0	2	1	0	3	0	1
2. Passive Power Conversion	6	2	3	0	1	0	0
3. Electrical Insulation	7	0	0	6	5	0	0
4. Electrical Conduction	2	1	0	4	1	0	0
5. Structural Support & Protection	1	0	0	0	0	1	0
6. Thermal Management	8	5	3	1	0	0	6
7. Other	0	0	0	0	1	0	4

Fig. 5. Results for Group Three, session one.

The following captures additional details provided by Group Three on the highest-ranking items.

Electrical Insulation for Transformers: The degradation rate for pressboard insulation is quite high, and the mechanism for degradation is not well understood. Given that cellulosic insulating materials degrade over time, transformers are typically designed with extra thickness. This makes the transformer physically larger.

Over time, chemical reactions within the transformer can promote the formation of gases. These gases accelerate the decline of the transformer's useful life, and transformers can be difficult to replace. Electro-chemical batteries undergo similar chemical reactions and produce gases as a byproduct, but they do not need to be replaced when gassing occurs. The transformer industry would benefit from the development of self-healing insulation that is designed with the ability to remedy these problems.

Magnetics for Transformers: Magnetics form the core of conventional transformers, critical for converting between AC voltages. Using finite element models, the intrinsic characteristics of a magnetic material can be altered (Steinmetz coefficient, permeability, thermal conductivity, etc), and the performance of the device can be evaluated (losses and parasitics), under the influence of external magnetic fields, or in a power electronic circuit. Through modeling, the performance of new materials can be predicted by conducting simulations with material parameters measured through experimentation. Current finite element software models do not adequately capture the physics of the most advanced materials (i.e. nanocomposites). There is a need for improved "inputs" to finite element models that better capture the detailed physics of advanced materials and the interplay between core geometry and overall performance.

In addition to the analytical design of intrinsic material properties, the process of manufacturing passive materials can be greatly enhanced. Processes must be developed for manufacturing amorphous and nano-crystalline alloys/cores. Rapid solidification and alloy processing are two potential processes with projected benefits. Additive manufacturing for magnetics can create new possibilities for devices with highly specialized magnetic properties.

Electrical Insulation for Cables and Conductors: Fouling of insulators, by salt, dirt, debris, or ice, can lower the insulating capability of conductors, resulting in flashovers and overhead transmission line outages. This adversely impacts the reliability of the bulk power system. Methods must be developed to prevent the build-up of foreign materials on electrical insulators. These methods should be easily applied and at a low cost in the field.

Electrical Insulation for Protection Devices: There are opportunities to enhance the electrical insulation properties of protective devices. Flash-overs, arcs, and other faults can be mitigated by enhancing the quality and effectiveness of the solder used to connect components and subsystems. Next-generation surge arrestors must offer enhanced protection against common disturbances like lightning strikes, which cause considerable damage to grid equipment every year. It is well known that electronegative gases make effective electrical insulators. However, SF_6 is the only chemical variant that has found broad application in the power industry. Despite its performance benefits, there are environmental concerns associated with the use of this product. Alternative gases may offer performance benefits, while ensuring the safety of technicians and eliminating environmentally harmful emissions.

Thermal Management: Electrical efficiency lies at the heart of the thermal management issues. Thermal management is an issue that currently limits the performance of transformers. Across the spectrum of grid components, thermal management systems are used to handle the heat generated from the inefficiencies of operating electrical equipment. Improving the efficiency of electrical components is an approach that can guarantee reductions in thermal management needs.

Electrical insulation is required for the safe operation of grid components. However, electrical insulating materials do not function well for thermal management purposes. As electrically conducting circuit elements produce heat, thermal management systems are needed to remove the heat from the conducting elements (whether they are cables, semiconductor switches, or transformer cores) to prevent damage and instabilities. If electrical insulators could be developed at low cost, which provide electrical protection, and simultaneously dissipate heat effectively, the reliability of the grid would be enhanced.

Beyond the need to balance electrical insulation with thermal conductivity, and to enhance component efficiencies, FACTS systems have particular needs in regard to thermal management. Mechanical systems are used for cooling semiconductor switching devices in FACTS installations. Mechanical systems are often the source of reliability concerns, and they require regular maintenance. Achieving effective cooling using passive technology would reduce costs, while enhancing the efficiency of FACTS systems.

A full listing of the ideas discussed by Group Three during session one is provided in Appendix B.

4. INNOVATIVE MATERIALS

4.1 OVERVIEW OF BREAKOUT SESSION TWO

Breakout session two focused on the following topic area and focus question:

- *Topic area:* Innovative materials with the greatest potential to overcome technical challenges

- *Focus question:* Drawing on the technical challenges discussed in the prior session, what are innovative materials that have the greatest potential to improve grid components by 2035?

During the breakout session, each group identified innovative materials with the potential to address technical challenges for grid components. Participants were able to draw on the technical challenges discussed in the first breakout session, but were not limited to addressing those challenges exclusively. Participants used the matrix introduced in the Workshop Scope and Process section of this report to identify the application areas that had the potential to be impacted by the innovative materials introduced.

4.2 GROUP ONE RESULTS

During breakout session two, Group One was asked to respond to the second focus question presented. The group identified innovative materials with the potential to address the technical challenges that limit the performance of grid components. Participants then ranked the materials in terms of their potential. The number of votes received for the innovative materials are shown in Fig. 5.

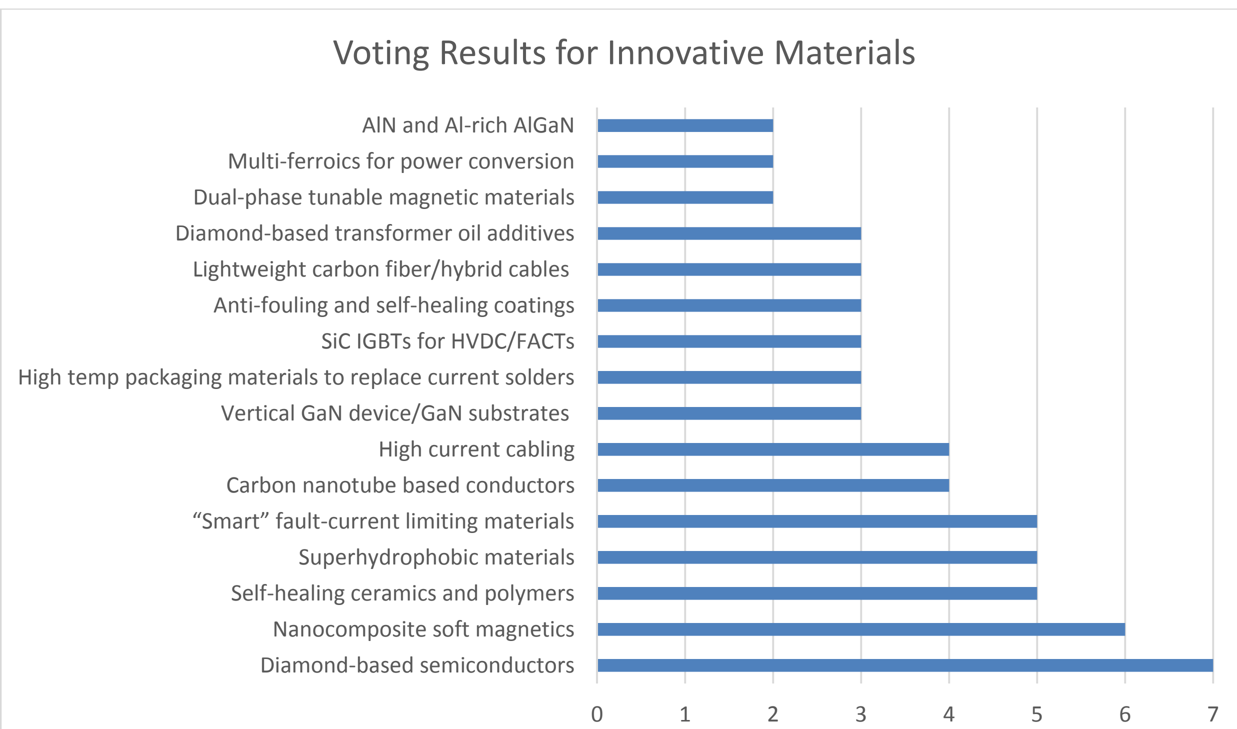

Fig. 6. Results for Group One's Voting Results for Innovative Materials.

The following captures additional details provided by Group One on the highest-ranking items identified by the group.

Diamond-Based Semiconductors: Diamond is a suitable WBG semiconductor material that is applicable to HVDC systems and FACTS. Like other WBG materials, diamond offers high breakdown voltage capabilities and the ability to switch at high frequencies. Compared to other WBG materials, diamond offers the best thermal conductivity. Due to this characteristic, diamond-based power electronic circuits may provide superior thermal management system performance, compared to other technologies.

Nanocomposite Soft Magnetics: Nanocomposite soft magnetic materials have the potential to create a disruptive impact in the field of passive power conversion for electrical transformers. These nanocomposites offer low-loss operation when utilized at high frequencies. The creation of soft magnetics from nanocomposites has been demonstrated, resulting in systems with improved energy efficiency and power density. However, the resulting magnetic material tends to be brittle and lacking in mechanical strength. Commercial alternatives such as Metglass can be utilized in a similar manner, but they can only be manufactured to a limited thinness. This has a direct impact on the operating characteristics of wind core transformers.

Self-Healing Ceramics and Polymers: Self-healing ceramics and polymers are material choices with the potential to address technical challenges with electrical insulation in transformers. Ceramics or polymers, such as perovskites, are an example of a material that could quickly recover if damaged. In addition, polymers with high thermal conductivity but low electrical conductivity may be explored for thermal management applications such as heat sinks. Phase-changing materials may be explored in thermal management applications for better cooling of transformers and power converters.

Superhydrophobic Materials: Super hydrophobic materials should be explored for insulators and conductors to help enhance reliability by preventing the buildup of ice on conductors. However, scalability needs further study, since current coatings cannot be quickly, easily, cost-effectively applied to a vast expanse of conductors across the transmission and distribution network. Anti-fouling and self-cleaning coatings may also be explored to enhance the reliability of transmission systems.

"Smart" Fault Current Limiting Materials: Protection systems can be enhanced through the incorporation of smart fault-current limiting materials. These materials would have the ability to dynamically alter intrinsic properties when exposed to fault conditions. In doing so, these materials can prevent damages resulting from disturbances on AC and DC networks. Developments in smart protection materials can enhance the reliability and resilience of the grid.

A full listing of the ideas discussed by Group One during session two is provided in Appendix C.

4.3 GROUP TWO RESULTS

During breakout session two, Group Two was asked to respond to the second focus question. The group identified innovative materials with the potential to address the technical challenges identified during the first breakout session. Participants then ranked the materials in terms of their potential. The number of votes received for innovative materials are shown in Fig. 7.

