Open access • Report • DOI:10.2172/1404914

High Efficiency and Low Cost Thermal Energy Storage System — Source link

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Published on: 29 Sep 2017

ANL/NE-C2016-16141

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Final CRADA Report

Nuclear Engineering Division

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Final CRADA Report

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September 29, 2017

Argonne NATIONAL LABORATORY

Non Proprietary

Final CRADA Report

Date: September 29, 2017

CRADA Number: 2016-16141

CRADA Title: High Efficiency and Low Cost Thermal Energy Storage System

CRADA Start/End Date: September 12, 2016 to September 30, 2017

Argonne Dollars: $300,000

Participant Dollars: $75,000

Argonne PI: James J. Sienicki

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BgtL, LLC — $75,000
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DOE Program Manager: Tom Miller

Summary of Major Accomplishments:

1Background on BgtL

BgtL, LLC (BgtL) is focused on developing and commercializing its proprietary compact technology for processes in the energy sector. One such application is a compact high efficiency Thermal Energy Storage (TES) system that utilizes the heat of fusion through phase change between solid and liquid to store and release energy at high temperatures and incorporate state-of-the-art insulation to minimize heat dissipation. BgtL's TES system would greatly improve the economics of existing nuclear and coal-fired power plants by allowing the power plant to store energy when power prices are low and sell power into

Summary of Major Accomplishments:

the grid when prices are high. Compared to existing battery storage technology, BgtL's novel thermal energy storage solution can be significantly less costly to acquire and maintain, does not have any waste or environmental emissions, and does not deteriorate over time; it can keep constant efficiency and operates cleanly and safely. BgtL's engineers are experienced in this field and are able to design and engineer such a system to a specific power plant's requirements. BgtL also has a strong manufacturing partner to fabricate the system such that it qualifies for an ASME code stamp. BgtL's vision is to be the leading provider of compact systems for various applications including energy storage.

BgtL requests that all technical information about the TES designs be protected as proprietary information. To honor that request, only non-proprietay summaries are included in this report.

2 Objectives

The objectives of this work are:

1) To develop a conceptual design for a full-size transportable TES unit utilizing molten aluminum alloy as the high temperature phase change material that can be utilized with a Sodium-Cooled Fast Reactor (SFR) Nuclear Power Plant (NPP) or a coal-fired power plant;
2) To identify how TES can be integrated together with a SFR NPP or coal-fired power plant to increase the plant electrical output when electricity is in greater demand and decrease the plant electrical output when electricity is in lesser demand while the power plant continues to operate in a baseload fashion at a constant thermal power level;
3) To develop a computer code modeling the transient performance of a TES unit that can be utilized to optimize the TES unit design;
4) To optimize the TES conceptual design for use with the Advanced Fast Reactor (AFR)-100 SFR Small Modular Reactor (SMR) NPP;
5) To investigate a rough cost estimate for the aluminum alloy-based TES approach versus other energy storage technologies;
6) To develop a conceptual design for a testing facility and a small-scale prototype TES unit for future testing at Argonne National Laboratory (ANL); and
7)To recommend future work for the continuation of TES development under the GAIN Program.

3 Aluminum Alloy Properties for TES Applications

The BgtL, LLC (BgtL) TES concept uses aluminum alloy as the high temperature phase change material. Pure aluminum (Al) has a melting temperature of 660 °C. By varying the alloy composition, the freezing/melting range can be selected to lie in a desired interval below the Al melting temperature. For example, as shown by the aluminum-magnesium phase diagram, by alloying with 10.83 weight % magnesium, the melting/freezing range can be spread between solidus and liquidus temperatures of 508.3 and 600 °C, or by alloying with 35.6 weight % magnesium can be lowered to a single eutectic temperature of 450 °C. Thus, the phase change temperature can be selected to match up well with the maximum intermediate sodium loop temperature of a SFR or the maximum steam temperature of a coal-fired power plant through selection of the appropriate alloy composition. The high thermal conductivity of aluminum alloys makes it practical to conduct thermal energy into and out of the alloy during phase change.

Summary of Major Accomplishments:

Pure aluminum undergoes a significant volume expansion upon melting of 7 % by volume. The large volume expansion or contraction upon melting or freezing of the aluminum alloy must be accommodated in the design of a TES unit. Molten aluminum and molten aluminum alloys are highly corrosive to steels and other structural materials some of which can be dissolved away in minutes [1]. Thus, for a TES unit to work successfully, it is necessary to protect structural materials from attack. Data exist that suggest materials that might be resistant to attack by molten aluminum alloys [1].

