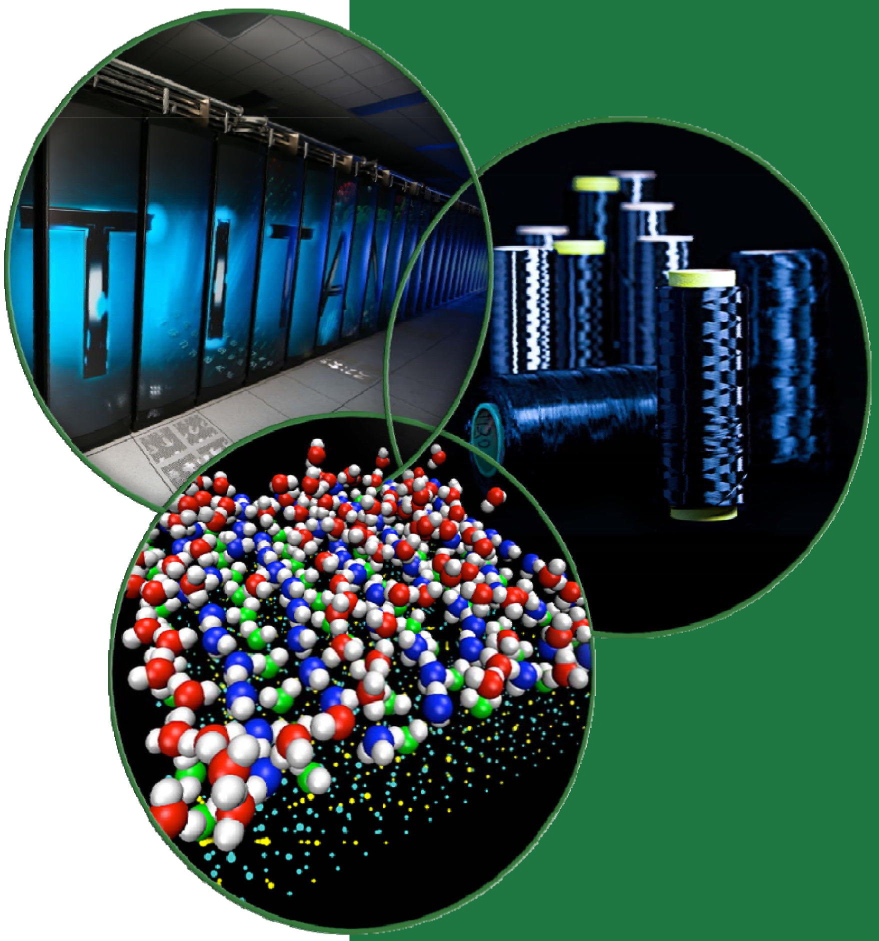
Grid Components Landscape:
Challenges and Opportunities



Dominic Lee
Sustainable Electricity
Oak Ridge National Laboratory

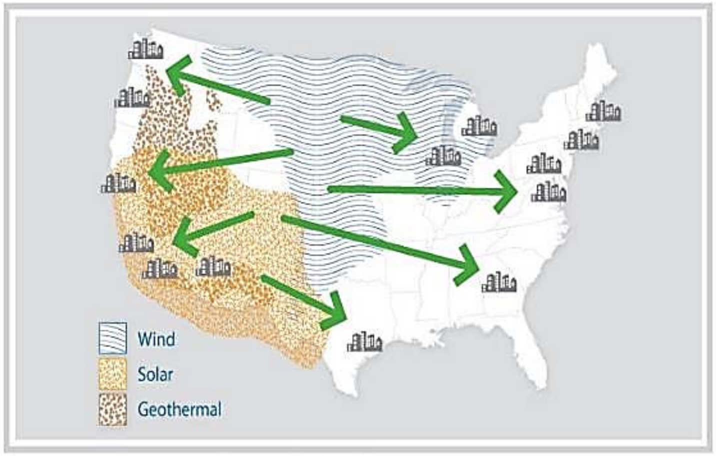
Next-Generation Grid Components R&D Program Planning Workshop

August 17, 2016
Pittsburgh, PA

OAK RIDGE
National Laboratory

Evolving energy mix and threats will affect how electricity is delivered

Evolving energy mix



Source: AWEA and SEIA: "Green Power Superhighways" - February 2009

Potential threats

- **How will these changes impact the transmission and distribution networks?**
- **What innovations must be made to what hardware to ensure reliable and affordable electricity?**

Five categories to consider

Transformers

Power transformers
Distribution transformers
Solid-state transformers
Others
…

Cables & Conductors

Conductors
Cables
Connectors
Others
…

Flow Control

HVDC Converters
FACTS
Voltage regulators
Others
…

Protection Equipment

Breakers
Arresters
FCLs
Others
…

Sensors

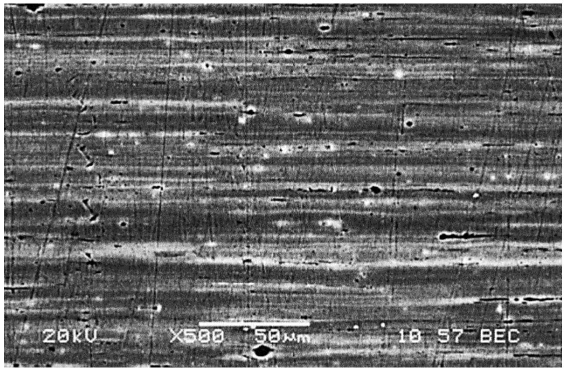
High strength, low cost materials can increase the ampacity of OH lines

e.g. Deformation Processed Metal-Metal Composites –DMMC (Ames Lab):

Conductive-matrix nano-filament composites
that is deformed under high strain
can exhibit very high strength

+

Low cost, low density,
highly conductive metals



Al + 9%Ca

	ACSR	Al-20%Ca *
Density (g/cm^3)	3.43	2.47
Strength (MPa)	304	660
DC cond 20°C (μΩm)$^{-1}$	38.1	36.2
Elastic modulus (GPa)	85	60

