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AN ASSESSMENT OF THERMAL STORAGE SYSTEMS AND THERMOMECHANICAL EFFECTS FOR PULSED REACTORS*

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Pulsed operation of fuion power plants has severe impact on all major reactor components. This analysis focuses on the sensitivity of one subsystem, the breeding blanket, to pulsed operation in terms of thermal storage requirements and thermomechanical effects. For analysis, a water-cooled Li_2O breeding blanket (400 MWth, 3.45 MW/m^2 neutron wall loading) was chosen. With the operating temperature window, 800/410°C for Li_2O, thermal analysis shows that for the coolant-in-tube design (STARFIRE) there would be 10 rows of coolant tubes in the radial direction of the blanket. Since the thermal inertia of the blanket is larger further away from the first wall, the mixed mean temperature of coolant from all regions will dictate the design requirements for the thermal storage system. Three representative blanket regions were analyzed under four burn scenarios (startup/shutdown time = 10 s, steady-state time = 3600 s, and dwell time = 0, 30, 90, and 200 s) to estimate the thermal storage requirements. The size of the thermal storage system is dictated primarily by the energy deficiency that occurs during the dwell/startup and shutdown phase, although time/temperature response of the heat transfer fluid is critical to the design. Only pressurized water/steam and hot sodium thermal storage systems are considered for this study, since alternative systems are not attractive for heat storage of the order of 11 MWh to 230 MWh. An estimation of the size of thermal storge vessels that can be built utilizing current technology shows that reactor systems with dwell times much in excess of 50 s may not be economically viable due to the enormous size of the storage units. An approximate cost analysis indicates that the minimum cost of the thermal storage system may be of the order of \$30-70 M.

Introduction

The results of the Blanket Comparison and Selection Study [1] indicate that the two most viable breeding blankets are (1) a solid breeder blanket cooled either by pressurized water or helium; and (2) a liquid breeder blanket consisting of either lithium-lead eutectic (17Li-83Pb) or liquid lithium. Blanket designs such as the STARFIRE [2] and DEMO/STARFIRE [3] that operate under steady state are less complex compared with pulsed reactors, although the majority of the design and operating problems such as tritium permeation and recovery, heat transport, thermal energy conversion system, safety, etc., are common to both types. However, from the standpoint of power conversion, pulsed mode operation has significant impact on the balance of the plant design, since during the low- or non-power producing part of the reactor operation, a means must be provided to generate power at a relatively constant rate. Hence, one of the primary requirements for a pulsed reactor is that it must have a thermal storage system along with the associated auxiliary equipment. An analysis of the thermal storage requirements for the two systems is described below.

Description of Breeding Blankets

To assess thermal storage requirements and thermomechanical effects of pulsed operation, detailed burn cycle analyses were carried out for a water-cooled Li_2O breeding blanket. For the self-cooled lithium blanket only an overall analysis based on thermal storage requirements was performed. The details of the two blanket designs are presented in Ref. 1.

Design and Operating Conditions

For a given neutron wall loading the primary design considerations are the operating variables for the coolant, breeding material, and structural material. The operating conditions for the heat transport system are essentially similar to those of the current pressurized water reactors. The thermal hydraulic analysis is based on these data and operating conditions:

Structural material	Stainless steel
Breeding material (sphere-pak)	Li_2O (85% TD)
Breeder density (g/cm^2)	1.71
Neutron wall loading (MW/m^2)	3.4
Coolant	water
Coolant inlet/outlet temperature (°C)	280/320
Breeder temperature window (°C)	800/410
Surface heat flux (W/cm^2)	10-100
Thermal conductivity of Li_2O	3.4
Blanket size, length and width (m)	3 × 2
Coolant tube, i.d./o.d. (mm)	10/12.5
Thermal barrier between coolant channel and breeder material	SS felt, He, Li_2ZrO_3

Liquid Breeder Blanket

For the liquid breeder blanket, only self-cooled blankets (i.e., the coolant serves both as the heat transfer medium as well as the tritium breeder) are considered. Since this design is still in the early stages of development, no transient analysis of this design has been undertaken during the scope of the current burn cycle analysis. However, an overall thermal analysis was carried out to size the thermal storage systems and to compare the relative cost of thermal requirements for the two types of breeding blankets.

