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Phenomenon Identification and Ranking Table Development for Future Application Figure-of-Merit Studies on Thermal Energy Storage Integrations with Light-Water Reactors

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There are no standard prioritization criteria for evaluating thermal energy storage options for use in integrated energy systems. A framework for proposing, analyzing, and presenting energy storage integration with power producers and users is presented, along with a specific figure-of-merit study based in this framework. This basis for evaluating storage technologies can provide a structure for the energy industry to analyse and prioritize energy storage in different applications and environments. The phenomena identification and ranking table (PIRT) presents a series of design questions specific to energy storage applications. The figure-of-merit study, built in this PIRT framework based on a nuclear-renewable hybrid energy system using thermal energy storage to produce power and provide process energy for a secondary user, successfully identified specific technologies to use based on the project requirements. Expanding the library of projects using this framework will expand the deployable options for energy storage and increase its potential for energy security.

Keywords: thermal energy storage, integrated energy systems, hybrid

I. INTRODUCTION

Global electrical grids continue to integrate renewable energy sources alongside existing nuclear, coal, hydro, and natural gas generation. The influx of supply from solar and wind power has resulted in an increased net demand variability on the grid. Selling electricity is becoming uneconomical for other baseload plants as the marginal price of electricity, set by the marginal cost of net supply, frequently decreases. Because renewable energy is often incentivized and thus allows for profitable operation at low and negative marginal costs, high penetrations of renewable energy can cause the marginal cost of net supply to be very low or negative. The net demand shift is causing a paradigm change in the profitable operations of baseload power plants. These price shifts are reflected both in daily prices and in the valuation of ancillary services,

such as spinning & nonspinning reserves. Interest in energy storage is increasing with this new reality, and government policy is also changing (FERC order 841) to accommodate the industrial interest in energy storage. Electrical, mechanical, chemical, electrochemical, and thermal energy storage technologies are being researched globally to increase our ability to use energy on demand and produce it when needed [1]. The concentrated solar power (CSP) industry has increasingly used molten salt tank systems to flatten their power production profiles over daily cycles, while still only collecting heat during daylight hours. In this way, CSP is overcoming the grid challenges of renewable intermittency by becoming as steady of a power source as possible. Other industries are looking to affect the inverse change: to produce power at constant rates and then distribute that energy during the intermittent production lulls the grid is now experiencing.

In the U.S., nuclear energy has overwhelmingly been used to generate baseload electricity. While nuclear reactors may be able to flexibly operate, nuclear reactors should operate at maximum power as often as possible to recover the large capital costs incurred by their construction. Economically, two-thirds of the cost of a nuclear plant is incurred as up-front capital, with only about 12% appearing as variable fuel, operations, and maintenance [2]. Thus, the marginal income lost by reducing power or shutting down is not matched or reflected in the reduced operating costs.

Idaho National Laboratory (INL) is supporting research in integrated energy systems, investigating how nuclear energy can be used outside of traditional electricity generation [3]. One opportunity is the Joint Use Modular Plant (JUMP) program, a NuScale Power Module (NPM) that was scheduled to come online in 2029 to be used for research, development, and demonstration purposes. A primary goal of JUMP is to demonstrate an integrated energy system (IES) with thermal energy storage (TES) integrated with an operating light-water reactor (LWR) in a real-world environment. Thermal energy storage is preselected due to the unique direct

storage and reactor integration challenges and because TES imposes fewer energy transformations. The JUMP program can demonstrate a variety of TES applications by using an energy storage system that is directly integrated into the thermal energy conversion cycle of an NPM. The heat stored in the TES could be used for energy arbitrage, load following, industrial process heat, thermal buffering, or ancillary product production. The relatively short timeline of the JUMP program incentivizes the need for energy storage selection mechanisms. The JUMP program provides an opportunity to evaluate the specific process of integrating industrial technologies such as gasoline production or hydrogen production within a single energy park with a nuclear reactor.

The JUMP program is an opportunity to begin industrywide discussions on the most important criteria for storage selection in nuclear power systems. Key characteristic questions of IES with storage are organized via a Phenomena Identification and Ranking Table (PIRT) system that will be applicable to nuclear and non-nuclear IES. This PIRT will establish a framework for developing application-specific figure-of-merit (FOM) analyses for future storage integrations within Integrated Energy Systems (IES). This paper uses the JUMP program as an example FOM based on the proposed PIRT.

TES technologies investigated in the FOM study are underground storage in aquifers or boreholes; hot and cold water storage; geothermal storage; solid media storage, focusing on concrete; steam accumulators; thermochemicals; phase change materials or latent heat storage; and sensible heat storage, focusing on molten salts and thermal oils.

Section II discusses the phenomenon identification and ranking table (PIRT) for general thermal energy storage integration with nuclear reactors, presented as a series of engineering questions. In Section III, the JUMP program IES research goals are presented including thermal applications, storage technologies, and a description of the NPM. The TES FOM results are

presented in Section IV. Section V includes a discussion of the effectiveness of the PIRT and subsequent FOM and their applicability to other IES.

II. PHENOMENA IDENTIFICATION AND RANKING TABLE

To select a single energy storage technology for a specific application, many parameters are considered. While these may not be "phenomenon" in the traditional sense of the word, the PIRT method can be used to evaluate the various characteristics of storage technologies and their deployment. The PIRT process lists phenomena – physical parameters, engineering approximations, component conditions, or system conditions – relevant to a particular subject to qualitatively rank criteria in their importance. The composite set of questions becomes a frequency-of-relevance based framework for establishing FOM studies for IES deployments. The PIRT framework is designed for flexibility across energy source types, energy storage technology types, and energy applications. Each aspect of the PIRT framework will be presented as an engineering design question.

The PIRT questions for thermal energy storage methods include the following:

1. Is the storage technology deployable in an appropriate timeframe?
2. How compatible is the storage technology with the energy source?
3. Can the storage technology effectively store energy for the future application?
4. Can the storage technology allow for increased market penetration and operational flexibility?
5. Can the storage technology allow for a sufficient size of storage?
6. What is the time required to change between operational modes when using this storage technology?
7. How often can the storage technology be used and cycled?
8. Will the dynamics of the storage technology lead to periods of unavailability?
9. How much does the storage technology cost?
10. What is the lifetime of the storage technology, especially when compared to the energy source and energy applications?
11. Will the storage technology increase the geographic requirements of the system?
12. Will the storage technology add to the concerns identified in the environmental evaluation of the system?