* *Estimated*

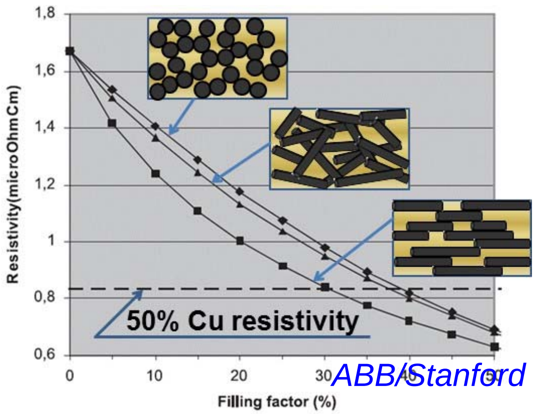
Ames Lab

Issues:

- Starting materials
- Processing/ Manufacturing
- Stability

Low resistance materials can reduce losses, size and weight of components

Ultraconductive copper – UCC (ICA, UCF, etc.)
- Cu + CNTs (expansive)
- Higher electrical conductivity, strength, thermal conductivity



ABB/Stanford

Issues:
- Mechanisms
- Processing
- Process stability –
  - Not repeatable
  - Not predictable

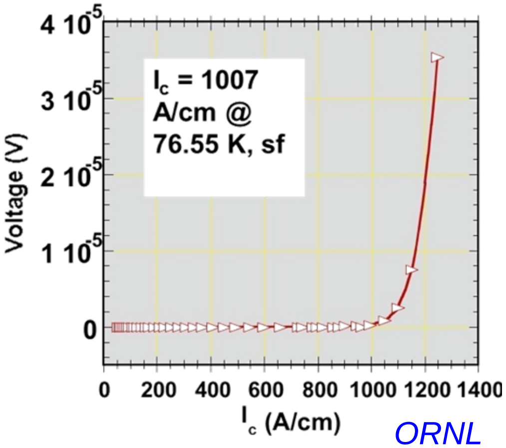
Covetic Nanomaterials (DOE-AMO, NLs, U Md)
- Metal + Carbon
- Higher electrical conductivity, strength, thermal conductivity

Type	%IACS	Condition
6061	47.4	Conv T6
3%C 6061	47.8	T6 ground
	56.1	T6 EDM
	67.3	As extruded
EC-1350	61.8	Elect grade

USNA

Issues:
- Mechanisms
- Processing
- Process stability?