Burn Cycle

The transient thermal hydraulic and thermomechanical analysis is based on a reactor power profile such as shown in Fig. 1. The following burn cycle scenarios have been used in the transient analysis:

Startup time (zero power to full power), s	10
Steady-state time (at full power), s	3600
Shutdown time (full power to zero power), s	10
Dwell time (zero power), s	0,30,90,200

For simplicity, the startup and the shutdown ramps have been assumed to be linear. Dwell time of 0 s represents a limiting case for a pulsed power reactor, and the minimum economic penalty associated with pulsed-mode operation.

Thermal Storage System

The analysis of the thermal storage system may be divided into two parts. The first part is associated with the energy deficiency that occurs during the shutdown, dwell, and startup periods of reactor

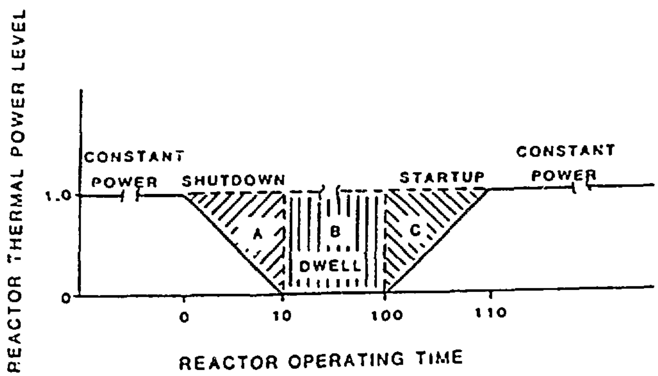

Fig. 1. Reactor power profile.

operation. Hence, consideration of the amount of sup plemental energy requirements is independent of the type of breeding blanket. The second part consists of transient temperature response of the entire reactor system and, in particular, the mixed mean temperature of the coolant that enters the energy conversion segment of the power reactor.

Transient Temperature Response

For the blanket design consdiered herein, there will be ten breeder regions representing ~0.50-m thick blanket. Hence, the mixed mean temperature from the ten breeder regions will dictate the sizing of the thermal storage components such as the steam drums, pipes, valves, pumps, heat exchangers, turbines, flow controllers, and numerous other auxiliary equipment. Experience gained from the study of the thermal storage requirements for WILDCAT [4] indicate that an acceptable assessment of the thermal storage system can be carried out with analytical data based on only three representative blanket regions. Hence, only three blanket regions, as listed in the tabulation below, were used (note: 100% region refers to blanket regions near the first wall and 5% region refers to blanket region near reflector/shield).

Region:	1	2	3
Percentage:	(100%)	(25%)	(5%)
Nuclear heating rate, (W/cc)	41.1	10.3	2.06
Coolant tube, i.d. (mm)	10	10	10
Module length (m)	3	3	3
Coolant velocity (m/s)	5.0	2.9	1.7
Breeder region radius (mm)	13.69	20.14	34.43
Number of coolant tubes	73	50	29

The transient temperature responses were calculated for blanket modules corresponding to the coolant exit locations. These include the temperature response of coolant, cladding, and the Li_2O breeder. For the Li_2O breeder, only the maximum and the minimum temperatures (and thus the temperature gradient) are included. Since the initial temperature of the reactor is not known a priori, the transient temperature response during the first few cycles is not meaningful. Hence, the temperature response during the second and the subsequent cycles were considered. Table 1 summarizes the minimum temperatures that occur during the zero power period. Since the volume of the blanket region associated with each coolant channel in an exponentially decreasing nuclear power field increases as the blanket regions are located further and further away from the first wall, the thermal inertia of regions in the radial direction (depthwise) increases. This effect can be observed from data shown in Table 1 where, for example, Region 3 temperatures do not decrease as much as the corresponding temperatures either in Region 2 or in Region 1. Similarly, the temperature differences across blanket regions away from the first wall are larger.

As expected, the changes in the coolant outlet temperatures and temperature gradients in the Li_2O blanket increase as the dwell times increase. If the dwell times are sufficiently long, the temperature of components are expected to decrease to the coolant inlet values. From the data presented in Table 1, it may be observed that the dwell times have to be greater than 200 s for all of the components to cool down to inlet temperature (assuming the decay heat to be small). When the dwell times are of the order of 200 s, only Region 1 cools down to the inlet temperatures.

