FINAL TECHNICAL REPORT &
RESEARCH PERFORMANCE PROGRESS REPORT

a. Recipient Award Identification Number **DOE SMES**

b. Federal Agency and Organization Element to Which Report is Submitted **DOE Office of Science – Chicago**

c. Federal Grant or Other Identifying Number Assigned by Agency **DE-SC0021489**

d. Project Title **Integration of Superconducting Magnetic Energy Storage (SMES) Systems Optimized with Second-Generation, High-Temperature Superconducting (2G-HTS) Technology with a Major Fossil-Fueled Asset**

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g. Submission Date **3/11/2021**

h. DUNS Number **867393167**

i. Recipient Organization **American Maglev Technology of Florida, Inc., 8030 1st Coast Hwy Suite 106, Amelia Island, FL 32034**

j. Project/Grant Period **2/22/2021 to 2/21/2022**

k. Reporting Period End Date **2/21/2022**

l. Report Term or Frequency: **Final Report**

EXECUTIVE SUMMARY

Utility companies and fossil fueled generation assets are seeking combinations of “hybrid energy storage” to allow power to be provided in advance of, and to otherwise complement, peaking natural gas-fired generation. The DOE defines hybrid energy storage systems as those which involve “multiple energy generation, storage, and/or conversion technologies that are integrated—through an overarching control framework or physically—to achieve cost savings and enhanced capabilities, value, efficiency, or environmental performance compared to the independent alternatives.”

Growth of intermittent wind and solar supply resources results in short duration energy price spikes and longer duration storage needs, for example after sunset and during storm events. Storage technologies can complement a fossil fueled combustion peaking turbine, which generally require 10 to 20 minutes to start, by immediately supplying energy (0 minutes start time). On occasion these price spikes last mere minutes and can be fully served by the storage unit. This might avoid the fuel costs, emissions and maintenance costs of starting a combustion turbine. For more sustained events the fossil unit can be started and supply against the demand after the start up. Longer-duration energy storage technologies (greater than 4 hours) would provide the needed capacity to enable less frequent starts, slower ramping, reduced turndowns and unit shutdowns, grid voltage regulation, an extended fossil plant facility lifetime and various other benefits for more efficient operations at a power plant.

American Maglev Technology of Florida Inc. (AMT) learned during the Phase I program based on interactions with NRG Energy (NRG) that energy storage such as superconducting magnetic energy storage (SMES) can qualify as a Black Start unit in most markets, ensuring orderly re-start of grid operations and fossil fueled power plants and serving as an important asset of hybrid energy storage technology. In conjunction with the University of Houston (UH), AMT and NRG are working together to scale up low-cost, high- efficiency, second-generation high-temperature superconducting (2G-HTS) technology for deployment across several markets, with a primary focus on the commercial development of utility grid-scale SMES (g-SMES) systems.

When integrated with fossil energy generation, g-SMES is a transformative, disruptive energy-storage technology in the form of a “magnetic battery.” The geometry of the device creates a highly contained electromagnetic field, and the energy is released by discharging the coils. Due to the zero electrical resistance and infinite conductivity of a superconductor, the stored energy remains constant in the coil without any degradation until it is discharged. This ensures instant charging and access capabilities, with efficiency exceeding 95%. In this program, new storage solutions equipped with 2G-HTS technology ranging from transit scale (~ 1 MWh) to grid scale (500+ MWh) will be investigated and optimized for integration with a major utility power plant. This technology approach has the potential to be significantly less expensive than comparable battery systems employing conventional lithium-ion battery chemistry. The depth of discharge approaches 99% compared to no more than 80% with chemical batteries, safely and without danger of fires, as has become apparent in lithium-ion based storage projects[i],[ii],[iii],[iv]. The cryocooling required to maintain continuous 24/7 operation for the SMES is in the 1 – 2 % range of energy use — well within practical and economic objectives.

Ultimately the program confirmed that the novel g-SMES design can meet the performance and financial requirements of the fossil power plant industry, while exhibiting continuous grid-voltage regulation; cost-effective, peak-hour energy storage with almost infinite life; increased input/output efficiency; and the capability to undergo millions of charging cycles, without degradation, representing a significant improvement over lithium ion and other conventional storage technologies.

We believe wide scale deployment of this technology is feasible and practical when compared to the higher life cycle cost and relatively short lifespan of chemical batteries. Based on these findings, the future for deployment of SMES at many fossil-fueled power plants exceeding 100MW capability is bright. Further de-risking g-SMES technology would pave the way for the construction of a subscale prototype. Eventually, scaled-down versions of SMES are expected to be competitive with the multi-billion-dollar lithium-ion market for a wide range of commercial, industrial, and transportation uses. There is long-term potential for commercialization and widespread deployment of this disruptive technology, which would spawn a new worldwide supply chain and create domestic, high-tech manufacturing jobs in the green industry.

I. ACCOMPLISHMENTS

a. What are the major goals and objectives of this project?

In a Phase I collaboration with UH (Advanced Manufacturing Institute – UH) and consultants American Electromechanics and Western Carolina Ingenuity, AMT designed and simulated new, lower-cost g-SMES systems designed with ultra-high ampacity, low-cost 2G-HTS technology developed by UH. Integrating UH's Advanced 2G-HTS tape into g-SMES systems is expected to reduce the historical capital cost of the technology by an order of magnitude to reach a price point more conducive to widespread market adaptation. Ultimately, this energy-storage concept must show promise for a significant improvement over the current objective for storage technologies developed at large scale, with a capital cost of less than $100 per kWh for g-SMES systems exceeding 500 MWh.

The primary objective of Phase I was to further define SMES technology's capabilities as "hybrid energy storage" integrated with a fossil-fueled power plant at reasonable cost with minimal environmental impact, creating an attractive investment opportunity for the DOE and private sector. In conjunction with partners UH, NRG Energy (NRG) and Burns & McDonnell (B&M), we studied the potential for g-SMES to offer continuous grid-voltage regulation, cost-effective, peak-hour energy storage with almost infinite life, compatibility with the grid, and the capability to undergo millions of charging cycles without degradation. High-voltage interconnection schematic designs were completed, as well as a general arrangement and preliminary layout for a g-SMES system on the campus of two of NRG's fossil-fueled power plants in the metropolitan Houston area — Green's Bayou and TH Wharton.

Research and development efforts during Phase I included the down-selection of coil topology and solenoid design, taking into account numerous variables including, but not limited to, magnetic field size, required length of HTS tape, AC losses, structural feasibility and manufacturability. Preliminary designs of subscale systems (power conditioning and cryocooling) were completed with a focus on cost and compatibility.

We also completed the critical design of a subscale g-SMES system, with a comprehensive evaluation of its technical and economic feasibility. An integrated g-SMES system normally will be charged during lower priced off-peak periods such as nighttime and/or midday when solar supply is peaking, with the capability to supply up to four continuous hours of 125-MW service once or twice daily and other lower rates of discharge to the extent available within the SMES. The system, by design, would offer continuous availability up to the full extent of the state of charge of the SMES in contributing to peak-capacity needs, supplying grid voltage regulation, and guarding against service breaks, interruptions, and brown-outs. The final critical design (525 MWh) represented a 5% increase over the preliminary design to address the demand for black-start capability (in the event of a catastrophic grid failure). The operating schedule under consideration in this phase of research is shown in Table 1.

Table 1 Operating schedule of g-SMES system

Mode	Time		SOC	
	Begin	End	Begin (GJ)	End (GJ)
Charging	0:00	4:00	90	1890
Persist	4:00	16:00	1890	1890
Discharging	16:00	20:00	1890	90
Persist	20:00	0:00	90	90

Using the latest laboratory data from UH, actual plant-level data from NRG, and real-time utility industry data from B&M, it appears at this stage that a g-SMES system optimized with 2G-HTS technology can meet these benchmarks and make a compelling economic case for the deployment of a subscale (1 MWh) prototype and eventually a future large-scale (525 MWh) prototype system at an existing fossil asset.

AMT has secured commitments from NRG and B&M to assist with commercialization and the commercial deployment of a prototype g-SMES system integrated with one of NRG's fossil asset facilities, subject to a successful extensive technology de-risking program. To support the marketability of the product and future phases of development, the critical design results must continue to align with the targeted estimated energy capital cost of $100/kWh.

b. What was accomplished under these goals?

<u>Task 1</u>: Preliminary SMES Design (AMT & UH)

We developed an incremental, modular design of a smaller-scale g-SMES system to de-risk a future full-sized prototype system large enough to interest owners of aging fossil-fueled power plants. In order to accomplish this objective, our team did a "bottoms up" review of the scientific and technical literature surrounding efforts in high temperature superconducting development efforts and in the basic topology of magnetic energy storage systems.

At the core of this work is the latest developments by US DOE AMO and UH in the development of advanced **2G-HTS TAPE.** Without the prior breakthroughs in this HTS technology, it would not be possible to conceive of a cost-effective g-SMES system. The advances in HTS design and development are summarized below. Our efforts in the deployment of this new HTS tape assumed the appropriate investment in high output manufacturing equipment will be completed in the next two to three years in order to support high-yield production of high-performance 2G-HTS tape in sufficient quantities at mass-manufacture pricing in order to support national deployment of SMES technology for hybrid fossil plant operation.

The laboratory work at UH was based on performance of several commercially available HTS conductors, as well as on the critical current (I_C) performance of the Advanced 2G-HTS conductor based on thick (2-4.5 μm) $REBa_2Cu_3O_7$ (REBCO, RE = Rare Earth, Figure 1) developed by UH. The advanced HTS conductor has been demonstrated to deliver over 5 kA/mm^2 of critical current at 4.2 K, 14 T, which is over five-fold increase over Nb_3Sn and about a ten-fold increase over commercial REBCO HTS wires[v]. As the stored magnetic energy directly scales with the in-field critical current capacity of the conductor used, this provides a direct route for potential 5-10 fold reduction in wire quantity needed for a commercial SMES system.

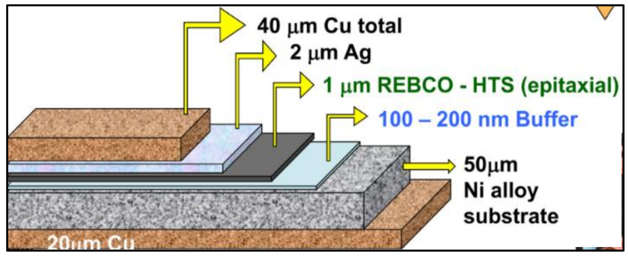


Figure 1 The REBCO stack developed at UH contains less than 1% of rare earth materials, eliminating dependence on foreign governments for supply.

UH also performed studies on the feasibility of optimizing the design towards exposing the HTS REBCO conductor to magnetic field oriented parallel to the ab-plane of the REBCO layer. We have recently demonstrated that at 4.2 K, significant increase in critical current is achieved in UH high performance tapes in field orientations B||ab-plane compared to the corresponding I_C performance at field orientations B||c-axis of the superconductor REBCO layer. For example, the pinning force (F_P), directly proportional to the product of I_C and applied field B, has been shown to reach 6 TN/m^3 at B||ab compared to 2 TN\m^3 at B||c, when both are exposed to B=15 T. This constitutes further 3-fold increase in potential stored energy per unit length of HTS superconductor. Combined with 5-10-fold increase over commercial conductors at B||c, orienting the tape to B||ab provides a potential for 15-30-fold increase in critical current density and thus 15-30-fold decrease in the amount of superconductor needed for the same stored energy.

We explored another route toward further reduction in the amount of HTS conductor needed — an increase in operating field. We have identified earlier the pinning force F_P, rather than critical current, as the main parameter that determines the amount of stored energy per unit length of superconductor wire. This has also been reported in previous literature[vi]. While the pinning force at 4.2 K saturates to a constant value of ~2 TN/m^3 in UH Advanced-HTS films above fields of 5 T when B||c, the pinning force at B||ab increases near-linearly with field up to the highest measured fields of over 30 T[vii]. As can be seen in Figure 2, at B||ab, increasing the operating field from 15 to 20 T increases pinning force from 6 to 8 TN/m^3 compared to 2 TN/m^3 at field orientation B||c. At field level of ~28 T, the pinning force reaches 10 TN/m^3, which is a five-fold increase over B||c, which in turn is 5-10-fold higher than the performance of commercial superconductors at the same orientation. As such, this constitutes a potential for 50-fold decrease in the amount of superconductor needed.

