# Energy Storage: Improving Fast Reactor Economics

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*Metallic fueled fast reactors can load follow without adverse consequences to the fuel. However, when used in this manner, capital recovery becomes very difficult, because of the lower duty cycle. By incorporating existing solar thermal storage designs with a fast reactor like General Electric-Hitachi S-PRISM, the reactor can operate at a 90% capacity factor while providing 99.9975% of all electricity. All of this was done with existing technology and materials. The only component not already commercially deployed and with unknown costs is the reactor.*

*The conceptual design used salt storage tanks and pumps built for the Andasol 1 project in Spain. These tanks were coupled with one S-PRISM power block. Peaking capacity uses 210 MW(e) of simple combustion turbines with the turbine exhaust also heating the salt. Power conversion of the salt's heat uses a thermodynamic model of a Rankine cycle typical in coal plants. The cost of the thermal energy storage added $45/kW(e) to the overall cost of the project.*

*While hybridization of energy systems is not new, our approach brings hybridization to practical reality and allows direct conversion of existing coal plants to nuclear generating stations. Preliminary cost estimates of such brownfield repowering are $110/MW-hr, with greenfield sites at $145/MW-hr. These costs are not the cost of baseload power. They are the cost of ALL electricity including peaking and reserve margin. No other combination of existing technologies achieves these economics.*

## INTRODUCTION

Nuclear reactors have the lowest marginal cost of any thermal power source, however they have some of the highest capital costs of any power generation source.[1] This split in costs makes reactor projects very expensive forcing utilities to run their reactors at near peak capacities. The problem of using nuclear reactors to load follow is not a technical one. It never was a technical problem. In fact, the first power reactor ever built, S-1W, was for naval applications – designed for rapid power transients. The issue was and is always one of economics and fuel performance. While navies around the globe spend considerable research dollars perfecting load following fuels, commercial reactors have not. Metal-fueled reactors solve the problem of fuel performance, however the problem of economics remains. The design presented in this paper focuses entirely on addressing the economics of load following.

While this design has significant impacts on improving reactor safety, allowing for a more flexible duty cycle, reactor safety is not addressed in this paper. Instead it focuses on the economics and the overall design philosophy – material selection done as part of a scoping and feasibility study. The design can be adapted to other higher temperature reactors, or even used as a bottoming cycle for those reactors, such applications were not considered, as they do not address Used Nuclear Fuel disposition.

## DESCRIPTION OF THE ACTUAL WORK

### Part I: Energy Storage Conceptual Design

Our design is fundamentally different from the class of ground storage designs proposed by others.[2] The fundamental approach taken to meet variable duty cycles is to compartmentalize the capital costs of various components and then optimize each compartment for its specific task. The act of modular specialization improves the overall performance of the system. Instead of having one super system that can do everything, putting optimized blocks together achieves similar performance characteristics with less capital input. This is a fundamental characteristic of biological systems. Also borrowed from biological systems is the idea of throwing nothing out and using vestiges of the past in slightly different fashions, e.g. limited use of fossil fuels and repowering existing power stations.

The design started by taking two tanks 36 m in diameter and 17 m tall, roughly the size of Andasol 1 and attaching them to two 840 MW(t) S-PRISM modules. The salt used in storage was "Solar Salt" a binary mixture of 60-40 $NaNO_3$ – $KNO_3$, costing $0.50/kg.[3]

Using equations of state for the salt, the model was integrated with 4-years of electricity demand for the Bonneville Power Administration, BPA, (2007-2010), divided into 5-minute increments.[4] We determined the tank level using a simple logic function to maintain minimum tank level for salt pump protection integrated with the salt equations of state in the discretized form of the fundamental equation of thermodynamics.

While the initial design significantly improved economic and operational performance, it did not meet the needs of the utility, supplying ~ 90% of all electricity. The next step was to integrate (5) 42.1 MW(e) GE MS-6001B combustion turbines. These turbines supply electricity directly to the grid when tank levels fall to 35%. The 548 °C exhaust gas from the turbines is cooled with salt from the cold salt tank and added to the hot tank.

The two main materials used are carbon steel (<320 °C) and SS 316L (<550°C). SS-316L is used in all heat exchangers except the turbine exhaust gas coolers, because it is compatible with sodium, water, and solar salt. The turbine exhaust gas cooler uses Inconel Alloy 617. All materials are widely available and entail no special considerations. Heat exchangers can be shell and tube or compact designs. Our design uses Heatric heat exchangers. Fin plates are used in; the sodium, exhaust gas, and salt systems. Printed circuit plates are used for the high-pressure power conversion system.