The temperature response for 90-s dwell are shown in Figs. 2-4. As expected, the maximum variation in temperatures occurs for Region 1 due to its having the least volume of material. Since Region 1 has the least thermal inertia, its temperature recovers most rapidly during the next cycle. Similarly, the recovery of coolant temperatures is directly related to the breeder volumes. It may be observed from Figs. 2-4 that it takes almost 3000 s for Region 3 to fully recover from the cyclic operation.

Thermal Storage Requirements

As indicated earlier (1) the size of the thermal storage system depends on the energy deficiency that occurs during shutdown, dwell, and startup phases of the power reactor; and (2) the characteristics of the thermal storage system are dictated by the bulk average temperature of the coolant leaving the blanket modules. Hence, for a given burn cycle, the energy storage requirement for a solid breeder blanket or a liquid breeder blanket would be the same, although the same thermal storage system may not be appropriate for two entirely different blanket concepts.

For the solid breeder blanket, the bulk average temperature of the coolant was estimated by:

$$T_{avg} = \frac{\sum^{i=N} W_i T_i n_i}{\sum_{i=1} W_i n_i} ,$$

where

T_{avg} = Bulk average temperature of the coolant at blanket exit

W_i = coolant flow rate for Region i

T_i = Coolant exit temperature for Region i

N = Total number of blanket regions.

n_i = Number of coolant tubes in Region i.

The time/temperature history of the mixed coolant (T_{avg}) for the 90-s dwell is shown in Fig. 5.

The integral of the power curve in Fig. 1 (shaded area) determines the total energy deficiency during the shutdown/dwell/startup phases. The actual time/temperature response of the mixed mean coolant will dictate the design details of the thermal storage and control systems. It can be noted that as the dwell time increased from 0 to 200 s, the mixed coolant temperature decreases from 313°C to ~290°C, and it takes progressively longer time to approach steady state. It should be noted that the power conversion system (heat exchangers/evaporators, steam turbines, condensers, feedwater heaters, etc.) is based on coolant outlet temperatures of 320°C. The power conversion system can no longer be kept in operation when the coolant outlet temperature drops below 290°C. Hence, the necessity of a thermal storage system arises.

For a 4000-MWt reactor, the energy deficiency varies from 11 MWh to over 230 MWh. This quantity of energy must be supplied in a matter of a few hundred seconds in order to operate the power conversion system in a stable manner. Several thermal storage systems, such as packed columns of metals or ceramics, and chemicals, were considered for energy storage. However they did not appear to be practical if the thermal energy is to be withdrawn in a relatively short period of time. Energy storage in pressurized water, which can be withdrawn as steam by flashing, or energy storage in a high temperature liquid metal which can be fed into a heat exchanger/evaporator unit appear to be practical, although such systems are considered to be at the upper end of the existing technology. Analyses have shown that pressurized water/steam system is suitable for the solid breeder blanket, and hot sodium reservoir would be practical for the liquid lithium blanket. A brief description of the two systems and the corresponding cost analyses are presented below.

Pressurized Water/Steam System

Figure 6 schematically shows the pressurized water/steam thermal storage and power conversion system, which consists of heat exchanger/evaporator units, high pressure and low pressure steam turbines, condenser and condensate storage vessels, feedwater heaters, condensate return (high pressure and low pressure) pumps, generators, and the control system. During the steady-state period, steam flows from the primary steam generator/evaporator unit to the low-pressure turbines. The turbine exhaust after condensation is returned to the evaporators through the feedwater heaters. A bypass stream of blanket coolant flows into the thermal storage units. During shutdown, dwell, and storage periods, as the blanket coolant temperature drops below the steady-state value (v.z., below 320°C), steam is withdrawn from the high-pressure thermal storage units by flashing. The high-pressure steam drives the high-pressure turbine, and mixes with the low-pressure steam from the regular steam generator/evaporator units via the reheater and flows through the low pressure turbines. A portion of the condensate after passing through the feedwater heaters is fed back into the thermal storage unit via booster pumps. The major components, except the control system as discussed above, are shown in Fig. 6. During the next phase of this study, an assessment of the control system and design details of the auxiliary equipment will be made.

