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REQUEST FOR ADMISSION TO Ph.D. CANDIDACY

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GTID# 902796247

Print Name: Cal (First) Richard (Middle) Abel (Last)

PART I. THESIS TOPIC

Thesis Title: Integrating Thermal Energy Storage and Nuclear Reactors: A Technical and Policy Study

Brief Description: **(DO NOT EXCEED SPACE PROVIDED BELOW)**

Combining two previously unrelated technologies, solar Thermal Energy Storage (TES) and mid-temperature nuclear reactors creates a novel synergy. The combined system allows nuclear energy to expand beyond baseload electricity improving the fundamental economics. The design uses established technologies and materials that are commercially available. The only "new" component is the reactor. The study uses the Integral Fast Reactor (IFR), the most commercially ready fourth generation design The TES replaces IFR's entire intermediate loop. This study explores the implications of this design change to reactor safety, mission profile, and economcis.

The main purpose of the study is to examine the kinetic response of the nuclear TES system using real world data and develop: a normal reactivity control strategy for the reactor, a methodology for estimating needed energy storage capacity, and evaluate system responses in various casualty situations. Routine transient response and control modeling is done using a state space methodology. The system is modeled under various casualty conditions using an established reactor simulation code, RELAP5-3D, to verify satisfaction of the General Design Criteria.

The study will show how to size and integrate the IFR-TES into an existing electrical utility, using actual data with a methodology to estimate environmental and economic parameters that impact storage sizing. The combined system will aim to resolve many challenging economic and policy problems, e.g. scalable and economic carbon free energy. This study examines the consequences of wide scale implementation of this technology identifying the key policy constraints that limit its impact and recommending potential solutions.

Approved by:

______________________ Signature of Student

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Eric Loewen, GE

PART II. COMPREHENSIVE EXAMINATION

The above student passed the Comprehensive Examination on ___/___/___ and is admitted to Ph.D. candidacy in

______________________ ______________________ (Graduate Coordinator)

NOTE: If minor has been approved, please attach a copy to this form.

PART III. ADMISSION TO CANDIDACY

This student is admitted to candidacy for the Ph.D. Degree in ______________________ on ___/___/___

______________________ (Vice Provost for Graduate Education and Faculty Affairs)

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1 Introduction

Nuclear power plants generate energy with life-cycle near-zero emission of greenhouse gases and particulates. However, there is over one trillion dollars stranded in infrastructure related to coal transportation and mining and to fossil power plants,[3] and irrespective of nuclear power advantages it is economically not viable to simply abandon this infrastructure. The purpose of this study will be to explore the idea of repowering existing infrastructure with nuclear power. The goal is to validate the proposed approach of effectively decarbonizing electricity production by reusing as much of existing infrastructure as possible. Our hope is that by reusing existing capital assets to the maximal extent possible, we can minimize the cost of regulatory compliance, particularly the proposed rules on green house gas emissions.[4]

The existing fleet of Light Water Reactors (LWR) are only economically effective at high capacity factors acting as baseload energy.[5] Their complexity and size precludes many utilities from even considering a new reactor project. Additionally, their large size forces utilities without expansive networks to build surplus transmission capacity in the event of a forced outage with a large LWR. Grid limitations also impact the adoption of renewable energy sources because of the construction costs and difficulty in obtaining adequate right of way for the new transmission lines.[6] Our remaining choice for addressing the changes in environmental regulation is natural gas, but here too we run into problems such as limited pipeline capacity, volatile natural gas market prices with significant fluctuations due to supply and seasonal affects.[7, 8]

It is imperative for an economy to have low stable energy prices to sustain long term growth.[9, 10] We are seeing the impact of high energy prices in Germany,

$352/MW-hr, causing electricity to become a luxury.[11, 12] The impact is not lost on areas with low energy prices.[13] Comparing the state of Georgia with Germany, per-capita, Georgians use 5,400 kW-hr/yr while Germans use 1,700 kW-hr/yr [14, 15], spending $665/yr and $600/yr per person respectively. Electricity has a significant impact on the standard of living. The average Georgian citizen consume 317% more electricity spending only 10% more than their German counterparts. As a result Georgians can afford to live in bigger houses with more amenities.