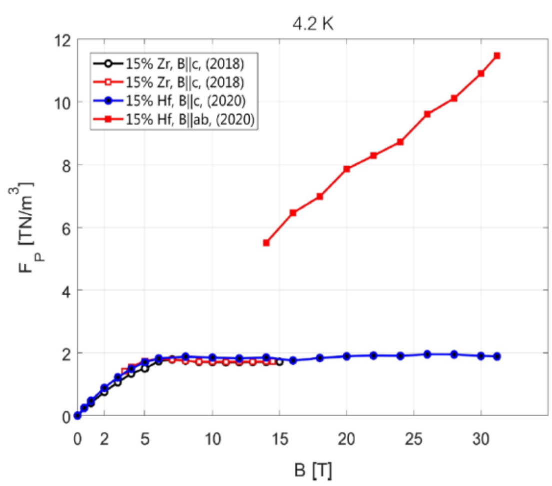


Figure 2 Pinning force of Advanced HTS REBCO Superconductor developed at UH in 2020, at 4.2 K and field orientations B||c and B||ab.

Ongoing work at UH funded by AMT and the federal government (including ARPA-E) is focused on reducing the materials cost for 2G-HTS tape. It is envisaged that with high-yield manufacturing capabilities and establishment of economies of scale, one meter of REBCO-based tape (composed of 30% nickel, 40% copper and 30% other low-cost, non-rare-earth materials, with a total weight of 4.5 grams) could be produced for approximately the cost of a nickel (composed of 25% nickel and 75% copper, with a total weight of 5 grams). According to the U.S. Treasury, the federal government's 2021 cost to manufacture a nickel is $0.07. While we realize that this is a cost objective that may not be realized, we do believe that the cost of advanced HTS Tape in mass production will be reduced to less than $10 per meter and, with further advancements, perhaps even less than $1 per meter.

SMES TOPOLOGY INVESTIGATION

SMES is a simply elegant, elegantly simple technology. Large quantities of mass-produced, advanced 2G-HTS tape are wound into pancake coils, and the coils are assembled into SMES units. The quantity of tape and the size of the SMES unit can become quite large, but it is a simple and passive construction, with no moving parts and no maintenance. As long as the device is kept cryogenically cold, the energy will be stored indefinitely. And, given the advances in solid state silicon carbide (SiC) devices that are used to charge and discharge the SMES coils, the stored energy is available at power levels up to 125MW, available in a fraction of a cycle.

Using standard, off the shelf power electronics, our Team determined that the SMES units totaling 1890 GJ (or even more) would require partitioning into 18-GJ increments. The requirement to create discrete segments that are electrically independent yet magnetically coupled appears to be a unique (and possibly patentable) approach to SMES topology.

It is the electrically independent and magnetically coupled approach that delivers the highest energy storage per meter of tape, which is the key performance parameter that our Team has sought to optimize.

Forming the coils into SMES topologies, we first explored the options with the use of a simple torus (Figure 3) composed of solenoids, each controlled by a suite of power conditioning equipment. We looked at many different sizes and shapes, with different relationships for the solenoid bore (D) and toroidal effective diameter (S).

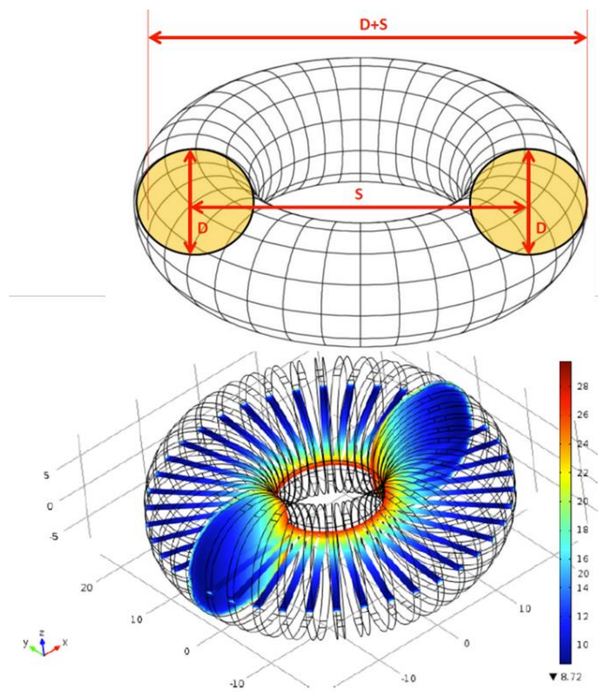


Figure 3 Simple torus approach for grid-scale SMES

In addition to the simple torus, our Team also studied dozens of different sizes, shapes, and configurations in the design of the energy storage toroid, including circle torus, rectangle, square, infinite solenoids, parallel infinite solenoids, parallel solenoids with semi-toruses, stacked solenoids, and even squished solenoids. For each shape and configuration, we also studied dozens of bore shapes, including circle bore, D – shaped bore, triangle bore, flat rectangle bore, square bore, and vertical bore (up to ten stories tall!).

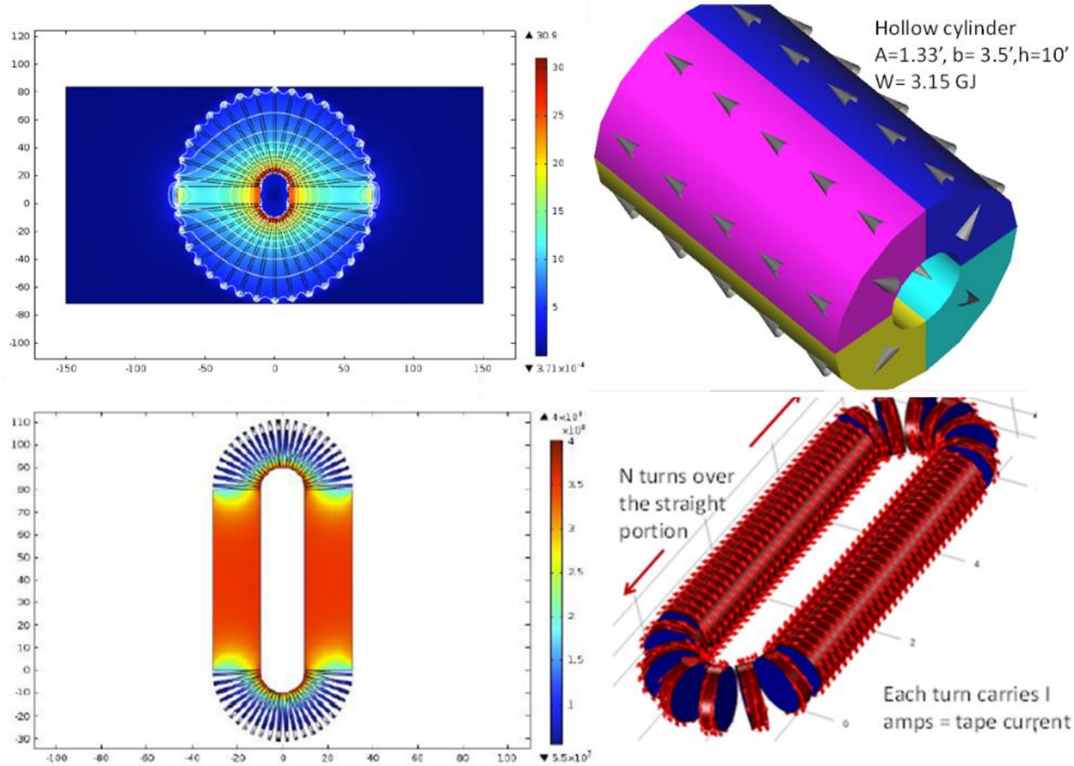


Figure 4 Various topographies and geometries of the SMES system, include novel bore shapes

This wide search of possible g-SMES topologies revealed some interesting results, and after much discussion and peer review among our team, it was agreed that the simple torus provides an elegant solution that can store enough energy to provide 125 MW for 4 hours duration and is the preferred geometry from a storage and cost standpoint. The simple torus provides highest wire utilization efficiency, defined as total length of required superconductor tape divided by total energy stored. In addition, the simple torus eliminates leakage fields associated with open-volume designs, such as solenoids. Finally, the simple torus generates a magnetic field tangential to the tape — which opens the possibility of utilizing the critical current of Advanced 2G-HTS at or near B||ab-plane orientation, which opens the potential of further three-fold increase in performance (and thus further three-fold reduction in the required amount of tape), totaling 15-30-fold reduction in the amount of required tape, number of layers and other related aspects that otherwise increase the complexity and cost of the device. A simple torus would require between 6.5 million and 8 million meters of 2G-HTS tape. At grid scale, the torus would be divided into 102 individual solenoid units that each can store 18 GJ. As independent electrical systems that operate with their own controls, own power modules, and own electrical systems, the solenoids are magnetically coupled and work together to achieve a 280% advantage because of magnetic inductive coupling.

Coil Layout

The coil arrangement shown in Figure 7 has two desirable features. First, the coils for the whole system can be arranged in a torus. In that arrangement, the magnetic field density couples to neighboring coils and leakage field is minimized. Second, all coils can be wound using a simple spool for the platen. They can be supported around their perimeter with a carbon composite support belt. The toroidal arrangement of the 102 solenoids that make up the grid-scale SMES looks like the rendering shown in Figure 5:

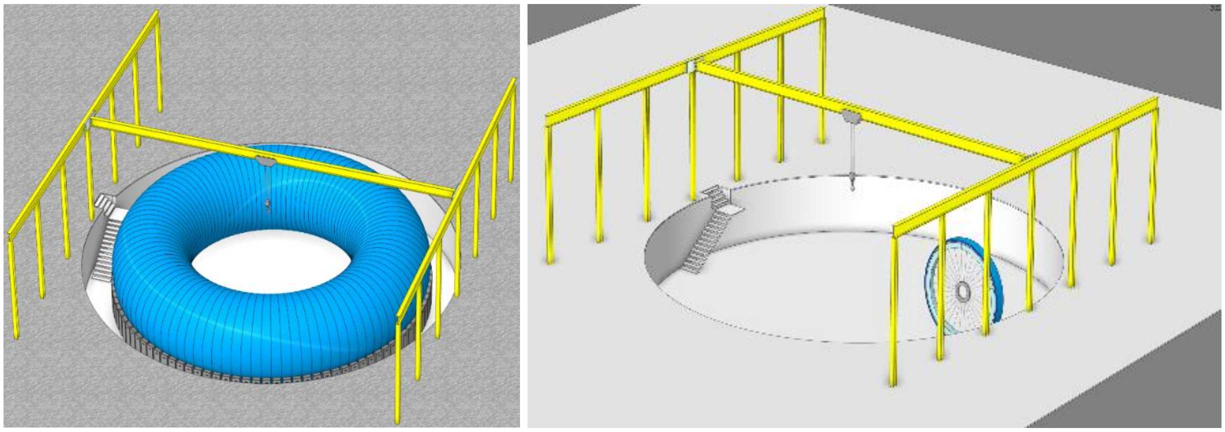


Figure 5 Rendering of g-SMES arrangement adjacent to a fossil asset facility

Each of the solenoids is arranged conceptually as shown in Figure 6. Each solenoid is independently controlled by a Current Voltage Controller (CVC) box designed by AMT. The CVC performs essential safety functions and provides the link to the HTS coil that makes the coil load appear to be like any battery storage or PV solar farm to the fossil asset central control.

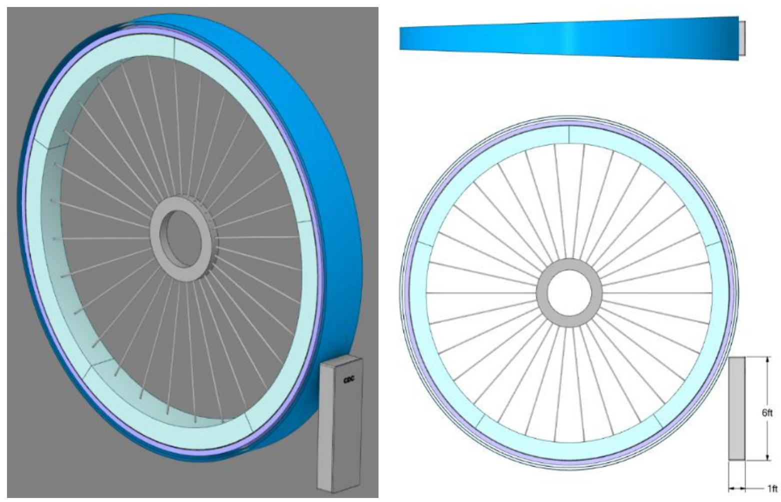


Figure 6 Arrangement of solenoids and associated CVC boxes

Nested Coils – An Opportunity for Significant Savings

As the design of the simple torus was advanced in Phase I, our Team also looked at nesting of pancake coils within the outer solenoid shape to increase the energy storage density. The constrained mathematical optimization seeks to maximize overall energy storage while keeping the maximum tape exposure magnetic field density to be 32 T or smaller. Both “D” shapes and “O” shapes were considered in the optimization. Nested circular cylinders will be much easier to support and wind using existing mandrels. Figure 7 shows how 5-cylinder ring systems are built up to achieve a 16-block torus, with each block spread over 36°.