Liquid-Metal Breeder/Coolant

The liquid-metal blanket and heat transport system consists of a self-cooled lithium blanket, sodium reservoirs, lithium-to-sodium intermediate heat exchangers, and sodium/water steam generator/evaporator units (similar to liquid-metal-cooled fast breeder reactor). The operating conditions for this breeder blanket are as shown below:

Lithium inlet/outlet temperature (°C)	300/500
Sodium inlet/outlet temperature (°C)	290/490
Steam temperature (°C)	455

Figure 7 schematically shows the major components of the thermal storage system. It consists of lithium-to-sodium heat exchangers; heat accumulators; sodium-to-water evaporator/superheaters; turbine-generator; sodium and lithium circulating pumps; clean-up and purification systems (cold traps) for sodium; inert-gas pressurization systems; and a safety release system. The principle operation of this system is based on storing thermal energy in the sodium vessels which are designed to accumulate hot sodium. During the low power or nonpower producing period of the reactor, energy is withdrawn at a constant rate (i.e., at the same rate as during the steady-state power phase) from the sodium vessels via the intermediate heat exchangers. The amount of energy (i.e., the volume of hot sodium) that is withdrawn during the low/zero power period is made up during the steady-state operation through a side stream of hot lithium supplied from the reactor blanket.

Cost Estimate

The cost analysis is divided into two parts. In the first part, cost analysis is carried out based on zero dwell time and 10 s each for startup and shutdown times. Hence, the first part represents the minimum cost of the thermal storage system and the economic penalty for a pulsed reactor. In the second part, a cost estimate is made based on additional components that would be necessary to supplement the thermal storage system for each 10-s dwell or other nonpower generating periods. The estimated cost of the thermal storage system for the two blankets is given below.

- Li_2O breeder: Total cost ($M) = 71 + 3.7 × dwell, s
- Lithium breeder: 32 + 1.9 × dwell, s

Comparison of Costs

Examination of the cost of the thermal storage units for the two systems indicates that the costs for the liquid-lithium breeder is significantly lower. The primary reason for the low cost of the liquid-metal system is due to low-pressure operation of the thermal storage systems (200 psia liquid-metal breeder versus ~2000 psia for water-cooled solid breeder). It should be noted, however, the added cost of tritium containment such as double-wall pipes, penalty for heat exchangers due to added thermal resistance of double-wall pipes, tritium cleanup, and recovery systems have not been included in this analysis. Although tritium-related costs could significantly increase the cost of the thermal storage systems for the liquid lithium-cooled reactors, it is expected that due to low-pressure operation the cost of the thermal storage for the liquid-metal blanket will still be lower than the cost of the pressurized water-cooled blankets. Additionally, they would be much simpler to operate.

Thermomechanical Analysis

For the design and operating conditions given above, the heat flux over the coolant tubes varies from a maximum of ~100 W/cm^2 to $\leq$30 W/cm^2. The maximum thermal stresses induced by the temperature gradients across the coolant channels is <5 MPa. However, the primary stress due to high pressure (~15 MPa) water is the order of 55 MPa. During cyclic operation the temperature gradients across the coolant tubes are not significantly larger than the steady-state values. Hence, thermal stresses in the coolant tubes due to cyclic operation is not considered to be a problem for the solid breeder blankets.

Discussion of Results

Transient analysis of a Li_2O solid breeder blanket indicate that breeder regions near the first wall will cool down to approximately the coolant inlet

TABLE 1

Minimum Temperature During Cyclic Operation of Li_2O Breeding Blanket

Region:	1				2				3			
Dwell time (s):	0	30	90	200	0	30	90	200	0	30	90	200
Coolant	312	297	287	280	316	310	303	292	319	317	315	311
Cladding[a]	345	315	294	281	349	333	320	303	352	338	335	329
T_{min}	394	342	304	282	402	382	357	323	409	391	388	377
T_{max}	807	586	398	287	840	773	659	491	850	829	810	759

[a]Temperature in cladding node (midpoint of cladding thickness).