Thermophysical properties were estimated by Argonne for 35.6 and 10.83 wt % Mg aluminum alloys. For the former eutectic composition, a heat of fusion of 365.8 kJ/kg is estimated. For the latter, an effective specific enthalpy change over the melting range of 498.7 kJ/kg is estimated.

4 Example of TES Utilization with a Coal Power Plant

Two TES units could ideally be utilized to temporarily increase the electrical power output by a coal plant by a factor of three during an interval of high electricity demand when consumers are willing to pay a higher price for electricity by charging the TES units during an interval of low electricity demand when the price of electricity is low. In this case, a 1350 MWt coal plant with a supercritical steam cycle nominally outputting 550 MWe is assumed. The supercritical steam temperature exiting the boiler is 593 °C and the pressure is 24.1 MPa. Feedwater is returned to the boiler or TES at no less than 260 °C. Each TES unit can be charged in four hours such that the total energy storage is 1350 MWt × 8 hours. Each TES is coupled to its own supercritical steam cycle power converter. Discharging the two units simultaneously over four hours provides a total electrical output of 3 × 550 MWe = 1650 MWe. Thus, the baseline full-size TES unit can store 1350 MWt × 4 hours of energy and can be charged or discharged in 4 hours. Each TES unit needs its own dedicated supercritical steam cycle power converter.

A separate significant benefit of TES is that it eliminates the detrimental effects of thermal cycling of the coal plant components (i.e., the boiler, steam lines, turbine, etc.) that would otherwise be needed to perform load following [2]. As the U.S. electrical grid continues to evolve, load following may be forced upon power plant operators as a means of offsetting the variable nature of electricity generation from the ever increasing contribution of renewable energy sources [2]. Thermal cycling from load following shortens the life of these components and can force the power plant owner to retire a power plant earlier than originally planned.

5 Conceptual Designs of Full-Size TES Units

Argonne developed conceptual designs for full-size TES units. Alternate approaches involving alternate configurations were covered. Drawings for the alternate approaches were prepared by Argonne.

6 Coupling TES to a SFR

The Advanced Fast Reactor (AFR)-100 SFR employs a supercritical carbon dioxide (sCO2) Brayton cycle power converter [3 and 4]. The AFR-100 power level is 250 MWt. Heat is transferred from the intermediate sodium loops to the CO2 through sodium-to-CO2 heat exchangers. The intermediate sodium enters the heat exchangers at 528 °C and exits at 373 °C. An idealized TES technology for the AFR-100 would be charged with sodium heat carrier fluid entering the TES at 528 °C and when discharging would heat CO2 with sodium entering the sodium-to-CO2 heat exchanger at 528 °C. The idealized preferred technology when charging would return intermediate sodium from the TES at 373 °C and when discharging would cool the sodium exiting the sodium-to-CO2 heat exchanger with CO2 to 373 °C.

Alternate schemes for coupling the AFR-100 to aluminum alloy-based TES were investigated by Argonne. A scheme that effectively meets the requirements was identified by Argonne. It enables more electricity to be delivered to the electrical power grid when demand is high and less electricity to be delivered when demand is low.

7 Coupling TES to a Coal Plant with a Supercritical Steam Cycle

The coal-fired plant without TES is assumed to generate 1350 MWt of thermal power and incorporate a supercritical steam cycle with an electrical power output of 550 MWe. The boiler steam exit pressure and temperature are 24.1 MPa and 593 °C, respectively [5]. The feedwater is returned to the boiler at 260 °C.

Alternate schemes for effectively coupling aluminum alloy-based TES to the assumed coal-fired plant were identified by Argonne.

8 Preliminary Cost Estimate Comparison of Aluminum Alloy-Based TES with Other Energy Storage Technologies

A preliminary cost estimate comparison was carried out by Argonne for the case of energy storage coupled to a coal plant. Lithium-ion batteries are a current state-of-the-art solution for energy storage. While typical figures of merit for lithium-ion batteries vary in the literature, fairly representative values are an energy density of 620 W·hour/Liter, capital cost of 150 $/(kW·hour), round trip efficiency of 0.80, and 1,500 number of usable cycles. In particular, lithium-ion batteries have a short useful life in terms of number of charging/discharging cycles. With these numbers, the capital cost just for batteries to store 550 MWe of power over 4 hours is $ 330,000,000. In terms of capital cost per unit of stored energy per cycle, this is 12.5 cents/(kWe·hour·cycle). However, after 1,500 cycles, the batteries will need to be replaced incurring another capital expenditure.

