Exergy Analysis of Thermal Energy Storage options with Nuclear Power Plants

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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.

Keywords: Nuclear Power Plants, Thermal Energy Storage, Exergy Efficiency, Energy Density

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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 [1]. 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 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 [2]. 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

74 shown in Figures 1-3, and Table 1 shows key features of the different reac-
 75 tor systems. The basis of selection of these designs is to analyze a broader
 76 spectrum of reactor operation temperatures and to understand the impact of
 77 substantially different thermo-physical properties of the reactor coolant. The
 78 mode of thermal storage integration is however kept similar in all possible
 79 combination of NPPs and TES systems.

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

Figure 2: Modular high-temperature gas-cooled reactor integrated with a packed bed storage system with alumina spheres as the packing material.

80 2.1. Light-Water NPPs

81 Light Water Reactors (LWRs) produce saturated steam to operate steam
 82 turbines on the Rankine cycle principles and are the most widely estab-
 83 lished type of NPPs throughout the world. LWRs are further categorized as

Figure 3: Pebble bed fluoride-salt-cooled high-temperature reactor integrated with a two tank storage system with molten nitrate molten salt as storage medium.

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. The PWRs have intermediate heat exchangers or steam generators which transfer the thermal energy of the pressurized water to the secondary coolant i.e. water and convert it into steam to operate a steam-turbine to produce electricity. There are small modular designs for both PWRs and BWRs, which are categorized as LW-SMRs. 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. 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 exchanges heat between RC and HTF can be housed inside the reactor containment building. The hot HTF is brought outside the reactor containment building to store energy in a TES system. Nevertheless, the secondary reason for the need of this heat exchange process arises due to the compatibility issues of different TES systems and HTF requirements. In case of existing NPPs, the reactor containment building layout is generally does not have enough flexibility to add additional heat exchange equipment of large scale. But in the new light water NPP designs such as LW-SMRs, this design provision in the reactor building layout can be made.

Due to the presence of additional resistances in the heat exchanger, the actual storage inlet temperature T_{in} is lower than the RC outlet temperature and thus is dependent upon the effectiveness of an indirect heat exchange process or design. Irrespective of the design details of heat exchange equipment, the heat transfer between two streams can be solved using the effectiveness values to obtain the HTF temperature during storage cycles. The operating temperatures and RC properties are provided in Table 2 for the LW-SMR [3].

2.2. Advanced NPPs with advanced coolants

In recent years the focus for new nuclear power plants has been on higher operating temperatures to improve overall plant efficiency and increase the outlet temperature of the main coolant. Increasing the outlet temperature allows for other possible applications such as hydrogen production or petroleum refining, in addition to higher efficiency power cycles. The performance of thermal energy storage options is also highly dependent upon temperature, as concluded by many previous studies[4, 5, 6, 7, 8].

2.2.1. Modular High-Temperature Gas-Cooled Reactor

MHTGRs utilize helium for the RC flowing through the graphite moderated core, where the outlet temperature of helium can reach temperatures of

1000 °C and higher, leading to higher thermal-to-electrical energy efficiency than that of light-water cooled NPPs, using an intermediate heat exchanger coupled with a helium-brayton cycle. Helium also has advantage of being a safer RC over water due to no threat of film boiling or two phase flow causing a reactor accident. In this study the focus is on a prismatic bed MHTGR design that has a electrical output of 286 MW(e) and the reactor system is rated at 600 MW(th). The operating conditions and RC properties at the average temperature are listed in Table 2 for the MHTGR [9]. Similar to LW-SMRs described before, the philosophy of safety requires a secondary HTF to transfer thermal energy from RC to a TES system located outside the containment. In case of gas-cooled reactors, one of the major apparent difference is in the higher temperature differences between inlet and outlet conditions. This is attributed to lower density as compared to liquid coolants leading to relatively smaller energy carrying capacity. Due to higher temperature differences, if the effectiveness of heat exchange process between RC and HTF, is poor it leads to proportionate losses thereby resulting in larger differences between the reactor outlet temperature and storage inlet temperature. Thus, the impact of heat exchange process effectiveness must be investigated more carefully for MHTGRs.