Superconductors-HTS (companies)
- 77K operation
- Zero DC resistance

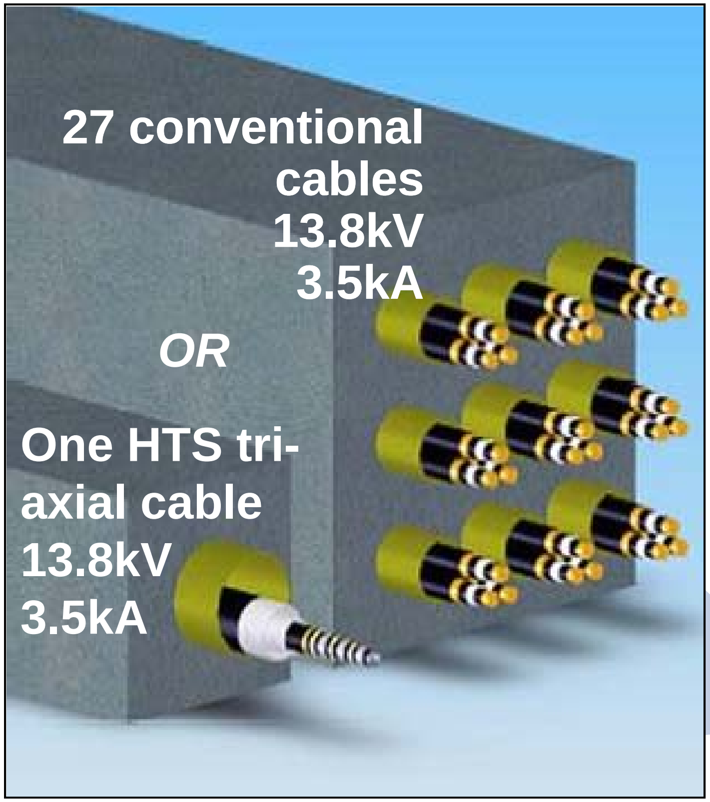


ORNL

Issues:
- Cost
- AC losses
- Cryogenics

Impact on components: HTS example

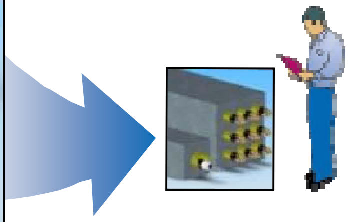
Power Cables



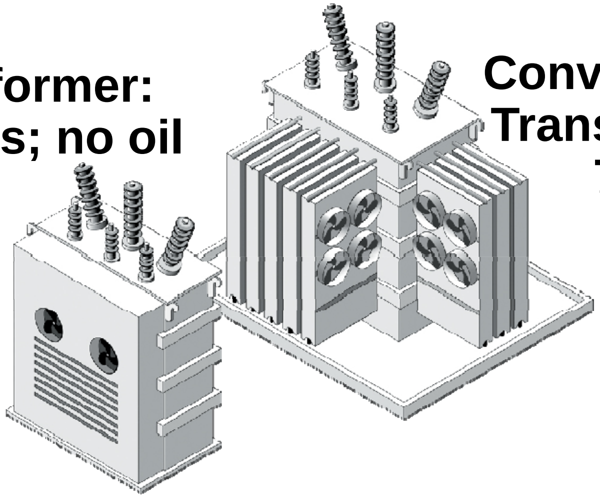
27 conventional cables
13.8kV
3.5kA

OR

One HTS tri-axial cable
13.8kV
3.5kA

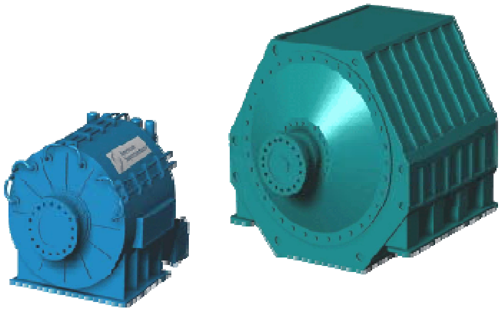


HTS Transformer:
44 tons; no oil



Conventional Transformer:
75 Tons;
23,000 liters of oil

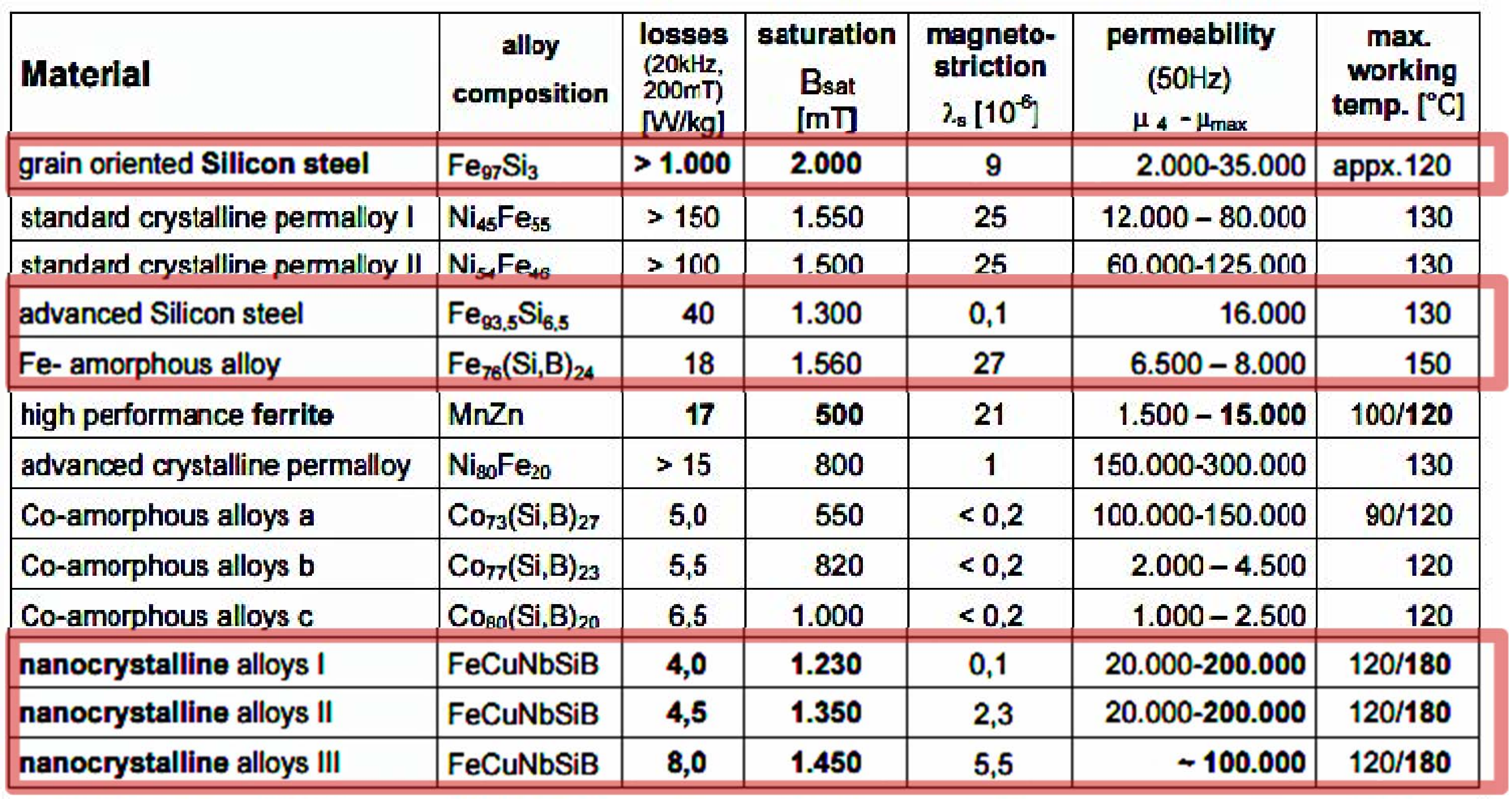
Conventional Motor



HTS Motor for Navy

Half the size and weight of conventional components

Novel soft magnetics can enhance the performance, reduce weight and size of grid components



Material	alloy composition	losses (20kHz, 200mT) [W/kg]	saturation B_{sat} [mT]	magneto-striction λ_s [10^{-6}]	permeability (50Hz) μ_4 - μ_{max}	max. working temp. [°C]
grain oriented **Silicon steel**	$Fe_{97}Si_3$	**> 1.000**	**2.000**	9	2.000-35.000	appx.120
standard crystalline permalloy I	$Ni_{45}Fe_{55}$	> 150	1.550	25	12.000 – 80.000	130
standard crystalline permalloy II	$Ni_{54}Fe_{46}$	> 100	1.500	25	60.000-125.000	130
advanced Silicon steel	$Fe_{93,5}Si_{6,5}$	40	1.300	0,1	16.000	130
Fe- amorphous alloy	$Fe_{76}(Si,B)_{24}$	18	1.560	27	6.500 – 8.000	150
high performance **ferrite**	MnZn	**17**	**500**	21	1.500 – **15.000**	100/**120**
advanced crystalline permalloy	$Ni_{80}Fe_{20}$	> 15	800	1	150.000-300.000	130
Co-amorphous alloys a	$Co_{73}(Si,B)_{27}$	5,0	550	< 0,2	100.000-150.000	90/120
Co-amorphous alloys b	$Co_{77}(Si,B)_{23}$	5,5	820	< 0,2	2.000 – 4.500	120
Co-amorphous alloys c	$Co_{80}(Si,B)_{20}$	6,5	1.000	< 0,2	1.000 – 2.500	120
nanocrystalline alloys I	FeCuNbSiB	**4,0**	**1.230**	0,1	20.000-**200.000**	**120/180**
nanocrystalline alloys II	FeCuNbSiB	**4,5**	**1.350**	2,3	20.000-**200.000**	**120/180**
nanocrystalline alloys III	FeCuNbSiB	**8,0**	**1.450**	5,5	**~ 100.000**	**120/180**

MAGNETEC GmbH

Issues:
- Cost
- Manufacturing
- Form factor

High voltage, high power Wide Bandgap semiconductor devices are emerging

POWERAMERICA

$70M DOE-AMO funds to accelerate the adoption of advanced semiconductor components made with SiC and GaN into a wide range of products and systems.

