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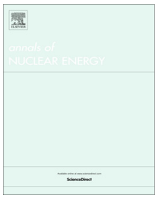

Exergy analysis of thermal energy storage options with nuclear power plants

Jacob Edwards[a], Hitesh Bindra[a,*], Piyush Sabharwall[b]

[a] Department of Mechanical and Nuclear Engineering, Kansas State University, Manhattan, KS 66506, United States
[b] Idaho National Laboratory, Idaho Falls, ID 83402, United States

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ABSTRACT

Storing excess thermal energy in a storage media, that can later be extracted during peak-load times is one of the better economic options for nuclear power in future. Thermal energy storage integration with light-water cooled and advanced nuclear power plants is analyzed to assess technical feasibility of different options. Various choices of storage media considered in this study include molten salts, synthetic heat transfer fluids, and packed beds of solid rocks or ceramics. Due to limitations of complex process conditions and safety requirements there are only few combinations which have potential integration possibilities. In-depth quantitative assessment of these integration possibilities are then analyzed using exergy analysis and energy density models. The exergy efficiency of thermal energy storage systems is quantified based on second law thermodynamics. This study identifies, examines, and compares different energy storage options for integration with modular NPPs, with the calculated values of energy density and exergy efficiency. The thermal energy storage options such as synthetic heat transfer fluids perform well for light-water cooled NPPs, whereas liquid storage salt show better performance with advanced NPPs as compared to other options.

1. Introduction

Nuclear power plants (NPPs) have negligible carbon emission rates as compared to their fossil fuel counterparts, but their inability to follow grid load demands make them economically less competitive. The reason behind this economic disposition for NPPs is because of various associated technical complexities. These technical challenges include the adequate handling of reactivity swings caused by time-varying fuel and moderator temperatures, a higher fuel-failure probability due to thermal-structural cycling, and spatial variations in xenon concentrations. Although there are presently some reactors around the world that are operating with flexible load-following capabilities, such operation is restricted to slowly-varying powers, 2–3 times a day, and only up to 80% of the fuel cycle. On the other hand, most of the fossil fueled plants can supply peak-loads by adding more fuel and, thus, can generate far more revenue during those peak hours. The use of NPPs for peak load following is quite complex due to technical constraints associated with reactor behavior. Thus, a more convenient and effective method to facilitate load following by NPPs would be to integrate energy storage. If the grid demand is reduced, then the excess reactor thermal power or plant electrical power is stored in an integrated storage device. This stored energy can be released to the grid when demand is higher than what the NPPs can produce at 100% reactor power (Forsberg and Curtis, 2013). There are many options for storing either the thermal energy from the nuclear reactor or the electricity from the turbo-generator in the power cycle, with both having their advantages and disadvantages respectively. Thermal, mechanical, and electrical energy storage are the most commonly used storage options. Thermal energy storage is the energy stored in the form of heat in well-insulated solids or liquids, as either sensible heat, stored within a single phase media, or latent heat, stored within phase change materials. Thermal energy storage options include but are not limited to molten salt, packed beds, heating oils, ionic liquids, phase change materials and steam accumulators. Mechanical energy storage is any kinetic or potential energy stored within a device and electrical energy storage resides in the buildup of electrons within systems called electric condensers, which store the charges between two parallel plates when a voltage is applied. Mechanical storage options include but are not limited to compressed air, pumped hydroelectric, flywheels, whereas electrical storage options include batteries and capacitors. Electrical energy storage has the advantage of directly storing the final usable form of energy i.e. electrical energy, but disadvantages come from the high costs and

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[*] Corresponding author.
E-mail address: hbindra@ksu.edu (H. Bindra).

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irreversibility. Mechanical energy storage processes such as pumped hydro have higher degree of reversibility but disadvantages include non-negligible energy losses and substantially large space requirements for grid scale storage. Disadvantages with thermal storage is the low efficiency of the conversion process from thermal to electrical energy but with NPPs generating large amounts of thermal heat, a thermal energy storage system becomes advantageous. Therefore, among these various options to store energy, thermal storage is economically more competitive for NPPs as compared to electrical or mechanical energy storage options. However, the adoption of a particular thermal storage option is largely dependent upon the operating and process conditions of the nuclear heat source and reactor coolant. Light-water NPPs operate at lower temperatures than Next Generation Nuclear Power (NGNP) reactors and only use pressurized water as the main coolant, whereas NGNP reactors use molten salts or high temperature gasses as the main coolant. The critical step remains how to select and develop an ideal choice of heat transfer fluid or storage media (Bejan, 1978). Currently, there are some thermal storage solutions such as molten nitrate salt, also known as storage or solar salt ($40\%KNO_3 + 60\%NaNO_3$) and packed bed of alumina particles which present very low technological risk and a high deployment potential. These solutions can be good candidates for some of the advanced high-temperature reactors but have some limitations for integration into light-water cooled NPPs. Therefore, other materials such as synthetic heat transfer fluids need to be explored to evaluate the options to store thermal energy for light-water NPPs. An overall comparative economic analysis can help in decision making process for storage integration, however for new materials and methods it is difficult to estimate the actual costs or effective costs if those technologies are deployed in large scale. Thus, an energy density and exergy model are used to compare different technologies and materials in this study.