2.2.2. Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor

PB-FHR design has fluoride molten salt (FLiBe) as the RC with fuel and reflector in the shape of spherical pebbles. The molten salt circulates through the pebble bed core and obtains the core outlet temperature of 700 °C before exchanging its thermal energy to secondary cycle for power production, or a secondary molten salt coolant for other high temperature processes, such as hydrogen production. Molten salt as the RC has advantages of no high pressure requirements or gas-liquid two phase interfaces, and it also allows high temperature operation as compared to LWRs. Due to low vapor pressure at higher temperatures, it remains in liquid state at atmospheric pressure. The PB-FHR design is a 236 MW(th) reactor system, with a corresponding electrical power rating of 100 MW(e) at the base-load operation. Operating conditions and RC properties are provided in Table 2 for the PB-FHR [10]. Similar to design philosophy of the two reactors described above, all the RC system components remain within the containment and TES layout will be outside the reactor building. So the goal is to find a compatible HTF which can remove the heat effectively from the molten salt.

Table 1: Key features for the three discussed reactor types.

NPP type	LW-SMR[3]	MHTGR[9]	PB-FHR[10]
Reactor Coolant	Water	Helium	FLiBe
Working Fluid	Steam	Helium	Air
Reactor Thermal Power (MW_{th})	500	600	236
NPP electric output (MW_e)	158	286	100

Table 2: Thermal properties for Nuclear Power Plants reactor coolants for the three discussed reactor types.

NPP type	LW-SMR[3]	MHTGR[9]	PB-FHR[10]
Reactor Coolant	Water	Helium	FLiBe
Inlet/Outlet Temp. ($^{\circ}C$)	290/325	490/850	600/700
Density (kg/m^3)	900	2.7902	1889.15
Specific Heat (kJ/kg-K)	6	5.1903	2.4
Thermal conductivity (W/m-K)	0.0468	0.413	1
Viscosity (mPa-s)	1	0.0526	7.524

3. Thermal Energy Storage Options

Sensible TES is more robust and established than any other thermal energy storage systems[8, 11]. It has been shown by Bindra et al. [12] that sensible heat storage have much higher exergy efficiency for high energy density storage design as compared to other mechanisms. So, in this work integration studies are only performed with sensible TES. The temperature difference between cold state and hot state, and thermal capacity of the media determine energy density of sensible heat. Solid and liquid sensible heat storage solutions are most common and both offer advantages and disadvantages for storing thermal energy at different operating temperatures. Solids although have higher energy density can make the design and integration complicated due to the need of a tertiary heat transfer fluid. Liquids such as molten salt don't need a tertiary media as they have sufficient thermal capacity to be stored 'as it is' when they are hot without any pressurization requirements. However, liquid options can have more operating constraints which limit their operating range such as, most of the molten salts can not be used for light-water cooled NPPs because of their higher melting temperature, i.e. 200 °C or above, which compels the system to have an auxiliary heating mechanism such as electrical heating to ensure the molten salts remain in molten state even when the NPP is not operating or when not storing heat. Thus, an overall technical feasibility analysis must be conducted in selecting the type of TES system.

3.1. Various TES technologies

TES solutions which are discussed in this work are the well established materials and methods - storage salt ($40\%KNO_3 + 60\%NaNO_3$) two-tank storage, synthetic heat transfer fluids in two-tank storage configuration, and solid alumina particles in packed beds. Storage salt (nitrate) is popularly known as solar salt or molten salt, but in this paper in order to avoid confusion FLiBe will be the only salt referred to as molten salt. Figure 4 shows the NPP type integrated with the TES storage media options investigated in this study. The storage or secondary heat transfer fluid temperature in a nuclear energy system is limited to the temperature of the RC. There are two categories of secondary or storage media HTFs for NPPs: gaseous heat transfer fluids such as air or CO_2 , and storage salt or any other high temperature liquid. Gaseous phase heat transfer fluids, due to their low density and thus lower thermal capacity, act as a tertiary media for transferring heat