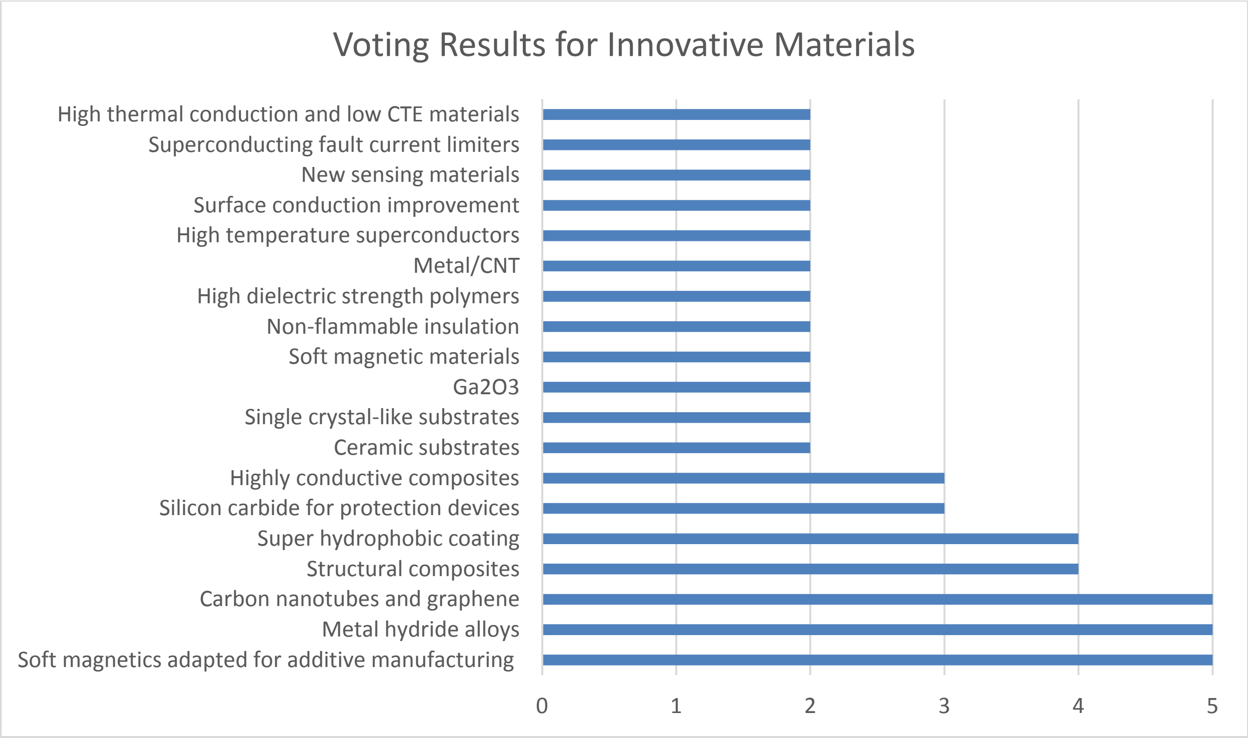

Fig. 7. Results for Group Two's Voting Results for Innovative Materials.

The following captures additional details provided by Group Two on the highest-ranking items identified by the group.

Soft Magnetic Materials Adapted for Additive Manufacturing: Benefits could be realized by adapting soft magnetic materials for use in additive manufacturing processes. Magnetics that are carefully "3D-printed" may exhibit lower parasitics, among other benefits. To date, the manufacturing of soft magnetic materials has been a hindrance to their widespread adoption.

Metal Hydride Alloys: Metal hydride alloys are a potential material to aid in the thermal management of transformers. Metal hydride alloys demonstrate enhanced heat dissipation, compared to standard transformer materials. Materials with a specific heat in the range of 1200–3000 kJ/kg could find broad application in thermal management.

Carbon Nanotubes and Graphene: Low dimensional carbon nanotubes and graphene have many potential properties that can improve the performance of grid components. Because of ballistic conductivity exhibited by these materials, creating conductors from carbon nanotubes could offer the same operating performance as room-temperature superconducting materials.

Structural Composites: Lightweight, high strength structural materials can reduce the weight of grid components and facilitate transportation from the manufacturer to the field. Innovative methods could be developed to enhance their resistance to complete structural failure in case of natural or man-made attacks, thereby enhancing the resiliency of the grid. Examples of these materials include reinforced polymer- and metal-matrix composites. Advanced manufacturing methods are needed to lower their costs while maintaining the expected performance.

Superhydrophobic Coatings: These surfaces emulate the water-repellent properties of some plants found in nature. Researchers have learned how to create surfaces with exceedingly uniform arrays of micro- and nano-features that, when properly treated, produce unprecedented water-repellent behavior that is very close to the theoretically most water repellent behavior possible. In addition to water (and ice), these surfaces have been found to be repellant to many viscous liquids and solid particulates. Research is still needed to enhance coating durability and to enable efficient and cost effective application to new and existing surfaces.

A full listing of the ideas discussed by Group Two during session two is provided in Appendix B.

4.4 GROUP THREE RESULTS

During breakout session two, Group Three was asked to respond to the second focus question presented. The group identified innovative materials with the potential to address the technical challenges identified during the first breakout session. Participants then ranked the materials in terms of their potential. The number of votes received for the innovative materials are shown in Fig. 8.

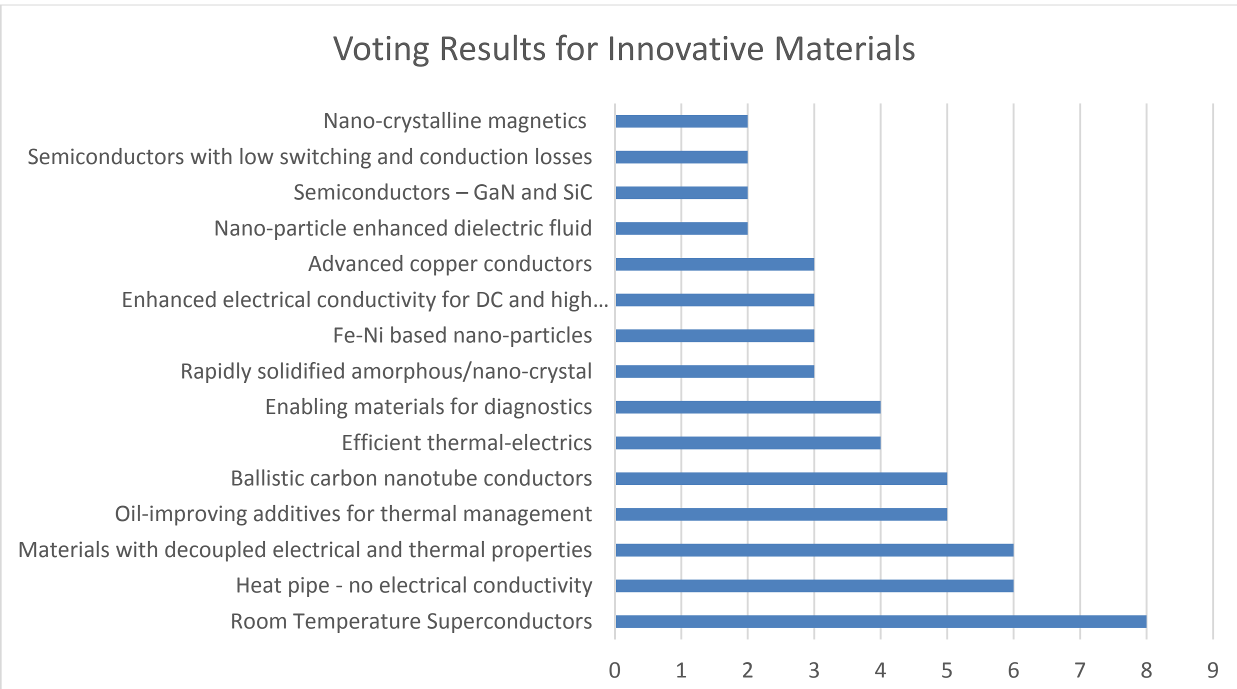

Fig. 8. Results for Group Two's Voting Results for Innovative Materials.

The following captures additional details provided by Group Three on the highest-ranking items identified by the group.

Room-Temperature Superconductivity: The search for superconductors beyond the copper oxide family with transition temperatures that narrow or bridge the gap to room temperature is a high-payoff basic research challenge. Accomplishing superconductivity at room temperature would greatly enhance power density, system capacity, and operating effectiveness. The key materials challenge is to find a room-temperature superconductor with no intrinsic anisotropy.

Materials with Decoupled Electrical and Thermal Properties: A separation between electrical conductivity and thermal conductivity can lead to materials with enhanced performance. An isotropic material could be developed that orients electrical conduction and thermal conduction in different directions.

Heat Pipes: Heat pipes are another technology for improving thermal management. Specifically, researchers should investigate the possibility of creating heat pipes from non-conducting composites, as opposed to aluminum, which is typical. This would result in a device that exhibits high heat transfer, with no electrical conductivity.

Oil-Improving Additives for Thermal Management: Oil additives have the capacity to enhance the lifetime and reliability of transformers. Additives, used as suspensions in transformer oil, have the ability to increase the thermal conductivity of the oil. Nanoparticle suspensions, such as nanodiamond, have been shown to be effective through experimentation. Various chemical processes can be used to enhance the quality of nanoparticles before introduction into transformer oil.

Ballistic Carbon Nanotube Conductors: Utilizing ballistic conductivity exhibited by carbon nanotubes (CNT) for electrical conductors would produce power lines and cables with performance that exceeds copper. Utilizing CNT in forms such as CNT yarns may have the potential to produce highly conductive flexible conductors with high mechanical strength characteristics. In addition, high conductivity materials may also be obtained by forming CNT-metal composites. The cost of CNT, however, have to be reduced substantially before the usage of these materials are economically feasible.

A full listing of the ideas discussed by Group Three during session two is provided in Appendix B.

5. R&D PATHWAYS

5.1 OVERVIEW OF BREAKOUT SESSION THREE

Breakout session three focused on the following topic area and focus question:

- *Topic area:* Developing R&D Pathways and Milestones

- *Focus question:* Working groups were asked to respond to prompts from a preprinted worksheet. Small groups of 2–4 participants used this worksheet to identify R&D pathways, milestones, and key stakeholders to most effectively develop specific grid components, leveraging the innovative materials identified in the prior session.

During the final breakout session, each group was asked to select several grid components and prepare R&D pathways for the development and application of innovative materials. Participants were instructed to devise pathways and milestones by completing the provided worksheet. Within each group, smaller subgroups were formed, each containing at least one materials expert and one component expert.

5.2 GROUP ONE WORKSHEETS

The resulting worksheets for Group One can be found in Fig. 9, Fig. 10, Fig. 11, Fig. 12, and Fig. 13. The subgroups in Group One focused on cables and conductors (Fig. 9) and HVDC/FACTS (Fig. 13) for one worksheet each, and three of the subgroups developed worksheets on transformers (Fig. 10, Fig. 11, Fig. 12), demonstrating that the group had a strong interest in materials development to improve the performance of transformers.

The different possible materials for development that were suggested for transformers (Fig. 10 and Fig. 11) include nanoparticles (e.g., nano-diamonds) for liquid cooling, WBG materials such as SiC or GaN, and thermal efficiency in transformer cores. Other suggestions related to the properties that the materials would possess, such as a coolant replacement or additives that have properties such as better thermal conductivity and a longer lifetime, better insulation, or better windings. For solid-state transformers (Fig. 12. Group One Worksheet - Solid State Transformers), participants suggested nano-crystalline soft magnets, better insulators, phase-change materials for thermal management, and WBG materials. The FACTS/HVDC subgroup (Fig. 13) focused on WBG materials (e.g., diamond, AlN, SiC, and GaN), while the cable and conductors subgroup (Fig. 9) focused on materials such as superhydrophonic coatings, carbon nanotube conductors, and better insulation.

