Proposed Heat Storage and Recovery Facility Design for Korean Nuclear Power Plants using Ultra Large Floating Barge

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1. Introduction

The Korean government, following policy recommendations from a select committee, has established a plan to gradually phase out coal and nuclear power generation, while expanding renewable energy to 20% of the power supply by 2030, and to higher levels beyond that date. To meet these goals, it is expected that more solar and wind power installations will be required. In addition, Korea energy policy goals as spelled out by MOTIE recommend that research efforts be directed in the following areas: (i) large scale commercial projects, (ii) integrated planning with renewable, intermittent sources, (iii) early adoption suitable for deployment, and (iv) integration with key Korea industries (i.e., construction, shipbuilding, component manufacturing).

To address these policy recommendations and research goals, a large scale thermal energy storage system using commercially ready technology and which leverages key Korea industrial advantages and capabilities is outlined here. With heat supplied by secondary side steam from Korean Nuclear Power Plants (NPPs), the system can be readily scaled to store in the range of 5,000 to 60,000 MWt-hr, with significant economies of scale towards the higher end of the range.

2. Background

Proposed here is a massive and scalable heat storage facility, the Ultra Large Barge (ULB) to store heat from Korean NPPs during off peak periods. This proposal is follow-up research to considerations for heat storage and recovery configured as an Oil Storage Tank Farm (OSTF) [1]. The previously proposed NHS&R System is based on Thermal Energy Storage (TES) with 20% of nuclear heat stored during periods of low electricity demand and returned via increased output of the NPP Turbine-Generator (T/G) during periods of high demand. Stored energy is supplied via high pressure steam extracted from the NPP steam cycle as transferred to high temperature synthetic oil (e.g., Therminol 66). This oil then transports, transfers, and stores the energy in the form of sensible heat in a packed bed of Hornfels rock. Details of the steam side of this cycle are described elsewhere [2] while the expanded and refined thermal energy storage side of the NHS&R System is detailed here.

The temperature of steam exported for heat storage sets the upper bound for the NHS&R System operating temperature and hence the upper bound Carnot cycle efficiency. Therefore the Main Steam (MS) System is selected as the heat extraction location for each of the analyzed cases with condensed steam returned to the deaerator. The volumetric flow rate for the Heat Transfer Fluid (HTF) (i.e., high temperature oil, Therminol-66) scales inversely the temperature range of the oil (i.e., the temperature difference between the hot and cold oil). This range along with required storage volumes is examined parametrically using three storage cases.

Case S1: This case analyzes the heat storage system configuration and performance for a temperature range of 60°C.

Case S2: This case assumes a temperature range 90°C. Here, storage operations require less steam extracted from the cycle, with returned condensate exhibiting lower enthalpy than for Case S1.

Case S3: This case considers a temperature range of 130ºC. Again, less steam is exported from the MS System as compared to the other two cases.

For NHS&R operations, the HTF experiences a change in temperature from low temperature (T_c) to high temperature (T_h) during storage (steam-to-oil heat transfer). The desired thermal power Q to be stored is 800 MWt. Assuming eight (8) hours of charging, the stored energy for diurnal operations is 2.3×10^{10} kJ.

For the storage volume, two cases are considered, 'wet' and dry' storage. With wet storage, the rock bed is flooded, while for dry storage, the bed is drained. Dry storage considerably reduces the cost of the storage medium, as crushed rock is much cheaper than synthetic oil.

Required HTF mass flow rates and storage volumes can be determined as:

$$\dot{Q}_s = \dot{M}_o.\{C_{po}\}.(T_{h,o-} T_{c,o}) \quad 1$$

$$\dot{Q}_s = \dot{M}_o.\{h_{h,o} - h_{c,o}\} \quad 2$$

$$\dot{M}_o = \frac{\dot{Q}_s}{\Delta h_o} \quad 3$$

$$V_o = \frac{\dot{M}_o.\Delta t_s}{\rho} \quad 4$$

$$Vs = \frac{\dot{Q}_s.\Delta t_s}{\{\pi\varepsilon.(\rho_o.C_{po})\} + \{(1-\varepsilon).(\rho_r.C_r)\} * \Delta T} \quad 5$$

Where Vs is the volume of bulk storage (m^3)
$\dot{Q}_s$ – Heat storage rate (kW)

ε - Hornfels rock porosity of 20%
M_o - Oil mass flowrate (kg/s)
$h_{h,o}$, $h_{c,o}$ - Enthalpy of hot & cold oil,
Δt_s - Storage period (second),
ת = 1 for 'wet' storage and 0 for 'dry' storage

V_o is the Therminol-66 required volume.
As previously described [1], Hornfels rock is assumed as the storage medium with properties per Table 1.

Table 1: Hornfels Rock Properties

Property	Value
Bulk density, kg/m^3	2667
Porosity, %	20
Heat capacity, kJ/kg-K	0.960

Presented below are the mass flow rate for the HTF, and the unit storage volumes per 1000 MW$_t$-hr for both wet and dry storage (for the three temperature ranges described above).