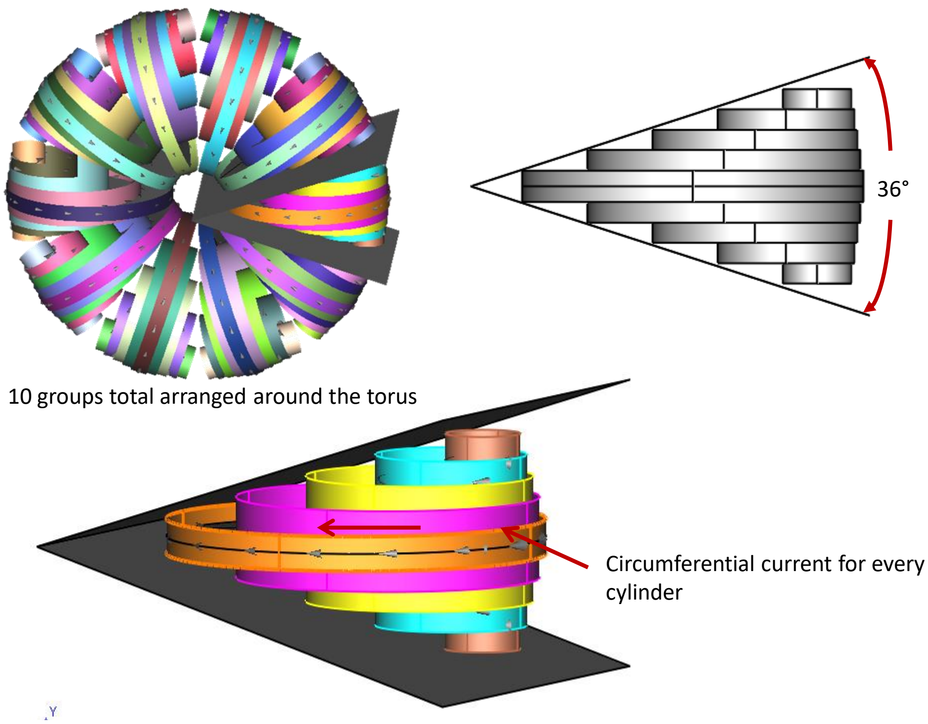


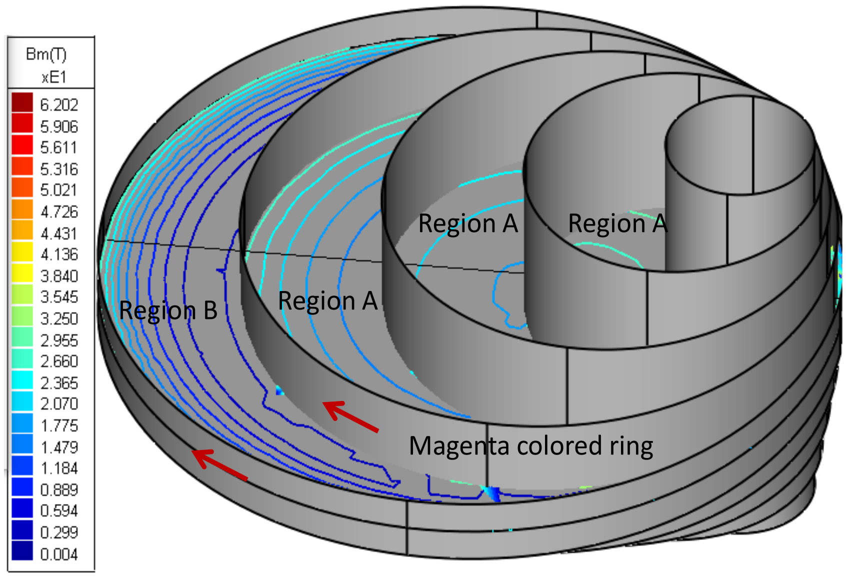
Figure 7 Cylinder arrangement for energy storage.

The optimization used is as follows:

$$Maximize\ W_{energy\ storage}\ \ subject\ to\ B_{mid-plane} < B_{\max}. \tag{1}$$

B_{max} is the largest B field suitable for the cooling employed and the high temperature superconducting tape. The current for every cylinder is an unknown and the structure must be analyzed with all energy groups in place (for this smaller scale example is 16 units placed every 36°). Notice that the rings positioned at a further radius from the torus center, i.e., the yellow, cyan, and copper rings, are extruded with a higher cylinder height. The black planes in the lower inset of the figure span 36°.

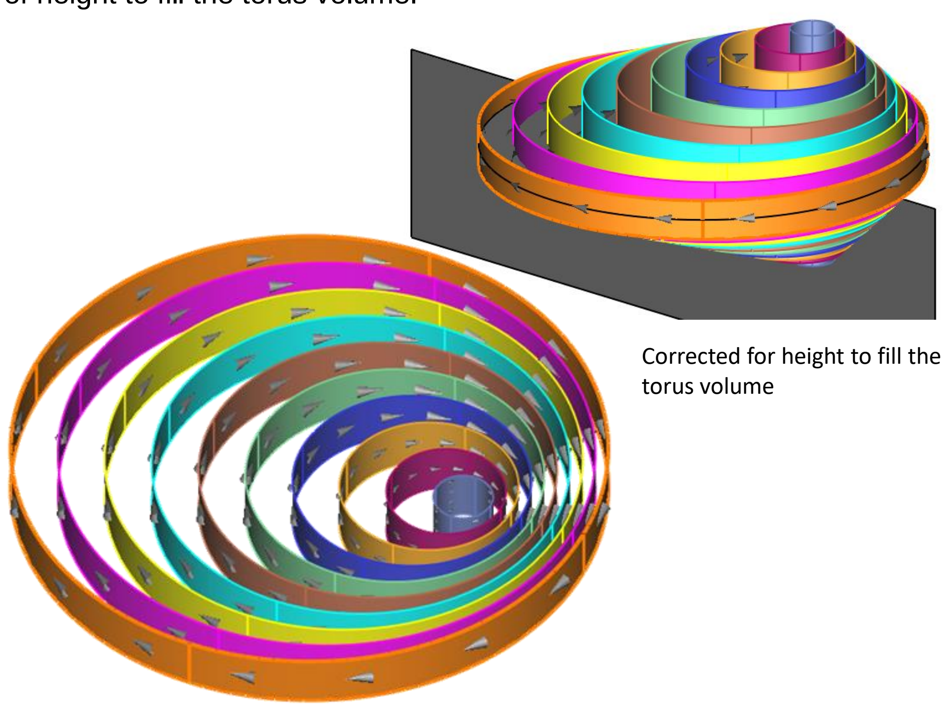
The objective is to fill the useable space in the torus with as much active tape current as possible to maximize energy storage per unit volume. The outermost ring, the orange ring, is typically excited with the largest excitation current. But the nested ring placement brings another option to the table. If the next largest ring, which is magenta colored, is excited with current in the same direction (see the red arrow), it will support the orange ring's B field in Region A, but it will oppose its B field in Region B (Figure 8). Since energy is proportional to B^2, by this means the total energy can be increased while decreasing the B field strength adjacent to the outermost orange HTS ring.



Energy storage = 3.04e08 J

Figure 8 Mid plane B field contour plot for a 10-group system; each group has 5 nested rings.

The second objective that can be achieved follows from the optimization. The best B field for overall energy storage is one in which the B field remains close to the maximum B field tolerated by the tape and the cooling temperature. The contour plot shown in Figure 8 gives a visual picture of where additional rings should be positioned to approach this objective. The proposed redistribution of internal rings is shown in Figure 9; the upper inset of the figure shows the adjustment of height to fill the torus volume.



Corrected for height to fill the torus volume

Spacing of 10 rings within the perimeter of the original orange colored ring

Figure 9 Redistribution of internal rings to achieve a more homogeneous B field distribution < 32 T.

This approach appears to offer great potential for a 200% increase in energy storage capability for the same HTS tape length. Estimation of mechanical loads through a future Finite Element Analysis (FEA) will provide a cross-validation of the optimized geometry as well as a deeper level of design details. The distribution of the magnetic field orientation relative to the position of the superconductor tape will give an indication of possible improved ring positioning to improve the optimization constant. We believe that these efforts are novel and will be useful for other high magnetic field solutions such as commercial fusion, medical imaging, and other applications of the advanced HTS tape.

Phase I SMES Performance Specification

Based on the Phase I efforts to investigate the best topology that will make the most effective and efficient use of the advanced 2G-HTS tape, we have developed the design for a prototype solution that meets the engineering standards of our technical team as well as the marketing and commercial requirements as outlined by NRG, including a minimum operating size of 500 MWh plus 25 MWh for black start capability at the fossil plant (Table 2).

Table 2 g-SMES Performance Specifications

Energy Storage	**1890GJ (500MWH + 25MWH Black Start)**
Critical Current (Ic) on HTS tape	**6000 amps at 5K and 31T**
Operating Temperature	**5 deg Kelvin**
Coolant	**LHe, LH2, and chilled water jacket**
Operating Magnetic Field	**> 31T**
Total length of HTS tape	**8,000,000 meters (maximum)**
Total number of splices	**10,000 splices within and between coils**

SMES Power Electronics

Our Team implemented the “magnetically coupled / electrically independent strategy” as well as the use of commercial off the shelf SiC power electronics devices in the Phase I design effort. The functional requirements of charging and discharging the SMES coils have been conceptually partitioned into what is referred to as the Current Voltage Converter (CVC) and the Power Conditioning System (PCS) (Figure 10).

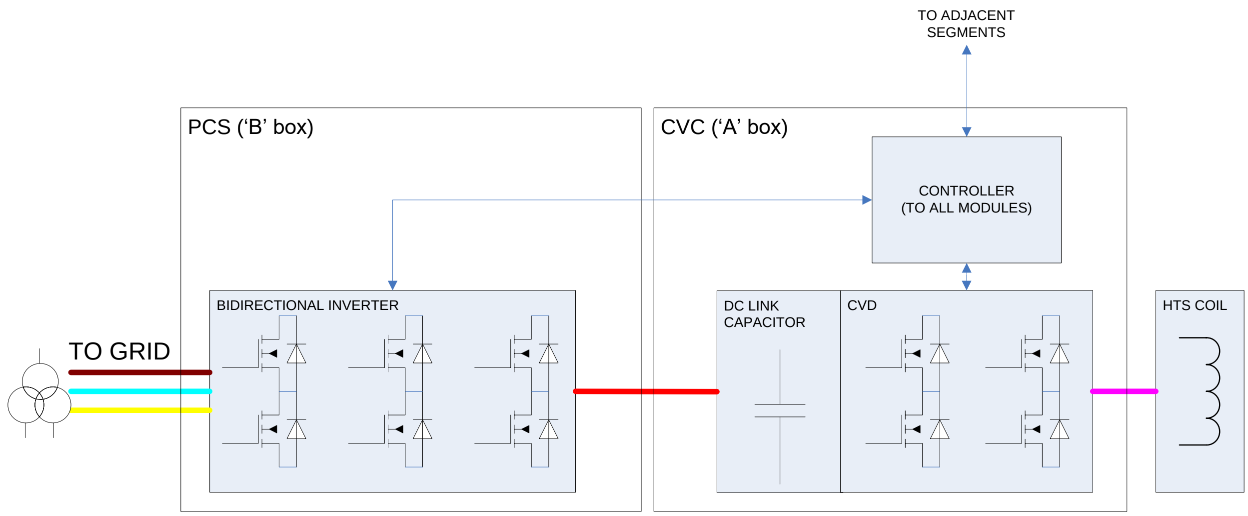


Figure 10 Conceptual schematic diagram of SMES layout

The CVC handles both high voltages and high currents. 6th generation IGBT devices, such as the Mitsubishi CM2400HC-4X are utilized to provide the necessary voltage ratings (Figure 11). The 6th generation devices are also amenable to parallel operation which will allow the high currents to be achieved.