Our focus was to develop a solution that reuses existing infrastructure and relies upon technologies already commercially deployed or at least demonstrated at commercial scale (e.g. pool type Sodium Fast Reactors, SFR, ready for commercial deployment). The design needs to be able to integrate with coal, combustion turbines, and combined cycle plants. The reactors need to also operate at a high capacity factor to have favorable capital recovery. To be able to load follow, integrate with existing infrastructure, and have the reactors operate at a high capacity factor, we incorporated thermal energy storage. In the past, the Nuclear Regulatory Commission, NRC, was reluctant to consider allowing even advanced reactors from connecting directly with Power Conversion Systems that were not considered during the licensing of the reactor without implementing additional measures.[16] Our primary purpose is to show how using energy storage separates the reactor from the load and can be used to provide operational flexibility and scalability for utilities.

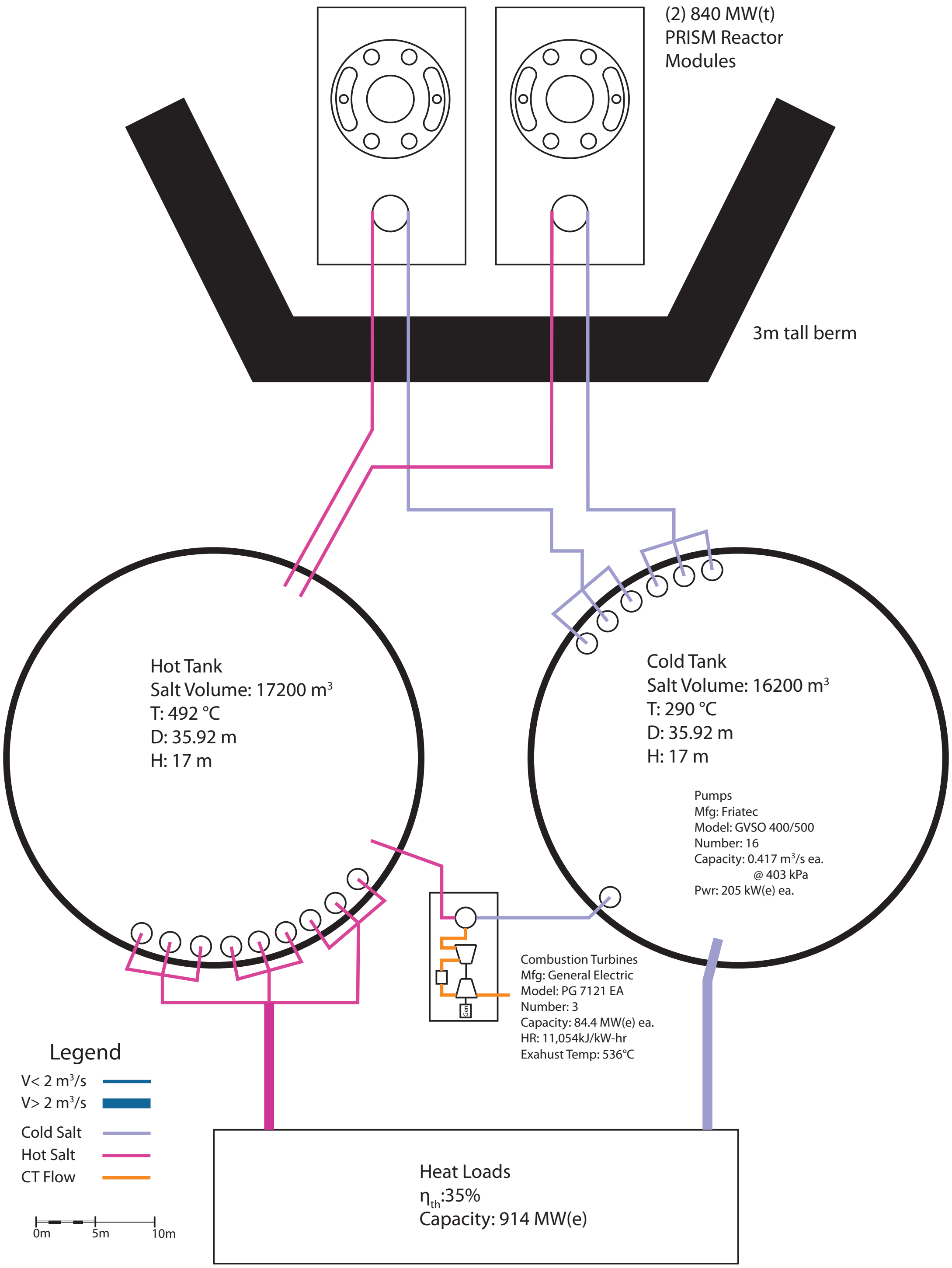

Figure 1 nTES overhead view