Table 2: NHS&R Design Parameters

Case	60°C	90°C	130°C
HTF Mass Flow Rate[1]	5,612	3,871	2,741
HTF volume – Wet[2]	4.94	3.29	2.27
Hornfels Volume – Wet[2]	19.76	13.15	9.08
HTF Mass – Dry[3]	-	-	-
Hornfels volume – Dry[2]	29.30	19.53	13.52

1) kg/s
2) 10^3 m^3
3) Not including pipe, transfer tank, and heat exchanger volume.

As described above, this storage can be configured as part of an ultra large barge, designed and manufactured by the Korea shipbuilding industry.

3. Korean Shipbuilding Industry

The Korean shipbuilding industry is well-positioned to remain globally competitive in custom design construction technology. Shipbuilding is routinely among the top three most valuable Korean export industries [3]. Korea has demonstrated world class technology through application of the modular approach to ship building, an approach developed in the 1980s (i.e., the block construction method). Block construction leverages Korean expertise in automated welding and programmable robots, dramatically reducing construction schedules and costs.

A ULB integrated storage facility represents new technology which aligns well with Korean industrial capabilities. Similar to past projects with customer unique specifications, the proposed ULB design concept is less technically challenging that current projects for the transporting, storing and processing of liquefied natural gas. The proposed application, although larger in scale, is similar to applications for floating power generation as seen in the Dominican Republic, New Guinea, and Brazil.

To cite other examples, the Geoje shipyard owned and operated by Samsung Heavy Indutries has developed and built the first Arctic Shuttle-Tanker and LNG-FPSOs (LNG - floating, production, storage, offloading unit) in the world, and has pioneered new market developments by developing innovative products such as LNG-FSRU (floating storage regasification unit), a form of ULB for storing LNG. SHI's technological excellence has been highly recognized in the global markets.

The Hyundai Heavy Industries shipbuilding group is also among the world leading shipbuilders maintaining a ~15% share of the world shipbuilding market. HHI uses high level automation and new production technologies ranging from welding robots, cutting-edge technology with modern equipment, and is capable of building special projects in various fields such as drillships, semi-submersible rigs, FPUs and FPSOs. The design and construction of floating barges is not new to Korea with past successess and a strong reputation. Adapting such technology to sustaining NPPs to integrate in the energy mix with a high fraction of renewable supply may represent a new market opportunity.

3.1. ULB Energy Storage

The proposed scale of the ULB storage facility ranges up to a 450 m length by 60 m width barge. A facility on this scale could accommodate several stacked heat storage tanks. Such a unit represents storage of approximately ten (10) times the diurnal requirements outlined here (>2x10^{14} J). This scale would permit a single ULB facility to store thermal heat capable of producing 20 GW-hr, or nearly an entire day of the output of a 1000 MWe NPP. This facility could then provide emergency backup power in the event of severe weather (e.g., typhoon) which completely curtailed renewable sources (i.e., wind and solar).

Shown in Fig. 1 below is the pumping station which connects the barge to the heat source plant. Tanks measuring120 m in length by 8 m in diameter are considered, but are not a customer requirement. Eight meter (8 m) diameter horizontal tanks are considered to be compatible with maximum rolled steel plate sizes and would minimize welding.

After the construction of ULB, horizontal tanks to house the packed bed of hornfels rocks are stacked and then shipped to the NPP site. This facility is designed to stack tanks in such a way to allow drain down of the heated rock beds to minimize the required volume of expensive HTF.

The ULB facility is fully scalable. The interface equipment to the NPP is a fixed cost, constrained by heat transfer rates which are compatible with the existing NPP steam plant. However, the stored energy content can be scaled upward at very low cost, primarily driven by the cost of steel and crushed rock.

3.2. ULB Design Considerations

The design of the ULB must meet the operating conditions, strength, serviceability and safety requirements. It must be durable, visually pleasing to the environment and cost-effective. An appropriate design service life prescribed depends on the importance of the structure and the return period of natural loads. This facility could outlive NPP with a service life of about 50 to 100 years.

The ULB concept for heat storage described here does not require a hull design with proportion, streamlined or hydraulically load dragged (i.e., it is only required to be transported once to the NPP site). In addition, there is no requirement for self-propulsion or space for machinery or crew.

This only requirements relate to the spaces required for the packed bed horizontal tanks, for safe personnel access, and for the pumping station/system for transfer of oil to and from the storage tanks. The pumping station is comprised of pumps, piping, and other control systems connected to the heat transfer buildings (HSB and HRB).

3.3. Site Specific Application

Floating ULB structures can be designed and built in two ways as identified by E. Watanabe et al. (2004) [4].