218 from the primary system to solid thermal energy storage which has much
 219 higher thermal energy density. The temperature difference between the cold
 220 state and hot state of the liquid determines the energy density. As mentioned
 221 earlier, storage salts because of their higher melting temperature, i.e. 200 °C
 222 cannot be used for LWRs such as SM-LWRs which requires the system to
 223 have auxiliary heating mechanism such as electrical heating to ensure the
 224 molten salts will remain in molten state even when the NPP is not operat-
 225 ing. This auxiliary heating system will lead to higher parasitic losses and can
 226 lead to lower efficiency for LWRs. Thus, the alternative ideal fluid to transfer
 227 and store this thermal energy should be a liquid near the RC temperature
 228 at atmospheric pressure, has a melting point below the room temperature,
 229 has sufficient thermal capacity and is also stable up to the operating re-
 230 actor temperature. The only types of fluids which satisfy all these criteria
 231 and pose low technological risk are synthetic HTFs such as Therminol66
 232 (modified terphenyl) or DowthermT (mixture of $C_{14} - C_{30}$ alkyl benzenes).
 233 However, these operating temperature challenges do not play any significant
 234 role for advanced reactor designs which have primary system at much higher
 235 temperatures as compared to melting temperature of storage salts. There-
 236 fore advantages and challenges of different thermal storage media should be
 237 evaluated based on overall performance of the integrated system. The com-
 238 parison of thermal storage media properties for low temperature and high
 239 temperature integration are reported in Table 3 and Table 4, respectively.
 240 The concept design for the various TES integrated options for the NPP types
 241 and TES types can be seen in Figures 1-3. Figure 1 is of an LWR integrated
 242 with the two storage tank option for either Therminol or Dowtherm as the
 243 storage media. Figure 2 shows a MHTGR integrated with a single alumina
 244 packed bed storage system utilizing air as the HTF, and Figure 3 has a PB-
 245 FHR integrated with a two storage tank system for Solar salt as the storage
 246 media.

247 4. Exergy and Energy density quantification model

248 The disadvantage of the heat transfer in the heat exchanger between
 249 the RC and HTF for storage is that it reduces the top temperature during
 250 storage and in turn exergy efficiency of the system. The heat exchange
 251 process between HTF and RC is an important component of the model which
 252 involves indirect heat exchange to the HTF of the TES system. Due to the
 253 presence of additional resistances in the heat exchanger, the actual storage

Table 3: Thermal properties for Therminol and Dowtherm (at average temperatures for energy storage i.e. 570 K)

Storage type	Therminol66[13]	DowthermT[14]
Density (kg/m^3)	816	687
Specific heat (kJ/kg-K)	2.531	2.767
Thermal conductivity (W/m-K)	0.096	0.075
Viscosity (mPa-s)	0.44	0.39
Min. operating Temp. (K)	270	263
Max. operating Temp. (K)	588	618

Table 4: Thermal properties for Solar salt and Alumina (at average temperatures for energy storage i.e. 900 K)

Storage type	Solar Salt[15]	Denstone-99 Alumina[16]
Density (kg/m^3)	1790	3930
Specific heat (kJ/kg-K)	1.560	1.195
Thermal conductivity (W/m-K)	0.51-0.60	9.685
Viscosity (mPa-s)	1.3-1.6	NA
Melting point (K)	415	NA
Max. operating Temp. (K)	1000	NA

Figure 4: NPPs matched with potential TES options

inlet temperature T_{in} is lower than the RC outlet temperature and thus is dependent upon the effectiveness of an indirect heat exchange process or design. Irrespective of the design details of heat exchange equipment, the heat transfer between two streams can be solved knowing an effectiveness for the heat exchanger to obtain the HTF temperature. Irrespective of the design details of heat exchange equipment, the generic heat transfer model can be written as,

$$(T_{RC} - T_{HTF}) = f(\epsilon, \dot{m}) \quad (1)$$

where, T_{RC} is RC temperature, T_{HTF} is HTF inlet temperature to TES, ϵ is the overall heat transfer effectiveness in the heat exchange process, and $\dot{m}$ is the coolant flow rate.