For thermal energy storage, a popular technology that is currently envisioned for use with solar power tower Concentrating Solar Power (CSP) power plants is two tank energy storage using liquid salt. The salt, called solar salt, consists of a eutectic mixture of sodium nitrate and potassium nitrate. A problem with solar salt is that it decomposes at high temperature limiting the maximum salt temperature to about 565 °C. Although other salts than solar salt have been proposed for extension to higher temperatures, none have yet been proven to work satisfactorily. The report, "Concentrating Solar Power Gen3 Demonstration Roadmap," NREL/TP-5500-67464, National Renewable Energy Laboratory, January 2017 [6], contains cost estimates for liquid salt thermal energy storage systems. The capital cost of a system to store 2,700 MWt·hour of energy is $53,000,000. For 1,350 MWt of energy stored for four hours, the stored energy is 5,400 MWt·hour. The estimated cost for a pair of two tank liquid salt storage systems is thus $106,000,000. A power converter is needed to transform the stored thermal energy into electrical power. Assuming that the capital cost of a superheated steam cycle power converter is about $1,000/kWe, the power converter cost to generate 550 MWe is $550,000,000. Thus, the total cost is $656,000,000. Assuming a 30 year lifetime and a plant availability of 0.9, the cost per unit electrical power output per cycle is 3.0 cents/(kWe·hour·cycle). This is significantly lower than the estimate for lithium ion battery energy storage.

Summary of Major Accomplishments:

For BgtL's proposed aluminum alloy thermal energy storage, a preliminary cost estimate was carried out by BgtL. Their estimate of the cost of aluminum alloy thermal energy storage is less than that of two tank liquid salt thermal energy storage. However, liquid salt cannot be used with the baseline coal power plant because of the salt decomposition at high temperature while aluminum alloy can be used and matched to the supercritical steam temperature exiting the boiler.

The aluminum alloy TES technology is applicable to any coal power plant. It is thus applicable to all of the industrial scale, small utility scale, and large utility scale market segments. The aluminum alloy TES is competitive with alternative current commercial and emerging technologies including lithium ion batteries and two tank liquid salt thermal energy storage. The latter is limited in temperature range by decomposition of salt limiting the maximum temperature to a value of about 565 °C. Although other salts than solar salt have been proposed for extension to higher temperatures, none have yet been proven to work satisfactorily. The aluminum alloy-based TES can be used at higher temperatures up to 660 °C. The capital cost per unit of stored energy per cycle for the aluminum alloy TES is competitive with alternative technologies especially lithium-ion batteries. This is the main commercial benefit of the aluminum alloy TES technology. The above commercial assessment is adequate in demonstrating the potential for a lower capital cost per unit of stored energy per cycle compared with lithium-ion battery energy storage and thermal energy storage using two tanks of liquid salt.

9 TES Unit Transient Performance Computer Code

A Fortan computer code was developed by Argonne to calculate the transient charging and discharging performance of TES units. The code models the transient heat exchange processes taking place between the aluminum alloy and the heat carrier fluid such as sodium or carbon dioxide for applications involving coupling of TES to a SFR with a sCO2 Brayton cycle power converter. The computer code is fast running enabling the user to carry out many calculations to find an optimal design.

10 TES Unit Transient Performance Calculations

The new computer code was applied by Argonne to determine the transient charging and discharging behvaior of full-size TES units. It was established that TES units can be practically designed that meet the requirements for charging and discharging in numbers of hours consistent with uilization on a daily twenty-four hour cycle. For specific application to the AFR-100 SFR, a charging and discharging time interval of twelve hours each is assumed. It was established that the aluminum alloy can be heated essentially through the melting transition during the charging phase in the required amount of time and cooled essentially through the freezing transition during the discharging phase in the required amount of time.

11 TES Unit Optimization

Many calculations were run byArgonne to optimize the design of modular TES units for use with the AFR-100. Each module is limited in size to be transportable following manufacturing in a factory. Babcock & Wilcox states that their mPower Small Modular Reactor (SMR) is rail shippable to any point in North America in an envelope of 15 feet (4.6 m) by 75 feet (23 m) and 500 tons (450 tonnes) [7]. These limits were assumed for each TES module. An optimized design was determined by Argonne. The optimized design incorporates a cylindrical vessel with a diameter equal to or slightly below 4.6 m

(15 feet). The height is well below the 23 m (75 feet) limit and the mass is below the 450 tonnes (500 tons) limit. Each module is transported with the aluminum incorporated in a solid state. The velocity of sodium or CO_2 was limited to keep the pressure drop through the TES unit less than 0.1 MPa (i.e., about one atmosphere).