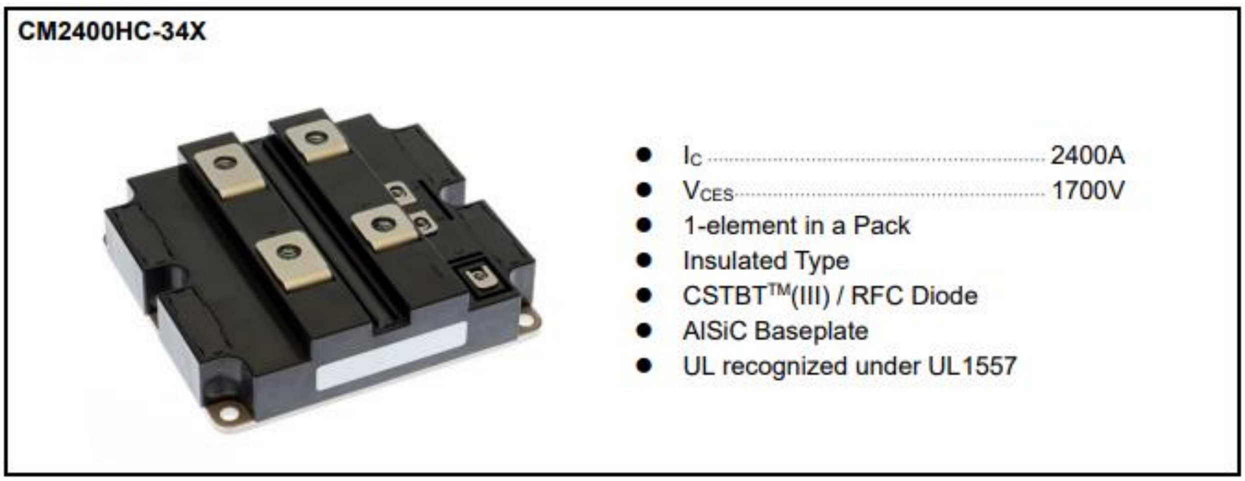
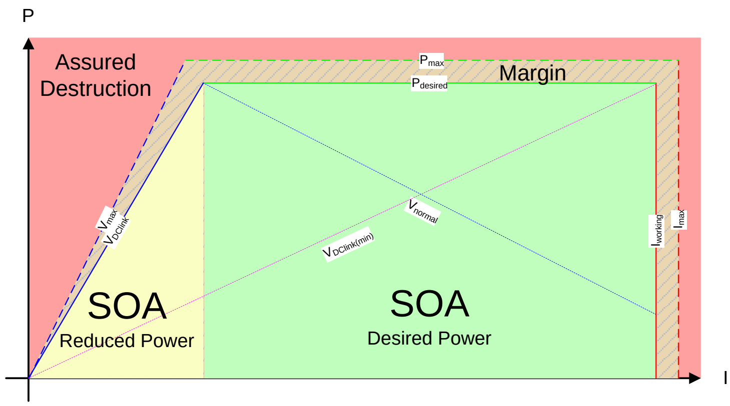


Figure 11 Candidate IGBT device for use in SMES CVC

The CVC maintains the operation of its associated SMES solenoid segment within a safe operating area to maximize the amount of power both inserted and extracted at the specified power level as shown in Figure 12 below. Energy is inserted or extracted from the DC Link capacitor, which in turn interfaces with the PCS, such that the desired working voltage is maintained.



NOTES:
W=5MWh (18GJ)
Vmax = 1700V (CM2400HC-34X module max)
VDClink = 1500V (chosen to give adequate margin)
Imax = 6500A (chosen to match HTS tape Jc)
Iworking = 6400A (chosen to match HTS tape)
Pdesired = 1MW (chosen to utilize 99% of energy)
Pmax typically result of system design thermal considerations not in SMES magnet. TBD
Peak power could be 9.6MW (1500V * 6400A)
Minimum current for Pdesired would be 666A. Thus 1.1% of energy would not be available at Pdesired.
Run-time would be 500 hours

V_{max} - Maximum voltage that could be applied to PC before destroying switching devices
V_{DClink} - Voltage chosen for rail on switching devices
$V_{DClink(min)}$ - Minimum DC link voltage that can attain $P_{desired}$ at any current level
V_{normal} - Effective voltage produced by PWM from $\pm V_{DClink}$ necessary to attain $P_{desired}$
P_{max} - Maximum power levels that can be inserted/extracted without destruction (usually thermal issue)
$P_{desired}$ - Power level that we would like to insert or extract energy at from the SMES magnet
$I_{working}$ - Maximum working current level we would use with SMES magnet
I_{max} current - Maximum current level before destruction. Could be because of critical current Ic or switching device limitations

NOTES:
- V_{max} can be from a couplet of causes:
    - o Limitation on voltage that can be applied to SMES magnet
    - o Switching devices chosen
- P_{max} typically result of system design thermal considerations not in SMES magnet
- I_{max} can be from varied causes
    - o Critical current I_c of SMES magnet
    - o Switching device chosen
    - o Other system limitations such as wire size, etc
- It's possible that $I_{working}$ and I_{max} could move based on variables like cryogenic temperature

Figure 12 Operating area of CVC

The concept is the CVC is intended to be a bespoke and purpose-built controller for the SMES HTS coil shown at right. Each of the 102 individual SMES solenoid sections would have its own unique CVC. Our Team has designed the CVC and would expect to simulate, build, and test one of these boxes during a future. These CVC and PCS boxes are linked to the fossil-fueled power plants central control via existing communication link equipment and proprietary and hardened communications protocols, with minimum staffing and operating requirements. The Team has matured and advanced the design and selection of electronic components for the CVC design (Figure 13).

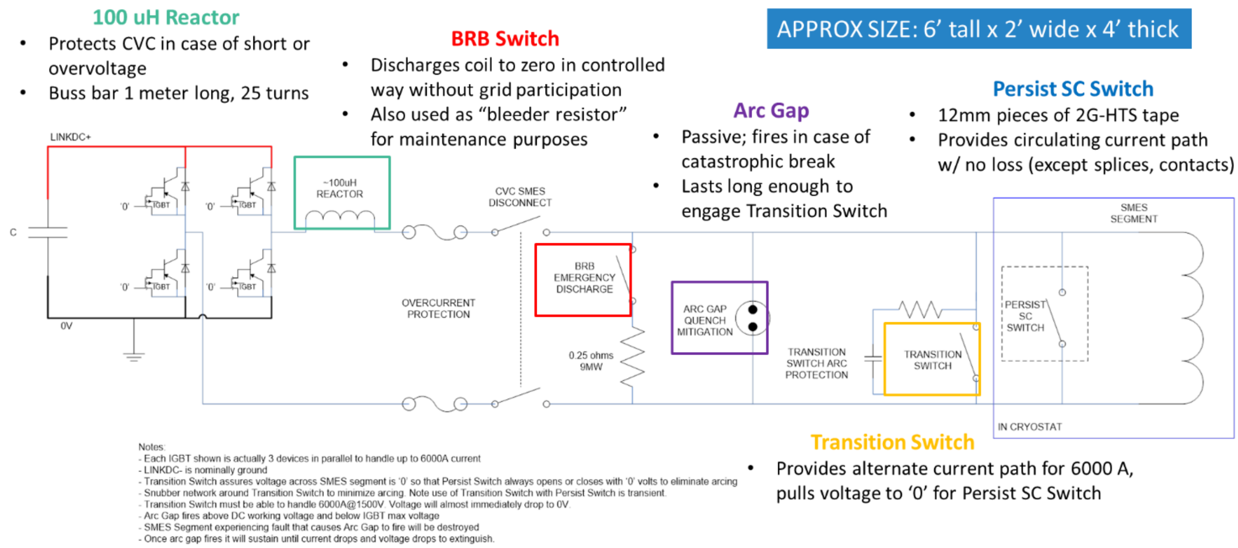


Figure 13 AMT's evolved CVC design and schematic

The CVC performs essential safety functions and provides the link to the HTS coil that makes the coil load appear to be like any battery storage or PV solar farm. The CVC interfaces quintessential current device (HTS coil) to voltage centric world. DC Link voltage can be chosen to suit voltage capabilities of HTS coil and semiconductor devices used. DC Link capacitor only serves as a waypoint between input/output sources and HTS coil, and grid connections can then utilize transformers to match grid voltage to DC Link voltage. Multiple input sources can be accommodated, and utility grid connections can be to single grid or multiple grids.

In contrast to the CVC, the PCS is intended to be a bi-directional inverter from an existing and validated electronic equipment supplier. Each PCS is responsible for managing the charging and discharging of three (3) of the CVC units as well as regulation of the operating voltage from 1500 volts at the CVC to 34kV output from the PCS. Final voltage regulation to grid voltage at 134kV is accomplished by means of an autotransformer.

With the support of NRG and B&M, an approporate and cost effective PCS device was selected (Figure 14). Thirty four (34) of the PCS boxes shown above will be required for the grid-scale hybrid fossil asset battery system described in Task 2.

Freemaq Multi PCSM inverter

- 3-level IGBT topology
- Integrated enclosure
- Easy maintenance
- Modular
- Avoids no-load losses
- No liquid cooling needed

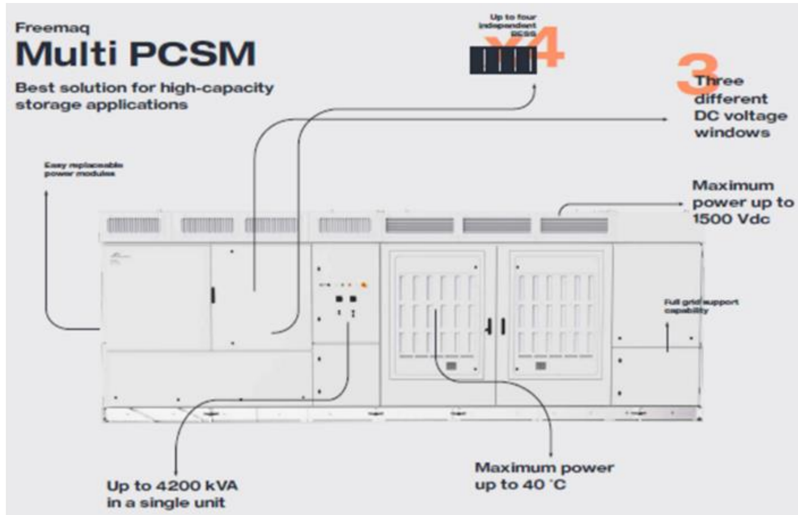


Figure 14 Compatible, cost-effective PCS solution sourced by AMT and B&M

Critical Cryocooling Systems

In addition to its own power conditioning system, each solenoid has its own separate multi-layer thermal cryogenic shell used to maintain critical temperatures. The cryo shell is cooled on the innermost layer with a liquid helium closed loop system, a vacuum barrier, and an outer liquid nitrogen outer cooling system (Figure 15). The entire device is maintained at 5 degrees K with an outer water jacketing system.

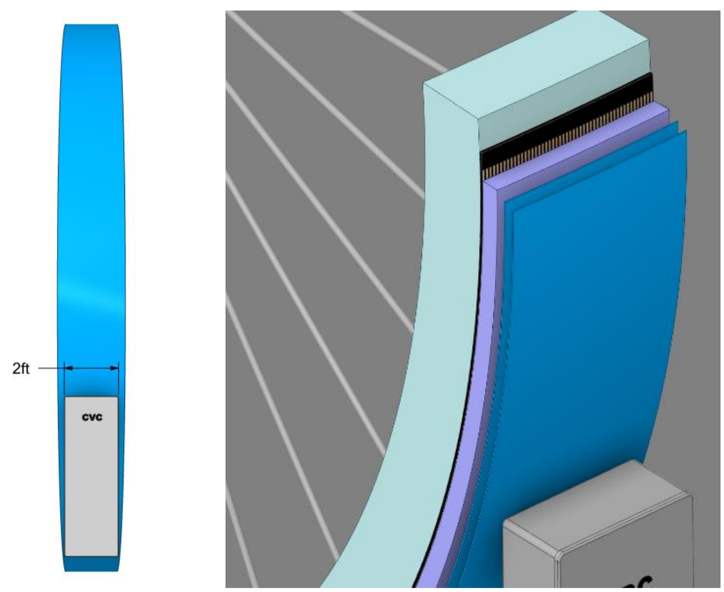


Figure 15 Cryocooling layer shown on the outer shell of the solenoids

During Phase I, significant design development work was accomplished in order to advance the outer shell of the SMES. The containment vessel shown in Figure 15 is designed to keep helium enclosed and to provide structural support to bear with the strong electromagnetic forces, all while keeping space between the outer shell and coils. This minimizes the peak thermal losses. A cross-sectional view is shown in Figure 16.