For present study of system exergy quantification, the following assumptions can simplify the analysis: a) the temperature difference between the RC and HTF streams remains constant throughout the flow path inside the heat exchanger, and b) the overall heat transfer coefficient is only dependent upon the minimum heat transfer coefficient across the heat exchange equipment. Based on these assumptions, inlet temperature for energy storage can be estimated. Therefore, introduction of thermal storage reduces the temperature at which energy is produced. Thus storage leads to exergy destruction due to heat transfer resistance. The effect of exergy reduction due to reduction in temperature of energy transfer reduces the **exergy** ultimately going to the power block.

4.1. HTF Temperature

In this problem both inlet and outlet temperatures of RC are fixed as they govern reactor behavior directly and any changes in that will involve serious considerations for reactor safety and regulatory aspects. Using these fixed RC inlet and outlet temperatures, the inlet and outlet temperatures of

HTF can be evaluated using standard heat exchanger design equations. **Rate of enthalpy transfer** per unit change in the temperature labeled as C_r and C_f , are used to compute the fractional temperature change ratio C_m , i.e. the ratio of change in temperature of the minimum enthalpy fluid to maximum enthalpy fluid (Equations 2-4).

$$C_r = \dot{m}_r c_{p_r} \quad (2)$$

$$C_f = \dot{m}_f c_{p_f} \quad (3)$$

$$C_m = \frac{C_r}{C_f} \quad (4)$$

The subscript 'r' denotes hot side fluid i.e. RC and 'f' denotes cold side fluid i.e. storage HTF. So first the effect of this heat exchange process is modeled and then the HTF temperature is obtained for the storage inlet condition. With the assumption that temperature differences remain constant between the RC and HTF and using the fractional temperature change ratio and setting an effectiveness for the heat exchanger depending on the RC and HTF, the HTF outlet temperature is calculated using equations 5-7.

$$\Delta T_f = C_m \Delta T_r \quad (5)$$

$$T_{f,in} = T_{r,in} - \frac{\Delta T_f}{\epsilon} \quad (6)$$

$$T_{f,out} = T_{f,in} + \Delta T_f \quad (7)$$

It should be noted that if effectiveness ϵ is not known, NTU must be known to compute the effectiveness for a particular heat exchange process. In this work the range of effectiveness is selected based on temperature data in the primary and secondary side across heat exchangers.

4.2. Exergy modeling

Exergy efficiency is an effective indicator to find the actual value of TES integration in power plants. Extensive work on exergy analysis of TES systems has been performed for the storage and recovery stages of the TES cycle

300 [12]. From this previous work the exergy of the inlet fluid/gas storing the
 301 thermal energy in a TES system is given by

$$\Xi_{st} = \int_{t_p} \{\dot{m}C_{pf}(T_{r,in} - T_0) - \dot{m}C_{pf}T_0 \ln(\frac{T_{in}}{T_0})\}dt \quad (8)$$

302 where, C_{pf} is the specific heat of fluid and T is the temperature. The energy
 303 is stored in the TES unit for a time period (t_p), where it is then recovered
 304 and the exergy of the outlet fluid is equal to

$$\Xi_{re} = \int_{t_p} \{\dot{m}C_{pf}(T_{f,out} - T_0) - \dot{m}C_{pf}T_0 \ln(\frac{T_{out}}{T_0})\}dt \quad (9)$$

305 The subscripts 'in,' 'out,' and '0' represent 'inlet,' 'outlet,' and 'reference'
 306 conditions respectively. The fractional exergy recovery or exergy efficiency
 307 of the storage system is computed for evaluating the economics. The basic
 308 model of converting dynamic temperature output information from storage
 309 system to exergy parameters has been detailed previously [17].

$$\eta_{th} = \frac{\Xi_{re}}{\Xi_{st}} \quad (10)$$

310 Dimensionless temperature, $\theta = \frac{T_f - T_0}{T_r - T_0}$, is used to simplify the exergy
 311 calculations to

$$\eta_{ex} = \frac{\int_{t_p} [\theta + \frac{1-\eta_{carnot}}{\eta_{carnot}} \ln(\theta_f(\frac{\eta_{carnot}}{1-\eta_{carnot}} + 1))]dt}{\int_{t_p} [1 + \frac{1-\eta_{carnot}}{\eta_{carnot}} \ln(\frac{1}{1-\eta_{carnot}})]dt} \quad (11)$$

312 where, η_{carnot} is the Carnot efficiency based on reference temperature, T_0 and
 313 outlet temperature of RC, T_r . The electrical energy density is dependent
 314 upon exergy efficiency of thermal storage system which is in turn dependent
 315 upon temperature of reactor operation and heat exchanger performance.