The figures in this section provide more information on the key challenges and desired outcomes for these components, as well as the development approaches, major R&D tasks, and key stakeholders for the materials suggested by the subgroups.

Fig. 9. Group One Worksheet - Cables and Conductors

DESCRIPTION OF KEY CHALLENGES:

- Temperature limits
- Environmental resistance
- Capacity – higher DC
- Decreased losses
- Lifetime of insulation

DESCRIPTION OF DESIRED OUTCOMES:

- New cable systems with 50% more conductivity than copper
- Ice / water / contaminant phobic
- Higher temperature capacity
- Longer life insulation

Material: Superhydrophobic Coating	Material: CNT Conductors	Material: Insulation (Cellular insulation; aerogels, lattice fiber reinforced foam; self healing)
Describe a possible approach to developing these material in the T&D component, including 3-5 major tasks in the near-term (<3 years), mid-term (3-6 years) and long-term (7-10 years).		
• Refine chemistry for enhanced durability • Develop coating / application processes amenable to electric power industry • Short & long term testing of coating chemistries and application methods	• Develop suitable materials for cable application including % CNT in Cu, measure properties and develop processing methods • Develop prototype cable and measure properties.	• Develop and test insulation materials to determine temperature capability and stability • Narrow down selection, further testing, and then integrate with cable systems • Determine mechanisms for increased properties.
For the major R&D tasks, define near-term, mid-term, and long-term milestones that can be used to measure progress in development.		
• Target 3 – 5 year lifetime with 75% of performance • Less than 10% added cost	• Material chemistry: Processing methods – 5 years • Prototype cable – 7 years • 50% improvement over copper	Test to: • Increased temperature capability • Increased life – 3-5 years • Identify promising systems – 2 years
Describe the role key stakeholders will play in overcoming the grid component challenges.		
• National Labs, coating manufacturers, cable manufacturers, utilities	• Academia, National Labs, cable manufacturers, utilities	• Academia, National Labs, industry, vendors, cable manufacturers, utilities

Fig. 10. Group One Worksheet - Transformers (1)

DESCRIPTION OF KEY CHALLENGES:

- Thermal management (Problems with high temperature operations of transformers)
- Packaging in solid-state transformers - High Voltage, High Current, High Temperature requirements
- High voltage, high current devices
- Improved insulation (extend lifetime of transformers)
- High switching frequency requirements in devices, transformers

DESCRIPTION OF DESIRED OUTCOMES:

- Low cost
- High efficiency
- Reliable
- Resiliency

Material: Nano Particles (Nano Diamonds) in liquid cooling Better thermal management, longer lifetime	**Material:** SiC/GaN/Other Ultra-WBGs 10-30kV Device	**Material:** Thermally Efficiency Cores Improves lifetime
Possible approach to developing these material in the T&D component, including 3-5 major tasks in the near-term (<3 years), mid-term (3-6 years) and long-term (7-10 years).		
• (< 3 years): Addition of Nano-particles to oil cooler systems to improve thermal management or present – generation transformers • (3-6 years): Addition of Nano-particles to other liquid solvents. • (7-10 years): Addition of Nano-particles to polymers for air cooling	• (< 3 years): Gen substrate for vertical devices • (3-6 years): Low-doped, thick epilayers/drift layers • (7-10 years): Large area substrates (For low cost)	• (< 3 years): Search for material with higher thermal efficiency that could serve at cores for solid state transformers (SSTs) • 3 – 6 years): Test the material with the SSTs to test the parasitics/Thermal performance • (7-10 years): Construction of systems with the material to enhance performance
For the major R&D tasks, define near-term, mid-term, and long-term milestones that can be used to measure progress in development.		
• Improvement of lifetime of present – generation transformers by > 50% (->3 years) • Improvement of lifetime of vehicle-based systems by >50% (3-6 years) • Improvement of lifetime of semiconductor devices, S.S.Ts by > 50% (7-10 years)	• 10-30 kV Switches Available (10 - 100A) • 10-30 kV @ 100 - 1000 A • Cost Parity with Si • Reliable (W.R.T. Si)	• Material with > 50% thermal performance • Transformers with >50% efficiency • Improvement in systems performance (> 50%)
Describe the role key stakeholders will play in overcoming the grid component challenges.		
• National Labs that can test the material in systems to prove the utility • Universities with materials development experience • DOE, Academia	• National Labs that can test the device in vehicles & grid • Universities with materials development experience • DOE • Industry (vendors)	• National Labs with experience in material development and system testing • DOE • Industry (vendors)

Fig. 11. Group One Worksheet - Transformers (2)

DESCRIPTION OF KEY CHALLENGES:

- Cooling
- Packaging; Scaling (High Temp)
- Time to manufacture & other manufacturing issues (moisture)
- Size & weight (Efficiency & Reliability are good)
- Fault survivability

DESCRIPTION OF DESIRED OUTCOMES:

- Passive @ larger scale – Greener oils/Coolants. Higher temp operation to reduce cooling needs
- Light weight; durable (thermal/mech.); Damage tolerant (Physical & electrical)
- On-Demand, custom manufacturing processes (foster). Modular design → for faster/easier replacement of failed components.
- Non-catastrophic failure. Self-extinguishing. (? Easier w/modular design).

Material: Coolant Replacement or Additive	Material: Better Insulations → Extended Life	Material: Better windings (increased conductivity)
Better thermal conductivity; longer lifetime (reduced replacement and monitoring); benign/ environmentally friendly	High temperature; high thermal conductivity; self-healing	Decreased I^2R losses; run cooler

Describe a possible approach to developing these material in the T&D component, including 3-5 major tasks in the near-term (<3 years), mid-term (3-6 years) and long-term (7-10 years).

• Near Term: (Develop) Passive additives for increased performance and life • Mid Term: (Develop) Coolant replacement. Possible solid-state design. • Long Term: (Develop) [Pumpless] Active fluid cooling. Redesign w/alternative cooling paradigm	• Near Term: Develop high-temperature insulation for extending life. • Mid Term: Develop higher thermal conductivity for increased performance (runs cooler) • Long Term: Develop self-healing insulation to extend life.	• Near Term: Optimize fields delivered to core (high performance computer modeling) • Mid Term: Advanced manufacturing techniques • Long Term: Carbon nanotubes, covetic materials

For the major R&D tasks, define near-term, mid-term, and long-term milestones that can be used to measure progress in development.

• Near Term: Increase thermal conductivity by 25-50% • Mid Term: Increase thermal conductivity. by 2x, at same or better lifetime • Long Term: Equivalent or greater performance in package at ½ the size or smaller (2035)	• Near Term: 20-30% life extension • Mid Term: 5x increased thermal conductivity; increased avg. lifespan by reducing failure → 50% life extension. • Long Term: double lifespan	• Near Term: Increase performance by 20-30% • Mid Term: New designs with 50% plus performance improvement • Long Term: Increase conductivity (possibly 2 x)

Describe the role key stakeholders will play in overcoming the grid component challenges.

• All	• All	• All

Fig. 12. Group One Worksheet - Solid State Transformers

DESCRIPTION OF KEY CHALLENGES:

- Insulations – degradation w/ temp and dV/dt
- Thermal management – higher temps & heat fluxes
- Wide bandgap devices – power density
- Soft magnetic – losses @ higher frequencies & temps

DESCRIPTION OF DESIRED OUTCOMES:

- Solar inverters (NOW)
- Micro-grid scale devices (Near Future)
- "Local" grid scale (mid-term)
- Long range transmission scale (including DC) (Long term)

Material: Nano Crystalline Soft Magnets	**Material:** Insulators	**Material:** Phase Change Materials (Thermal Management)	**Material:** WBG Materials
Higher energy efficiency; size/weight reduction/ high temperature capability; mechanical property improvement	Self-healing; high breakdown voltage; thermal stability	High heat flux capability; high dielectric constant; tunable phase change (temperature/ pressure)	
Describe a possible approach to developing these material in the T&D component, including 3-5 major tasks in the near-term (<3 years), mid-term (3-6 years) and long-term (7-10 years).			
• Near Term: TRL1 studies to identify candidate materials • Mid Term: Deploy one material to micro-grid applications • Long Term: Deploy to higher performance	• Near Term: TRL1 studies to identify candidate materials • Mid Term: Deploy one material to micro-grid applications • Long Term: Deploy to higher performance	• Near Term: TRL1 studies to identify candidate materials • Mid Term: Deploy one material to micro-grid applications • Long Term: Deploy to higher performance	• Not identified
For the major R&D tasks, define near-term, mid-term, and long-term milestones that can be used to measure progress in development.			
• Low losses • High temperature operation	• Measure breakdown voltage • Higher temperature operation	• Measured latent heat for phase change • Increased dielectric constant	• Higher power density
Describe the role key stakeholders will play in overcoming the grid component challenges.			
• Suppliers/integrators/ OEMs. • Point Users • Research community (national labs/academia)	• Suppliers/integrators/ OEMs. • Point Users • Research community (national labs/academia)	• Suppliers/integrators/ OEMs. • Point Users • Research community (national labs/academia)	• Suppliers/integrators/ OEMs. • Point Users • Research community (national labs/academia)

Fig. 13. Group One Worksheet - FACTS/HVDC

DESCRIPTION OF KEY CHALLENGES:

- Need availability of high voltage switching devices (phase 1: 15 - 50 kV; phase 2: >50 kV) availability of high current switching devices (phase 1: 10 - 100 A; phase 2: 100 - 1000 A)
- Reliability and Lifetime
- Packaging and thermal management
- High switching frequency (10 – 100 kHz)
- Higher efficiency → low conduction and switching losses

DESCRIPTION OF DESIRED OUTCOMES:

- Low – cost
- High efficiency
- Reliable
- Expanded deployment of HVDC/FACTS
- High voltage & current, fast switches

Material: SiC/GaN 10-30 kV devices	**Material:** Diamond/ AlN and other WBGs 15 kV devices

Describe a possible approach to developing these material in the T&D component, including 3-5 major tasks in the near-term (<3 years), mid-term (3-6 years) and long-term (7-10 years).

SiC/GaN:

- GaN substrates for vertical devices
- Near-term: low-doped, thick epilayers / drift layers
- Mid-term: large-area substrates (for low cost)

Diamond/ AlN and other WBGs:

- Mid-term:
  - Low defect density single crystal material
  - Lattice-matched substrates
  - Doping (n & p) – dopants are deep in gap
- Long-term:
  - Selective area doping
  - Ohmic contacts
  - Packaging

For the major R&D tasks, define near-term, mid-term, and long-term milestones that can be used to measure progress in development.

SiC/GaN:

- Near-term: 10-30 kV switches commercially available (10-100A)
- Mid-term:
  - 10-30 kV device at 100-1000 A
  - Cost parity with silicon
  - As reliable as silicon

Diamond/ AlN and other WBGs:

- Mid-term: 50 kV switch and diodes
- Long-term: 100 kV switch and diodes
- Mid-term: 4” single-crystal diamond and AlN wafers
- Long-term: 6” wafers

Describe the role key stakeholders will play in overcoming the grid component challenges.