There were several designs of energy storage systems to consider.[17] Storage systems are dictated by the considerations of selecting the reactor design. The most promising storage design is the storage of sensible heat using high temperature salts. One of the most cost effective salts is solar salt, 60 $NaNO_3$ – 40 KNO_3.[18] It has an operational temperature range of 250°C–600°C and is already commercially deployed, e.g. Andasol Project in Spain.[19, 20] This provides an adequate operational envelope for mid temperature reactors especially the SFR. Additionally, the coolant is chemically compatible with sodium, requiring no special precautions in the event of their mixing. Figure 1 shows the proposed layout of the integrated storage system. Figure 2 shows a design simplification that contains all sodium inside the primary sodium pool.

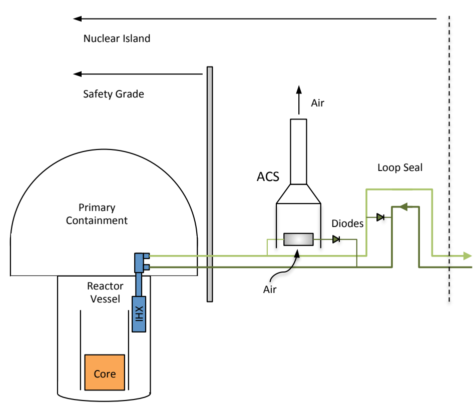

Figure 2 nTES Auxillary Cooling System (ACS) piping elevation

We chose General Electric-Hitachi's (GE-H) Power Reactor Innovative Small Module (PRISM), Figure 3 and 4, as the most mature SFR design.[2, 16] Because the reactor is a GE-H design and GE is a major vendor of combined cycle plants, we used GE's extensive line of combined cycle modules as they would be likely candidates in any contracted project.