13. How long can the storage technology remain unused between cycles before it requires some form of intervention?
14. What kinds of regulatory challenges are anticipated?
15. How will ownership, liability, and revenue-sharing be divided among the power producer, storer, and user?

Each of the PIRT criteria will be evaluated with categorizations of every (E), frequent (F), and rarely (R) that will indicate how often a specific application will need to include that question in its FOM study. The importance of the various contributors is dictated by specific FOM studies.

1. Is the storage technology deployable in an appropriate timeframe? The technology readiness levels used later in this study are from the Technology Readiness Assessment Guide distributed by the Department of Energy in 2011 [5]. It is expected that every project will need to evaluate storage options based on their current and likely TRL level at the time of deployment. Therefore, a value of E is assigned for the PIRT on this criterion.

2. How compatible is the storage technology with the energy source? Mechanical, electrical, and thermal energy sources are clearly different domains. Within these domains, different ranges and types of storage and energy transfer may exist. For example, from a thermal energy storage consideration, an interconnect with a light-water nuclear reactor may occur at steam conditions of 3.5–7MPa (500–1000psia), at temperatures approaching 315°C (600°F), with possible steam superheat of about 55°C (100°F), while, in a coal plant, steam may be at 17MPa (2400 psia) and 540°C (1000°F). An ideal energy storage mechanism will be able to utilize this heat as directly as possible, and, therefore, different technologies may be advised for different integration scenarios. As more storage deployments are made, theoretical matching will be replaced with libraries of experiential knowledge for storage technologies. This question can be recast as the storage charging efficiency. Every project will need to ensure that their storage technology can effectively charge with the energy source, so a PIRT of E is assigned for this

criterion.

3. Can the storage technology effectively store energy for future applications? This question can be broken down into two subquestions for a given application. First, can the storage technology effectively store energy over the given time period needed by the application? Second, is there a good discharge mechanism to move the energy into the specific application? This question deals with a storage's discharge and housing efficiencies. While question 2 dealt with the compatibility of the storage with the energy source, this question ensures that the compatibility with the energy application is addressed. And, returning to the above example, a hot and cold water storage facility may have a high housing efficiency over a day, but it would not be compatible as an intermediary for process steam storage. Likewise, a large sensible heat system such as molten salt may be useful for process heat but would struggle with housing efficiency in a seasonal storage environment. The storage timeline and application needs must be considered. Once again, it is expected that all applications will need to address this question, and so a PIRT of E is assigned.

4. Can the storage technology allow for increased market participation and operational flexibility? Increased ancillary services market participation may arise from the introduction of energy storage systems by allowing a power producer to create operational reserve capacity. Spinning and nonspinning reserves markets are location-specific and will change with every new system competing for its remunerations. Operational flexibility in this case is the ability of the power producer to alter their production stream in order to change their market participation to suit their needs: storing to create capacity credits or to avoid selling at a loss and discharging to earn discharged reserve credits and selling for higher profits. This question deals very specifically with the engineering application and may be avoided depending on the system setup. For systems looking at providing a buffer for process heat, it may not be practical to investigate

any increased market participation as the system goal shifts from electricity production. Therefore, a value of F is assigned to the PIRT for this category.

5. Can the storage technology allow for a sufficient size of storage? While many storage technologies may be built in parallel or series to increase the overall storage size, there may still be technical limits that exist. Pumped-hydro facility sizes are generally capped when the physical size and weight of the stored water becomes economically infeasible to maintain. Likewise, salt storage tanks face similar challenges, as material considerations limit their heights and diameters. Other storage technologies, such as concrete, expect to be limited only by the amount of land available, as they are designed in a very modular fashion. Ensuring that enough storage can be created is essential for large applications. A PIRT of E is assigned for this category.

6. What is the time required to change between operational modes when using this storage technology? This can also be called "ramp time." To compare the ramp times of technologies, the system designer must also understand their ramp time needs. Legal, physical, and operational requirements may all restrict ramp times. Many characteristics, such as storage mechanism, medium, charging and discharging processes, system configurations and control lag times may have impact on ramping capability. While some systems, such as batteries, should be able to switch between charging and discharging almost instantaneously, storage systems depending on changing fluid paths may incur longer minimum ramps. The relationship between the requirements' ramp time and the longest technology ramp times may allow some designers to ignore this question. A PIRT of F is assigned in this category.

7. How often can the storage technology be used and cycled? Cycle frequency can dictate what kinds of storage technologies can be used for short-cycle applications. The difference between this question and the question of ramp time is in the storage technology's potential need to completely discharge or charge to be useful again. System characteristics may cause

significant thermal and mechanical stresses while cycling that may need to be mitigated simply by being offline. Similar to ramp time, such concerns are dependent on the application. Due to systems that will be able to ignore this criterion, a PIRT of F is assigned in this category.

8. Will the dynamics of the storage technology lead to periods of unavailability? This question pertains to system realignment due to nonlinearities in the storage system. An example of this is a thermocline tank in which the thermocline layer has expanded, creating a more isothermal system than is desired. By not having hot and cold sections set in the tank, the storage tank now becomes ineffective until these two distinct sections can be re-established. Again, systems with long cycle lengths may be able to ignore questions of temporary unavailability, while it may be of great importance to short-cycle systems. A PIRT, of F is assigned in this category.

9. How much does the storage technology cost? There are two overall costs figures that must be calculated in storage systems: energy capacity ($/kWh) and power capability ($/kW). Each project will need to do specific cost analyses, as costs are likely dependent on system size and use characteristics. Designers must ensure that comparisons are based on as equal of operating conditions as possible and balance out their system with the underlying cost assumptions in quoted prices. Every project will need to investigate costs, and so a PIRT of E is assigned in this category.

10. What is the lifetime of the storage technology, especially when compared to the energy source and applications? The storage lifetime will impact the system cost and should be included. The definition of storage lifetime may vary depending on the technology. Batteries are often considered “dead” once they cannot charge past a certain percent, while other technologies may require refueling or part replacements. A PIRT of E is assigned to this category.

11. Will the storage technology increase the geographical requirements of the system? There are two potential geographical challenges associated with energy storage. The first is whether the site can physically manage the storage, and the second is whether the system owners have enough space to properly connect the systems. This step may also require a legal understanding and evaluation of any storage plan. A PIRT of E is assigned in this category.