SiC/GaN:

- National Labs
- Industry (device manufacturers, others)
- DOE – Power America Institute
- Academia

Diamond/ AlN and other WBGs:

- National Labs
- Universities
- Industry
- DOE, Academia

5.3 GROUP TWO WORKSHEETS

The resulting worksheets for Group Two can be found in Fig. 14, Fig. 15, Fig. 16, Fig. 17, and Fig. 18. Group Two showed a wide range of interest in T&D components, with each of the worksheets covering a different main topic and some overlap occurring between each of the subgroup's ideas. The first worksheet (Fig. 14) focused on conductors and cables, suggesting materials such as Al/Ca highly deformed metal matrix composites, aluminum and carbon/CNTs, and high temperature superconductors. The materials suggested for connectors and cables windings systems (Fig. 15) are a surface-doping joint compound, a metal or carbon nanotube composite, and a graphene composite. Fig. 16, representing output from the power electronics for T&D subgroup, covered a much wider range of components. Materials/properties suggested to overcome key challenges and reach desired outcomes are Ga_2O_3, HF magnetics, and high electric strength. For protection devices (Fig. 17), participants also suggested high-temperature superconductors, as well as a solid-state device with specific properties, chemical bonds/phase change materials, or improved conductors. Finally, the last worksheet (Fig. 18) covered a component popular in Group One—transformers. The materials suggested are non-flammable insulation, new dielectric materials, a novel core material with lower losses, and a smaller superconductivity material.

The figures in this section provide more information on the key challenges and desired outcomes for these components, as well as the development approaches, major R&D tasks, and key stakeholders for the materials suggested by the subgroups.

Fig. 14. Group Two Worksheet - Conductor/Cable

DESCRIPTION OF KEY CHALLENGES:

- Increased ampacity for existing tower capacity
- Thermal management (Joule heating) improvement
- Reduced conductor resistivity
- Improved thermal stability and lifetime
- Resilience in off-normal conditions (includes environment)

DESCRIPTION OF DESIRED OUTCOMES:

- Cable replacement with much higher ampacity and lower density (3x)
- Capable of reducing actual interior temp. (-50^{o} C)
- Lower conductor resistivity (-50%)
- Higher max. operating temperature (+50^{o} C)
- Ability to perform at design level for 30-40 yrs**.**

Material: Al/Ca Highly Deformed Metal Matrix Composite	Material: Al & Cu/CNT Composite	Material: HTS
Describe a possible approach to developing these material in the T&D component, including 3-5 major tasks in the near-term (<3 years), mid-term (3-6 years) and long-term (7-10 years).		
• Develop industrial powder production for Ca (fine) • Improve industrial capacity for high priority Al powder • Enhanced powder extrusion capacity for direct rod production • Develop option reinforcement volume % for M(Ca, Sr) • Determine max impurity content tolerable	• Transfer Ca powder production method to industrial partner • Demonstrate high purity Al powder production at partner plant • Demonstrate 1 – step direct extended rod at industrial partner • Demonstrate max. conductivity and strength	• Not identified
For the major R&D tasks, define near-term, mid-term, and long-term milestones that can be used to measure progress in development.		
• Activation, dispersion joining percolation • Conductivity • Strength • CTE • Resistant to environment	• Increase conductivity by 20x by 2035. 2x by2020, 10x by 2025 • Increase strength by 50x by 2020, 10x by 2035 • Reduce CTE by 2x by 2025 • Increase oxidation resistance by 5x in 2025, 10x by 2035	• Not identified
Describe the role key stakeholders will play in overcoming the grid component challenges.		
• Cable and wire manufacturers • Powder producers (Al, Ca, other) • Distribution and Transmission Utilities • National Labs • EPRI	• Powder and CNT producers. (Al, Cu) – production of particulate • Wire and cable manufacturers • Distribution and transmission utilities • Universities • National Labs	• HTS manufacturers • Distribution and Transmission Utilities

Fig. 15. Group Two Worksheet - Connectors and Cable Windings Systems

DESCRIPTION OF KEY CHALLENGES:

- Increased ampacity and conductivity
- Thermal management
- Joule heating, corrosion, oxidation
- Surface conductivity
- Sensing and resilience

DESCRIPTION OF DESIRED OUTCOMES:

- Advanced connector system can ensure remove weakest link
- Connector operating temp is lower than conductor temp
- Reduce resistivity by 10x
- Increase surface conducting through material/design 5x
- Passive sensing / protection to environmental

Material: Surface doping, joint compound	**Material:** Metal/CNT composite Reduce conductor resistivity and joule heating. Reduce CTE delamination	**Material:** Graphene Composite Coating on connectors and cable, windings to protect
Describe a possible approach to developing these material in the T&D component, including 3-5 major tasks in the near-term (<3 years), mid-term (3-6 years) and long-term (7-10 years).		
• Connector system functioning and design • Pilot doping material; joint compound developed to improve surface conducting • Field performance evaluation	• Understand electron/phonon scattering to reduce resistivity and increase strength • Understand reaction (oxidation) to increase reliability • Develop key material processing	• Understand electron/phonon scattering to reduce resistivity and increase strength • Understand reaction (oxidation) to increase reliability • Develop key material processing
For the major R&D tasks, define near-term, mid-term, and long-term milestones that can be used to measure progress in development.		
• Connector system performance tool for target service environments to improve T&D system performance and control flow • Advance connector system to increase ampacity by 5 times, 10 times resilience, less energy loss by 25%	• Conductivity increase by 5x by 2020, 15x by 2025, 20x by 2035 • Antioxidation increase by 15x by 2025, 25x by 2035	• Conductivity increase by 5x by 2020, 15x by 2025, 20x by 2035 • Antioxidation increase by 15c by 2025, 25x by 2035
Describe the role key stakeholders will play in overcoming the grid component challenges.		
• EPRI • Power utilities • DOE • Local government • University	• Universities • DOE • National Labs	• Universities • National Labs

Fig. 16. Group Two Worksheet - Power Electronics for T&D (HVDC Connector, FACTS, solid state transformer, solid state circuit breaker)

DESCRIPTION OF KEY CHALLENGES:

- Cost effective high voltage, high frequency, high temp device
- High insulation, high temperature package is lacking
- Low loss, high flux magnetics
- Need for much better thermal management solution

DESCRIPTION OF DESIRED OUTCOMES:

- WBG Material reach silicon cost parity and large wafer size
- Low loss, high frequency magnetics same flux density as steel
- Cost for T&D power electronics converter <$50/kVA

Material: Ga$_2$O$_3$ (> 10x better intrinsic performance than Sic; Pathway for low cost growth)	Material: HF Magnetics Increase power density and efficiency of smart transformers	Material: High dielectric strength For ultra-high voltage (10 – 50 kV) power switch packaging (high thermal conductivity)
Describe a possible approach to developing these material in the T&D component, including 3-5 major tasks in the near-term (<3 years), mid-term (3-6 years) and long-term (7-10 years).		
• < 3 year: 1) epi growth in 3-inch substrate; 2) U.S. manufacturing of 3-inch substrate • < 3-6 year: 4-inch substrate and epi growth • < 7-10 year: 6 in substrate and epi growth	• < 3 year: computational materials science to model microstructural evolution of Fe-based nano-crystalline alloys • 3-6 year: Develop manufacturing methods to realize high flux, low loss nanostructures • > 7-1 year: Scale manufacturing to meet T&D component production volumes	• 3 year: combinatorial study for high thermal conductivity, high dielectric compound • 3-6 year: lab scale synchronize candidate compositions, device integration • 7-10 year: pilot scale production and reliability testing
For the major R&D tasks, define near-term, mid-term, and long-term milestones that can be used to measure progress in development.		
• Active material and device research program focusing on material growth and device demonstration	• < 3year - Fe-based nanostructures with diameter of grains < 10 nm and Bsat > 1.8 Tesla • 3-6 year > 1.8 Tesla nanocrystaline alloy with core loss equivalent to FINEMET • > 7-10 year: scale manufacturing to > 100,000 units per year	• 10x improvements in dielectric strength • Same thermal compatibility as today's technology
Describe the role key stakeholders will play in overcoming the grid component challenges.		
• University, national lab small & large business in material, device and power electronics area	• Academia and DOE labs for computational and characterization • Industry for CAPEX and now manufacturing facilities • Utilizes for build out of T&D systems	• Not identified

Fig. 17. Group Two Worksheet - Protection Devices

DESCRIPTION OF KEY CHALLENGES:

- Protection devices need to quench, absorb, or handle
- Large voltages, currents, temperatures very rapidly
- Reliably and repeatedly, rapid recovery

DESCRIPTION OF DESIRED OUTCOMES:

- Max 80,000 A Breaker
- Lower Losses
- Lower environmental impact
- Lower O&M
- Faster than 6 cycles
- High reliability and repeatability

Material: HTS	**Material:** Solid State Device	**Material:** Chemical Bonds, Phase change materials	**Material:** Improved Conductors
Low loss; low environmental impact; can limit in ½ cycle; quick recovery	Replace SF_6, no arcing; can provide DC protection	High energy absorption; better thermal management	Stronger withstand to energy helps repeatability
Describe a possible approach to developing these material in the T&D component, including 3-5 major tasks in the near-term (<3 years), mid-term (3-6 years) and long-term (7-10 years).			
• Improve manufacturing reliability • Improve thermal conductivity of HTS • Nano-diamond (?) • Higher temperature super conduction	• Address di/dt transients • Improve heat extraction/ thermal management	• Improve understanding of material under operating environment	• Explore high conductivity; strong materials for contacts (breakers/switches)
For the major R&D tasks, define near-term, mid-term, and long-term milestones that can be used to measure progress in development.			
• Limiter needs to interrupt in ½ cycle • Recovery under load (fast) – instant; 15 sec; 30 sec • Cost competitive	• Demonstrate DC breaker • Reduce cost comparable to conventional breakers • Demonstrate use for lightning arrestor	• Heat extraction and material testing	• Not identified
Describe the role key stakeholders will play in overcoming the grid component challenges.			
• Superconducting wire manufacturers • FCL OEMs • Universities	• WBG manufacturers • Industry (vendors)	• Not identified	• Not identified

Fig. 18. Group Two Worksheet - Transformers

DESCRIPTION OF KEY CHALLENGES:

- Safety (Risk of explosion, flammability)
- Dielectric strength of the insulation/thermal performance
- Modularity
- Cost
- Losses

DESCRIPTION OF DESIRED OUTCOMES:

- Inherently safe (no explosions, risk of fire, resilient against attacks)
- Reduction in size due to high performance of materials
- Cheaper
- Intelligent (sensors)
- Low losses

Material: Non Flammable Insulation Prevent explosion	**Material:** New Dielectric Material Higher fields	**Material:** Novel Core Material Lower losses	**Material:** Superconductivity Material Smaller size
Describe a possible approach to developing these material in the T&D component, including 3-5 major tasks in the near-term (<3 years), mid-term (3-6 years) and long-term (7-10 years).			
• Search for non-flammable materials with good dielectric strength • Look for additives that suppress the boiling point	• Nano dielectrics, nano diamonds • Replacement of cellulose insulation	• High performance magnetic core materials, low eddy current losses	• Low cost superconducting material • Low AC loss wire • Fault current limiting
For the major R&D tasks, define near-term, mid-term, and long-term milestones that can be used to measure progress in development.			
• Developed non-flammable insulation dielectric (2020) • Field tested transformers (2025)	• 30% improved dielectric (2020) • 50% improved dielectric (2030)	• 50% reduction at the same flux density of steel • 80% reduction at the same flux density of steel (2035)	• 10x AC Loss reduction per 1 km • 5x reduction of cost
Describe the role key stakeholders will play in overcoming the grid component challenges.			
• DOE • Utilities • Universities • Industry	• DOE • Utilities • Universities • Industry	• DOE • Utilities • Universities • Industry	• DOE • Utilities • Universities • Industry

5.4 GROUP THREE WORKSHEETS

The resulting worksheets for Group Three can be found in Fig. 19, Fig. 20, Fig. 21, and Fig. 22. While the worksheet component topics were varied, they mirrored the interests of Groups One and Two and covered cables and conductors, properties of multiple components (e.g., cable interconnectors and transformers), transformers, and FACTS/HVDC.