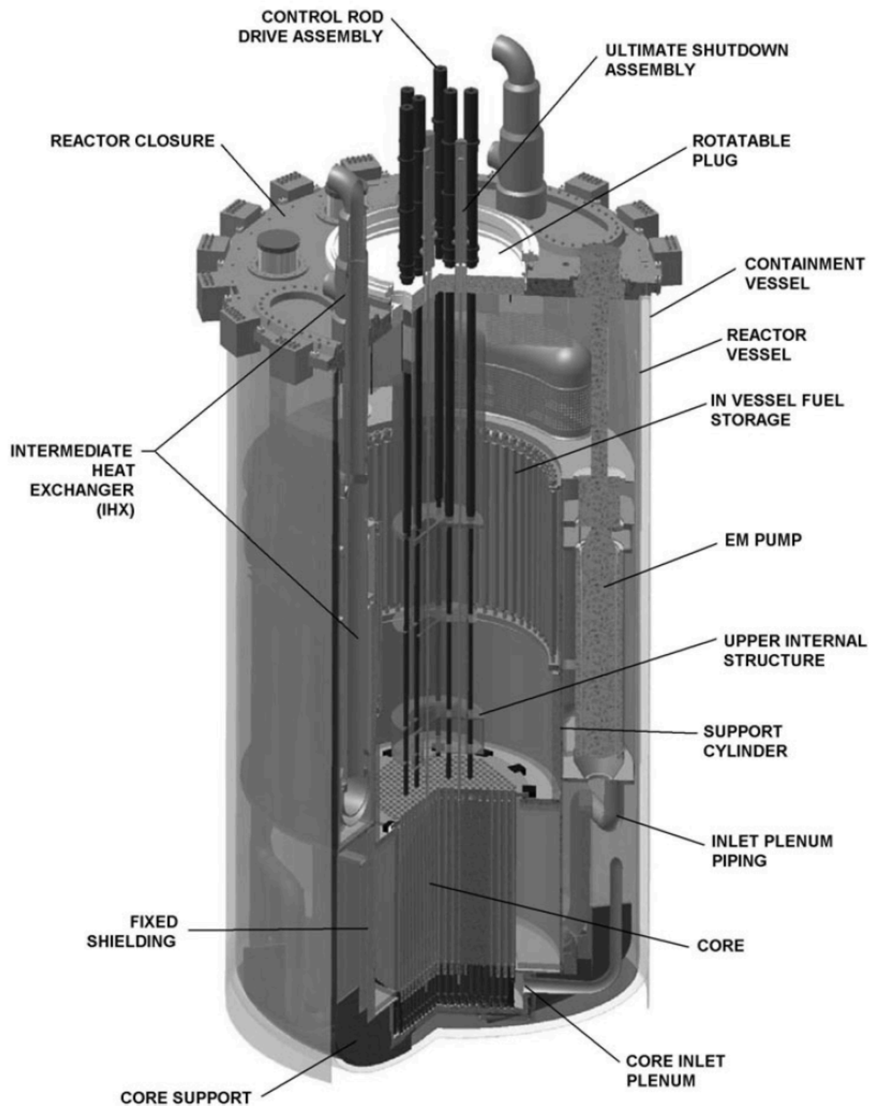

Fig. 3. PRISM reactor module.

Figure 3 PRISM reactor module taken from Triplet et al.[2]