Property	Si	4H-SiC	GaN	Diamond
Bandgap (eV)	1.12	3.26	3.45	5.45
Breakdown Field (kV/cm)	300	2200	2000	10000
Thermal Cond (W/cm·K)	1.5	4.9	1.3	22
Dielectric const.	11.9	10.1	9	5.5
e Mobility (cm^2/V·s)	1500	1000	1250	2200
Hole Mobility (cm^2/V·s)	600	115	850	850

Commercial

SiC MOSFET
1.7 kV, 300 A
Rds(on): 8 mΩ

SiC JFET
1.2 kV, 38 A
Rds(on): 45 mΩ

SiC Schottky
1.2 kV, 160 A
Rds(on): 10 mΩ

Research

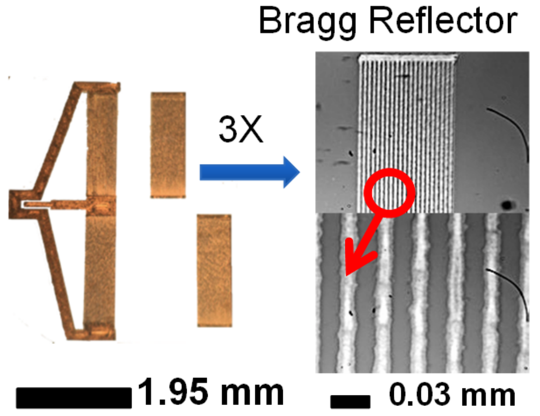
SiC Schottky 15 kV,250 mΩ-cm^2
SiC MOSFET 15 kV, 10A
SiC IGBT 15 kV,20 A
SiC GTO 8 kV,100 A-cm^2
SiC p-GTO 22 kV,20 A

OAK RIDGE National Laboratory

Sensors are essential for situation awareness, health monitoring

e.g. Low cost, passive, wireless, direct-print sensors (ORNL)

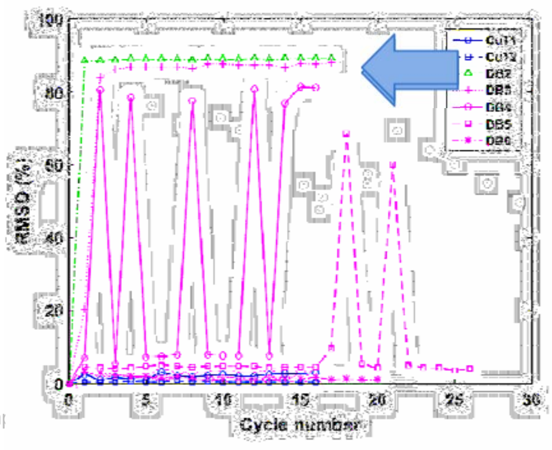
- SAW passive, flexible platform, stick-n-peel
- Modalities
  - *Physical*
    - Temperature
    - Pressure
    - Humidity
    - Strain / vibration
  - *Electronic*
    - Current flow
    - Voltage
    - Charge
  - *Chemical*
    - CO_2
    - CH_4
    - VOCs



ORNL

Printed SAW Test Device
10-15 µm feature size

e.g. Structural integrity smart patch (ORNL)



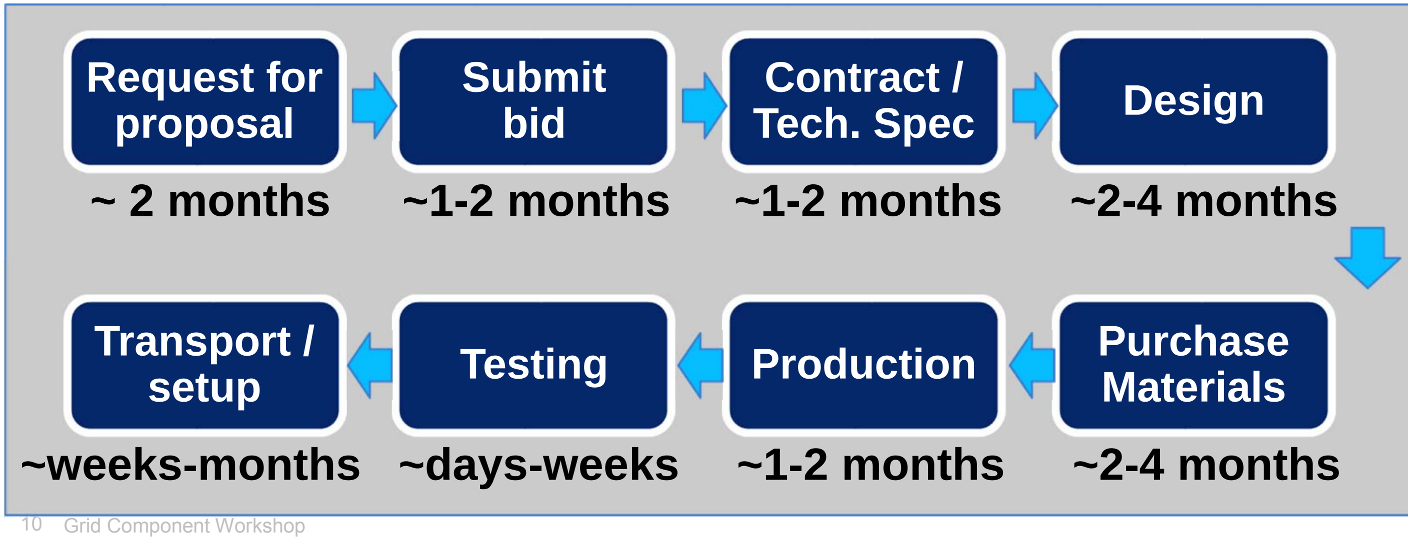
- PZT-based sensor.
- Measure electromechanical impedance, which is affected by the mechanical integrity of the structure
- Root mean square deviation (RNSD) of conductance related to
  - ❑ Damage index
  - ❑ Fatigue, etc.