12. Will the storage technology add to the concerns raised in the environmental evaluation of the system? Energy storage is being investigated not only for its potential economic benefit but more so for its ability to help curb harmful emissions in the energy sector. Therefore, the storage itself should be investigated for its environmental impact. It is not expected that many storage technologies will cause great concern in this area, but it will be a requirement for every application. Therefore, a PIRT of E is assigned in this category.

13. How long can the storage technology remain unused between cycles before requiring intervention? Storage technologies may require some amount of constant energy or priming in order to remain useful. A system that is constantly used may not need to address this concern, while systems with longer cycles might. This is a very application-specific concern, and so a PIRT of R is assigned in this category.

14. What kinds of regulatory challenges are expected? Many power and industrial industries must accommodate oversight and introducing novel systems may increase scrutiny. Specifically, in the nuclear industry, first-of-a-kind storage implementations that use nuclear subsystems will require extensive safety analyses and legal discussions regarding what needs to be licensed. In all industries, it is expected that a learning curve will develop new standards, so PIRT of F is assigned in this category.

15. How will ownership, liability, and revenue-sharing be divided among the power producer, storer, and user? One may argue, with merit, that this is a legal issue and not an

engineering issue. However, when evaluating a storage system and making the business case for it, the contract structure has a significant impact on the economic evaluation. Furthermore, the expected agreements between producers, storers, and users may impact the energy distribution priorities and thus the profitability and market potential of systems with storage. In some systems, there may only be one or two parties involved. Therefore, a PIRT of F is assigned in this category.

Overall, 15 significant engineering design questions have been proposed as widely relevant to using energy storage integrated with nuclear power systems. Each question has been evaluated based on the frequency with which it will appear as a major decision point in the engineering design process. This paper investigates such an engineering design process and presents a FOM discussion based on these investigative questions. Table I summarizes the PIRT evaluation.

Table 1. Summary of PIRT assignments for the engineering questions.

Engineering Design Question	PIRT Value	Engineering Design Question	PIRT Value
Technology readiness	E	Storage Cost	E
Energy Source Compatibility	E	Storage Lifetime	E
Effective Energy Storage	E	Geographical Requirements	E
Market Participation and Operational Flexibility	F	Environmental Concerns	E
Storage Size	E	Necessary Interventions	R
Ramp Time	F	Regulatory Challenges	F
Cycle Frequency	F	Contracting Structure	F
Unavailability Frequency	F		

III. PROJECT FOR FIGURE-OF-MERIT STUDY OF ENERGY STORAGE SYSTEM BASED ON PRESENTED PIRT

As discussed in the introduction, INL is collaborating with NuScale on the JUMP program for research, development, and demonstration purposes. One research component of this project is integrated energy systems (IES). The full JUMP integrated energy system will include an NPM, thermal energy storage, and the ability to maneuver thermal energy streams between multiple applications. An FOM study on the thermal energy storage technology is done for the future JUMP system. The quantitative values of the FOM study were decided via discussion among the authors based on the requirements and operating characteristics JUMP would likely encounter. The NPM, thermal applications, and market requirements are discussed in sections III.A-III.C. III.D introduces the TES technologies evaluated by the FOM study.

III.A NuScale

The NuScale Power Module is an integral pressurized-water, small, modular reactor designed to operate over its full 250MWt range cooled by natural circulation. The Nuclear Regulatory Commission approved the safety design completely in 2020 [6]. The NPM is cooled via natural circulation, successfully eliminating the need for reactor coolant pumps [7]. Heat is transferred to the secondary side via two helical-coil steam generators within the reactor pressure vessel. Sample graphics of the core and primary coolant system are shown in Figure 1.

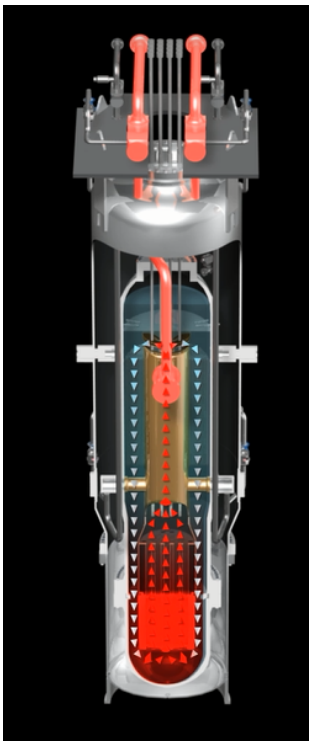

Figure 1. Major NPM components and flow path from NuScale [8].

The reactor operates at 250 MWt with primary coolant temperatures of around 310°C (590°F) [9]. This temperature and pressure, along with the efficient helical-coil steam generator, leads to secondary loop design pressure, temperature, and flow rates of 3.4MPa (500 psia), 302°C (575°F), and ~301,000 kg/hr (532,000 lbm/hr), respectively [10]. The introduction of energy storage may introduce reactor feedback as the feedwater temperature is impacted through IES operation. Control systems should be able to operate the reactor safely by shifting specific operation depending on the system operational mode.

III.B Electrical Grid Security Ancillary Services Markets

Power producers earn additional revenue by participating in electrical grid ancillary service markets. Participation is dependent on a site's abilities to provide frequency and supply control to an operating grid. The seven U.S. market operators have different rules regarding

reserve response times and minimum operating times for reserve market participation. The value of participation is also interconnect specific. The minimum reserve response time is reported at ten minutes and the longest minimum operating time is two hours. These values govern some FOM value selections in Section IV.

III.C Large Thermal Energy Applications

Thermal energy storage can be used as a buffer system between a nuclear reactor and a high-energy-input thermal application. The JUMP program is evaluating several applications, including high-temperature steam electrolysis, coal gasification, gasoline production, pulp and paper milling, chemical manufacturing, and water desalination. By targeting industries that use large quantities of steam at LWR output temperatures and pressures, the portfolio of applications for nuclear energy can expand. Some of these applications may be able to be integrated with JUMP for application research purposes, and others are included for general LWR consideration.