2. Nuclear power plants considered

Firstly, different NPPs which can be considered as potential candidates for TES integration will be briefly described with the sufficient details in the process system conditions. For this analysis three NPP designs are selected – light water-cooled small modular reactors (LW-SMR), the modular high-temperature gas-cooled reactor (MHTGR) and pebble-bed fluoride-salt-cooled high-temperature reactor (PB-FHR). The schematics of each type are shown in Figs. 1–3, and Table 1 shows key features of the different reactor systems. The basis of selection of these designs is to analyze a broader spectrum of reactor operation temperatures and to understand the impact of substantially different thermophysical properties of the reactor coolant. The mode of thermal storage integration is however kept similar in all possible combination of NPPs and TES systems.

2.1. Light-water NPPs

Light Water Reactors (LWRs) produce saturated steam to operate steam turbines on the Rankine cycle principles and are the most widely established type of NPPs throughout the world. LWRs are further categorized as Boiling-Water Reactors (BWRs), Pressurized-Water Reactors (PWRs) and LW-SMRs (Light water small modular reactors). BWRs produce steam directly through core heat transfer and require more attention to ensure safety of thermal storage and will not be considered in this study. PWRs consists of the nuclear reactor where pressurized light water is circulated to remove the reactor heat and transfer it to a secondary side, via steam generator that transfers the thermal energy of the pressurized water to produce steam that runs through the turbine in the outer Rankine cycle loop. On the other hand, BWRs do not have two loops and the reactor coolant i.e. light water gets directly converted into steam which is then used as a working fluid to do mechanical work. There are small modular designs for both PWRs and BWRs, which are categorized as LW-SMRs. Due to thermodynamic and heat transfer limitations, both types of the LWRs produce steam at 280 °C or less. At these temperatures, thermodynamic efficiency is close to 35%, therefore adding thermal energy storage should not deteriorate the exergy efficiency substantially. The two routes of storing heat energy in LWR plants are – directly storing the energy from working fluid i.e. steam, or extracting thermal energy from primary coolant into energy storage media. Due to latent heat of steam the direct heat recovery from steam into storage media is associated with pinch point. Therefore BWRs are naturally in a disadvantageous position for thermal storage integration as compared to PWRs. In the PWRs, the losses due to heat transfer between the pressurized water and steam is one of the significant reasons for the exergy destruction. Therefore ideal configuration for storage integration is to store the energy from the primary reactor coolant i.e. pressurized light water. However, in NPPs the reactor coolant is considered as one of the intermediary layers for radioactivity containment, so for safety measures the coolant is generally not allowed to leave the containment building. This safety philosophy and large volume requirements for TES systems, postulate the thermal storage integration to NPPs via heat exchange between reactor coolant (RC) and secondary heat transfer fluid (HTF). Thus for nuclear safety requirements the heat exchanger which

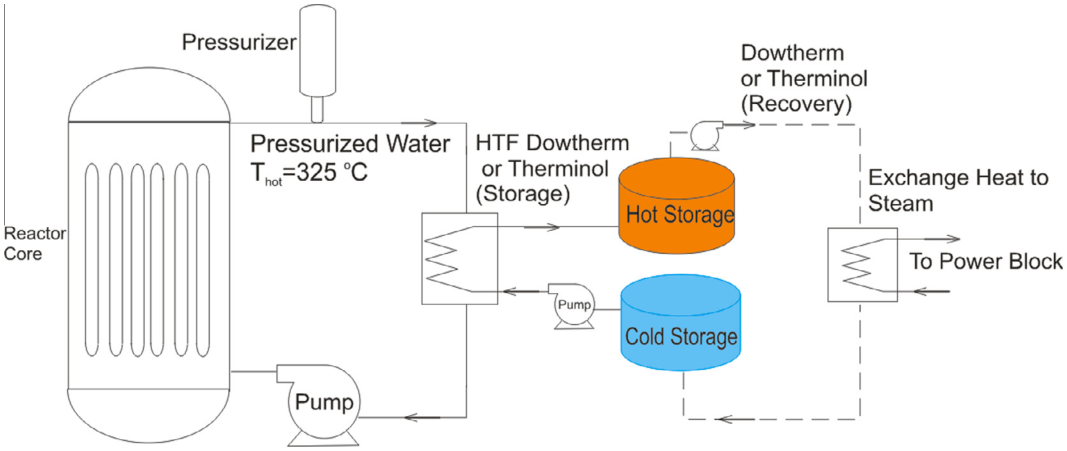

Fig. 1. Light-water small modular reactor integrated with a two storage tank system with either therminol or dowtherm as storage medium.