The largest commercial salt pump available is the Friatec GVSO 400/500, 21 are used in the system. One pump provides salt to the combustion turbines, 12 are used to supply the power conversion system and the remaining 8 pumps are used for the reactors, 4 per reactor. The system is designed to operate at 100% capacity with one pump in a maintenance condition for each reactor/BOP loop. The tanks/pumps/heat exchangers are a simple system with most periodic inspections done without interfering with system operation. The pumps are designed for equipment rotation and online maintenance. Overall the energy storage system should have no impact on the Effective Forced Outage Rate

The operational design philosophy is similar to that of aircraft carrier systems. Where two reactors operate independently or in a cross-connected fashion, e.g. one reactor's salt pumps can provide flow for heat rejection to the other side's reactor. Normal operations are done with the reactors isolated from each other. Only during abnormal operations are the two systems cross-connected. Here, if both reactors' salt systems are lost the reactors rely on the Auxiliary Cooling System or the Reactor Vessel Auxiliary Cooling System for thermal coupling to the Ultimate Heat Sink.[5, 6]

Extending the design philosophy of NUREG-1368, the salt storage design should assuage any concern the Nuclear Regulatory Commission (NRC) has on not having regulatory prevue for the Balance of Plant (BOP).[6] By removing regulatory oversight of the NRC over the BOP, it is possible to use the heat from the reactor for purposes other than generating electricity with no artificial cost inflation. The energy storage provides additional buffering from a reactor allowing stately shutdowns of any downstream load; minimizing shock to sensitive systems. Additionally, a reactor trip would not change electrical load as under most circumstances the combustion turbines would have adequate time to start and replace the heat supply lost with the reactor. Conceivably, there could be minimal downtime or even a reduced output vice a complete shutdown. All of these characteristics are attractive for chemical processes and electricity generation.

Another feature afforded by energy storage is that the grid balancing authority can have operational control of the combustion turbines and the BOP, for both voltage and frequency. The stored energy in the storage tanks can be managed across the entire grid allowing load dispatchers to instantly respond to changes in demand or forced outages anywhere inside or outside the service area. All of which improves the quality of electrical service to the consumers.

**Part II: Economics and Operations**

To estimate the overall costs, the BPA generated an average power of 12,180 MW(e) and a peak power of 20,571 MW. 10.5 power blocks replaced BPA's entire generation portfolio. This left a conventional reserve margin for peak loads of 22.8% and is consistent with North American Electric Reliability Corporation guidelines.[7]

The reactor plants used a two-year outage schedule, with the reactors at the 10 dual unit sites alternating years. By adjusting the outage schedule to coincide with seasonal demand, the needed thermal storage for a dual unit site became 1.78 GW(t)-hr, not 1 GW(t)-yr estimated by others.[2]

The BOP was 934 MW(e) for each dual unit site. All cost estimates are referenced to this capacity, for ease of calculation. The cost of the 1.78 GW-hr of storage was $45/kW(e) based off of Kearny's 2002 numbers. These costs projections may vary substantially depending on the operational data of the key components; however, the impact of the cost sensitivity of the storage on the overall electricity cost is negligible. Using EIA's cost estimates for conventional combustion turbines, the fraction of the sites total cost for the 5 installed CT's was $217/kW(e) referenced to the BOP rating. For the greenfield cost estimates the BOP cost $1,200/kW(e).

We estimate the cost for the reactor portion based off of EIA's cost estimates for a dual unit Light Water Reactor (LWR) and GE-H estimates of PRISM costs on par of a LWR. Because the salt is compatible with the sodium, the hydrogen explosion suppression system was removed. All coolant interfaces are not chemically reactive. The cost savings from this simplification are not included due to overall price uncertainty. The assumed cost of a full power block of S-PRISM reactors plus a GE-H designed BOP is $5,280/kW(e) with the nuclear island being $4,080/kW(e). Because the reactor in the design presented here is undersized compared to the BOP the nuclear island in this design costs $2,717/kW(e).