As early as 2001, there was an understanding that nuclear power would be capable of playing a role in the production of hydrogen through thermochemical splitting or through electrolysis [12]. Hydrogen has many uses including oil refining, chemical production, clean fuel cells, and potentially an integration into natural gas networks. High-temperature steam electrolysis (HTSE) is a well-developed technology most suited to interface with LWRs; some energy requirements are presented in Table II. [13].

HTSE requires steam at ~850°C as an input into the solid-oxide electrolysis cells. Nuclear power can provide the latent heat to produce steam input at about 300°C and allow another source, such as electric topping heaters, to provide the required superheat. This combined thermal and electric process could be entirely provided by a nuclear power plant, such as an SMR.

Table II. Inputs and outputs of HTSE using nuclear and electric heat, from [13].

	Description		Unit	Value
Inputs	Water		kg s^{-1} [metric ton yr^{-1}]	4.48 [141]
	Air		kg s^{-1} [metric ton yr^{-1}]	23.3 [734]
Outputs	Hydrogen		kg s^{-1} [metric ton yr^{-1}]	0.4015 [12.7]
	(Oxygen)		kg s^{-1} [metric ton yr^{-1}]	3.186 [100]
	CO_2		kg s^{-1} [metric ton yr^{-1}]	0 [0]
Utility summary	Power consumption	Total	MW_e [MW_{th}]	61.2 [192.5[a]]
		Electrolyzer	MW_e [MW_{th}]	45.5 [143.2[a]]
		MSCS	MW_e [MW_{th}]	10.1 [31.6[a]]
		FWP	MW_e [MW_{th}]	0.0127 [0.0401[a]]
		ETHs	MW_e [MW_{th}]	5.61 [17.7[a]]
	Power generation	SGT	MW_e [MW_{th}]	7.89 [24.8[a]]
	Nuclear process heat		MW_{th} [MW_e]	14.6 [4.63[b]]

Another fuel requiring significant processing energy is gasoline. Producing gasoline from crude oil requires large amounts of thermal and electric energy. While petroleum refining plants produce some of their steam and electric power directly on site, they do require offsite input [14]. Coupled nuclear generation can provide, potentially more efficiently, the offsite electricity and steam production required in this industry, as over half of the steam requirements of petroleum refineries are below 2MPa (300psig), which is below the steam discharge pressure of LWRs [15]. An SMR deployment to support petroleum plant needs has been previously researched in the context of nuclear-renewable hybrid energy systems. This work found that the integration of nuclear energy into this process is possible and can provide energy generation stability and economic benefit [16] [17].

One of the largest users of process steam in the U.S. is the pulp and paper industry. The 2014 Manufacturing Energy Consumption Survey (MECS) data shows that 11% of manufacturing energy was used by the pulp and paper industries, with over 50% of that energy produced offsite [18] [19]. Kraft pulping, sulfite pulping, washing, refining, bleaching, and drying processes all use steam pressures between 200–1000kPa (30–150psia) and temperatures below 175°C (350°F) [15]. Figure 2 shows a diagram of the paper mill processes [20].

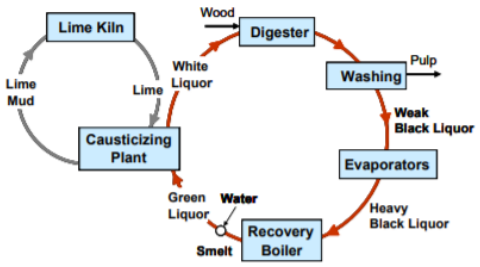

Figure 2. Liquor use in the Kraft recovery process, taken from [20].

Large thermal and electrical requirements at appropriate LWR steam pressures and temperatures make pulp and paper mills ideal candidates for cogeneration integration with SMRs or LWRs buffered by the TES.

Other chemical manufacturing processes use steam for many different processes either as a source of heat or by direct injection [15]. Ethylene, ammonia, urea, styrene, polystyrene, sodium hydroxide, PVC, acetone, benzene, toluene, xylene, sodium carbonate, polybutadiene rubber, styrene butadiene rubber, and butyl rubber manufacturing processes all use steam within NuScale design pressures [15]. MECS data show that in 2014, chemical manufacturing accounted for about 33% of the total manufacturing energy use [18]. Furthermore, MECS data state that more than 60% of offsite energy production was made by natural gas, which should allow for avenues of applications of nuclear heat from LWRs [19].

Producing water via desalination occurs through thermal distillation or through reverse osmosis (RO). RO plants now account for about 69% of global water production [21] [22]. RO technology is normally the cheapest available, due to its energy requirements being as low as 0.5 kWh/m^3 of clean water produced [23]. RO also produces less brine compared to other technologies, making the plants more environmentally friendly [21] [22]. As large consistent producers of thermal energy, nuclear reactors are candidates for integration with desalination plants [23]–[25].

III.D TES Options for FOM Study

Thermal energy storage was preselected by the research team for a few reasons. Active and future nuclear reactors are large thermal energy generators, and higher system efficiencies are achievable with fewer energy transformations. Second, there is nuclear industry interest in thermal integration with existing and future light-water reactors. Thermal energy storage should facilitate this integration. Third, thermal energy storage integrated with a nuclear reactor is unique relative to other energy storage forms and requires further research to understand the integrated system behavior prior to its deployment outside of a national laboratory research, design, and development setting. Electrical or mechanical storage technologies would be indirectly connected with a nuclear reactor via the charging and discharging energy transformation mechanism. The integration point is thus outside of the thermodynamic cycle of the nuclear system and there is not expected feedback.

Thermal energy storage technologies evaluated in the FOM study include underground storage in aquifers or boreholes, hot and cold water storage, geothermal storage, steam accumulators, solid media storage focusing on concrete, thermochemicals, phase change materials or latent heat storage, and sensible heat storage focusing on molten salts and thermal oils.

Underground thermal energy storage (UTES) stores energy in aquifers or boreholes. Aquifer storage holds warm and cold water in separate storage sections underground to lessen seasonal heating and cooling loads by discharging warm water and storing cold water during winter months and the opposite during warm months [26] [27]. Borehole storage is similar in concept but instead uses water only as a working fluid and heats or cools an underground medium [28] [29]. An interface between a nuclear reactor and the UTES would likely be

facilitated by a water-water heat exchanger. Because of the low maximum temperatures in aquifers and in underground locations, it is possible that the interconnect point may use waste heat (downstream of the low-pressure turbine) in a near-condenser operating method. If high-temperature heat (such as using steam bypassing the turbines) is used, care would need to be taken to not overheat the UTES.