316 4.3. Packed bed of solid rocks

317 As mentioned before, high temperature solids such as alumina or gravel
 318 are good candidates to store energy at very high temperatures (beyond the
 319 operating range of RC temperatures). However, they need a tertiary HTF
 320 to transfer heat from the RC. Therefore, modeling heat transfer between
 321 tertiary HTF and the TES(solids) involves an additional step[18], thus an
 322 energy balance must be solved numerically to find the temperature of air

323 exiting the packed bed during recovery. This model can be written as set
 324 of two coupled differential equations and has been presented in detail in a
 325 previous work[12].

$$\frac{\partial}{\partial t}(\rho_f C_{pf} T_f) + v \frac{\partial}{\partial x}(\rho_f C_{pf} T_f) = \frac{\partial}{\partial x} \left[k_f \frac{\partial T_f}{\partial x} \right] - h_{fs}(T_f - T_s) - \beta_w(T_f - T_0), \quad (12)$$

$$\frac{\partial}{\partial t}(\rho_s C_{ps} T_s) = \frac{\partial}{\partial x} \left[k_f \frac{\partial T_f}{\partial x} \right] + h_{fs}(T_f - T_s). \quad (13)$$

326 where, k is thermal conductivity, h_{fs} is fluid-solid volumetric heat transfer
 327 coefficient and β_w is the wall heat transfer coefficient. The boundary and
 328 initial conditions for this packed bed model can be described for storage
 329 and recovery cycles independently. In the storage cycle, hot HTF from heat
 330 exchanger enters from the one end and during the recovery cycle HTF enters
 331 at ambient temperature from the other end. More details on the model
 332 descriptions can be obtained from previous references[12, 17]. The outlet
 333 temperature of HTF during the recovery cycle is then used to compute the
 334 exergy as described in the Eqn. 11.

335 4.4. Energy density

336 In case of thermal storage, the costs are directly related to the ability of
 337 recovered heat to provide useful work. Thus an exergy model which takes
 338 into account thermal energy losses, additional work requirement and entropy
 339 generation due to mixing or dispersion effects will be developed. Based on
 340 the reactor operation temperature, cycle efficiency and exergy efficiency of
 341 the storage system can be determined as explained before. If total thermal
 342 energy density of the storage system is known it can be used to compute
 343 electricity units stored per mass of storage material.

$$e_{d,th} = C_p(T_{c,out} - T_{amb}) \quad (14)$$

344 where $e_{d,th}$ is the thermal energy density and T_{amb} is the ambient tempera-
 345 ture. In case of storage salt the lowest possible temperature is its melting
 346 point, T_{mp} which replaces T_{amb} for the TES density calculations, which would
 347 dramatically reduce their energy density for existing nuclear power plants. It
 348 should be noted that T_{amb} is used considering that storage HTF will first de-
 349 rive energy to be stored from feed-water loop starting from condenser outlet

Figure 5: MHTGR integrated with alumina packed bed storage.

Figure 6: MHTGR integrated with nitrate molten salt storage.

Figure 7: PB-FHR integrated with alumina packed bed storage.

Figure 8: PB-FHR integrated with nitrate molten salt storage.

(close to 20°C). Thermal energy density can be converted to effective energy density using,

$$e_d = e_{d,th}\eta_{exer} \quad (15)$$

where, e_d is the effective thermal energy density based on exergy efficiency.

5. Results

This study evaluates the exergetic performance of different materials and methods to store thermal energy of NPPs. The analysis was conducted for thermal storage integration with existing and future generation NPPs based on the plant design data from literature[3, 9, 10]. The study reveals that there

Table 5: Effectiveness and C_r values for the varying RC and HTF proposed combinations.