Group Three showed a wide range of interest in T&D components, with each of the worksheets covering a different main topic. The first worksheet (Fig. 19) focused on conductors and cables, with carbon nanotubes, thermally conductive insulators or electrical conductive thermal insulators, and room temperature superconductors identified as possible materials. For Fig. 20, the subgroup's output that was not focused on a specific T&D component, but rather on materials that could have a wider impact, listing a new copper or aluminum alloy; fluids with thermoelectric, phase change, or magnetic core properties; or iron alloys as possible materials. Similar to the other two groups, Group Three completed a worksheet on transformers (Fig. 21), with a focus on a nano-enabled coolant or dielectric fluid with beneficial properties, HTSs, low resistance winding, and semiconductors among suggested materials. Finally, the last subgroup (Fig. 22) focused on one material for FACTS and HVDC (high-temperature ancillary components) that could address thermal and electrical insulation.

The figures in this section provide more information on the key challenges and desired outcomes for these components, as well as the development approaches, major R&D tasks, and key stakeholders for the materials suggested by the subgroups.

Fig. 19. Group Three Worksheet - Cables and Conductors

DESCRIPTION OF KEY CHALLENGES:

- Transmission lines, thermally limited, losses
- Underground cables, heat, capacity
- Transformer windings

DESCRIPTION OF DESIRED OUTCOMES:

- Not identified

Material: CNT Improve conductivity	**Material:** Thermally conductive insulator (grafboard/macor); electrically conductive thermal insulators	**Material:** RT-Superconductor
Describe a possible approach to developing these material in the T&D component, including 3-5 major tasks in the near-term (<3 years), mid-term (3-6 years) and long-term (7-10 years).		
• Coat a conventional conductor • Maybe the coating could also be ice-phobic • Transformer may also be a good application	• Find a cheap process based material to find the right properties	• Materials discovery
For the major R&D tasks, define near-term, mid-term, and long-term milestones that can be used to measure progress in development.		
• Scalability – need long/high capacity conductors • Defects – low defect rate required to realize conductivity improvement • Cost – must add minimal cost	• Find the right steps in a trial and error engineering effort with a commercial entity (with right material)	• Not identified
Describe the role key stakeholders will play in overcoming the grid component challenges.		
• Utilities have little incentive to innovate • National laboratories/universities can do basic science and demonstration • Manufacturers need to incorporate into products	• Not identified	• Not identified

Fig. 20. Group Three Worksheet - Component not Identified

DESCRIPTION OF KEY CHALLENGES:

- Electrical conductivity for cable interconnects
- Thermal management for energized components (e.g., transformers)
- Dielectric materials for capacitors
- Transformer core materials for 60 Hz

DESCRIPTION OF DESIRED OUTCOMES:

- Reduction in resistance (% to be determined)
- Increased efficiency and life span)
- Higher temperature and voltage isolation
- Lower cost, domestically produced, higher efficiency

Material:
Copper or Aluminum Alloy

Material:
Fluids
Thermoelectric; phase change; magnetic core

Material:
Iron Alloys

Describe a possible approach to developing these material in the T&D component, including 3-5 major tasks in the near-term (<3 years), mid-term (3-6 years) and long-term (7-10 years).

Copper or Aluminum Alloy:

- Define losses as they exist in cable interconnects today
- Define current manufacturing processes
- Pursue materials and processes that offer easy replacement
- Pursue materials and processes that require significant modifications

Fluids:

- Define possible pathway modifications to existing devices
- Enhancing thermal properties for insulation mediums (oil)
- Explore thermal harvesting materials
- Explore phase change materials

Iron Alloys:

- Explore improvements to existing core materials
  - Alloy development
  - Manufacturing
- Rapid, large scale, solidification process development
- Amorphous alloy development
- Next generation 60 Hz core materials leveraging advanced manufacturing (nano crystal, nano particle)

For the major R&D tasks, define near-term, mid-term, and long-term milestones that can be used to measure progress in development.

Copper or Aluminum Alloy:

- Laboratory scale testing by year 3
- Scaled prototype by year 5
- Laboratory scale demonstration and cost/benefit for next generation interconnects by year 5
- Pilot scale in a utility by year 10

Fluids:

- Laboratory scale testing by year 3
- Scaled prototype by year 5
- Laboratory scale demo and cost/ benefit for next generation thermal management materials by year 10
- Pilot scale by year 10

Iron Alloys:

- Scaled prototype of alloy/process by year 3
- Business case validation by year 3
- Factory specifications/ large scale lab by year 5

Describe the role key stakeholders will play in overcoming the grid component challenges.

Copper or Aluminum Alloy:

- Academia – computational analysis
- National laboratories – computational analysis
- Industry – manufacturers, material providers
- Utilities
- DOE

Fluids:

- Academia – computational analysis
- National laboratories – computational analysis
- Industry – manufacturers, material providers
- Utilities
- DOE

Iron Alloys:

- Academia – computational analysis
- National laboratories – computational analysis
- Industry – manufacturers, material providers
- Utilities
- DOE

Fig. 21. Group Three Worksheet- Transformers

DESCRIPTION OF KEY CHALLENGES:

- Thermal management
- Inconsistencies within devices and materials

DESCRIPTION OF DESIRED OUTCOMES:

- Not identified

Material: Nano Enabled Coolant/Dielectric Fluid Better heat transfer; longer unit life; self-healing; water cool transformer improvement	**Material:** High Temperature Superconductor No losses; better dewar or cryofluid; higher voltages; drivers toward attractiveness of HVDC	**Material:** Low Resistance Winding Reduce I^2/R loss; smaller devices/ lighter weight; higher flux material/ fewer shorts	**Material:** Semiconductors Improve device consistency; allows for fewer devices; reduction of failures
Describe a possible approach to developing these material in the T&D component, including 3-5 major tasks in the near-term (<3 years), mid-term (3-6 years) and long-term (7-10 years).			
• Understanding real life transformer fluid • Modeling of convection/heat transfer in nano fluid and the effect of hybrid materials of properties • Material/fluid stability/lifetime • Experimental analysis of fluid after use/time trials/breakdown • Evaluate materials for self-healing for dielectrics and shorts/faults	• Not identified	• Not identified	• Not identified
For the major R&D tasks, define near-term, mid-term, and long-term milestones that can be used to measure progress in development.			
• Understand current fluid material systems and identify failures • Perform all standard tests/practices currently utilized on transformer fluid on hybrid system • Validate improvement provided by hybrid fluid on standard fluid • Time trial simulation application under standard conditions • Analysis under failure/worst case conditions	• Not identified	• Not identified	• Not identified
Describe the role key stakeholders will play in overcoming the grid component challenges.			
• Utilities – must be open minded • Component manufacturers – provide equipment; fault simulation; design • Industry/academia – identify/manufacture additive materials • Current oil suppliers	• Not identified	• Not identified	• Not identified

Fig. 22. Group Three Worksheet - FACTS/HVDC, Thermal and Electrical Insulation

DESCRIPTION OF KEY CHALLENGES:

- Ensuring ancillary and control components thermal rating keeps pace with WBG technology
- Improved thermal transfer to enable higher density
- Ensure electrical insulation and parasitic properties work for high density

DESCRIPTION OF DESIRED OUTCOMES:

- Control and ancillary components made from GaN, SiC capacitor made of glass (?) and high temperature magnetics
- Longer life (20-40 years) and/or higher density connectors with cost effective thermal transfer material
- High electrical insulation material enabling high density conversion

Material:
High Temperature Ancillary Components

Describe a possible approach to developing these material in the T&D component, including 3-5 major tasks in the near-term (<3 years), mid-term (3-6

- Short-term: High temperature drivers integrated with IGBT/MOSFET High temperature module
- Mid-term: Proof of concept from high temperature control integrated circuits (FPGAs etc.) and capacitors
- Long-term: Fully integrated polar and control module

For the major R&D tasks, define near-term, mid-term, and long-term milestones that can be used to measure progress in development.

- Operating driver and power device running at 200ºC
- Control integrated circuits operating at 200ºC

Describe the role key stakeholders will play in overcoming the grid component

- Not identified

APPENDIX A. LIST OF PARTICIPANTS AND WORKSHOP AGENDA

APPENDIX A. LIST OF PARTICIPANTS

First Name	Last Name	Affiliation
Iver	Anderson	Ames Laboratory
David	Beatty	Mitsubishi Electric Power Products, Inc.
Sudipta	Chakraborty	National Renewable Energy Laboratory
Quanfang	Chen	University of Central Florida
Kerry	Cheung	U.S. Department of Energy
Madhu	Chinthavali	Oak Ridge National Laboratory
Joe	Cresko	U.S. Department of Energy
Yutian	Cui	The University of Tennessee
Jim	Davidson	Vanderbilt University
Suman	Debnath	Oak Ridge National Laboratory
Ayman	El-Refaie	GE Global Research
Michael	Ennis	S&C Electric Company
Daniel	Freeman	Schneider Electric
Debbie	Haught	U.S. Department of Energy
Jeff	Hildreth	Bonneville Power Administration
Alex Q.	Huang	NC State University/FREEDM Center
Daniel	Hudgins	Nanofoundry, LLC
Jake	Hundley	HRL Laboratories LLC
Mark	Johnson	U.S. Department of Energy
Frank	Johnson	GE Global Research
Robert	Kaplar	Sandia National Laboratories
David	Kerns	Vanderbilt University
Alex	King	Critical Materials Institute
John	Kovacich	Eaton Corporation
Caroline	Kramer	Energetics Incorporated
Dominic	Lee	Oak Ridge National Laboratory
James	Maguire	AMSC
Brian	Marchionini	Energetics Incorporated
Scott	McCall	Lawrence Livermore National Laboratory
Scott	McWhorter	Savannah River National Laboratory

Govindarajan	Muralidharan	Oak Ridge National Laboratory
Geraldo	Nojima	Eaton Corporation
Paul	Ohodnicki	National Energy Technology Laboratory
Richard	Ord	Electric Power Research Institute
Burak	Ozpineci	Oak Ridge National Laboratory
Parans	Paranthaman	Oak Ridge National Laboratory
Ridah	Sabouni	Energetics Incorporated
Thomas	Salem	Clemson University
Joe	Schatz	Southern Company
Venkat	Selvamanickam	University of Houston
George	Shurina	Mitsubishi Electric Power Products, Inc.
James	Simonelli	Gridco Systems
Emmanuel	Taylor	U.S. Department of Energy
Robert	Tenent	National Renewable Energy Laboratory
Leon	Tolbert	The University of Tennessee / ORNL
Darren	Tremelling	ABB Corporate Research
Ivan	Vlassiouk	Oak Ridge National Laboratory
Jy-An	Wang	Oak Ridge National Laboratory
Matthew	Willard	Case Western Reserve University
Nikolaus	Zant	ABB Corporate Research

WORKSHOP AGENDA

Day 1: Wednesday August 26, 2015.