Hot and cold water storage, or chilled-water storage, is the process of storing heated or chilled water in onsite tanks to shift demand from peak to off-peak hours most commonly used for daily heating, ventilating, and air conditioning cycles [30]–[32]. Generally, the temperature limits of these systems are simply that the water must remain liquid. Steam content would over-pressurize the system and ice storage requires growth locations and specific expansion mechanisms. Similar to UTES, the interface would most likely be a water-water heat exchanger, but, as the highest temperatures would be higher than the UTES, a steam bypass would likely be required to maximize volumetric storage efficiency. For chilled-water storage, the system would use electricity to power the chillers to build up the stored liquid content.

Geothermal storage refers to a new concept of storing highly-pressurized water in more-highly-pressurized deep rock beds to maintain liquid storage with a higher energy density (note that this is different than geothermal power, which draws power from naturally occurring underground heat sources) [33]. Geothermal storage could allow for direct steam removal and storage from a turbine bypass stream. So long as the underground pressure is higher than the steam pressure, the underground reservoir should be able to maintain its integrity and energy content. If direct steam insertion is not allowed due to regulatory limits, an intermediate heat exchanger could facilitate the energy transfer. Because geothermal storage can store and subsequently discharge steam, it could be used to provide extra steam to boost a turbine or for process steam applications.

The final water-based TES technology evaluated was steam accumulators: pressurized water tanks that maintain highly pressurized water-steam equilibrium conditions. Sliding-pressure Ruths-type accumulators were considered as typical steam accumulators in this analysis [34] [35]. Steam accumulators directly accept steam to store energy. Similar to geothermal storage, how the steam insertion occurs may be dependent on whether steam generator steam is allowed to exit the system. Steam bypassing the turbine could be inserted into steam accumulators or transfer heat across a water-water heat exchanger to provide steam into the accumulators. The primary downside for steam accumulators is the sliding-pressure aspect of their storage, which may preclude their application for constant temperature applications.

Firebrick thermal energy storage uses resistance heaters embedded in ceramic bricks to store heat, before discharging it using forced air currents [36]–[38]. Firebricks would be heated by the electricity output from the nuclear turbine-generators to store heat in the bricks. Gas flowing through the bricks is heated to release the stored energy. This energy could then be transferred into the steam system, using a gas-water heat exchanger, or it could be used for process heat in an industrial application. Described as thermal batteries, firebrick systems are like steam accumulators in that they decrease the operating temperature during discharge. The high-temperature nature of the firebrick systems does indicate that they may be able to nonlinearly produce constant temperature heat across a strictly-controlled heat exchanger.

Concrete storage uses specially-designed concrete poured over steel pipe frames to create a solid thermocline, charged by a working fluid flowing in one direction and discharged by a working fluid flowing through those pipes in the opposite direction [39]–[41]. Steam bypassed from the turbine could be used to heat the concrete structure directly. These systems are touted as being highly modular in their construction capability. As they produce a thermocline, the ideal system would need to balance the effects of piping losses in series systems and the disadvantages

of shorter thermoclines in parallel systems. The concrete storage discharge could be at nearly equivalent conditions as the charging fluid and thus would likely be able to be used in power peaking systems and for process heat.

Thermochemical energy storage involves a reversible reaction that is endothermically driven during charging and exothermically reacts during discharge to transfer energy between the chemical reactants and the working fluid [42]–[44]. A heat exchanger would be necessary for its interactions with a nuclear reactor, as the steam would not be inserted into the chemical reaction. During the endothermic charging, heat from turbine bypass steam would provide the energy necessary to drive the reaction. The products from this reaction are stored and then re-reacted in a system that would remove the heat via a heat exchanger. It is impractical to discuss the actual operating temperatures briefly, as there are many variables that must be accounted for in one of these systems. Thermochemical energy storage density is much higher than any of the sensible heat technologies, but research has not indicated a long-term, repeatedly cyclable reaction to target for applications.

Phase change materials store latent heat by repeatedly melting and freezing a media to accept or discharge heat [42],[46]–[51]. The storage density of phase change materials is very high, because of the relative amount of latent heat to sensible heat in most materials. Technological limitations, so far, are similar in nature to thermochemical storage, in that specific material selection at typical chemical process temperatures and long enough material cyclical fatigue lifetimes have not been demonstrated. Theoretically, if the heat exchangers were fully developed enough, such that good heat insertion and removal becomes possible, a system designer would be able to precisely select operation temperatures based on their requirements. The interface would need to be a heat exchanger, interacting with steam and water on one side and a solid-liquid system on the other side. While liquid-gas systems are physically possible

(indeed water-steam is such a system), the system now must be able to accommodate the gaseous pressure, which would reduce the energy storage density and greatly increase fabrication costs. Depending on eventual design, it is likely that a single heat exchanger, using steam to charge and water to discharge, could interact with the materials to insert and remove heat and carry it to its other applications.

Liquid sensible heat systems (SHS) heat and cool a fluid that remains liquid throughout the entire process, separating the hot and cold fluids either via multiple storage tanks or via thermocline [47], [52]–[63]. The main technologies investigated in this report are thermal oil and molten salt SHS. The mechanisms for this storage are nearly identical to that of a chilled-water storage. In a two-tank system, a cold reservoir of fluid sits until pumped to accept heat via a heat exchanger and, after it leaves this exchanger, it is stored in a separate hot tank. It is also possible to store the fluid in a single tank, with the hot and cold fluids separated by a thermocline, if a few material property conditions (such as a high density change with temperature and low thermal conductivity) are met. Thermal oils, while expensive, are considered in this report due to their low freezing point and their boiling point that is generally higher than JUMP operating points. Already used in solar power systems, thermal oils are well understood and therefore should be readily available for use. Molten salt systems are a similarly well-understood technology used primarily in the solar power industry and are well known for being good storers of heat. For nuclear applications however, their relatively high freezing point may cause issues when using LWR produced steam to charge them. To make the systems cheaper, it is possible to lower the amount of working fluid and instead store heat using a packed rock bed or pebble bed as the heat storage medium. Similar to firebrick storage, packed pebble beds suffer from a reduced outlet temperature prior to the actual complete dispensation of heat from the storage system. A two-tank system would not suffer from these effects as much, especially if mixing was forced in the

hot tank.