Large power transformers: Expansive, large, heavy and takes long time to replace

Voltage Rating (Primary-Secondary)	Capacity MVA Rating	Approx. Price	Approx. Weight & Dimensions (tons / ft)
Transmission transformer			
Three-Phase			
230-115 kV	300	$ 2M	170, 21W x 27L x 25H
345-138 kV	500	$ 4M	335, 45W x 25L x 30H
765-138 kV	750	$ 7.5M	410, 56W x 40L x 45H
Single-Phase			
765-345 kV	500	$ 4.5M	235, 40W x 30L x 40H

LPTs2011 Estimates

Large Power Transformers and the US Electric Grid: DOE-OE 2012 & 2014 update



Request for proposal
~ 2 months

Submit bid
~1-2 months

Contract / Tech. Spec
~1-2 months

Design
~2-4 months

Purchase Materials
~2-4 months

Production
~1-2 months

Testing
~days-weeks

Transport / setup
~weeks-months

Procurement can take up to 18 months or more.

LPT Challenge: Fast replacements

Status:

Spare Programs:

STEP, SED, SpareConnect, Grid Assurance, DOE Transformer Reserve Study, private agreements…

Novel designs:

e.g. Siemen's GIC-safe power transformers

Siemens

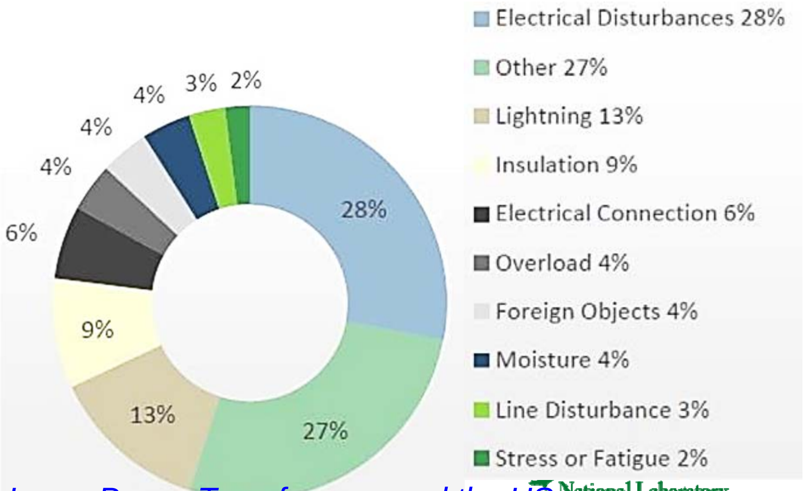
DHS Recovery Transformer (RecX):

- 3 single-phase 345-138kV modules, 600MVA
- Installed CenterPoint Energy substation: 106 hours
- Energized: March 17, 2012
- 99% efficient, 14% fixed impedance, designed for 5-10 yrs

EPRI. ABB, CPE, DHS

Opportunities:

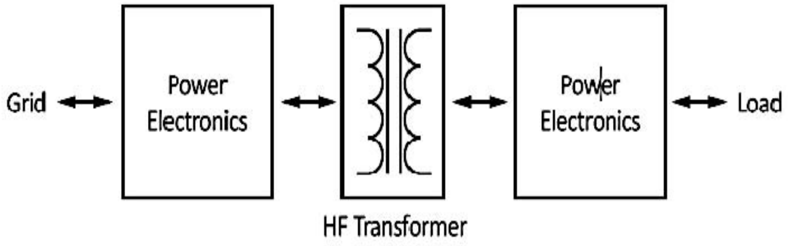
- **Flexible, adaptive, modular high efficiency designs with interchangeable parts**
- **Advanced materials: Soft magnetics, windings, insulation**
- **Approaches to extend LPT lifetime**



Large Power Transformers and the US Electric Grid: DOE-OE 2014 update

Solid State Transformer Challenge:

High voltage, high efficiency, low cost, small footprint



- Combine ss devices and HF transformer to reduce system size and weight
- Added functionalities: DC bus and services such as voltage regulation, reactive power, flow control, limit fault current …
- Issues: low efficiency, many devices (e.g. multi-level), expensive
- Prototype HF transformers showed nanocrystalline & amophous cores are possible candidates.

✓ *UNIFLEX Smart Grid:* 3.3 kV, 2 kHz amorphous core, 92% eff.

✓ *GE Substation:* 13.8 kV, 20 kHz nanocrystalline core, 98% eff.

✓ *EPRI DC Charger:* 2.4 kV, 20 kHz ferrite core, 96% eff.

✓ *ABB Traction:* 15 kV, 1.8 kHz nanocrystalline core 95% eff.

Opportunities:

- **Novel designs & converter topologies**
- **WBG devices, packaging, thermal management, insulation**
- **HF magnetics & windings**

Cables and Conductors Challenge:
Deliver affordable power to load centers

Conductors Status:

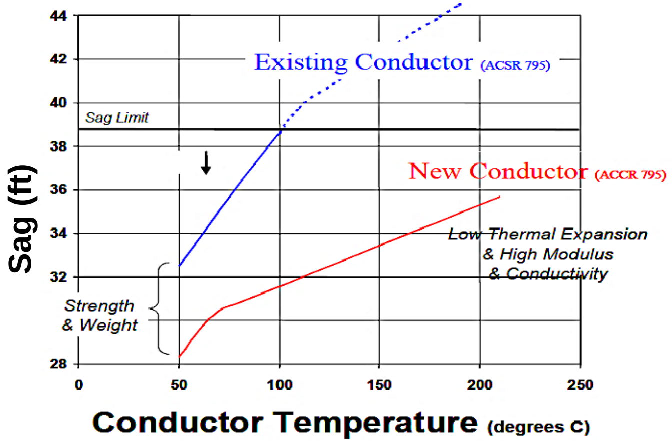
Reconductoring with High-Temp-Low-Sag (HTLS)

- 2X ampacity
- Lower CTE, less sag
- Higher strength to weight
- Operation temp > 200ºC
- HTLS more expansive, but lower overall cost

ACCR

ACCC

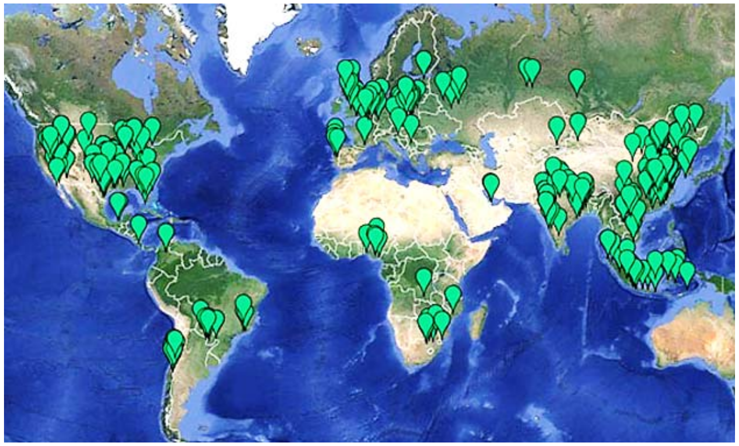
(Z)TACIR



3M-ACCR

Opportunities:

- **Low cost HTLS utilizing advanced high strength / low resistance conducting materials**
- **Low cost coating for thermal management, anti-icing etc.**

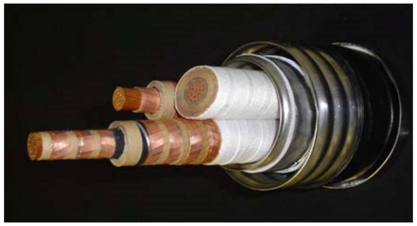


CTC-ACCC Projects

Cables: Functionalities vs Cost

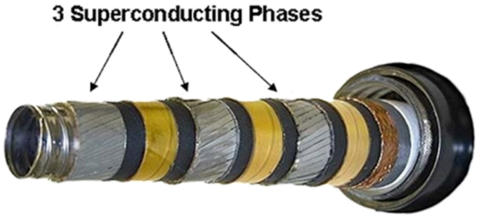
DOE Superconducting Cables

Albany National Grid AC



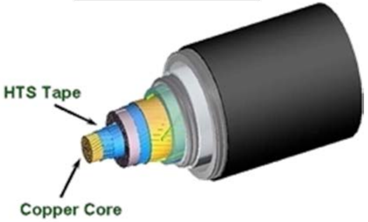
- 350 m, 34.5 kV, 800 A_{rms}, 48 MVA
- 2G HTS wire section

Columbus AEP AC



- 200 m, 13.2 kV, 3000 A_{rms}, 69 MVA
- Triaxial concentric

LIPA AC



- 600 m long, 138 kV, 2400 A_{rms}, 574 MVA
- Transmission voltage

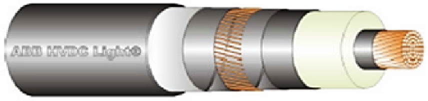
ORNL R&D DC

- 1 GW class
- Triax 2-layer
- Tested @ 9.5 kA, insulation 125 kV

Commercial:

e.g. ABB HVDC

- 640 kV (±320 kV), 900 MW

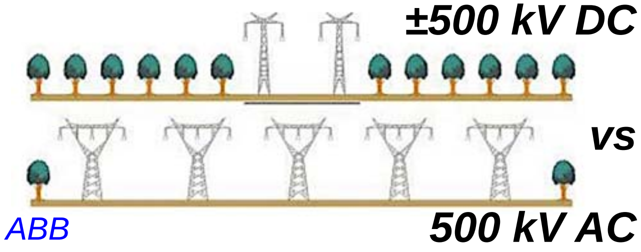


Opportunities:

- **Novel designs: reduce complexity, enhance reliability**
- **Insulations, thermal management**
- **HTS: Low AC loss, cryogenics**

HVDC Conversion Challenge: High voltage/power, low loss, small footprint

HVDC: long distance, underground, submarine, asynchronous, controlled power transfer, reduced right-o-way.


±500 kV DC

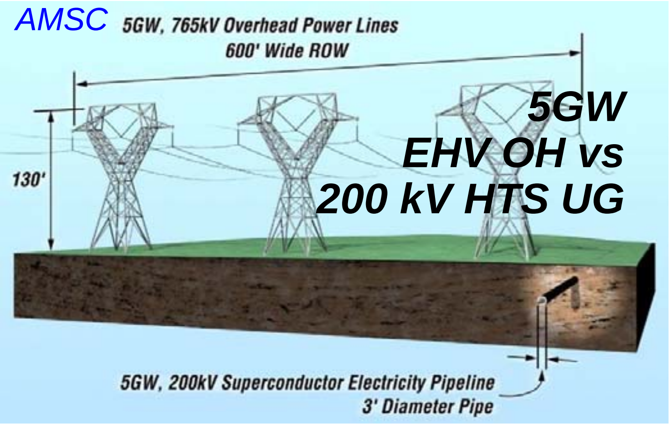
vs

500 kV AC

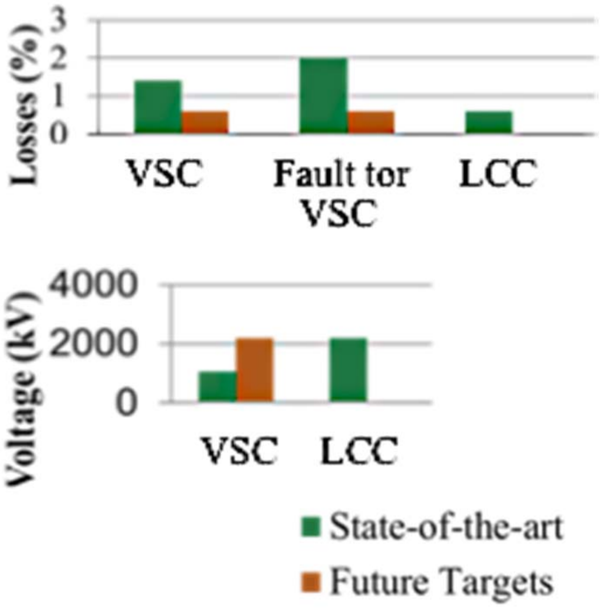
ABB

LCC: Thyristors
Large blocks: 1000s MW
High voltage: 1000 kV
Many filters

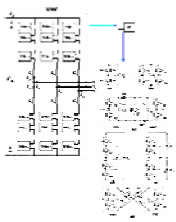
VSC: IGBTs
Small blocks: 100s MW
Lower voltage: 640 kV


AMSC

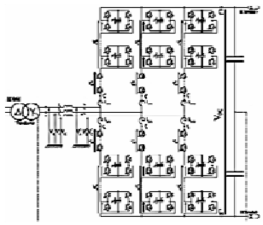
5GW EHV OH vs 200 kV HTS UG



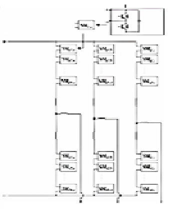
MMC



AAC



CTL



Opportunities:

- **Novel topologies, hybrid LCC-VSC?**
- **WBG-based converters**
- **Insulation and thermal management**

FACTS : Cost remains a major barrier

	1G FACTS	2G FACTS	3G FACTS
Typical Devices	SVC, TSC, TSR	TCSC, STAT-COM, SSSC	UPFC, IPFC
Function-alities	Reactive power compensation, voltage regulation,	Real/reactive power compensation, voltage/ current regulation, oscillation damping, limited dynamic and transient capability	Full power control, voltage/current control, oscillation damping, fault current limiting, full dynamic and transient capability
Control Type	Switching on/off or stepwise	Continuous	Continuous

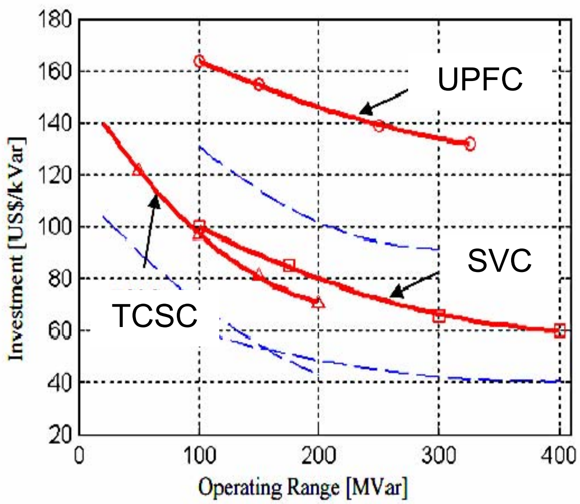


Fig. 3. Cost functions of the FACTS devices: SVC, TCSC and UPFC.
——: Upper limit: Total investment costs
------: Lower limit: Equipment costs

Cai et al. U. Duisburg-Essen, DE

D-FACTS: Distributively installed, clamp on power lines.
Work collectively to adjust line impedance.
e.g. Smart wire - distributed series reactors.
TVA Knox-Douglas line,
7.5 miles, 100 DFACTS, 1 yr

Smart Wire

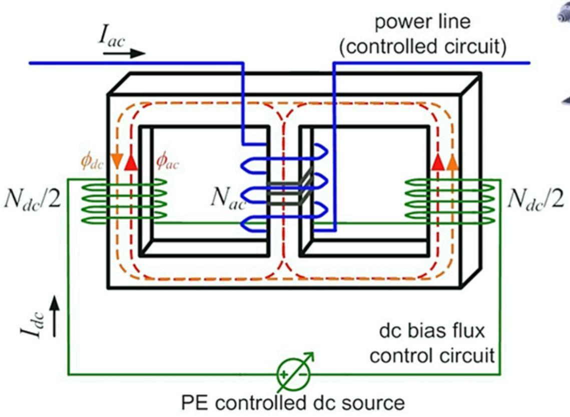
Opportunities:

- **High power HV WBG devices**
- **Optimize DFACTS locations for efficiency and cost**

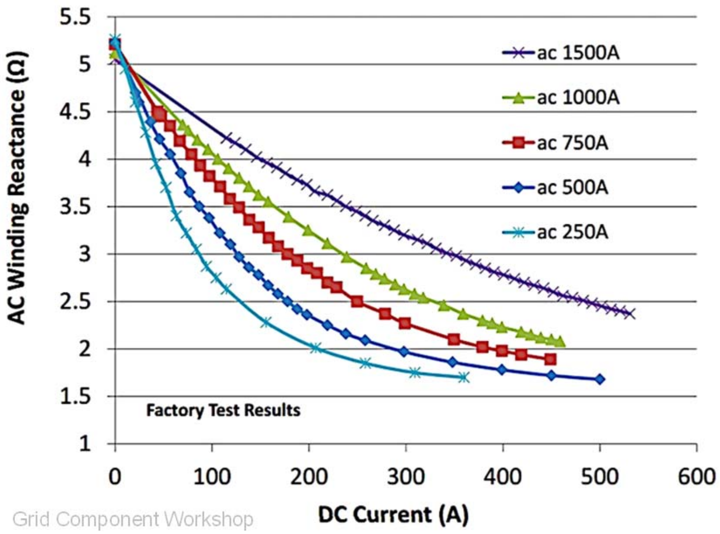
Continuous Variable Series Reactor may provide low cost continuous flow control

ORNL

- CVSR based on magnetic amplifier
- Power electronics (control circuit) electrically decoupled from power line (controlled circuit)



- A small current in control circuit produces bias flux that changes the reactance of main circuit & controls much larger current in power line.
- 1-Φ 115 kV, 1.5 kA prototype factory tested



Opportunities:

- **Improve design for smaller, lighter, lower cost**
- **Additional capabilities of device with different control schemes**

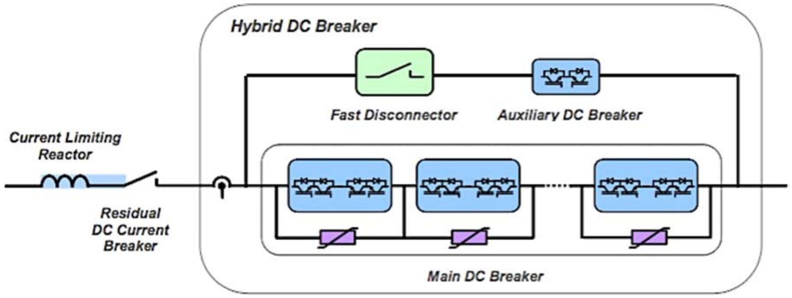
Protection Challenge: Changing systems architecture, variable generations n& faults

Emerging hybrid DC breakers are enablers for multi-terminal HVDC

Hybrid breaker would interrupt faults rapidly, possess better frequency switching ability, exhibit low losses and require less space.

e.g. ABB hybrid DC breaker:

- A bypass branch - auxiliary ss load commutation switch and ultra-fast mechanical disconnector & Main branch -- sections of ss DC breakers with arrester banks
- *Normal operation*: Current flows through bypass
- Fault:
  1) Auxiliary DC breaker commutates current to main breaker and disconnector opens.
  2) Main DC breakers break the current.
  - 5 ms opening time
- Alston ultra-fast "mechatronic" circuit breaker (UFMCB) Siemens DC commutation breaker (Metallic Return Transfer Breaker)