The complete system for brownfield installation cost \$2,979/kW(e) and the greenfield \$4,179/kW(e). The BOP operated at an overall capacity factor of 61.7% resulting in a Levelized Cost of Electricity of \$115/MW-hr for the brownfield and \$151/MW for the greenfield. This is 100% of all electricity consumed in the service area, not just baseload and *includes a 22.8% rolling reserve margin*. For comparison, S-PRISM by itself supplying baseload power, 90% capacity factor, is \$128/MW-hr by the same methodology (45% debt at 8% and equity at 14% and 4-year construction).[1, 8]

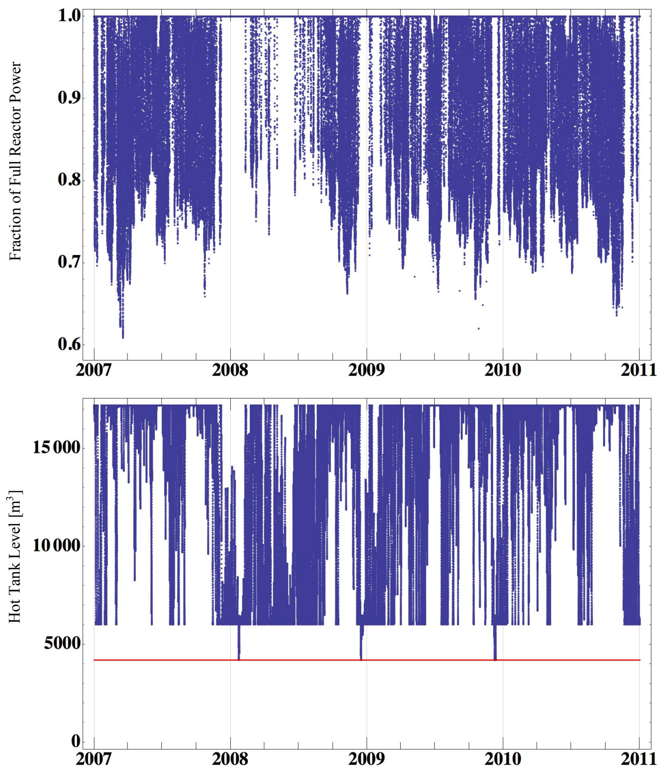


Fig. 1. Fraction of full power of reactors not in an outage and the level of an individual in-service salt storage tank.

Adding additional combustion turbines increases the capacity factor of the BOP lowering the overall cost of electricity. However, the fraction of energy produced from nuclear lowers from 99.9975% very quickly. The cost estimates here show a limiting scenario where the input from fossil fuels is effectively eliminated.

To minimize the cycling of the combustion turbines the pumps start sequentially at a hot tank level of 35% and all secure at 85%. Each CT sequentially starts until the level of the hot tank stops lowering or every CT is operating at full capacity. This strategy maintains an adequate tank level except for a period of four hours over a 4-year period. Figure 1 shows tank levels and the capacity factor for each operating reactor. Grid operators can readily adjust the combustion turbine operations and adjust tank levels based upon forecasted loads and demand. The duty cycle here is particularly challenging because it includes power produced by several GW of wind energy.

**CONCLUSION**

Our study shows the feasibility and practicality of implementing GW-hr energy storage with mid temperature reactors like GE-H S-PRISM. The economic cost of storage is 1.7% the overnight cost of the reactor, providing a significant increase in the operational capability of the reactor, complete load following with an average 90% capacity factor. The integration of combustion turbines allows rapid load response with the thermodynamic efficiency of a combined cycle plant, 43%.

Because the reactor is separated from the load the load can be fully controlled through remote operation by the dispatcher. Electricity can be purchased when rates are low and stored in the event of a forced outage. These and other operational characteristics make this technology attractive.

**FUTURE WORK**

The next step in this preliminary study is to assess the load following capability of the reactors and run various casualties to assess the reactor kinetic response to fully test the hypothesis of reactor kinetics being entirely separated from the load. Further work also needs to be done on economic optimization as a function of natural gas prices. There are other safety features, such as being able to bootstrap the grid, maintain reactor operations during a loss of offsite power, using non safety related combustion turbines in providing safety related power for the reactors, etc that require a more comprehensive and detailed safety evaluation.

**NOMENCLATURE**

*BOP* = Balance of Plant
*BPA = Bonneville Power Administration*
*(e) = electric*
*°C* = degree Celsius
*CT* = Combustion Turbine
*GE* = General Electric
*GE-H* = General Electric Hitachi
*GW* = gigawatt
*hr* = hour
*kg* = kilogram
*kW* = kilowatt
*LWR* = Light Water Reactor
*MW* = megawatt
*NRC = Nuclear Regulatory Commission*
*S-1W* = USS Nautilus prototype reactor plant
*S-PRISM* = Super Power Reactor Innovative Small Module

*SS* = stainless steel
*(t)* = thermal
*yr* = year

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