Time	Activity	Location
8:00 am	**Registration and Networking**, Coffee/Refreshments*	Building 4500N
9:30 am	**Welcome and Overview of Workshop** • *Kerry Cheung, U.S. Department of Energy (DOE)*	Weinberg Auditorium Building 4500N
10:00 am	**Plenary Presentations: Grid Applications Overview (15 min + 5 Q&A each)** • *Joe Schatz (Southern Company)* • *Richard Ord (EPRI)* • *Alex Huang (NC State FREEDM Systems Center)*	Weinberg Auditorium Building 4500N
11:00 am	**Break (15 min)**	Outside Weinberg Auditorium Building 4500N
11:15 am	**Plenary Presentations: Materials Development Overview (15 min + 5 Q&A each)** • *Debbie Haught (U.S. DOE)* • *Paul Ohodnicki (NETL)* • *Jim Davidson (Vanderbilt University)*	Weinberg Auditorium Building 4500N
12:15 pm	**Manufacturing Innovations (15 min + 5 Q&A)** • *Mark Johnson (U.S. DOE)*	Weinberg Auditorium Building 4500N
12:35 pm	**Breakout Session Instructions and Charge to Participants** • *Brian Marchionini, Energetics Incorporated*	Weinberg Auditorium Building 4500N
12:40 pm	**Working Lunch* (in breakout rooms)**	Breakout rooms: Building 5700 rooms A104, A106, & L202
1:30 pm	**Parallel Breakout Session 1:** *Key technical challenges across functional areas limiting grid component performance and capabilities through 2035*	
3:00 pm	**Break**	
3:15 pm	**Parallel Breakout Session 2:** *innovative materials that have the greatest potential to improve grid components by 2035*	
4:45 pm	**Break and return to Plenary Room**	Weinberg Auditorium Building 4500N
5:00 pm	**Report Outs** (*5-10 min debrief from each group, with Q&A*)	Weinberg Auditorium Building 4500N
5:30 pm	**Adjourn and instructions for next day**	

Day 2: Thursday August 27, 2015

Time	Activity	Location
8:00 am	**Coffee/Refreshments***	Breakout rooms: Building 5700 Rooms A104, A106, & L204
8:30 am	**Parallel Breakout Session 3:** *Developing R&D Pathways and Milestones*	
10:00 am	**Break**	
10:15 am	**Crosscutting Discussion**	Wigner Auditorium Building 4500N
10:45 am	**Next Steps and Adjourn** • *Kerry Cheung, U.S. DOE*	
11:00 am	**Lunch in ORNL cafeteria**	ORNL cafeteria
12:00 pm	**Bus Leaves for Tour of the ORNL Manufacturing Demonstration Facility (MDF) and Power Electronics Laboratory (tours 12:30-1:30)**	NTRC
1:30 pm	**Bus Returns to ORNL Main Lab, arriving ~2 pm**	

APPENDIX B. FULL LISTING OF PARTICIPANT CONTRIBUTION

This appendix compiles the full results of breakout sessions one and two for all three of the individual groups. The results of the first breakout session, where participants identified key technical challenges limiting grid component performance and capabilities, are provided in the first column. The results of the second breakout session, where participants identified possible innovative materials with the greatest potential to overcome those technical challenges, are provided in the second column.

Transformers

	Technical Challenges	Innovative Materials
1. Active Power Conversion (e.g., semi-conductors)	***Group One*** • Packaging for high power HV, UHV WBG Modules (creepages, cannot withstand high voltages) • Solid state transformers can be key enablers for future grid especially using WBG devices as well as HF magnetics • Lack of high-temperature packaging materials • Need high voltage capacitors for WBG converters: ~4 kV and high temperature >125 degrees C and volume constraints. Low package size, low ESL/low dielectric loss • Low PE device reliability and lifetime • Electrical insulation temperature limits cause low lifetime and reliabilities ***Group Two*** • Need smarter transformer for 100% DG • Need new, cheaper WBG material • Need “fail normal” integration of transformer & fractionally rated active components	***Group One*** • Vertical GaN device/GaN substrates • High temperature packaging materials to replace current solders (e.g., nanosilver); however, there are manufacturing challenges in producing them • Boron nitride (cubic form) • Zinc oxide • Dual-phase tunable permeability soft magnetic material • Diamond- larger bandgap • AlN and Al-rich AlGaN (it has doping challenges) • Ga_2O_3, other WBGs for high breakdown voltage (>50kV) o Note: Gallium is headed to being a critical material, availability only in Australia, South Africa, and Russia • Carbon nanotube conductors that are lighter (30-40% lighter than copper and increased conductivity for higher efficiency • Gel and ceramics (>>30 kV/mm)
2. Passive Power Conversion (e.g., magnetics)	***Group One*** • Conventional transformer life/reliability is mainly affected by thermal management; could benefit from lower losses in core and conductors as well as better thermal management • Solid state transformers can be key enablers for future grid especially using WBG devices as well as HF magnetics • Need higher energy efficiency (and corresponding lower heat generation) source of heat • Need increased transformer SST reliability (DC-DC conversion at HVDC/MVDC) ***Group Two*** • Lowest core loss for highest switching current • Large volume of high frequency (>100kHz) magnetic components causing low power density • Rare earth magnets NdFeB:Dy Sm_2Co_5; Sm_2CO_{17} Hard Soft Composites ***Group Three*** • Need accurate finite element models for high frequency (passive) materials to use in converter design (global and local effects) • Need manufacturing of amorphous and nano-crystalline alloys/cores (rapid solidification and alloy processing) • Need for transfer dielectric fluid to “engineer” the electric stress gradient to allow a reduction in size • Lack of scaling, modelling, and management of high power, high voltage, high frequency parasitics	***Group One*** • Nanocomposite soft magnets with low loss at high frequency. Currently available but brittle • Dual-phase tunable permeability soft magnetic material • Carbon nanotube conductors that are lighter (30-40% lighter than copper and increased conductivity for higher efficiency) ***Group Two*** • Soft magnetic composites adopted for additive manufacturing methods • High saturation magnetic, low core less soft, metallic soft magnetic materials ***Group Three*** • An oil improving additive such as processed particulate nano-diamond • Rapidly solidified amorphous/nano-crystal • Fe-Ni based nano-particles (core shell) • Low kHz-MHz electrical conductivity with high DC electrical conductivity (mitigate parasitics) • Nano-particle enhanced dielectric fluid for engineering electric stress in caps and transfer to shrink size • Nano-crystalline magnetic alloys with improved mechanical properties for core fabrication • Coreless transformer lightweight magnetic material for dielectric caps • Bulk amorphous soft magnetic alloys

3. Electrical Insulation	***Group One***
	• Solid state transformers can be key enablers for future grid especially using WBG devices as well as HF magnetics
	• Need insulation that is high performance (dielectric properties) and is cost-effective (leads to improved efficiency)
	• Need high thermal conductivity and low thermal conductivity
	  o Could reduce aging of transformer paper to extend system life (materials solution or other)
	• Temperature limits of electrical insulation is leading to low lifetime and reliabilities
		Group One
		• Self-healing ceramics and polymers, for example perovskites
		• Ceramic deposition materials:
		  o Geometry in copper
		  o Heat spreads, function of dielectric
		• Improved moisture gettering in transformer oil with diamond nanoparticles—extracts water from paper
		• Non SF_6 gas insulation
		  o E.g., echo efficient gas
		• Microwave transmission

	Group Two • Dielectric strength and thermal conductivity of fluid or solid ***Group Three*** • Degradation rate of pressboard ins too high • Need transformer insulation that is self-healing • Lack of understanding insulation degradation over time	***Group Two*** • Non-flammable insulation (dielectrics) • Nomex for transformer insulation

4. Electrical Conduction	***Group One***
	• Conventional transformer life/reliability is mainly affected by thermal management; could benefit from lower losses in core and conductors as well as better thermal management
		Group One
		• Carbon nanotube conductors that are lighter (30-40% lighter than copper and increased conductivity for higher efficiency
		• High current cabling
		  o Al/Cu manufacturing issues
		  o Installation needs to be easier
		• Covetic nanomaterials
		  o High conductivity (electrical and thermal)
		  o Al, Cu, Ag, Au, Zn, Sn, Fe
		  o 40% improved electrical conductivity from Al and Cu
		• 50% improved thermal conductivity from copper
		
		Group Three
		• Room temperature superconductor

5. Structural Support and Protection	***Group Three*** • Need to convert from metal to plastic to reduce structural weight	***Group One*** • Superhydrophobic materials
6. Thermal Management	***Group One*** • Conventional transformer life/reliability is mainly affected by thermal management; could benefit from lower losses in core and conductors as well as better thermal management • Lack of additive materials for transfer oil to reduce operating temperature • Need to reduce mass/volume of thermal management (insulation, heat exchanger) systems • Need forced convection without moving parts (smart materials) • Need fanless cooling of PE devices • Need improved thermal management materials • Solid state transformers can be key enablers for future grid especially using WBG devices as well as HF magnetics • Need higher energy efficiency (and corresponding lower heat generation) source of heat • Thermal management materials are inadequate ***Group Two*** • Need materials for passive thermal management ***Group Three*** • Need higher efficiency passives and higher thermal conductivity passives simultaneously	***Group One*** • Nanocomposite soft magnets with low loss at high frequency. Currently available but brittle • Functionalized nano-diamond additive for oil to increase thermal conductivity (TRL 3-4) • Adjustable/low curie temperature nano particles (ferromagnetic). E.g., iron oxide nanoparticles • Magneto-calorics effect for active cooling (more energy efficient) • Shape memory alloys with high cycle fatigue life • Thermoelectrics: direct thermal energy conversion • Next-generation aerogels- high temp, flexible, and fiber reinforced • Carbon nanotube conductors that are lighter (30-40% lighter than copper and increased conductivity for higher efficiency • Diamond-based materials (high thermal conductivity • Phase changing materials • High polymer conductivity polymers (thermal) • Thermal management materials • High thermal conductivity heat sinks • High temp/advanced packaging for power electronics • Improved degradation: high thermal conductivity polymers for heat spreaders. E.g., polymers with functionalized nanodiamond ***Group Two*** • Use of metal hydride alloys for energy (heat) dissipation (e.g., 1200 kJ/kg)
7. Other	***Group Three*** • Transformers:	***Group Two*** • Non-flammable insulation (dielectrics)

	o Bulky, not suitable for renewable deployment o Need to determine commercial grid needs	