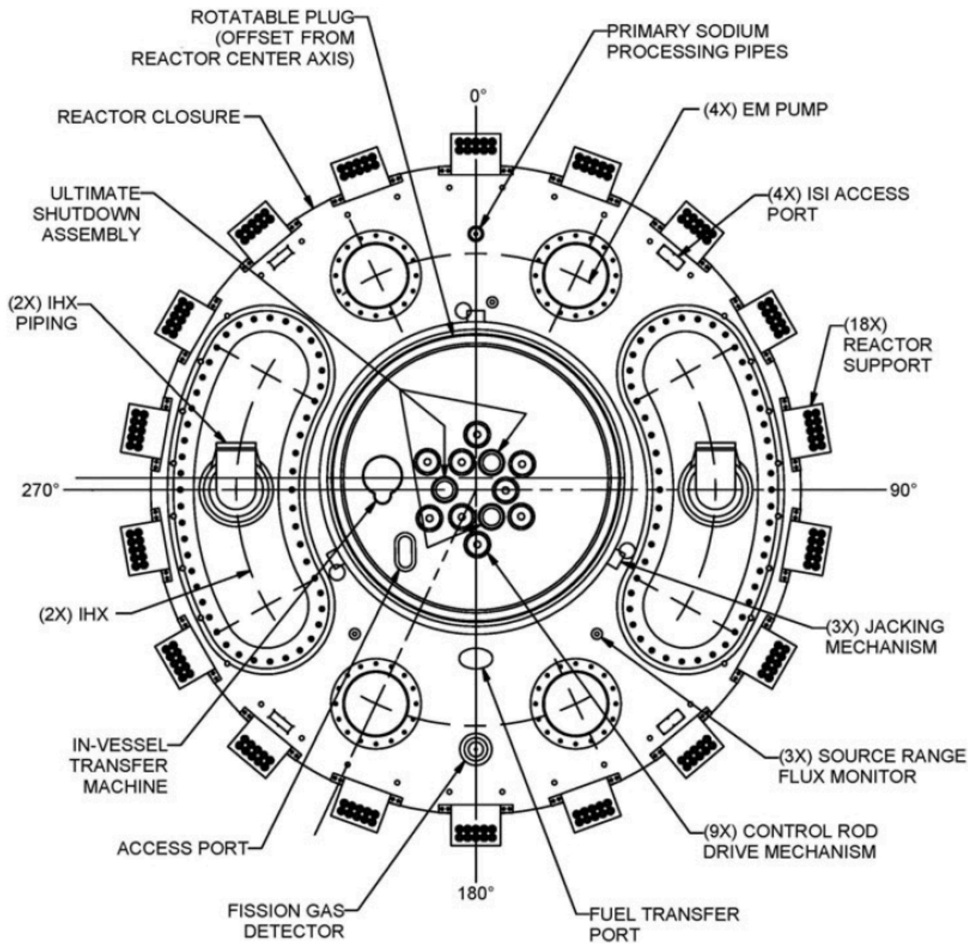

Fig. 4. Reactor closure penetrations.

Figure 4 PRISM reactor closure penetrations taken from Triplet et al.[2]

The two main goals of this research are to investigate with RELAP5-3D how the reactor responds and can be controlled by the operator while load following and how the simplified reactor configuration (Figure 2) responds to a loss of the salt storage system. We will also look at the economics of the design and suggest areas where additional engineering focus can be implemented to help make the project commercially viable under existing and potential electricity markets.

The design change of the nuclear island impacts the NRC's General Design Criteria (GDC) of 10CFR50. The research done here will also have to demonstrate that the GDC may be satisfied with adequate design choices. Preliminary economic analysis showed the market competitiveness of the overall system is driven by the construction costs, incremental capital costs, and operation and maintenance (O&M) costs. Capital cost of the system drives the majority of the cost, but their importance decreases as costs lower. O&M is the second most important driver in determining the Levelized Cost Of Electricity (LCOE). The next largest price driver is incremental capital costs. These are significantly affected by long-term maintenance.

The three cost considerations drove the decision to change the design of the nuclear island. Without cost optimization, our proposed system would not be a viable market alternative and be of no value to utilities and policy makers. Creating and demonstrating a conceptual design that is viable is our overarching purpose.

2 Scope of Work

The research to be done centers on two parts. The first part will take the proposed design of the nTES and evaluate its performance under normal and off normal conditions. The second part evaluates where and how the nTES can fit into the existing electricity market.

Evaluating the operational performance requires building a closed loop reactivity control model and determining the envelope of stability for the proposed scheme. With a defined operational envelope, the detailed design and the closed loop control model will be evaluated in RELAP5-3D to assess suitability and applicability of the approximations used to develop the closed loop control model. An important part of the developing the reactivity control schedule is to determine the reactivity addition rates which give adequate margin to core thermal limits and sufficient flexibility to meet intended operational demands. Once nTES is verified to meet its intended purpose, the RELAP5-3D model will be used to evaluate the plant under off normal conditions: pipe ruptures in the hot and cold leg piping between the loop seal and the storage tanks and the various reactivity addition accidents that can occur. Concurrent with these evaluations is, time permitting, evaluation of the performance of the plant entering a refueling outage to include examining long-term operations on the Auxiliary Cooling System, ACS.

Evaluation of how nTES can integrate into the electric market was done in large part in determining the design parameters: low capital cost, reduced O&M costs, redundant components, resilient operations on a small electric grid, and scalable design and construction. While most of these are desirable for any generation source, this part of the study will focus on exploring the consequences of those design choices and how the design resolves some of the unintended consequences of the gamut of regulation faced by all utilities. The market case for nTES is more than just the lowest cost of generation, but also the lowest delivered cost to the consumer.

3 Facility Design

A simple way of understanding the modularity of the nuclear Thermal Energy Storage, nTES, is to think of it as an energy bus much like an electrical switchboard. The salt storage tanks act like a battery buffering the temperature (voltage) variation of the bus. The heat from the reactors and the heat recovered from the combustion turbines act like electrical generators. Everything attached to the bus is in parallel. This allows a component (load or generator) to be removed from service through either forced or planned outage without affecting the entire system. It also allows scaled capacity additions, increasing the utilities' flexibility in adding/retiring smaller steps of capacity with demand fluctuations, helping to increase capital utilization without impacting grid stability.