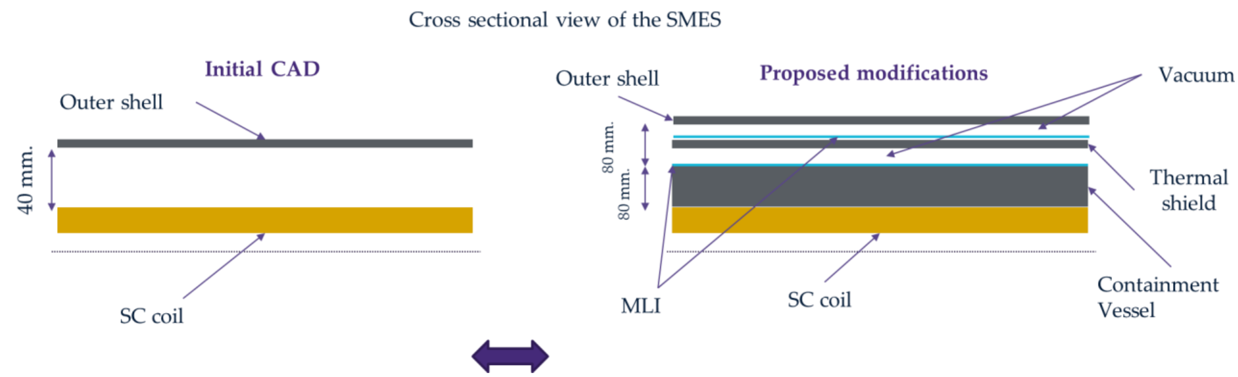


Figure 16 Design modifications to SMES cooling systems completed during Phase I

<u>Task 2</u>: Critical 500-MWh Design (AMT, UH, NRG, B&M)

With the huge and growing reservoir of design input developed in Task 1, our Team undertook the effort of siting and laying out the SMES battery system as a hybrid energy storage solution for an actual fossil asset. This work was undertaken with NRG and B&M. NRG selected two candidate sites for the Phase I hybrid design effort that are located in the greater Houston area, Greens Bayou and TH Wharton (Figure 17). These mature natural gas-fired generation peaking plants are excellent candidates for integration of SMES hybrid energy storage.

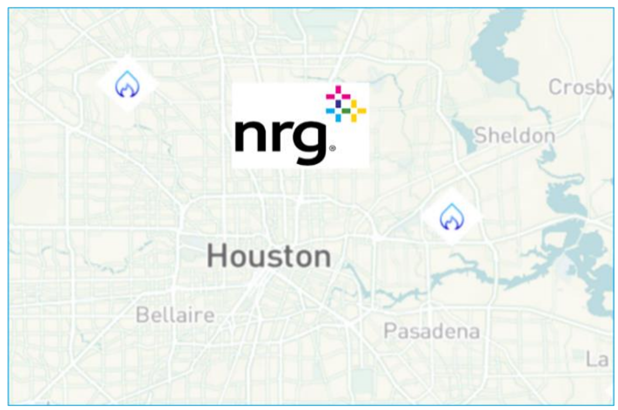


Figure 17 Site selection of NRG fossil assets in Houston

The work tasks in Phase I included the integration of design, performance, and siting to yield a structural model for full-scale SMES solution that can be prototyped. The device shape and size were optimized from Task 1 to deliver the target energy at the minimum cost. Finally, an interconnection design was completed for scaling up this 2G-HTS prototype to meet the requirements of a 1-MWh SMES prototype system.

As previously reported, NRG advised that the size of the fossil asset hybrid magnetic battery (also referred to as "SMES") has been set at 1890 GJ, or 525 MWh. It is designed to charge in four hours and then provide up to 125 MW of grid-connected power for a maximum four (4) hour period. The SMES is designed to be 98% efficient, meaning that approx. 98% of the energy placed in the SMES magnetic battery is fully accessible, with two percent lost in cooling and electrical losses during operation (Table 3).

Table 3 Power losses in a g-SMES system

Mode	Time		SOC		Power loss		
	Begin	End	Begin (GJ)	End (GJ)	Thermal losses (kW)	CL losses (kW)	**Total**
Charging	0:00	4:00	90	1890	16.2	0.10	**16.30**
Persist	4:00	16:00	1890	1890	16.2	0.19	**16.39**
Discharging	16:00	20:00	1890	90	16.2	0.10	**16.30**
Persist	20:00	0:00	90	90	16.2	0.01	**16.21**
						Average Power (kW)	**16.33**

As long as the SMES is kept cool and below critical temperature for superconducting, the SMES is available to receive or provide power at up to the 125 MW level. It is anticipated that once the SMES is placed into commercial operation, the SMES coil cryogenic system will be implemented to maintain operation temperatures below the system's necessary critical operating temperature. To the greatest extent possible, the cooling equipment needed to maintain appropriate cryo-temperatures will be served from SMES storage capabilities with energy purchased in off-peak pricing times and stored in insulated tanks so that cooling media is continuously available. Cooling equipment will be designed with isolation valving so that normal predictive maintenance can be accomplished without need to shut down the SMES. In addition to redundant equipment, a significant level of thermal capacity will be built into the SMES to support continuous operation.

The following figures depict additional progress achieved by our Team on Task 2 during Phase I.

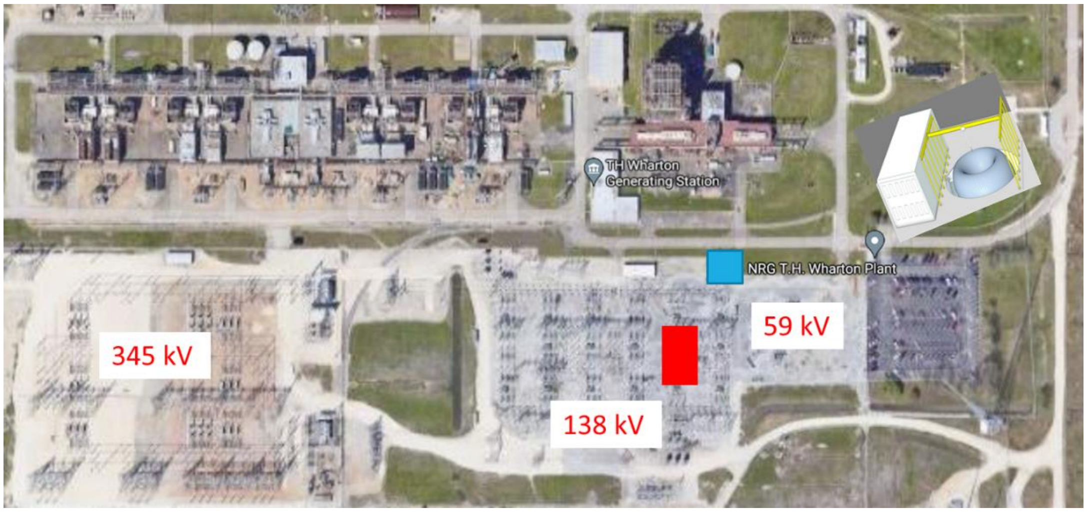


Figure 18 Site plans and SMES integration for NRG Greens Bayou (top) and NRG TH Wharton (bottom)

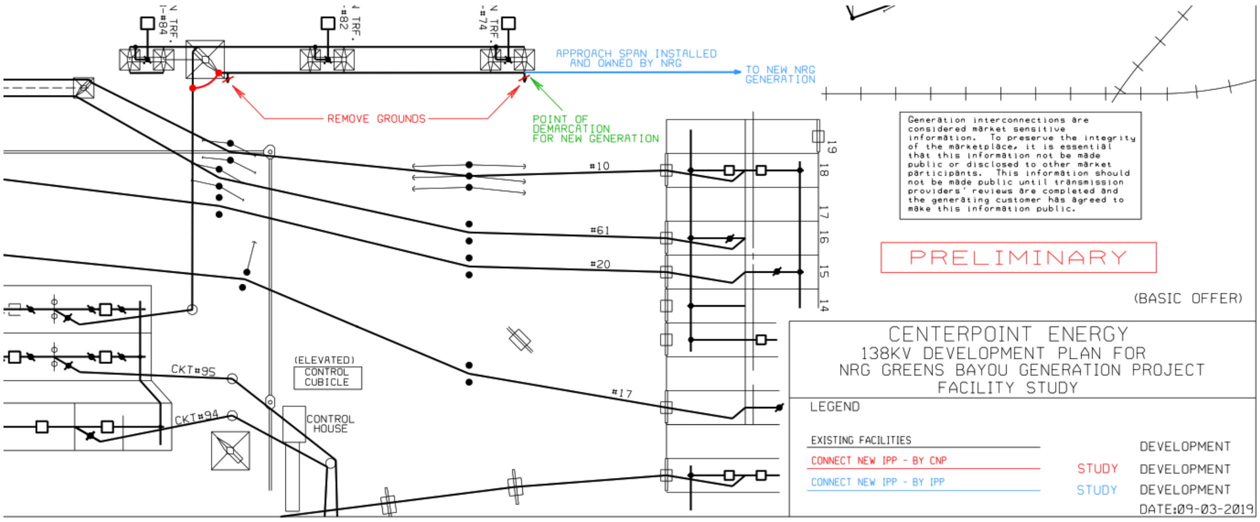


Figure 19 138 kV interconnection diagram at Greens Bayou (TH Wharton has a similar configuration).

Figure 19 above shows the conceptual grid interconnection scheme for SMES as Greens Bayou. The connection to the grid is a relatively simple bolt-on upgrade for this existing fossil plant.

Figure 20 below shows the basic layout for the SMES unit (approximatley 120 feet in diameter and 30 feet tall) and the electrical and mechanical equipment supporting the SMES. The entire footprint is less than two acres.

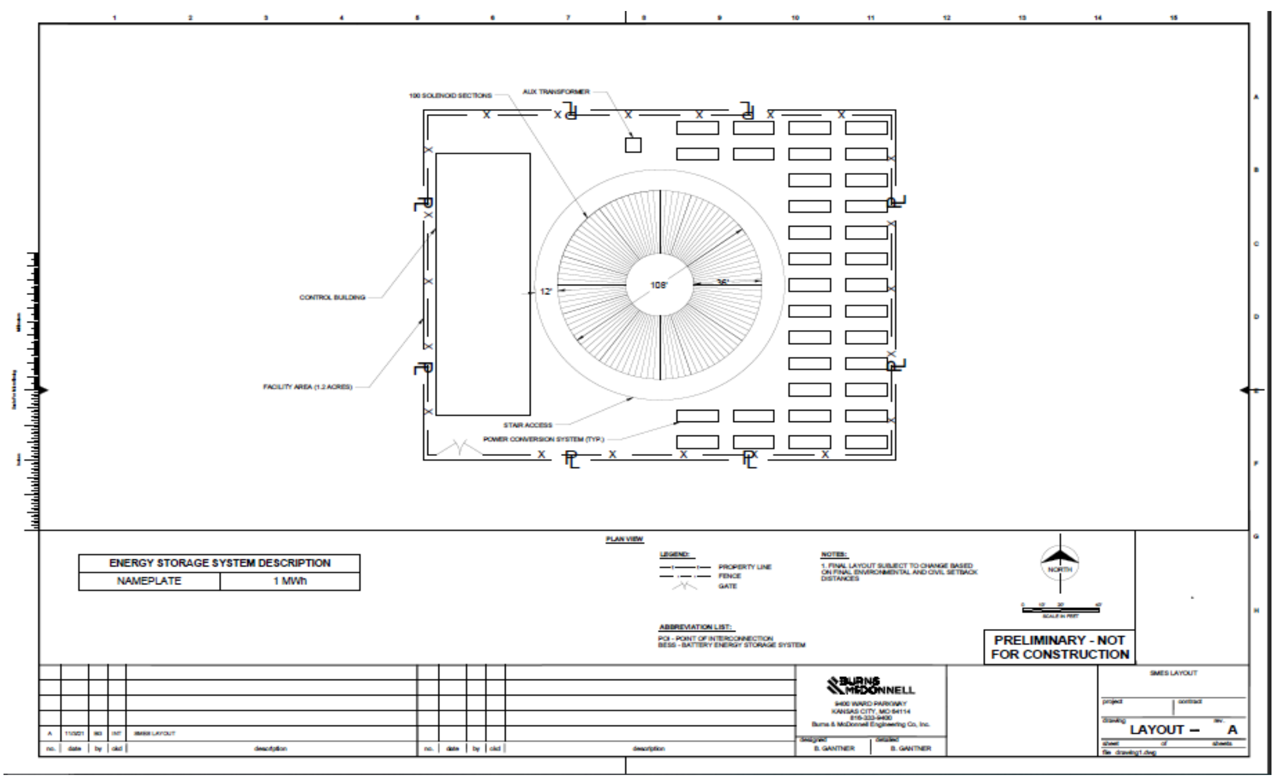


Figure 20 Facility layout plan completed by B&M

Figure 21 shows the conceptual one-line electrical diagram for connection of the SMES coils and CVC boxes to the PCS units described in the “SMES Power Electronics” section above. The new facility is grid connected by means of a 34kV to 138kV step-up autotransformer.