NPP/TES combination	Effectiveness (ϵ)	C_m
LW-SMR/Therminol	0.92	1
LW-SMR/Dowtherm	0.92	1
MHTGR/Nitrate Molten Salt	0.89	0.5
MHTGR/Air-Alumina	0.82	1
PB-FHR/Nitrate Molten Salt	0.92	1
PB-FHR/Air-Alumina	0.85	2

are various possible options to store thermal energy of next generation NPPs efficiently, but the options for existing NPPs are limited. Low technological risk sensible heat storage materials such as molten salt, concrete or alumina can be beneficial for high temperature NPPs. Development of new materials such as ionic liquids might be required for making storage integration to existing NPPs feasible. The values for the effectiveness along with the C_r values were set depending on the RC and HTF being integrated together. These values are given in Table 5 and the resulting exergetic efficiency of liquid thermal storage is 92-93%, while solid thermal storage is 77-78% if integrated with NPPs, as seen in Table 6.

The numerical values of storage inlet, outlet, exergy efficiency and energy density are computed based on the method and model presented in previous sections along with the thermal properties for Therminol-66 and Dowtherm-T listed in Table 3 and nitrate molten salt and Denstone-99 alumina listed in Table 4. The numerical results presented in Table 6 show that Therminol has equivalent exergy recovery but has slightly higher energy density for the lower temperature reactors. While for higher temperature reactors the nitrate molten salt storage media has higher exergy efficiencies but the alumina packed bed storage has higher energy density. As the energy costs are directly related to these functions, Therminol will perform better economically

Table 6: Performance of different thermal storage technologies integrated with corresponding NPPs, detailed earlier in the paper. Temperatures are given in Kelvin and energy density e_d in $kWhr/ft^3$.

Storage type	T_{Cin}	T_{Cout}	η_{ex}	e_d
<i>Storage Salt</i>				
MHTGR	647.75	827.8	0.9202	12.462
PB-FHR	591.3	691.3	0.9311	9.5974
<i>Alumina (Air HTF)</i>				
MHTGR	410.98	771	0.7684	22.3536
PB-FHR	464.71	664.71	0.7857	18.4419
<i>Therminol</i>				
LW-SMR	286.96	321.96	0.9349	4.815
<i>Dowtherm</i>				
LW-SMR	286.96	321.96	0.9349	4.44

and thermodynamically for LW-SMRs and for the MHTGR or PB-FHR, nitrate molten salt results in higher outlet temperatures, leading to the higher exergy efficiency and overall energy stored and recovered in the system.

6. Conclusions

This paper provides a conceptual presentation on the integration of NPPs with technically robust thermal energy storage solutions. Although a more detailed analysis with entire condensate and feed water system integrated to the energy storage solution is required for more accurate analysis, for the conceptual presentation a simpler approach based on energy density and exergy

analysis is adopted. Therminol and Dowtherm are commercially available robust technological solutions for this purpose and operate in the temperature range highly compatible with the existing PWRs and upcoming LW-SMRs. Whereas Alumina and Storage salt are more suitable for high-temperature NGNPs.

The analysis for lower temperature reactors shows that exergy recovery efficiency is around 90% and energy density values for the synthetic HTFs in this operating range are not expected to create practical challenges. The high temperature storage options, alumina and storage salt packed beds, show exergy efficiency of 78% and 92%, respectively. The overall exergy efficiency and energy density can be improved with higher heat exchanger effectiveness as shown in Figures 6-8. The liquid-type TES solutions show much higher thermal exergy efficiency as compared to solids, as presented in Table 6. It is anticipated that Alumina and Storage salt will consume non-trivial fraction of energy stored to compensate for losses such as auxiliary heating or pressure drop, but these are largely dependent upon plant layout, and details will be possible only with fixed details on plant layout. Nevertheless, the exergy analysis presented in this work will be useful for future economic analyses if the costs of storage materials are available at large scale. Further, TES integration will require heat exchange between RC and HTF, i.e. it will add equipment or physical boundary from where RC can potentially leak or escape. Therefore, the reactor safety analysis must be performed with these additional process loop and equipment in future.

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