12 Conceptual Design of a Small-Scale Testing Facility for Testing of a Prototype TES Unit

The next step in development of aluminum alloy-based TES should be to advance the state of development of BgtL's aluminum alloy TES technology through the design, fabrication, and testing of a prototype TES unit. The prototype unit will have a configuration that is scaled-down in floor area from a commercial-size system but is scaled one-to-one in height and incorporates the identical materials and technologies as a commercial-size system. Testing will involve the same conditions of temperatures, pressures, and scaled down flowrates of the carrier heat exchange fluid as in a commercial-scale unit in a SFR NPP. A secondary objective will be to test, improve if necessary, and validate the computer code developed by Argonne under this GAIN Project to predict the TES unit transient performance and optimize its design for application to future TES systems for SFR and coal power plants.

Argonne developed a conceptual design for a testing facility for testing a prototype TES unit. The appropriate size in charging and discharging power for a prototype TES unit was determined by Argonne. It was found that the charging and discharging power of a prototype TES unit with sodium heat carrier fluid and charging and discharging times of twelve hours each would be about 50 kW or less. Drawings of the testing facility concepts and alternate prototype TES units were prepared by Argonne.

13 Recommended Future Work Under a Future GAIN Award

BgtL with strong support from Argonne prepared a proposal for continuation of this work under a second GAIN award under the second year of the GAIN Program. The requested amount of $ 500,000 versus $ 300,000 for this award would have enabled significant additional progress toward commercialization. Unfortunately, that proposal was not awarded. BgtL and Argonne intend to submit a proposal to continue this work under the third year of GAIN. This report provides documentation of the accomplishments during this Project which is viewed as Phase 1 of a longer development effort. BgtL with strong support from Argonne will again submit a Request for Assistance under the third year of the GAIN Program to continue the work under a second phase.

In Phase 2 of this project proposed under a future Nuclear Energy Voucher program, BgtL will again work with Argonne to continue the development of the TES technology. BgtL will utilize Argonne's unique modeling and analysis capabilities, specifically, the new TES computer code that was developed at Argonne during Phase 1, which will be further developed in Phase 2 to optimize the design of TES units and TES systems for applications to different energy systems. Together with Argonne, BgtL will further refine TES system cost estimates including cost per unit of stored energy per cycle for applications to different energy systems. This will refine the case for commercialization of the aluminum alloy-based TES technology. Based on modeling, a small-scale prototype TES unit for testing under prototypical conditions shall be designed and fabricated. Argonne will also continue and complete the design of a new testing facility for reduced-scale TES system testing, procure parts and components, and carry out assembly. Testing with the small-scale prototype TES unit shall be initiated. This will be the first time that an aluminum alloy-based TES unit will have been tested. Depending upon the test results, it may be necessary to modify the TES unit design or materials and continue testing with the modified unit.

Successful continuation of this Project with a second phase will contribute to advancing nuclear energy deployment by developing a TES system with a melting/freezing range better matched to the reactor core inlet and outlet temperatures while reducing the cost per unit of stored energy per cycle. BgtL's TES technology can enable a SMR nuclear power plant (NPP) such as an AFR-100 SFR NPP to perform load following over a wide range of loads without having to change the reactor operating conditions. This reduces thermal stresses and thermal fatigue on reactor components thereby enabling load following and contributing to enhanced safety. On a small or isolated power grid, load following would be a requirement for a SMR NPP such as the Argonne AFR-100 SFR SMR design. With thermal energy storage, the reactor can be operated at essentially unvarying conditions using the TES system to store thermal energy when the demand for electricity is low and providing thermal energy at a greater rate when the demand for electricity is high.

Acknowledgements

Argonne National Laboratory's work was supported by the U. S. Department of Energy Gateway for Accelerated Innovation in Nuclear (GAIN) Program under Prime Contract No. DE-AC02-06CH11357 between the U.S. Department of Energy and UChicago Argonne, LLC. The authors are grateful to Hussein Khalil (Argonne) and John Howard Jackson (Idaho National Laboratory) who manage the GAIN Program at Argonne and INL. Special thanks go to Zhijun Jia, Cindy Jia, and Tom Parlow of BgtL. Figures were drawn by Lu Krajtl (Argonne).

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Summary of Technology Transfer Benefits to Industry:

The Fortran computer code developed by Argonne will enable BgtL to better design TES units to meet the requirements for charging and discharging for specific applications. BgtL will be able to optimize TES unit designs to make them more economical.

The schemes developed by Argonne for coupling aluminum alloy-based TES units to nuclear and coal power plants will assist in the development of the market for TES by showing potential customers how TES can practically be used with a heat source.

Other Information/Results: (Papers, Inventions, Software, etc.)

The scheme for coupling aluminum alloy-based TES to a SFR has been claimed as an invention by Argonne.

A Fortran computer code modeling the transient behavior of aluminum alloy-based TES units has been developed by Argonne.

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