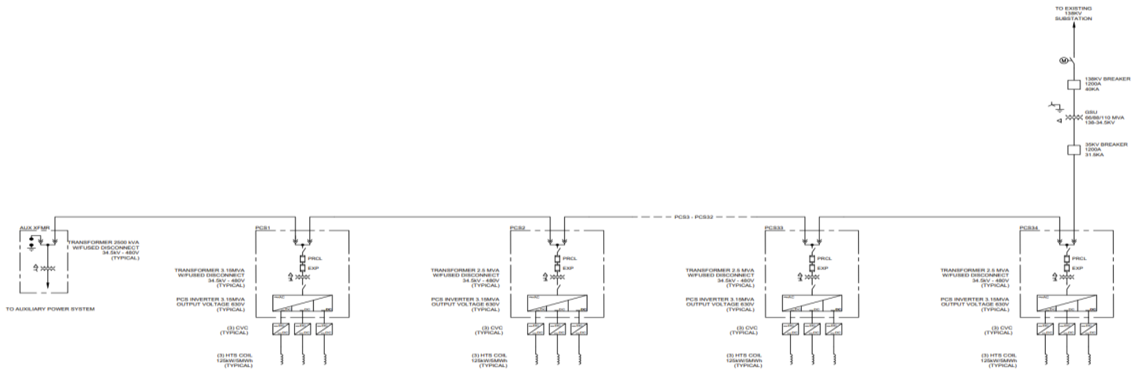


Figure 21 Conceptual One Line Diagram for SMES – NRG / Centerpoint Grid Interconnection

<u>Task 3</u>: Cost & Business Case Analysis (AMT, NRG, B&M)

For an investor to elect to make a significant capital expenditure (minimum $50 - 60 million) in a 21st century supplemental battery system for an aging fossil-fueled power plant, there must be a clear business case for both (a) the technological advantages of “hybrid energy storage,” and (b) a reasonable return on investment. For this task, we enlisted the assistance of NRG, B&M, and DOE commercialization consultant LARTA in the development of a cost model and business case that supports SMES deployment on site at a fossil-fueled power plant.

Whether by direct private investment by a utility company or energy supply asset owner, through cost-sharing schemes between private sector companies and the DOE, or other risk-sharing deployment arrangements, it all begins with a strong business case analysis that clearly demonstrates the return and benefit of this SMES hybrid energy storage project.

The initial results of this work are presented here and in the referenced Phase II proposal. It is our plan to share the Phase II submitted application details with the DOE Loan Program Office (LPO) for possible future loan opportunities. LPO finances large-scale, all-of-the-above energy infrastructure projects in the United States like the one we are proposing here. The LPO administers three distinct loan programs, but each offers a similar value to borrowers:

- LPO can provide first-of-a-kind projects and other high-impact energy-related ventures with access to debt capital that private lenders cannot or will not provide.
- LPO can provide flexible, custom financing that helps to meet the specific needs of individual borrowers.
- LPO encourages early engagement and is a valuable partner to applicants throughout the entire lifetime of a project.

LPO has issued more than $35 billion of loans and loan guarantees and has a proven track record including transforming existing energy infrastructure for these fossil assets as well as improving the lives of all Americans by catalyzing new energy technology and creating jobs.

NRG is experienced in developing, financing, operating, and buying/selling power from utility scale power resources. The essential commercial arrangements of utility scale power supply projects include long term, 10-year or greater, fixed revenue contracts, which secure project specific debt and equity investments. In NRG's opinion, revenue commitments to a SMES storage project should be assumed to be competitive with those of Lithium-ion Battery Energy Storage System (BESS) and on the order of ~$5.00 per kW-month for 10-years for the capacity. Such a commitment should provide sufficient Debt Service Coverage Ratio ("DSCR") to attract project that equity, construction financing, and initial term debt. Initial project(s) may require (and the prototype discussed here will most certainly require) government sponsored debt guaranties to support the new technology risks. The term debt is expected to be 5 to 7 years, followed by succeeding replacement arrangements.

According to the October 2021 Reports on Cost of Storage and Levelized Cost of Energy from Lazard, projects like the prototype SMES would be quite financially attractive According to the report, four-hour energy storage projects command attractive pricing for on-demand energy supply, with the storage projects needing $181 to 322 per KW-year to cover capital and operating costs (including depreciation, interest, taxes, and equity return), and the wholesale cost of energy priced between $181 and 232 per MWh.

Thus, it is apparent that lithium-ion BESS projects are attracting sufficient debt and equity financing to gain and even accelerate supply market share penetration. g-SMES would have to compete against lithium-ion BESS technology, but the technology will have significant advantages in capital cost, rate of degradation, operating cost and operating efficiency, as shown in Table 4.

Table 4 Prototype g-SMES Metrics

Storage Capacity	125 MW
Storage Duration	4 hours
Nameplate Energy Capacity	500 MWh
Black Start Capability	25 MWh
Operating days per year	350 days
Annual Storage	175,000 MWh

Based on the Lazard pricing estimates, g-SMES will generate approx. $40.25 million when viewed on capacity terms and $40.6 million when the value of the wholesale price of the sale of the stored energy is considered.

These revenue estimates include only energy delivery to wholesale customers. They do not include:

- Frequency regulation charges (ancillary service sold to ERCOT)
- Spinning / non-spinning charges (ancillary service sold to ERCOT)
- Resource adequacy
- Local incentive payments, if any
- Payments for Black Start capability

Lazard estimates that capital costs for storage range from 28% (low case) to 45% (high case) of project revenues. Operating and maintenance costs range from 6 – 13%. g-SMES charging may experience negative pricing for energy based on current and projected renewable energy penetration in Texas. Increasing numbers of hours in Texas have negative prices; this is most prevalent during early morning hours while the wind is blowing most strongly.

These same studies detail the Levelized Cost of Storage (LCOS) for existing chemical BESSs such as lithium-ion systems at $181 to $322 per kw-year. Competitive market participants like NRG would pay a facility for capacity, energy and ancillary services. At this level of pricing for the SMES facility and based on the strength of the Capacity Purchase Agreement from a customer like NRG, attractive debt financing with an Investment Rate of Return (IRR) in the range of 6% - 8% is likely, which would attract global investors. Once the initial project is completed and the technology risks resolved, the market opportunity indeed appears quite attractive, and the market risks are reasonably low. This revenue model will attract global private capital flows that will finance dozens of these g-SMES projects for customers like NRG that seek to sell energy to others. This will create thousands of new US high tech jobs and a whole new uniquely American high-tech industry.

Given capital costs that are 1/10 that of Lithium-ion BESS, low operating and maintenance costs and negligible degradation a g-SMES project would produce extremely attractive equity returns. These returns should be greater than those currently realized from renewable supply projects including Lithium-ion BESS, solar and wind. Those projects attract investment from global equity markets for projects earning 8% IRR. A g-SMES project would attract many of the same investors and be expected to produce much higher financial returns. Should this prove true, g-SMES would quickly gain market share and provide significant contribution to desperately needed controllable energy supply and reliability in support of intermittent renewable supply growth.

Hybrid Energy Storage

Phase I work revealed numerous advantages of SMES technology when married with natural gas peaking plants. Based on our team's analysis and peer review of the characteristics of the technology, we have identified the following advantages:

1. SMES can be integrated into existing fossil facilities without the need for a large construction footprint, a dedicated control center, or significant staffing of personnel. Ongoing operating costs are minimized, and the round-trip cost of energy storage is less than two cents per kWh stored. This "hybrid" enhances the value and market opportunity for energy generated by the fossil asset and also provides significant new benefits to the fossil asset in terms of better management of peaking plant operations as well as "black start" that is further discussed below.

2. SMES can help a utility respond to real-time price spikes in energy and ancillary services, a growing industry issue that also represents a new revenue opportunity as well as a new way to address a perplexing (and growing) issue for fossil peaking plant generation facilities. SMES can be made continuously available to address price spikes (Figure 22) in a cost-effective way[viii].

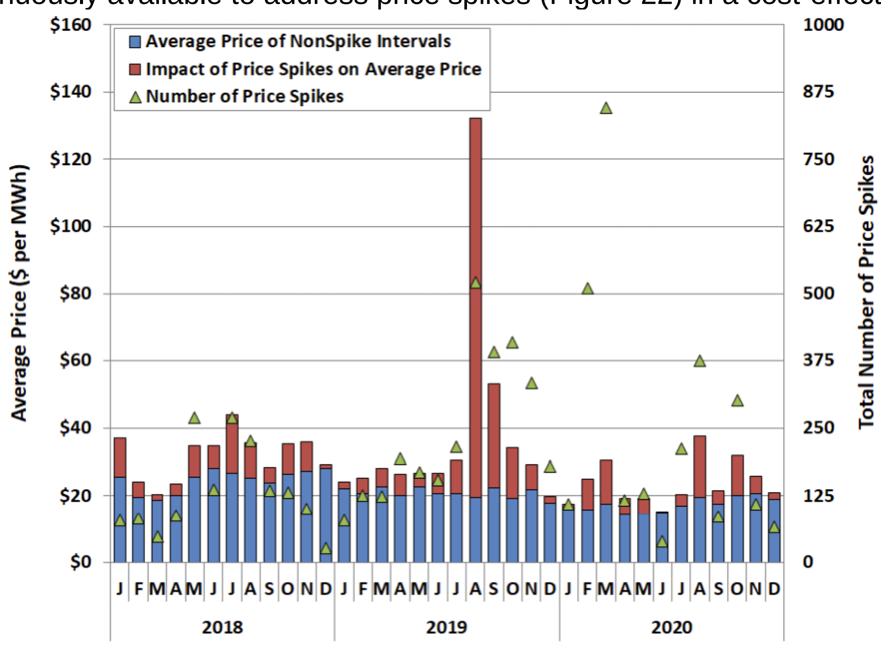


Figure 22 Price spike data provided to ERCOT by Potomac Economics, its Independent Market Monitor (May 2021)

3. Figure 23 shows the historical growth in the mismatch in demand by time of day for California, also referred to as the California Duck Curve. Other markets (WECC, ERCOT, ISONY) are experiencing similar market changes as solar gains market share. This chart illustrates the daily need for controllable supply resources (like grid-scale energy storage like SMES) given the growth of intermittent wind and solar. The need for fast ramp (duck neck) becomes more pronounced over time, and while different states like Texas are at different points on this “curve”, as more renewables are integrated into the energy mix, the more all states will come to look like the California experience that is shown here. The good news is that SMES can ramp much more quickly than a slower-startup fossil-fueled power plant. An attractive business model has been identified that allows the merchant utility company to receive excess baseload energy (including renewable energy) from other grid-connected third parties and accept payment for this energy storage as a merchant service. These periods of potential “overgeneration” represent a significant energy loss to the grid, but it also represents a significant revenue opportunity for companies like NRG when enabled with the technical capability to shift excess generation by up to twelve hours as peak loads ramp up, usually in the afternoons and evenings.