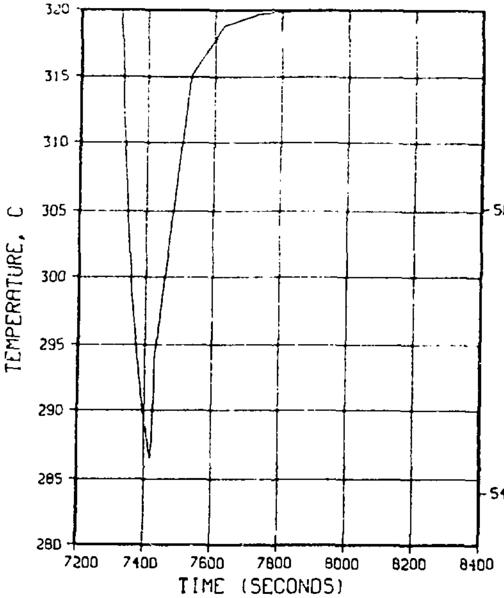

Fig. 2. Coolant temperature response: 90-s dwell/Region 1.

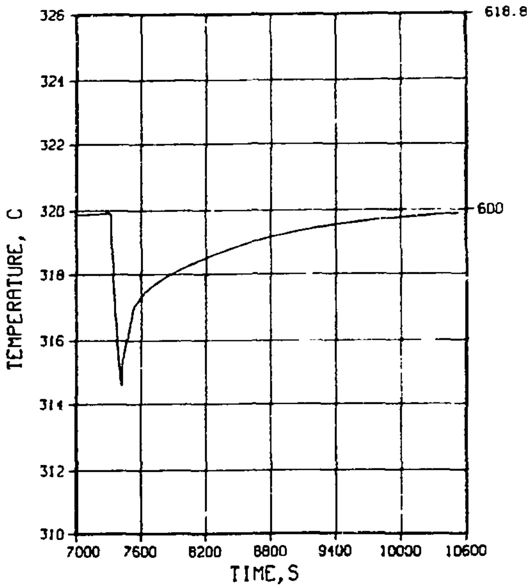

Fig. 4. Coolant temperature response: 90-s dwell/Region 3.

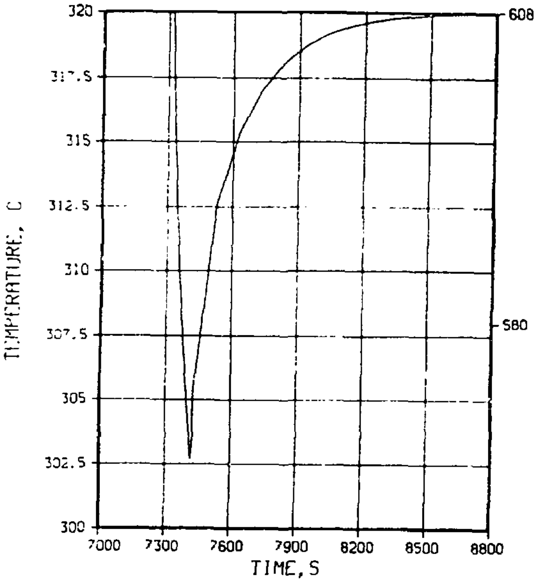

Fig. 3. Coolant temperature response: 90-s dwell/Region 2.

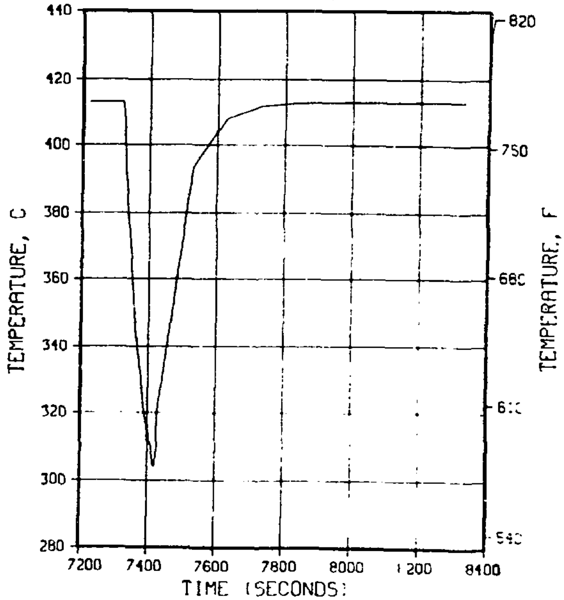

Fig. 5. Volumetric average temperature response: 90-s dwell.