IV. FIGURE-OF-MERIT STUDY

Thirteen categories have been identified for inclusion in the FOM study by the authors and expert discussion, based on the 15 potential PIRT questions identified in this article. These include technology readiness, charging and discharging compatibility, ancillary services market application, system capacity, ramp time, cycle frequency, realignment frequency, cost, lifetime, geographical requirements, environmental concerns, and thermal support requirements (PIRT 1-13). The FOM study results demonstrate the usefulness of the PIRT framework. The FOM assigned for each category, along with the scaling justification, are discussed.

1. **Technology Readiness Level**: TRL is extremely important to JUMP as the system must be fully designed in the next few years to be licensed and deployed by 2029. To give the proper weight, the FOM value equals the TRL (0–9 scale).

2. **Experienced technology integration with nuclear steam pressures and temperatures**: The NuScale reactor maintains a steam pressure of 2.7MPa and temperature of 300℃. Being able to directly use this steam achieves an FOM of 2, having to somewhat downgrade this steam gives an FOM of 1, and an FOM of 0 indicates no direct use of this steam.

3. **Capability to discharge high-quality heat**: The TES must be able to discharge its energy capacity as consistent high-quality heat. A system capable of discharging its entire store at above 175℃, identified as a specific thermal application integration point, was given an FOM of 2. A system capable of either a sliding pressure discharge with some above 175℃ or a system capable of discharging between 100–175℃, still boiling atmospheric steam, was given an FOM of 1. Otherwise, the FOM was 0 for this category.

4. **United States Electrical grid ancillary services market potential**: If a TES allows for participation in the frequency regulation market, an FOM of 2 was given. If a TES allows for participation in the reserves market, an FOM of 1 was given. Otherwise, a 0 was given for this category.

5. **Total Energy Capacity**: The total energy capacity for this system is estimated at 400MWh of heat. A system must therefore be able to manage that much energy. A system capable of this size was given an FOM of 2. One that could store 100MWh but not 400MWh was given a 1, and a 0 was given otherwise.

6. **Ramp Time**: Ramp time is associated with category 4 as well as energy arbitration and load following. Due to the most restrictive reserve market restrictions of 10 minutes, a ramp time to maximum power of 10 minutes or less was given an FOM of 2. A ramp time of less than an hour, for load following, is assigned a 1, and any ramp longer than that is given a 0.

7. **Cycle Frequency**: Cycle frequency is defined as the system's capability to charge and discharge. If a system can charge and discharge at will, an FOM of 2 was given. A system that could cycle only daily is given an FOM of 1, and a 0 is given to systems with longer cycles.

8. **Realignment Frequency**: Realignment is defined as the use of noncharging and nondischarging mechanisms to prepare the storage system for another cycle. A system that requires no realignment would always travel perfectly from state A to state B during charging and back to state A during discharging. Irreversibility or design constraints may not allow for a perfect cycle, and thus some backup mechanism may be required to reset the system to state A. If no realignment is required, an FOM of 2 is given. If realignment is required every cycle, an FOM of 0 is given, and an FOM of 1 is given for intermediate values.

9. **TES cost per kWh**: This value is evaluated after the total FOM is calculated, to be used as a selection method later.

10. **Technology Lifetime**: Technology lifetime refers to the time before the TES would need self-replacement. Like cost, this factor is considered after the FOM is calculated.

11. **Geographical insensitivity**: Because it is desired that SMRs with a TES be deployed globally with as little redesign as possible, geographical needs are considered. An FOM of 0 is given to a geographically specific technology, and an FOM of 1 is given to a TES without those requirements.

12. **Environmental Concerns**: Environmental concerns are important and can appear in multiple stages of TES use: construction, direct use, and during decommissioning. An FOM of 1 is given to a technology that does not have any significant environmental concerns, and an FOM of 0 was given to a technology with environmental concerns.

13. **Minimum turndown or thermal support requirements**. A system that needs heat tracing or a constant supply of heat is given an FOM of 0. A system that faces no concerns if heat is not constantly supplied is given an FOM of 1.

V. RESULTS & ANALYSIS

V.A FOM Results

Table III presents the overall results of this investigation. Two-tank SHS have the highest FOM value. Solid media and steam accumulators also have FOM values very close to two-tank SHS. These technologies are discussed in fuller detail. The FOM results based on the PIRT questions created an effective distribution of technology evaluations, allowing for specific selection. The detailed evaluations are presented in Table A.I. The maximum FOM score is 26.

Table III. Evaluation of Thermal Energy Storage Options.

Technology	**FOM**	**Technology**	**FOM**
Borehole UTES	14	**Aquifer UTES**	14

Hot and Cold Water	18	**Solid Media (Concrete)**	20
Firebrick	14	**Geothermal**	11
Thermochemicals	12	**PCMs**	16
Molten Salt – Thermocline	17	**Thermal Oil – Thermocline**	17
Molten Salt – Two-Tank	23	**Thermal Oil – Two-Tank**	23
Steam Accumulators	22	**AVERAGE:**	17.0

V.B Qualitative and Comprehensive Analysis

Two-tank TES systems, steam accumulators, and concrete are considered for TES selection, as the only three technologies to achieve a FOM of at least 20. From this point forward, molten salt TES and thermal-oil TES will be considered as separate from each other and exclusively refer to two-tank configurations. To continue making evaluations of these technologies, a project cost must be estimated (FOM 9) from the literature. The upper cost ranges were expanded on, due to a lower specific heat in the charging steam from nuclear reactors as compared to CSP, coal, or gas plants. Table IV compares the capital costs per unit of energy and power, estimated round trip efficiencies, and energy densities of these technologies.

Table IV. Energy and Power Cost Estimates for Potential TES technologies.

Technology	**Energy Cost ($/kWhe)**	**Power Cost ($/kWe)**	**Est. Round Trip Efficiency (%)**	**Energy Density (kwhe/m^3)**
Concrete	25-150 [1] [39]	500-3000 [1]	50%-92% [1] [63]	22-82.5 [1] [63]
Molten Salt	5-30 [1]	400-2100 [1]	40-93% [1]	170-420 [1]
Thermal Oil	8-16 [1] [65]	600-1400 [1] [64]	40-93%	100-300 [53]
Steam Accumulators	130-400 (Estimate)	1200 (Estimate)	70-90% [65]	20-30 [35]

Concrete costs are estimated from multiple sources [1] [39] [63]. The cost would ideally be as low as $25/kWhe for energy capacity. However, this does not take into account the lower temperature ranges available from LWR systems. Costs will also depend on the local fabrication costs of these systems. However, due to the low power density in concrete, the minimum project power cost is around a factor of 20 higher. A project cost estimate can be found as the greater of:

The cost estimate of using concrete storage, using the low and high ends of these estimates, is around $14–$84 million. Without further deployment of concrete TES, it is too early to tell which end of the cost range is more accurate for JUMP.