	FACTS Devices	
	Technical Challenges	**Innovative Materials**

1. Active Power Conversion (e.g., semi-conductors)	***Group One***
	• Packaging for high power HV, UHV WBG Modules
	  o Creepages
	  o Cannot withstand high voltages
	• Solid state transformers can be key enablers for future grid especially using WBG devices as well as HF magnetics
	• Lack of high-temperature packaging materials
	• Lack of power modules/packaging
	• Need high voltage capacitors for WBG converters: ~4 kV and high temperature >125 degrees C and volume constraints. Low package size, low ESL/low dielectric loss
	• High Vg, high density, high temperature, capacitors
	• High density/low parasitic capacitors and high reliability
	• Current breakdown voltage/current/frequency limitations of solid state /PE devices
	  o >6.5kV and >15 A, 15kV. Today Cree wans 250A
	  o HVDC converters (active power conversion) → limit on DC voltage vs components rating vs reliability
	  o High voltage devices fast switching
	  o High voltage and high current PE
	• Need better lightning and surge protection (cannot withstand high voltages)
	• Lack of effective passive cooling techniques for power electronics
	• Low PE device reliability and lifetime
	• Lack of gate drives and protection for WBG power electronics
	• Lack of understanding of failure mechanisms
	• Need better DC circuit breakers (more models, cheaper, reliable, vs mechanical)
	
	Group Two
	• Balancing cost vs. performances for magnetics for D-FACTS (switches)
	•
	
	Group Three
	• Lack of volt capabilities of IGBT limits viable topologies
		Group One
		• High temp packaging materials to replace current solders (e.g., nanosilver). Manufacturing challenges in producing them.
		• Dual-phase tunable permeability soft magnetic material
		• Better die attach/conductors than wire bonds in modules
		• High current/high voltage WBG semiconductors (>10 kV and >100 A)
		• Gel and ceramics (>>30 kV/mm)
		
		Group Two
		• 10X electric max improvement (i.e., ceramic substrate better than AlN)
		• Large area, low cost simple crystal-like substrates for WBF (preferably by R&R manufacturing)
		• Ga_2O_3 (WBG)
		
		Group Three
		• Semiconductors – GaN and SiC
		• Reducing loss in semiconductor low switching low conduction

2. Passive Power Conversion (e.g., magnetics)	***Group One*** • Solid state transformers can be key enablers for future grid especially using WBG devices as well as HF magnetics • High Vg, high density, high temperature, capacitors • Lack of high density/low parasitic capacitors and high reliability ***Group Two*** • Balancing cost vs. performances for magnetics for D-FACTS (switches) • Need capacitors for FACTS & HVDC that have long lifetimes and voltage capabilities • Large volume of high frequency (>100kHz) magnetic components causing low power density	***Group Two*** • Dual phase change magnetic material • High saturation magnetic, low core less soft, metallic soft magnetic materials ***Group Three*** • Nano-crystalline magnetics • Diamond film capacitors • CVD

	Group Three • Lack of scaling, modelling, and management of high power, high voltage, high frequency parasitics	
3. Electrical Insulation	***Group One*** • Solid state transformers can be key enablers for future grid especially using WBG devices as well as HF magnetics	***Group One*** • Non SF_6 gas insulation o E.g., echo efficient gas • Microwave transmission

4. Electrical Conduction	***None***	***Group One***
		• High current cabling
		  o Al/Cu manufacturing issues
		  o Installation needs to be easier
		• Covetic nanomaterials
		  o High conductivity (electrical and thermal)
		  o Al, Cu, Ag, Au, Zn, Sn, Fe
		  o 40% improved electrical conductivity from Al and Cu
		  o 50% improved thermal conductivity from copper

5. Structural Support and Protection	***None***	***Group One*** • Superhydrophobic materials ***Group Two*** • New sensing materials for power grid (smart materials)
6. Thermal Management	***Group One*** • Need forced convection without moving parts (smart materials) • Need fanless cooling of PE devices • Solid state transformers can be key enablers for future grid especially using WBG devices as well as HF magnetics • Thermal management materials are inadequate ***Group Three*** • Need higher efficiency passives and higher thermal conductivity passives simultaneously • Need to manage heat removal using passive means to enable low/no maintenance • Balancing electrical insulation vs. thermal conductivity	***Group One*** • Diamond-based materials (high thermal conductivity • Phase changing materials • High polymer conductivity polymers (thermal) • Thermal management materials • High thermal conductivity heat sinks • High temp/advanced packaging for power electronics • Improved degradation: high thermal conductivity polymers for heat spreaders. E.g., polymers with functionalized nano-diamond ***Group Two*** • 10x improvement in thermal conductivity coats for chips and modules ***Group Three*** • High heat transfer, no electric conductivity heat pipe with no conduction properties • Efficient thermal electrics
7. Other	***Group Three*** • Balancing electrical insulation vs. thermal conductivity	***Group Two*** • Silicon on insulators or better

	C. HVDC Converters	
	Technical Challenges	**Innovative Materials**

1. Active Power Conversion (e.g., semi-conductors)	***Group One***
	• Packaging for high power HV, UHV WBG Modules
	  o Creepages
	  o Cannot withstand high voltages
	• Solid state transformers can be key enablers for future grid especially using WBG devices as well as HF magnetics
	• High-temperature packaging materials
	• Lack of power modules/packaging
	• Need high voltage capacitors for WBG converters: ~4 kV and high temperature >125 degrees C and volume constraints. Low package size, low ESL/low dielectric loss
	• High Vg, high density, high temperature, capacitors
	• High density/low parasitic capacitors and high rel.
	• Current breakdown voltage/current/frequency limitations of solid state /PE devices
	  o >6.5kV and >15 A, 15kV. Today Cree wans 250A
	  o HVDC converters (active power conversion) → limit on DC voltage vs components rating vs reliability
	  o High voltage devices fast switching
	  o High voltage and high current PE
	• Need better lightning and surge protection (cannot withstand high voltages)
	• Effective passive cooling techniques for power electronics
	• Low PE device reliability and lifetime
	• Lack of gate drives and protection for WBG power electronics
	• Lack of understanding of failure mechanisms
	• HVDC limitations
	  o Economic vs distance
	  o DC fault resistant—fault clearing capabilities
	• Need better DC circuit breakers (more models, cheaper, reliable, vs mechanical)
	Group Two
	• HV, HF, HT switch is not available
	• Need WBG device packaging (high voltage, high temperature)
	Group Three
	• Need integrated control/intelligence
	• Advanced material for capacitors
		Group One
		• Vertical GaN device/GaN substrates
		• High temp packaging materials to replace current solders (e.g., nanosilver). Manufacturing challenges in producing them.
		• Dual-phase tunable permeability soft magnetic material
		• Better die attach/conductors than wire bonds in modules
		• Diamond- larger bandgap
		• SiC IGBTs (HVDC/FACTS)
		• High current/high voltage WBG semiconductors (>10 kV and >100 A)
		• AlN and Al-rich AlGaN (it has doping challenges)
		• Ga_2O_3, other WBGs for high breakdown voltage (>50kV)
		  o Note: Gallium is headed to being a critical material, availability only in Australia, South Africa, and Russia
		• Synthetic diamond that can be attached to copper or aluminum
		• Gel and ceramics (>>30 kV/mm)
		Group Three
		• Semiconductors – GaN and SiC

2. Passive Power Conversion (e.g., magnetics)	***Group One*** • Solid state transformers can be key enablers for future grid especially using WBG devices as well as HF magnetics • Need a higher energy efficiency (and corresponding lower heat generation) source of heat • Need a better component size/weight for mobile technologies; power density ***Group Two*** • Need capacitors for FACTS & HVDC that have long lifetimes and voltage capabilities • Need ultra-compact HV capacitor (would improve strength)	***Group One*** • Nanocomposite soft magnets with low loss at high frequency. Currently available but brittle ***Group Two*** • High saturation magnetic, low core less soft, metallic soft magnetic materials

	Group Three • Lack of scaling, modelling, and management of high power, high voltage, high frequency parasitics • Need to develop advanced material for capacitors • Need for DC application power capacitors that address the growing issue of power density increase	
3. Electrical Insulation	***Group One*** • Solid state transformers can be key enablers for future grid especially using WBG devices as well as HF magnetics	***Group One*** • Non SF_6 gas insulation o E.g., echo efficient gas • Microwave transmission

4. Electrical Conduction	***None***	***Group One***
		• High current cabling
		  o Al/Cu manufacturing issues
		  o Installation needs to be easier
		• Covetic nanomaterials
		  o High conductivity (electrical and thermal)
		  o Al, Cu, Ag, Au, Zn, Sn, Fe
		  o 40% improved electrical conductivity from Al and Cu
		  o 50% improved thermal conductivity from copper

5. Structural Support and Protection	***Group One*** • There are current HVDC limitations o Economic vs. distance • DC fault resistant—fault clearing capabilities	***Group One*** • Superhydrophobic materials
6. Thermal Management	***Group One*** • Need fanless cooling of PE devices • Need improved thermal management materials • Solid state transformers can be key enablers for future grid especially using WBG devices as well as HF magnetics • Need higher energy efficiency (and corresponding lower heat generation) source of heat • Thermal management materials are inadequate ***Group Three*** • Need higher efficiency passives and higher thermal conductivity passives simultaneously	***Group One*** • Nanocomposite soft magnets with low loss at high frequency. Currently available but brittle • Diamond-based materials (high thermal conductivity • Phase changing materials • High polymer conductivity polymers (thermal) • Thermal management materials • High thermal conductivity heat sinks • High temp/advanced packaging for power electronics • Improved degradation: high thermal conductivity polymers for heat spreaders. E.g., polymers with functionalized nano-diamond
7. Other		***Group Two*** • Silicon on insulators

	D. Cables and Conductors	
	Technical Challenges	**Innovative Materials**
1. Active Power Conversion (e.g., semi-conductors)	***None***	***Group One*** • Carbon nanotube conductors that are lighter (30-40% lighter than copper and increased conductivity for higher efficiency • Gel and ceramics (>>30 kV/mm)
2. Passive Power Conversion (e.g., magnetics)	***None***	***Group One*** • Carbon nanotube conductors that are lighter (30-40% lighter than copper and increased conductivity for higher efficiency
3. Electrical Insulation	***Group One*** • Need insulation that is high performance (dielectric properties) and is cost-effective (leads to improved efficiency) • Temperature limits of electrical insulation leads to low lifetime and reliabilities ***Group Two*** • Dielectric strength and thermal conductivity of fluid or solid • Need broad dielectric improvement and life (possibly from diamond) ***Group Three*** • Thermal fatigue and failure as ampacity increases • Strength vs. electrical conduction • Need "in the field" deployable protective coatings	***Group One*** • Superhydrophobic materials • Anti-fouling coating, i.e., self-healing coatings • Non SF_6 gas insulation o E.g., echo efficient gas • Microwave transmission ***Group Two*** • Heavily loaded, high temperature polymers containing ceramics like BiN, TiN, Si_3N_4 (with high thermal conductivity) • High dielectric strength polymers ***Group Three*** • SOL-based insulation/dielectrics • Anti-fouling/icing coating materials