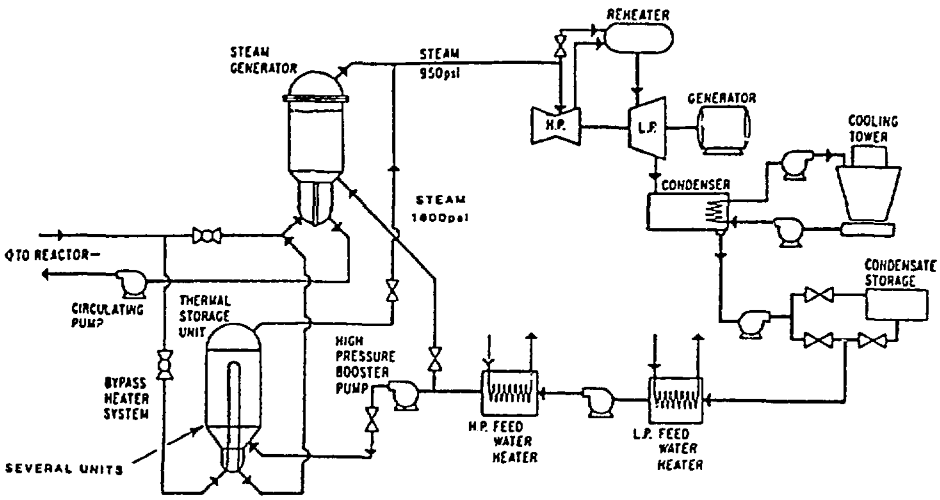

Fig. 6. Schematic of thermal storage system for water-cooled Li_2O blanket.

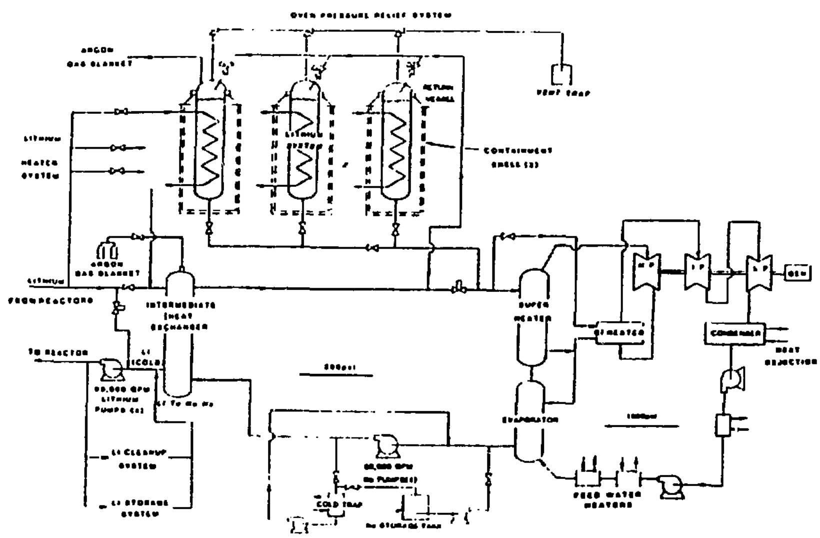

Fig. 7. Schematic of thermal storage system for self-cooled lithium blanket.

temperature when the dwell times exceed 200 s. While large temperature variations across the breeder may not adversely affect the integrity of the breeder of sphere-pak design, cooldown of the breeder below the lower operating temperature limit may have significant impact on tritium recovery. The induced thermal stresses across the coolant tubes during transient operation is low; no severe degradation of blanket life due to cyclic operation is anticipated.

Cyclic operation has a severe cost penalty. For zero dwell time alone the thermal system will cost 30 to 70 M$. The preliminary cost analysis shows that the thermal storage system for self-cooled lithium blanket to be less than that for the solid breeder blankets. However, the cost associated with tritium containment and recovery has not been included in these analyses. Detailed cost analysis of both systems is necessary before definitive conclusions can be made. The penalty in terms of adverse thermo-mechanical effects on major components appears to be minimal. Cost analysis indicate that systems with greater than 50 s dwell may not be economically viable.

The above conclusions are based on the desire to supply constant steam conditions in the turbine, and all costs are based on conventional equipment for the steam cycle. Optimized design for pulsed operation, inclusion of coolant volume in transfer lines, higher tolerance for power fluctuations, and larger allowable operational variations for critical components may reduce the cost of the thermal storage systems.

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