- Semi-submersible floating structures are raised above the sea level using column tubes or ballast structural elements to minimize the effects of waves while maintaining a constant buoyancy force.
- Pontoon-type floating structures lie on the sea level like a giant plate floating on water. This type of floating structures are suitable for use in calm water bodies. Large pontoon-type floating structures are termed Mega-Floats and consists of: (a) a very large pontoon floating structure, (b) a mooring facility to keep the floating structure in place, (c) an access bridge or floating road to get to the floating structure from land, and (d) a breakwater (usually needed if the significant wave height is greater than 4m) for reducing wave forces impacting the floating structure.

The pontoon type floating structure is considered suitable for Korean NPP sites (water body is not turbulent which is one of the criteria to consider), with advantages over the semi-submersible type in terms of:

- cost effectiveness, easy and fast to construct (components can be made at different shipyards, assembled and then shipped to NPP site).
- environmental friendly as they do not damage the marine eco-system, or silt-up deep harbours or disrupt the tidal/ocean currents,
- can easily be removed (if the sea space is needed in future) and scalable for more storage,
- the facilities and structures on Mega-Floats are protected from seismic shocks since they are inherently base isolated as shown in Fig. 2.

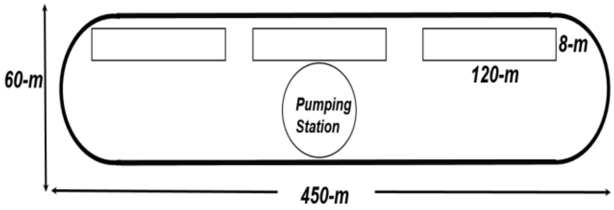

Fig. 1: ULB side view showing with dimensions

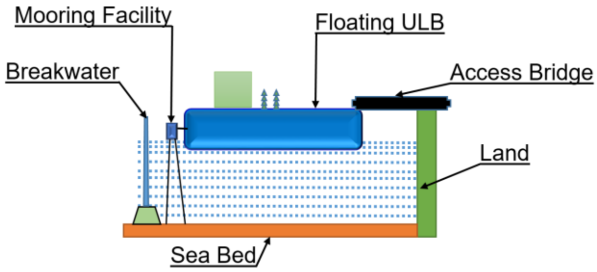

Fig. 2: Components of Pontoon Type Floating Structure

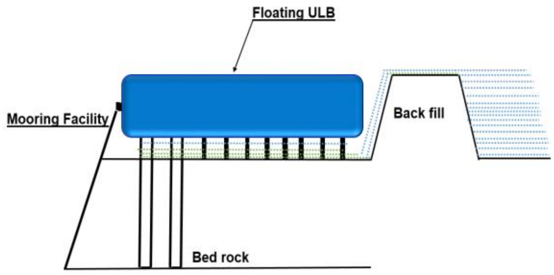

Fig. 3: Floating ULB structure

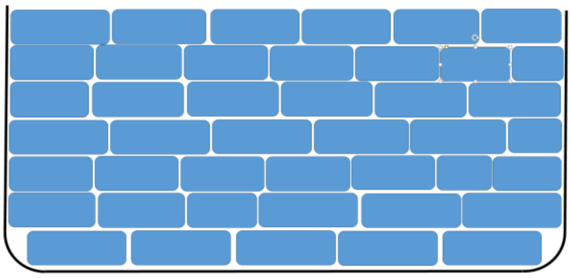

Fig. 3: Ultra Large Storage Barge

4. ULB Potential during Heat Recovery

Heat recovery from NHS&R can be carried out by either using an integrated or a stand-alone system [5]. Kluba and Field (2019) studied the optimization of NHS&R Rankine cycle with integrated heat recovery through the existing T/G set. A target recovery of 11% of NSSS power (~425 MW_t) was selected resulting in a fourteen (14) hour recovery period. Heat recovered can also be transferred to a cryogenic recovery cycle as proposed by Heo and Jeong, (2019), making use of integrating Liquid Air Energy Storage (LAES) with NPP supplied heat [6]. Li et al. (2014) also propose integrating a cryogen based energy storage with NPPs (NPP- CES system) [7].

5. Summary

The key advantage of large capacity ULB storage described here is scalability, and ability to store heat from more than one nuclear power plant. Since all nuclear sites in Korea house more than one unit, the ULB provides the potential to share the facility. Also, a floating ULB is seen to be easily adaptable to the global market since most plants are built near a body of water.

In addition, during national emergencies, a scaled up NHS&R facility (ULB) can provide substantial backup energy supply, thus enhancing the safety of the nuclear reactor. Finally, this facility not is expected to add any undue risks which could challenge control room operators in their duty to operate the reactor in a safe and reliable manner.

Floating barge technologies adapted to TES represents a promising option considering the following factors: (i) leveraging Korean technical leadership is ship design and construction, (ii) use of conventional technology, (iii) low capital requirements, (iv) moderate maintenance cost, and (v) long service life.

6. Future Work

Hydraulic analysis of the ultra large barge unit to determine the pumping power and also the round trip efficiency of the heat cycle is warranted as follow on analysis. In addition, the safety aspects (e.g., the design load effect, buoyancy, waves, current and wind effects on this design) should be looked into.

Acknowledgements

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