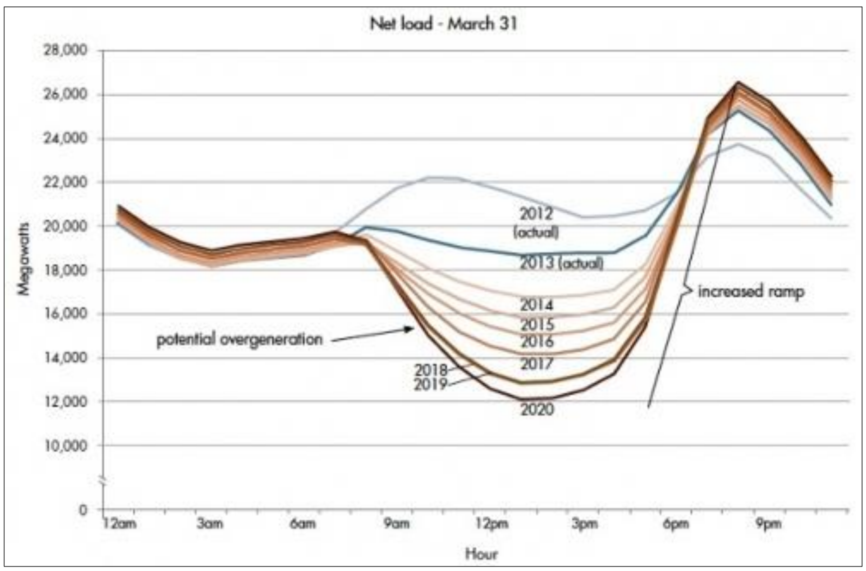


Figure 23 “Duck curve” representing demand-based energy generation over a 24-hour period

Energy storage is the problem of our generation, and it is also the great revenue opportunity. We have ample supplies of energy from fossil-fueled power plants as supplanted by growing renewable energy resources, but we don’t have those resources when they are needed most and must be dispatched. Hybrid energy storage co-located with existing fossil generation assets and connected to the grid offer the best opportunity to address time-of-day issues like the illustration above at a capital cost of less than $100 per kWh stored.

4. SMES inherently makes energy instantly available. Thus, it can be used as a “jump start” for a peaking fossil-fueled power plant as it slowly starts up, or it can potentially be enabled to avoid startup altogether for certain events that dissipate, thereby extending the lives of the assets, reducing operation and maintenance costs, and avoiding any downtime altogether in the event of a crisis. These characteristics have a direct impact on grid stability and help to avoid extreme fluctuations in demand imposed on the asset.

5. SMES has built-in black-start capabilities, with 5% of the total energy storage continuously available on demand in the event of a catastrophic grid failure. While 25 MWh of instant capability

is not groundbreaking when considering GWh levels of energy produced by any given fossil asset, NRG states that such capability would be a game changer in the event of a total grid failure.

The 2021 massive electricity generation failure in Texas resulting from Winter Storm Uri left blackout conditions for more than 4.5 million residents over several days and was responsible for hundreds of deaths and nearly $200 billion worth of associated damage statewide. Black start capability will be very valuable to the normal re-start of fossil generation plant equipment when the next winter storm occurs.

To continue this program, we would work with B&M to complete dynamic modeling of a SMES system in an NRG environment (Greens Bayou or TH Wharton in greater Houston) to fully simulate the technology's operation based on these stated characteristics. Dynamic modeling would not only better inform the grid-stability analysis, but it would also bring more clarity to the regulatory application process for the deployment of a full-scale prototype system.

Commercialization

In coordination with LARTA, we created a robust commercialization plan (CP) that illustrates the market landscape for this technology, estimates additional maturation requirements, gauges the market appetite, explores potential barriers for widespread adoption, and considers additional commercial partnerships for deployment. Please see the attached CP for these details.

SMES Capital Costs

An essential component of Phase I work was dedicated to the estimation of all capital and associated costs for the deployment of a SMES system onsite at an existing fossil asset facility.

Our estimates prior to Phase I based on a 2 GWh model were established as shown in Figure 23:

Figure 23 Estimated capital costs for a SMES system (from AMT's Phase I proposal)

After conferring with our utility partner, NRG, during Phase I regarding the minimum commercial size for hybrid energy storage co-located with the fossil asset, we right-sized the facility to 500 MWh plus 25 MWh for black start — or roughly 25% the size of our original concept. While this lowers the expected capital outlay from nearly $200 million to less than $50 million, it does present a loss of size and scale issue that makes the budgeting (and the goal $100 per kWh capital cost) much more challenging.

For a typical g-SMES in large-scale mass production of any size, more than two-thirds of the capital cost is expected to be spent on the advanced 2G-HTS tape developed at UH. There are between 6.5 and 8 million meters of tape in the current design. The ultimate cost of the tape will be wholly dependent on the mass production facilities for this HTS tape that will ultimately be used not only for SMES and other magnetic batteries but also for no-resistive-losses next generation high voltage transmission lines, current interrupters and transformers, medical imaging, commercial fusion, and many other uses of this novel material (see Commercialization Plan). We currently allow for a mass-produced price of approx. $3.75 per meter (or $31 million), but we expect that large-scale mass production would reduce this cost by an order of magnitude.

Costs for winding 102 solenoids and installing them into the g-SMES is estimated to be $3.2 million. The budget for the power conditioning system includes the cost of 102 CVC boxes ($1.2 million); 34 PCS boxes and outside switchyard ($900,000); a step-up transformer from 34.5 kV to 138 kV ($1,000,000); grid interconnection and installation ($1,300,000); and a reasonable contingency ($400,000).

The chiller plant, chiller piping, thermal storage, and other equipment including automated control system will be provided via a design-build contractor that could also take on significant O&M responsibilities. We have been provided a range of costs by several vendors and estimate this cost at $6 million.

In addition to these direct costs, we have included a budget of seven percent (7%) of the direct costs for engineering costs, or $3 million. A summary of capital costs is shown in Table 5.

Table 5 Summary of Capital Costs for 525 MWh g-SMES System (USD)

Superconducting Tape	$31,000,000
Conduit, Civil Works, Installation	3,200,000
Power Conditioning System	4,800,000
Cryocooler System	6,000,000
Engineering & Contingency	3,000,000
Total	**$42,000,000**

SMES Operating and Maintenance Costs

As g-SMES is an autonomous, operator-free operation (albeit a 24/7/365 operation), it is expected that the asset owner would assign a two-person crew to oversee the device's mechanical and electrical operations. Costs for ongoing operations are mainly the cost of energy for creating liquid helium and liquid nitrogen in closed loop systems, for the chilled water used for the SMES torus outer jacket, and for cooling the power electronics equipment. To the extent that this coolant is made during off-peak hours and stored in tanks, the electrical cost is a "negative cost," since it is anticipated that the utility company will actually be paid to receive this excess energy during nightly and early morning periods of "overgeneration." The large-scale storage of available coolant adds significant buffer to the system during very rare periods of aberrant operation when the utility grid may not be available to the g-SMES or active cooling equipment is off line for planned or unplanned maintenance activities.

Predictive and normal maintenance as well as on-call services for the chiller plant would be provided by the plant equipment supplier (e.g., Trane, Carrier, Mitsubishi, etc.) subject to a long-term service contract. We allotted $125,000 per year in our budget for maintenance contracts, but this could also be rolled into the first 10 to 20 years of service into the capital cost for the chiller plant. The normal predictive maintenance for these mature cooling systems is well understood and highly reliable; there are no new inventions required or associated with this aspect of the system; however, these are the only “wear items” and moving parts requiring vigilance and eventual servicing and normal replacement.

An important feature of SMES is that these moving parts are the only moving parts in the entire system. Unlike chemical batteries that often struggle to achieve 3,000 to 5,000 cycles, the useful life of SMES is almost infinite. We expect that advances in 2G-HTS (and XG-HTS) tape will eventually render this g-SMES version obsolete, perhaps decades before the completion of a useful life of perhaps 30 years of continuous operation. The significantly longer life for the SMES coils compared to the relatively short life and shallow depth of discharge for lithium-ion based chemical battery systems makes SMES the clear winner when life cycle costs are considered.

NRG reviewed the proposed SMES operation in conjunction with the operating plans for its fossil-fueled power plants at Greens Bayou and TF Wharton with the company’s risk management department. NRG concluded that no major impact to existing plant staffing will be required to accommodate normal NRG control room operations and ongoing operations and maintenance staff at those respective facilities. In addition, the unique design of SMES as 102 individually managed and monitored, electrically independent subsystems that can be operated even when one or more of the subsystems is not operational will afford NRG significant flexibility in limited self-insurance of the SMES facility. (NRG is already doing this with its chemical battery storage systems under development.) The intracompany charges for insurance for the g-SMES hybrid system are expected to be considerably lower than those currently paid for lithium-ion based systems associated with existing NRG fossil-fueled power plants due to lack of flammability and other competitive advantages of the system.

Conceptual Schedule

During Phase I, our team prepared a conceptual schedule for the development, licensing, engineering, construction, and start-up of the prototype grid-scale SMES on the fossil asset site. Our assumption was based on the award of the Phase II effort, and we would use this two-year period ending at the end of 2023 to also develop the financing package for the project. This work would be led by NRG in conjunction with the US DOE Loan Program Office (LPO). Given that this will be a project of national significance, it is anticipated that LPO assistance in the form of credit enhancement will be required to fully address the expectations of global investors regarding the first-time implementation. It is expected that financing would be in place for the project in mid-2024.

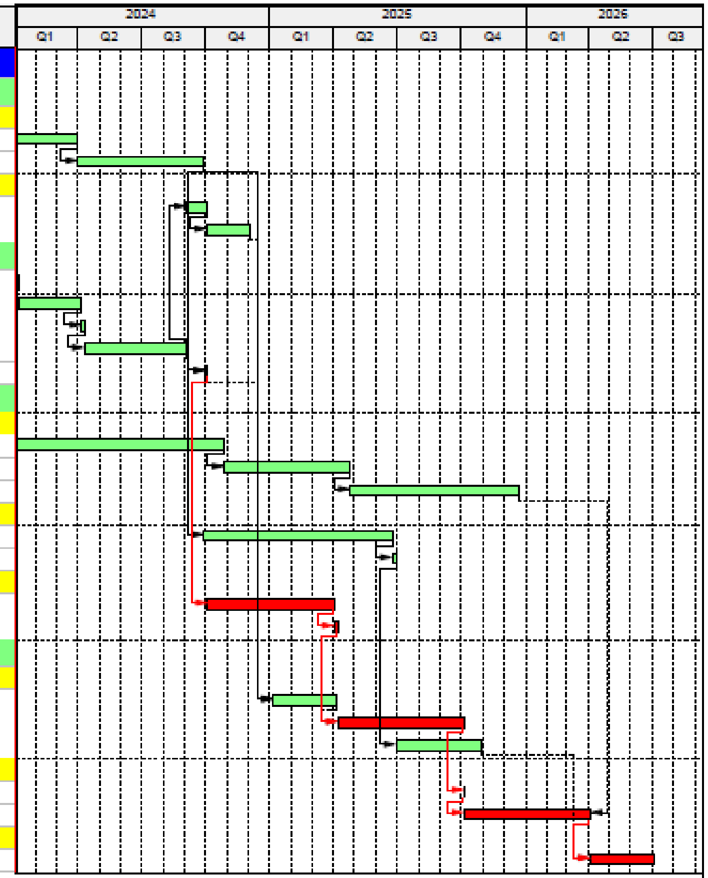
The critical path for the development of a g-SMES system is paced by the availability of the actual advanced 2G-HTS tape itself in mass quantities needed for the project. For this first project, once “Project Start” is achieved, the date that the overall contract is approved, we will require ten (10) months to procure and set up the specialized equipment needed to produce 2G-HTS tape. We would expect to be making large quantities of tape within six months of equipment startup, with all tape available at the end of 2025.

An Interconnection Application with Electric Reliability Council of Texas (ERCOT) and Centerpoint culminates in an initial System Impact Study 90-days later followed by a 6-month Full Impact Study, 6 months later and a SGIA (Interconnection Agreement) within 180 days of the FIS. We would submit a General Arrangement drawing, dynamic model and detailed technical descriptions of the project in the initial application. A local experienced engineering procurement and construction (EPC) contractor approved by the fossil-fueled plant owner will be hired by the end of month 3. In parallel with the, the preparation of architectural, mechanical, and electrical drawings would be completed by the EPC based on the package submitted to ERCOT.

Final construction documents will be submitted at the end of month 9. The EPC will select the mechanical design-build team by the end of month 9, allowing for six months for delivery of long lead chillers, pumps, and other cryocooling equipment. Chiller plant installation and start up would take approximately six months, from start of month 19 to end of month 24. Actual onsite construction can commence at the end of month 9 after project start. Site construction can be scheduled over a spring/summer period and be completed within 6 -9 months. Power conditioning equipment would be ordered when the permit is approved at the end of month 9. Lead times for this specialized equipment is expected to be nine months, with installation and testing to take place during months 18-21.