The intention for salt tank operation is to not take the tanks out of service. For this reason there are at least two reactors, multiple combustion turbines, and several Rankine Power Conversion System, PCS, attached to each set of tanks. Refueling outages are used to adjust for major fluctuations in seasonal demand. With at least one reactor on service the tanks will always have a means of restoring their level. Similarly, the PCS are redundant allowing seasonal adjustment and continued operation with a forced outage. The combustion turbines are another level of redundancy. The site can at some level always maintain electrical power and be able to restore power quickly after a station blackout without the need for offsite power. The redundancy and the ability to restore plant operation from on site is a critical design feature allowing the plant to bootstrap the grid.

3.1 Salt Selection

There are four salts compatible with large scale energy storage being examined by solar thermal designers: Solar Salt (60% $NaNO_3$, 40% KNO_3), Hitec (7% $NaNO_3$, 53% KNO_3, and 40% $NaNO_2$), HitecXL (48% $Ca(NO_3)_2$, 7% $NaNO_3$, 45% KNO_3), and $LiNO_3$.[18] These salts have maximum operating temperatures of 600°C, 535°C, 500°C, and 550°C respectively. With reactor core outlet temperatures at 100% power of 500°C and accident power transients limitations of primary components, 595°C, set by creep limits[16], the only compatible coolant that satisfies the entire operational envelope of

PRISM is Solar Salt. Solar Salt is also the least expensive salt, \$0.61/kg, with an overall cost of storage capacity of \$7.3/kW-hr(t), (2011 dollars).[18] Using salt tanks similar to the size of Andasol (H:17m D:35m) and salt temperatures of 492°C–290°C, each nTES tank has 1.96 GW-hr(t) of storage capacity for an installed cost of \$12 million (2011 dollars), less than 0.5% of the cost of the \$3 billion for a pair of 840 MW(t) First Of A Kind (FOAK) PRISM reactors.[19, 20] With the PCS being 914MW(e), 1.96 GW-hr is 2 hours 6 minutes of storage, \$5.7 million/hour of storage. The difficulty with adding more storage is loss of installation flexibility. The larger the tank the larger the surface area and the higher the heat losses, additionally, and the height of the tanks are constrained by pump height. Because of the constraints on geometry the tank radius must increase, taking up a larger portion of the site's real estate.

While the cost of storage in this configuration is very small, \$7/kW(t) of the reactor's overnight cost, and can be neglected due to cost uncertainties and small impact on price, the impact on reducing the overall cost of the reactors through system consolidation/elimination can be significant. However without a component level cost model, the determination of the extent of the cost savings is impossible. With (2) 840 MW(t) reactors the cost of 1 GW-hr(t) of storage is \$3.6/kW(t) of the reactors. Treating the storage as a component of the reactor simplifies estimating delivered cost of energy to the PCS. The cost of storage scales linearly with the overnight cost of the system.

3.2 Material Selection

The storage system is constrained in its material selection due to the chemical interactions of the salt with the metal. Careful consideration was needed to find materials that are compatible with coolants. The materials had to exhibit low general corrosion rates and prevent localized corrosion, e.g. crevice corrosion cracking. Additionally, materials need to withstand duty cycle and transient temperatures without failure.

Carbon steel exhibits adequate corrosion resistance (5mils/yr) at 460°C.[21] In solar thermal applications, carbon steel is limited to 300°C.[20] Carbon steel in nTES is similarly has an operational and transient limitation of 300°C. Stainless Steel (SS316) has corrosion rates of 0.03-0.04 mils/yr at 600°C.[21] SS316 is one of 5 alloys; SS304, SS316, 2.25Cr-1Mo, Alloy800H, and ASTM A213 Grade T91, allowed for structural applications under ASME Code Section III Subsection NH for high temperature structural integrity in nuclear applications.[22] SS316 exhibits low corrosion rates, <0.02 mils/yr, in the temperature range of the heat exchanger, < 500°C, and has low rates of decarburization in this temperature range.[23, 24] 9Cr-1Mo at 600°C has corrosion in salt < 0.9 mils/yr.[21] 9Cr-1Mo (ASTM A213 Grade T91) is widely used in combined cycle heat recovery steam generators.[25] T91 could also be used in the PCS steam generators.