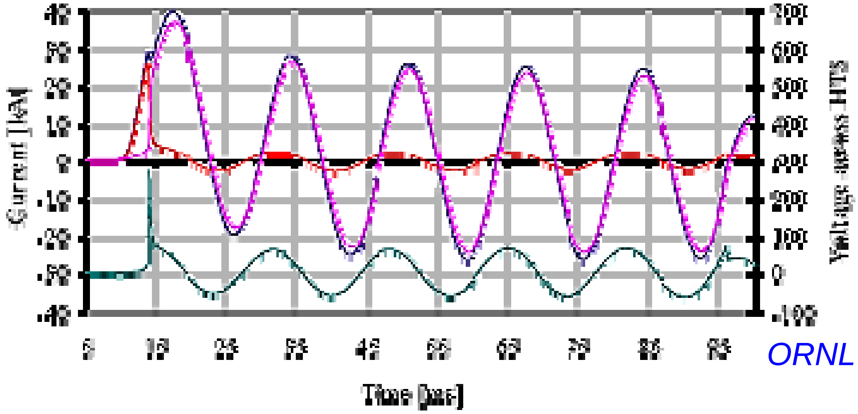


ABB

Opportunities:

- **Novel designs and topologies**
- **High power HV WBG**
- **Low loss compact SS CB**

Fault Current Limiters are designed to limit faults rapidly and then automatically reset



ORNL

Many superconducting FCL projects at distribution level:

Resistive

e.g. AMPACITY – Essen DE

3-Φ, 10 kV,
2.3 kA,
40 MVA

Limit 50 kA peak → <13 kA in 100 ms

Induction

e.g. DOE-Zenergy-SoCalEd

3-Φ, 12 kV,
1.2 kA,
25 MVA

Limit FC by 20%

Limited experience with solid-state FCL:

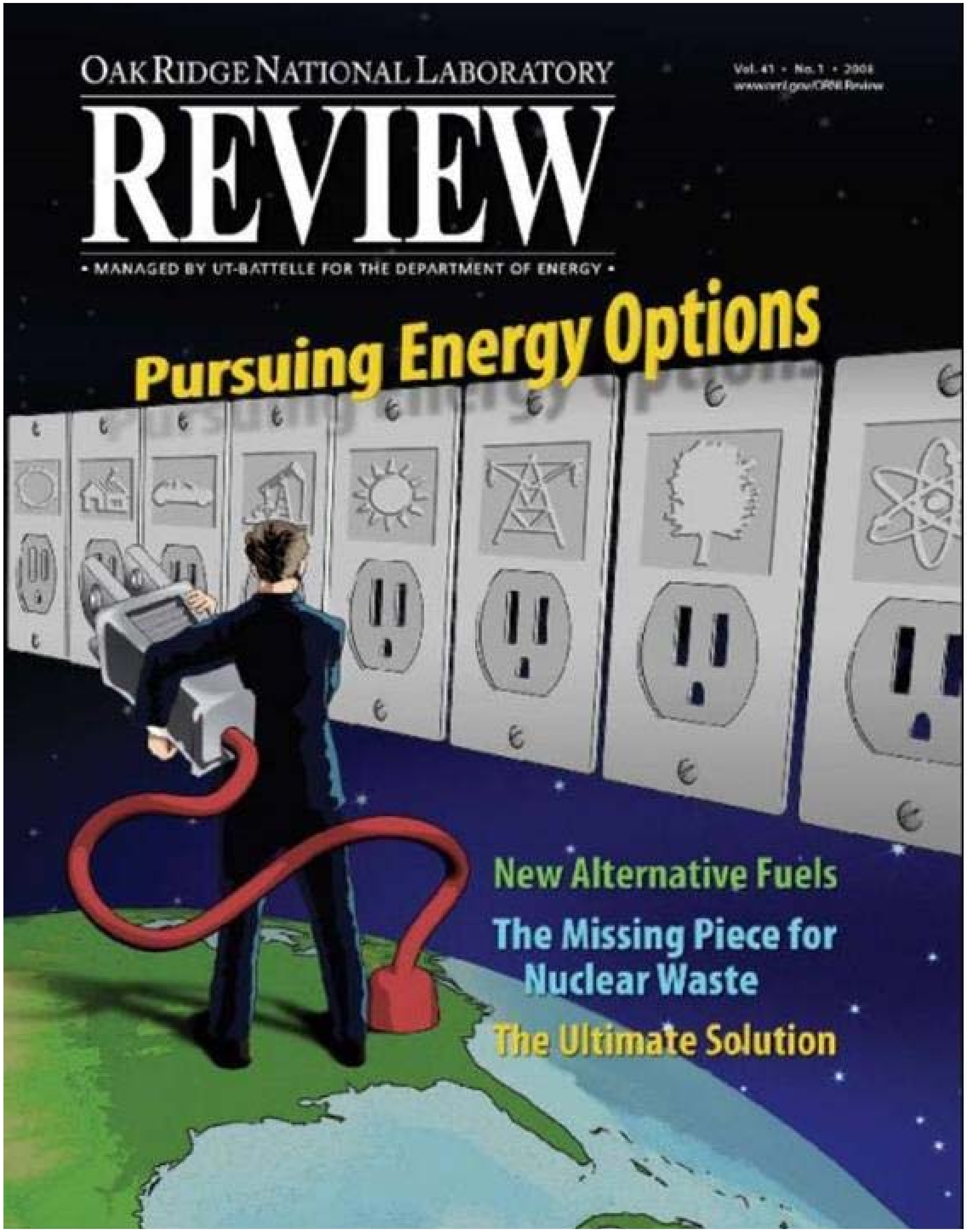
e.g. DOE-Silicon Power-EPRI

1-Φ, 15.5 kV,
1.2 kA,
25 MVA

Limit 55 kA peak → 21.6 kA

Opportunities:

- **Innovative hybrid FCLs**
- **Transmission level SFCL**
- **High power/voltage WBG for SSFCL**



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Pursuing Energy Options

New Alternative Fuels

The Missing Piece for Nuclear Waste

The Ultimate Solution

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DGE
oratory