The EPC will make the battery bay available for g-SMES installation at the end of month 21. Installation and testing of the g-SMES equipment will take six months. Testing and training would take place during months 28-30, with final completion in 30 months. A full depiction of this schedule appears in Figure 24.

Activity ID	Activity Name	Remaining Duration	Start	Finish
SMES DOE Study		653	02-Jan-24	02-Jul-26
SMES.1 Permitting		335	02-Jan-24	02-Dec-24
SMES.1.1 ERCOT/ Centerpoint		270	02-Jan-24	28-Sep-24
A1000	Prepare Package for Submission	90	02-Jan-24	01-Apr-24
A1050	Submit/ Receive Approvals and Execute Interconnect Agreement	180	01-Apr-24	28-Sep-24
SMES.1.2 Local Permits		90	03-Sep-24	02-Dec-24
A1130	Prepare Applications and Submit Drawing Packages for approval	30	03-Sep-24	03-Oct-24
A1230	Local Permit Approvals	60	03-Oct-24	02-Dec-24
SMES.2 EPC Award and Engineering		199	02-Jan-24	04-Oct-24
A1010	Issue RFP	5	02-Jan-24	07-Jan-24
A1020	Proposal Receipt, Evaluation and Contract negotiation	90	07-Jan-24	06-Apr-24
A1030	EPC Award - Engineering Release only	5	06-Apr-24	11-Apr-24
A1040	EPC Drawings (arch/ mech/ elect) needed for local permits	145	11-Apr-24	03-Sep-24
A1140	Issue EPC - FNTP	5	30-Sep-24	04-Oct-24
SMES.3 Equip and Materials		720	02-Jan-24	22-Dec-25
SMES.3.1 HTS Tape (AMT)		720	02-Jan-24	22-Dec-25
A1090	Procure and assemble specialized equipment to make advanced HTS tape	300	02-Jan-24	28-Oct-24
A1110	HTS Tape Production 50% Complete	180	28-Oct-24	26-Apr-25
A1120	HTS Tape Production - 100% Complete	240	26-Apr-25	22-Dec-25
SMES.3.2 Owner Procured, Long Lead		275	28-Sep-24	30-Jun-25
A1160	PO placement/ fabrication for Transformers and B Boxes	270	28-Sep-24	25-Jun-25
A1170	Owner procured equipment delivered to site	5	25-Jun-25	30-Jun-25
SMES.3.3 EPC, Long Lead		185	04-Oct-24	07-Apr-25
A1100	EPC PO placement/ fabrication (chillers, pumps and cyro cooling equipmment	180	04-Oct-24	02-Apr-25
A1150	EPC procured equipment delivered to site	5	02-Apr-25	07-Apr-25
SMES.4 Site Work		543	06-Jan-25	02-Jul-26
SMES.4.1 EPC		295	06-Jan-25	28-Oct-25
A1060	Mobilization and Site Prep	90	06-Jan-25	06-Apr-25
A1180	Chiller Plant Installation	180	07-Apr-25	04-Oct-25
A1190	Transformer and 'B Box Insall	120	30-Jun-25	28-Oct-25
SMES.4.2 AMT (gSMES Installation)		181	04-Oct-25	03-Apr-26
A1200	Battery Bay available to AMT	1	04-Oct-25	05-Oct-25
A1210	gSMES Installation	180	05-Oct-25	03-Apr-26
SMES.4.3 Testing and Final Acceptance		90	03-Apr-26	02-Jul-26
A1220	Acceptance Testing, Training and Final Completion	90	03-Apr-26	02-Jul-26



Actual Level of Effort | Remaining Work | ◆ | ◆ M..
Actual Work | Critical Remaining Work

Page 1 of 1

TASK filter: All Activities

Figure 24 Conceptual schedule of SMES prepared by NRG

c. What opportunities for training and professional development has the project provided? None.

d. How have the results been disseminated to communities of interest? Our team is considering preparing a manuscript for submission to IEEE or other peer-review body for scientific publication that we believe would advance the body of knowledge and create a deeper understanding of the field of study.

e. What do you plan to do during the next reporting period to accomplish the goals and objectives? The project performance period has ended.

III. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

1. Participants

1) Name: Tony Morris
2) Project Role: Principal Investigator
3) Nearest person month worked: 1.1
4) Contribution to Project: Mr. Morris coordinated all team meetings, directed research activities, reported on all progress, and authored technical reports.
5) Funding Support: DOE Phase I SBIR; internal funding from American Maglev
6) Collaborated with individual in foreign country: No
7) Country(ies) of foreign collaborator: N/A
8) Travelled to foreign country: N/A
9) If traveled to foreign country(ies), duration of stay: N/A

1) Name: Jordan Morris
2) Project Role: Research Support
3) Nearest person month worked: 0.8
4) Contribution to Project: Mr. Morris assisted the PI in research administration and drafting reports.
5) Funding Support: DOE Phase I SBIR; internal funding from American Maglev
6) Collaborated with individual in foreign country: No
7) Country(ies) of foreign collaborator: N/A
8) Travelled to foreign country: N/A
9) If traveled to foreign country(ies), duration of stay: N/A

2. Partners

1. **Organization Name**: University of Houston
2. **Location of Organization**: Houston, Texas
3. **Partner's contribution to the project**: Facilities, Collaborative research
4. **More detail on partner and contribution.** Dr. Goran Majkic led the research effort from UH and contributed significant research hours to the project related to 2G-HTS tape.

1. **Organization Name**: American Electromechanics Inc.
2. **Location of Organization**: Lebanon, Ohio
3. **Partner's contribution to the project**: Collaborative research
4. **More detail on partner and contribution**. Dr. Kent Davey contributed significant research hours to the project related to magnetic field analysis.

1. **Organization Name**: Western Carolina Ingenuity Inc.
2. **Location of Organization**: Robbinsville, NC
3. **Partner's contribution to the project**: Collaborative research
4. **More detail on partner and contribution**. Mr. T.V. Williams III contributed significant research hours to the project related to power conditioning and electronics design.

1. **Organization Name**: NRG Energy Inc.
2. **Location of Organization**: Houston, TX
3. **Partner's contribution to the project**: Collaborative research, in-kind services
4. **More detail on partner and contribution**. Mr. David Freeman, Mr. Steve Rose, Ms. Lindsey Davis, and Ms. Ashley Luttner shared plant and utility data and provided other in-kind support to the project.

1. **Organization Name**: Burns & McDonnell Inc.
2. **Location of Organization:** Kansas City, MO
3. **Partner's contribution to the project**: Collaborative research, in-kind services
4. **More detail on partner and contribution**. Mr. Chris Ruckman and Ms. Sowmya Ragothaman provided engineering consulting and other in-kind support to the project.

1. **Organization Name**: MotoCilino LLC
2. **Location of Organization**: Atlanta, GA
3. **Partner's contribution to the project**: Collaborative research
4. **More detail on partner and contribution**. Paul Cilino generated CAD/SolidWorks drawings of the proposed g-SMES system.

3. Other Collaborators

Have other collaborators or contacts been involved? Nothing to report.

IV. IMPACT

a. What is the impact of the project? How has it contributed?

This Phase I Project has facilitated a unique collaboration between DOE, conventional fossil utility leadership (NRG and Burns & McDonnell), and emerging high-tech development at University of Houston. The well-integrated symbiotic partnership has been managed by American Maglev Technology of Florida. The impacts resulting from this Phase I project include technical breakthroughs, new opportunities for radical cost reduction in long term energy storage, and emergence of near-term pathways to achieve these breakthroughs and realize long-term cost savings.

Cost-effective energy storage is the issue of our generation. Everyone knows this, both experts and the taxpaying public. We have enough energy, but we don't have to when we need it. Cost effective energy storage will allow cheap and efficient baseload energy from fossil assets and renewable resources to level the peaks in energy demand and avoid costly expensive strategies designed only to address huge and growing demand spikes, which only get sharper and more difficult to address as renewable energy makes a great contribution to our energy supply mix.

Until this project, it was generally seen that the only way to effectively accomplish grid-scale energy storage is through use of chemical batteries, using exotic materials like lithium-ion. Indeed, our industry partner, NRG, is currently developing battery storage projects, with reservations. The taxpaying public knows about these batteries, the limitations, and the need to throw away and replace these batteries every few years. This project has alerted our partners (and will, in the longer term, educate the public) that there is a new U.S. technology developed by DOE and the University of Houston that can take the place of chemical batteries like lithium-ion that will have near-infinite life at a cost that is a fraction of chemical batteries.

The project has given our team the opportunity to address and even begin to correct the “conventional wisdom” around superconducting technology, such as the cost of this material. The project has demonstrated that while it is true that superconducting tape is expensive in small quantities, there is nothing in the design of this advanced material that would prevent a radical reduction in per meter costs. When considering that 2G-HTS tape carries 1000X more current than conventional copper wire, the tape will be much cheaper when “cost per amp delivered” is considered, and this will only grow as the tape is used for the next generation of not only energy storage but also power grid transmission lines, motors, and many other uses. Our team has also investigated the worries about the cost of cryocooling, and for projects like grid scale energy storage, and our team has determined that the all-in costs of cooling for these projects are no more than 1 -2%. Compared to lithium-ion and the limitations of 80% depth of discharge, the cost of cryocooling appears quite reasonable. The impact of the project is that a new development pathway has been blazed that has the potential to lead to energy storage technology with a capital cost of less than $100 per kWh stored and an all-in cost (including capital costs) of stored energy at less than two cents per kWh.

The taxpaying public demands these energy storage solutions now. Through this unique partnership with NRG, sites in the greater Houston area have been identified where this breakthrough technology can be deployed in the next few years. NRG has led the team as together we have analyzed the unique economic landscape of long-term energy storage markets, and NRG has identified a merchant power market opportunity with the potential to provide attractive returns on invested capital. Managing the market risks are what companies like NRG do, and so with the general understanding developed in this project coupled with a greater comprehension of the technology risks associated with a 500-MWh project like this, our team can present a near-term go-forward plan that brings new technology solutions and new U.S. jobs to address this perplexing problem.

This project has identified a potential new solution, and the work done by the team has added color and definition to the proposed new solution. Our team has confirmed the great value to existing fossil assets through the addition of “hybrid” energy storage, and we have identified a practical first project that would lead to many, many more project opportunities as the technology risks are eliminated and the market opportunities are proven. The added side benefits to creating a mass market for HTS tape for medical devices and so many other existing and new devices will have strong positive economic and societal impacts for the rest of this century.

b. What was the impact on the development of the principal discipline(s) of the project?

These findings have created an interest among strategic and financial investors for near term applications and markets for 2G-HTS Tape. The project opportunity defined by this project is objective proof of the investment opportunity that building new mass manufacturing facilities for this superconducting tape can create. Since the HTS tape represents some 68% of the total cost of the grid-scale energy storage solution, investor focus and efforts to increase production while decreasing the cost of HTS tape by 1 to 2 orders of magnitude will also benefit the project economics and profitability and quickly increase the pace of “hybrid” implementation at America’s fossil generation plants. Making 2G-HTS tape plentiful and cheap, like microchips in 1957 and fiber optic cables in 1965, will accelerate other new applications of this U.S. material. The impact of this new “building block” material in ample quantities and cheap prices will open up opportunities to create new devices and solutions through the rest of this century, by engineers who have not been born yet.

c. What was the impact on other disciplines?

Armed with the knowledge base and unique findings of this project, our team has already won two new projects that seek to apply this advanced HTS tape. The first is for the U.S. Navy that seeks to build a radically smaller and more competent new transformer for the Electric Ships Program. The second is for DOE to use this HTS tape in a new generation of grid-scale power lines and other cable assemblies, called CABLE. While these are the first new products that will come from the groundbreaking work accomplished in this project, we expect that it will certainly not be the last.

d. What was the impact on the development of human resources?

Nothing to report.

e. What was the impact on physical, institutional, and information resources that form infrastructure?

Nothing to report.

f. What was the impact on technology transfer?

Nothing to report.

g. What was the impact on society beyond science and technology?

Nothing to report.

h. What percentage of the award’s budget was spent in foreign country(ies)? 0%

V. CHANGES/PROBLEMS. There were no changes/problems to report.

Carryover Amount. There is no carryover amount expected at the reporting period end date.

VII. DEMOGRAPHIC INFORMATION

Tony Morris – male, not-hispanic, white | tmorris@american-maglev.com
Jordan Morris – male, not-hispanic, white | jmorris@american-maglev.com

VIII. SPECIAL REPORTING REQUIREMENTS

Monthly briefings with the DOE TPOC were held throughout the 12-month performance period.

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