4. Electrical Conduction	***Group One***
	• Components are aging and corroding
	• Need to maximize strength/weight and conductivity in a single material: Better, stronger, lighter
	  o Lightweight, durable electrical conductors
	  o Thermal stability/conductor ability to move large amounts of power through a given cross section/area
	  o Economical conductors
	  o High voltage DC cables for underwater (too expensive and not reliable)
	• Need to move to next generation conductors (and cable assemblies) that will not degrade in performance over time (e.g., carbon fiber)
	Group Two
	• Need broad dielectric improvement and life (possibly from diamond)
	• Need advanced connector system, joint compound, surface doping, surface contact res.
	• Need maximum conducting capability, low weight (overhead) HVDC
	• Need room temperature conductors
	Group Three
	• Need higher conductivity cables
		Group One
		• Carbon nanotube conductors that are lighter (30-40% lighter than copper and increased conductivity for higher efficiency
		• Lightweight carbon fiber/hybrid cables
		• Room temperature superconductors
		• HTLS conductors: carbon core, single strand or multi-strand. Need high temperature operation and low sag
		• In-situ, aluminum-matrix composites, i.e., "self-standing aluminum" that doesn't need a steel core
		• Nano-twinned copper: strong without the usual conductivity losses. But it's hard to manufacture
		• HTS wires that are better than BSSCO
		• Carbon-based composite cables
		• High current cabling
		  o Al/Cu manufacturing issues
		  o Installation needs to be easier
		• Covetic nanomaterials
		  o High conductivity (electrical and thermal)
		  o Al, Cu, Ag, Au, Zn, Sn, Fe
		  o 40% improved electrical conductivity from Al and Cu
		  o 50% improved thermal conductivity from Cu
		Group Two
		• Highly conductive composites to achieve abnormal strength, low density, temperature stability
		• High conduction, high reliability conductive material (metal, CNT)
		• New or improved high temperature superconductors or new conductor alloys
		• Surface conductance improvement
		  o Corrosion inhibitor
		  o Doping
		  o Joint compound

		o Robust passivation ***Group Three*** • Room temperature superconductor • CVD • Room temperature superconduction • Ballistic carbon nanotube nano-composite copper or aluminum for ultra-conductive wire and bus • Super-hydrophobic insulation materials
5. Structural Support and Protection	***Group One*** • Need to maximize strength/weight and conductivity in a single material: Better, stronger, lighter o Lightweight, durable electrical conductors o Thermal stability/conductor ability to move large amounts of power through a given cross section/area o Economical conductors o High voltage DC cables for underwater (too expensive and not reliable) • Need electrical support structures (i.e., poles) with load-bearing capacity to withstand extreme weather ***Group Two*** • Need smart connector system (sensors) to promote early warning) • Transmission structures have complexity, strength, rigidity, aesthetics	***Group One*** • Co-mingled fiber composites, e.g., glass integrated sensing at a lower cost o Fiber-metal laminates (aluminum-glass fiber hybrids) (orphan card, seems like best fit?) • Superhydrophobic materials ***Group Two*** • Carbon nanotubes for conductors • Superhydrophobic coatings (high power) • Integrated PET sensor → connector health monitor system ***Group Three*** • Spiral welded towers
6. Thermal Management	***Group One*** • HTS infrastructure is not reliable enough (inadequate cryogenics) ***Group Two*** • Phonon scattering in mixed material/mixed phase systems • Need effective thermal management • Cost and performance of cryogenics/coolers for HTS FCL and cables	***Group One*** • Carbon nanotube conductors that are lighter (30-40% lighter than copper and increased conductivity for higher efficiency • Room temperature superconductors • Cellular insulation (aerogels, lattices, fiber reinforced foams). Need lower volume and mass and improved manufacturing techniques. For example: polyimine • Diamond-based materials (high thermal conductivity • High polymer conductivity polymers (thermal) • Thermal management materials • High thermal conductivity heat sinks • High temp/advanced packaging for power electronics • Improved degradation: high thermal conductivity polymers for heat spreaders. E.g., polymers with functionalized nanodiamond
7. Other	***Group One*** • Underground cables are too expensive (diagnostics and installation) ***Group Two*** • Underground cable, flexibility of cond. (Young's modulus of conductor)	***Group Three*** • High temperature (300ºC) solder with strength, ductility, and conductivity • Reduced temperature solders

	E. Protection Devices (e.g., breakers)	
	Technical Challenges	**Innovative Materials**
1. Active Power Conversion (e.g., semi-conductors)	***Group One*** • Need gate drives and protection for WBG power electronics • Lack of understanding of failure mechanisms • Current HVDC limitations • Need more models of DC circuit breakers that are cheaper, reliable, vs mechanical) ***Group Two*** • Need ultra-fast "arc-free" (long life) circuit breaker, < ¼ cycle ***Group Three*** • Non-Maxwell heat to electric conversion • Protection systems for a DC or solid state grid	***Group One*** • Gel and ceramics (>>30 kV/mm) ***Group Two*** • Silicon carbide for protection devices ***Group Three*** • WBC (SiC) for fast-acting breakers
2. Passive Power Conversion (e.g., magnetics)	***Group Three*** • Protection circuits for WBG devices (cost of manufacturing the WBG with existing infrastructure)	***Group Three*** • Nano-particle enhanced higher dielectric film polymer for DC and AC caps
3. Electrical Insulation	***Group One*** • Need insulation that is high performance (dielectric properties) and is cost-effective (leads to improved efficiency) • Lacking better power modules/packaging • Lightning and surge protection cannot withstand high voltages • Lack of scheduled maintenance on components, lack of sensors ***Group Three*** • Need low pressure electronegative gasses other than SF_6 • Surge arrester that stops lighting from damage, etc. • Need better solder	***Group One*** • Non SF_6 gas insulation o E.g., echo efficient gas • Microwave transmission ***Group Three*** • CVD • Bulk CVD diamond • Stable fluid with variable temperature for s/c temperature
4. Electrical Conduction	***Group One*** • Components are aging and corroding ***Group Two*** • High losses (at core reactors) ***Group Three*** • Need faster, high current breakers for s/c cable systems	***Group One*** • High current cabling o Al/Cu manufacturing issues o Installation needs to be easier • Covetic nanomaterials o High conductivity (electrical and thermal) o Al, Cu, Ag, Au, Zn, Sn, Fe o 40% improved electrical conductivity from Al and Cu o 50% improved thermal conductivity from Cu ***Group Three*** • Flexible copper with high ampacity that doesn't fatigue • Tin replacement for solder that is thermally stable, electrically conductive, corrosion resistant, and has no whisker growth
5. Structural Support and Protection	***Group Two*** • Lack of "fieldable" composite joining/repair technologies • Low cost medium modules, high tensile strength composite structures • Lightning arrestors with rapid energy dissipation w/o catastrophic issues ***Group Three*** • Need more corrosion-proof structures	***Group One*** • Superhydrophobic materials ***Group Two*** • Structural composites ***Group Three*** • Enabling materials for diagnostics
6. Thermal Management	***Group Two*** • Reliability (especially at high power)	***Group One*** • Diamond-based materials (high thermal conductivity • High polymer conductivity polymers (thermal) • Thermal management materials • High thermal conductivity heat sinks • High temp/advanced packaging for power electronics

		• Improved degradation: high thermal conductivity polymers for heat spreaders. E.g., polymers with functionalized nanodiamond ***Group Two*** • High thermal conductive, low CTE materials • High thermal conductivity coatings on HTS tapes for superconducting fault current limiters
7. Other	***Group Two*** • Need bi-directional protection and control components • Challenges for low cost sensors for in situ applications ***Group Three*** • Need better fault location and isolation	***None***

	F. Other Substation Components	
	Technical Challenges	**Innovative Materials**
1. Active Power Conversion (e.g., semi-conductors)	***None***	***Group One*** • Gel and ceramics (>>30 kV/mm)
2. Passive Power Conversion (e.g., magnetics)	***None***	***Group Three*** CNT-based power capacitors
3. Electrical Insulation	***Group One*** • Need insulation that is high performance (dielectric properties) and is cost-effective (leads to improved efficiency) ***Group Two*** • Dielectric strength and thermal conductivity of fluid or solid	***Group One*** • Non SF_6 gas insulation o E.g., echo efficient gas • Microwave transmission
4. Electrical Conduction	***Group One*** • Components are aging and corroding ***Group Three*** • Lack of breakers that make fast-last (no ARL)	***Group One*** • High current cabling o Al/Cu manufacturing issues o Installation needs to be easier • Covetic nanomaterials o High conductivity (electrical and thermal) o Al, Cu, Ag, Au, Zn, Sn, Fe o 40% improved electrical conductivity from Al and Cu o 50% improved thermal conductivity from Cu
5. Structural Support and Protection	***Group One*** • Need damage/flow tolerant ceramic ***Group Three*** • Need more corrosion-proof structures	***Group One*** • "Smart" fault-current limiting materials • Superhydrophobic materials ***Group Three*** • Corrosion resistant coating
6. Thermal Management	***Group One*** • Need damage/flow tolerant ceramic	***Group One*** • Diamond-based materials (high thermal conductivity • High polymer conductivity polymers (thermal) • Thermal management materials • High thermal conductivity heat sinks • High temperature/advanced packaging for power electronics • Improved degradation: high thermal conductivity polymers for heat spreaders. E.g., polymers with functionalized nanodiamond
7. Other	***Group Two*** • Need transformer bushings that can withstand physical attacks and self-clean	***None***

	G. Other	
	Technical Challenges	**Innovative Materials**
1. Active Power Conversion (e.g., semi-conductors)	***Group One*** • Lack of transformer SST: reliability (DC-DC conversion at HVDC/MVDC)	***Group Three*** • Morphologically engineering CVD diamond films
3. Electrical Insulation	***Group One*** • Need insulation that is high performance (dielectric properties) and is cost-effective (leads to improved efficiency)	***Group Three*** • Doping controlled passives
4. Electrical Conduction	***None***	***Group Three*** • Materials with decoupled electrical and thermal properties • Materials for solid state cooling (i.e., magneto-caloric/thermoelectric) • Phase change material
6. Thermal Management	***Group Three*** • For thermal management, need no moving parts • Need magneto-calorics • Active (power-driven) cooling	
7. Other	***Group One*** • Need new materials that resist arc-pitting at circuit-breaker contacts—present materials have supply chain issues • DC circuit breakers (more models, cheaper, reliable, vs mechanical) • Distributed generation – need to put generation next to the load to reduce power losses • Cybersecurity issues/concerns • Physical security issues, i.e., vandalism and terrorism • How to deal with big data coming from sensors of the future • Systems level reliability, resilience and integration and harmonization across components and functional areas • Linear, not on/off grid components → smarter appliances and "breathing" system with demand • Grid of the future: DC, grid components are blurred, like the solid state transformer • Inadequate "smart" materials that change material properties with current and voltage changes • Look to aerospace industry—dealing with lots of DC integration issues ***Group Three*** • Asset monitoring for condition based and predictive maintenance • Need to consider cyber threats • Long timeline for utility adoption	***Group One*** • Energy storage materials • Multi-ferroics for power conversion: control magnetism with an electric field. E.g., ferroelectrics • Integration of energy between the grid and production ***Group Two*** • Carbon nanotubes and graphene