The molten salt TES costs are more available due to existing data. Around half of the cost of molten salt storage systems is in the salt itself [64]. Prices quoted in the literature exclusively involve using relatively cheap salts (solar salt, HITEC) under large temperature deltas. Solar salt and HITEC have liquidus temperatures of 220°C and 142°C, leading to maximum JUMP temperature storages of 22°C and 99°C, which is much lower than the often used 295°C temperature changes found in the literature. Salt choice will have a significant impact on the cost of the system, and the percentage of the cost of salt may grow to more than 50% of the cost. Even so, minimum costs for molten salt systems are around $5/kWhe, and some estimations see the nuclear cost at around $13/kWhe [4]. The upper limit on salt referenced here is raised from the literature by a factor of three to account for the smaller temperature changes that JUMP will be able to use. The upper cost estimate of power is similarly altered. The cost estimate for molten salts is then between $11–$56 million.

Thermal oils are noted as being around 40–45% more expensive than molten salt for CSP applications [64]. Thermal oil costs more per unit of mass-energy in storage, and the maximum temperatures of thermal oils are lower than salts. In a nuclear system however, the maximum thermal-oil temperature is no longer the limiting factor, and the lower available temperatures lead to larger temperature changes being available in thermal-oil systems. By uprating the cost of thermal oil directly from the molten salt costs, we reached an estimate of about $8/kWhe–$16/kWhe. The minimum power cost is expected to be high as well, around $600/kW, with a maximum power cost of

$1400/kW. The total capital cost of this system would be between $17–$39 million.

Finally, steam accumulators are not typically used in a large-scale manner, and the cost of steam accumulators is highly dependent on pressures, locations, capacity, and discharge rates. The cost of steam accumulators is generally regarded as inhibitive and is typically only beneficial if the presence of an accumulator can reduce the size of a corresponding boiler and its fuel consumption [37]. A low-end capital cost estimate of accumulators is around $15/gallon. With accumulator energy density generally around 20–30kWht/m^3, this leads to a low-end estimate range of $53–$80 million for a 400MWht system [35]. The requirements for power would actually be even higher, as it could take around 6,200,000 gallons to meet power requirements, and the price per unit power is estimated at $1200/kWe [65]. Low-end and high-end project costs, along with cost uncertainties are presented in Table V.. For reference, the average module cost in the first NuScale 12-module plant is expected to be about $250 million [66].

Table V. TES project capital cost estimations for JUMP.

Technology	Low-End Project Capital Cost ($ million)	High-End Project Capital Cost ($ million)	Biggest Uncertainty
Concrete	14	84	Cost per unit power
Molten Salt	11	56	Impact of low ΔT, new salt selection
Thermal Oil	17	39	Specific oil pricing
Steam Accumulators	53	95+	Cost of steam accumulator unit, units needed to meet power requirements

Overall, steam accumulators are significantly more expensive than concrete, molten salt, or thermal-oil storage for nuclear plants. This expense prohibits their use. Concrete has the highest of the high-end project cost estimations, due to uncertainties in the amount of power that concrete can provide during discharge. Molten salt is potentially the cheapest TES option, at a cost of around $11 million, but how well prior molten salt estimations will hold up when nuclear temperatures are considered has not yet been investigated. This uncertainty leads to the increased high-end cost estimation. Thermal-oil storage, noted in molten salt research as being relatively expensive, has the smallest potential capital cost range, due to its simpler integration with LWR temperatures.

Project costs are one of the final items needed to fully compare the separate technologies for TES deployment. The other FOM item that has not yet been discussed is the technology lifetime. The expected lifetime for concrete systems is around 50 years, if the temperature is kept below 400°C. Molten salt systems do not have a listed lifetime and should last indefinitely with good material selection [4]. The thermal-oil lifetime depends on the amount of thermal cycling and how closely the system is operated to the oil boiling temperature. With proper tank buffering and maintaining temperatures 100°C below boiling point, oils should last at least 30 years. Finally, steam accumulators are very robust machines, whose lifetime depends on the purity of the water being used. As it is currently proposed to use nuclear secondary water, which goes through extensive chemical cleaning, accumulator lifetime is also assumed to be sufficient. Technology lifetime does not help discriminate any of these technologies.

One goal of the TES research, design, and development (RD&D) in the JUMP module is to demonstrate as much flexibility for nuclear heat application as possible. Power peaking and HTSE are projects that are intended to be demonstrated using JUMP, and other technologies may follow in the future. Power peaking requires high-

quality heat discharge, with the highest pressures possible, to either supplement an oversized turbine or to power a separate turbine. HTSE does not have steam pressure requirements, but higher discharge temperatures would lead to increases in system efficiency, by reducing the amount of required electrical topping heat. Other future projects may require constant temperature heat sources over the entire course of the TES discharge. Of the technologies still being considered, only molten salt and thermal oils consistently provide high-temperature and high-pressure heat in a technology that is highly developed. Both technologies would operate via a tertiary storage loop, seen in Figure 3, connected to the nuclear power conversion system via an intermediate heat exchanger. This indirect connection is also considered advantageous for the RD&D at JUMP, due to the thermal buffering between the first-of-a-kind nuclear interconnection with the storage and storage discharge mechanisms. It should also lead to simpler mechanisms for changing the auxiliary energy conversion process (power peaking, HTSE, chemical processing, etc.), as the buffer layer should isolate the processes during construction and testing.

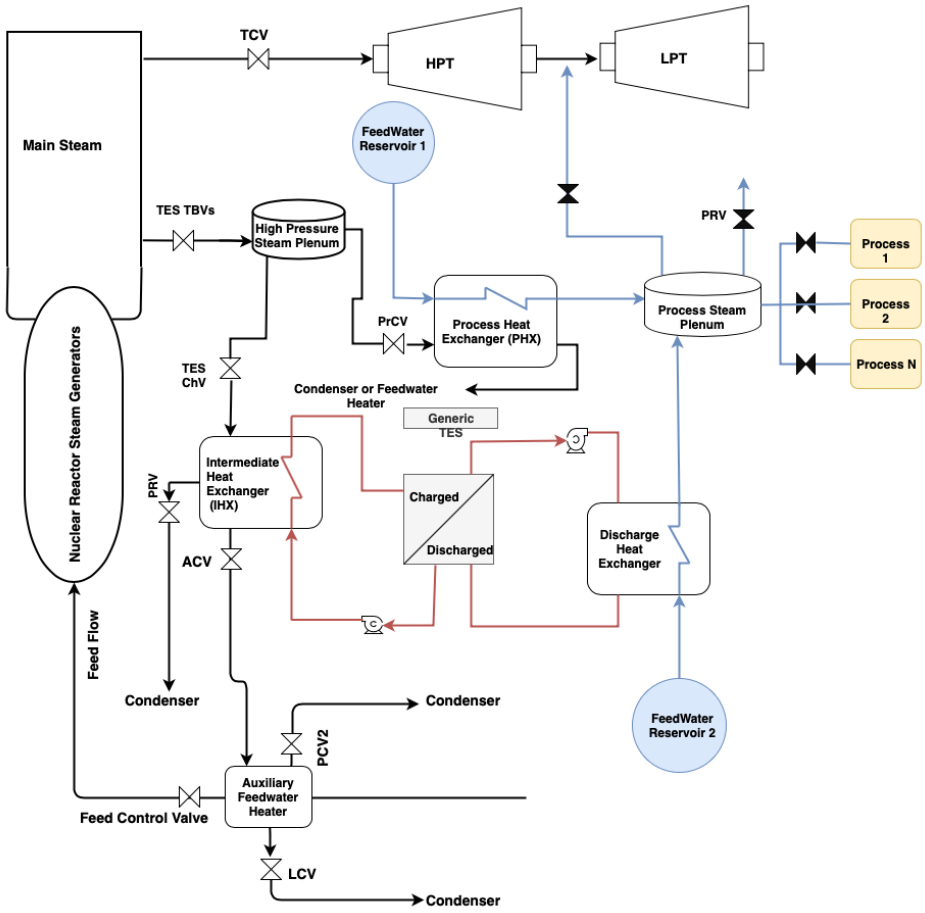

Figure 3. General TES integration for JUMP program.

V.C FOM Results Applicability

The FOM results are based on a theoretical IES of the JUMP program. The applicability of these specific FOM values to other nuclear IES projects is not directly investigated. There are effectively an infinite number of IES configurations and no single FOM study can account for all conceivable options. The results of this FOM are considered an appropriate reference for LWR IES options integrated with heat applications near reactor operating temperatures as the FOM criteria were in part based on the LWR NPM operating values. IES configurations with lower temperature application requirements and with seasonal requirements would need a new FOM study as the deployment system operating characteristics would be too distinct from expected

JUMP operation.

The PIRT framework as proposed provides a thorough basis for creating IES FOM studies in the future. Because the energy source and application needs will be different across IES applications, the PIRT is defined in general terms to allow for precise evaluations in the FOM stage of analysis.

VI. CONCLUSION

A generalized Phenomena Identification and Ranking Table evaluating the process of IES design has been proposed and demonstrated using the JUMP program's IES research goals. Ten thermal energy storage technologies with 13 specific systems were evaluated using FOM regarding their potential to integrate with LWR technology. Concrete, molten salt and thermal-oil sensible heat storages, and steam accumulators were identified as the ideal thermal storage technologies for this application. After including cost estimations and qualitatively comparing these technologies, it is recommended that either molten salt or thermal oil is used for implementation with the JUMP module. The FOM study built from the proposed PIRT framework successfully delineated various technologies within the specific technological requirements of this project. This PIRT framework is expected to be applicable to future IES deployments, providing engineers designing new IES a basis for the creation of additional FOM studies using their specific configuration and technological requirements.

VI.A Future work

Additional FOM studies within this PIRT context will build the library of energy storage projects undertaken or analyzed by energy producers. Novel arrangements, technology links, and diverse applications can increase the knowledge needed to deploy energy storage and hybrid systems to secure energy supply and demand for energy users

and the electrical grid.

Further research is needed in two significant areas regarding the TES. First, an in-depth analysis of the relative costs of thermal-oil and molten salt two-tank sensible heat storage systems must be completed. The analysis should include various research benefits of choosing molten salt or thermal oils. These include, but are certainly not limited to, an investigation of new low-temperature salts or a demonstration of the largest thermal-oil storage. Potential future developments of each technology (further salt discoveries or reductions in the cost of either medium) should also be considered for this decision. Second, specific configuration, optimal sizing, and operational techniques need to be investigated, to maximize the research opportunity provided by JUMP. Configuration questions include how to safely integrate chemical processes in energy parks with nuclear reactors. The decisions made herein could have significant impact on the growth of the nuclear power industry globally, potentially creating opportunities for a variety of nuclear applications with a successful TES and SMR integration.

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APPENDIX

Table A.I Full FOM category by category results.

Tech	TRL	Charge	Discharge	Ancillary Market	Capacity	Ramp	Cycle Frequency	Realignment	Geography Requirements	Environment Impacts	Turndown Requirements	Total
UTES	9	0	0	0	2	0	0	2	0	0	1	**14**
Hot/Cold Water	9	0	0	0	2	2	2	1	1	1	1	**19**
Concrete	5	2	2	1	2	2	2	1	1	1	1	**20**
Firebrick	3	0	2	1	2	2	1	1	1	1	0	**14**
Geothermal	2	1	2	0	2	1	2	1	0	0	0	**11**
Thermo-Chemicals	4	1	2	0	2	0	0	1	1	1	0	**12**
PCMs	4	1	2	1	2	1	1	1	1	1	1	**16**
Thermocline Molten Salt/Thermal Oil	5	1	2	1	2	2	2	0	1	1/0	0/1	**17**
Two-Tank Molten Salt/Thermal Oil	9	2	2	1	2	2	2	1	1	1/0	0/1	**23**
Steam Accumulators	9	2	1	1	1	2	2	1	1	1	1	**22**