The cold tank is made out of carbon steel ASTM-A516-70.[20] The cold tank piping is not made out of ASTM A106 carbon steel, recommended by Moore et al., due to issues of galvanic corrosion between stainless and carbon steels. All salt supply and return piping and the hot tank are SS321 or SS347. There needs to be galvanic protection where the cold pipes interface with the cold tank.

The IHX is T91, however, SS316 and SS304 were considered as viable candidates, but require strict chemistry controls on the salt increasing capital costs along with O&M. Selecting slightly more expensive materials in favor of reduced operational costs over the life of the plant appeared to be more prudent. Any final material determination is going to need careful engineering and cost consideration. The combustion turbine heat exchanger is T91, with supply and return piping made out of SS321 or SS347. The cold supply piping, in this application, being made out of SS321 or SS347 prevents degradation of the pipe due to the frequency of back flow initiation from cycling the combustion turbines. All of the components and piping are non-nuclear using conventional ASME codes. The exception is the IHX.[16] Figure 2 shows the safety grade boundary. The material configuration of the ACS prevents carbon steel from being exposed to higher temperatures seen in natural circulation decay heat removal.

SS304 and SS316 are susceptible to crevice corrosion cracking in the presence of impurities in the salt. This would require using more expensive salt that does not have trace impurities. For this reason Moore et al recommend using SS321 or SS347 in every application where SS304 and SS316 are used. While this is practical for the non-nuclear components, it does not satisfy the criteria for the IHX. However, T91 does satisfy the material selection criteria. T91 is well suited for sodium environments. It is being deployed in India's SFR for use in the steam generator.[26] T91 does not exhibit stress corrosion cracking in an impure molten salt environment making it the ideal material for the IHX.[20]

3.3 Heat Exchangers

All of the heat exchangers used in nTES are compact diffusion bonded heat exchangers made of T91 and are commercially available from manufacturers like Heatric. T91 is suitable for diffusion bonding, used in compact heat exchanger manufacturing.[1] Because of the lack of a high temperature design standard from the NRC, Heatric is unable to qualify these as nuclear components, but is following ASME code for high temperature nuclear applications.[27]

The heat exchangers are configured as Fin Plate Heat Exchanger (FPHE). This satisfies several purposes. First with the exhaust gas heat recovery, FPHE minimize the pressure drop across the heat exchanger, lowering the combustion turbine backpressure.[1] Second, sodium has a high heat transfer coefficient, necessitating larger channels to prevent plugging.[1] Third, less metal is needed to construct the heat exchanger per Number of Transfer Units (NTU) lowering the weight and cost.[1] Lower system differential pressure aids in establishing natural circulation in the ACS. Additionally, the ACS heat exchanger is also a FPHE to aid natural draft convection for heat removal.

There will also need to be heat exchangers on the PCS to generate steam. The purpose of this study is to look only at the nTES and excludes consideration of the PCS, beyond being an attachable component. The goal of the storage system is to provide a maximum possible temperature to the hot salt tank. If compact heat exchangers are used in the PCS, the salt side plates need to be FPHE. The selection of the PCS will determine if the heat exchanger is a printed circuit or a fin plate. These options are not affected by the use of a fin plate on the salt side. The ultimate configuration only affects the NTU seen on the salt side and thus the heat exchanger frontal area and the pressure drop.

3.3.1 Intermediate Heat Exchanger

Preliminary sizing was done to estimate the configuration of the IHX. Several different configurations of heat exchangers were considered, from conventional shell and tube, Printed Circuit Heat Exchangers (PCHE), and Fin Plate Heat Exchangers (FPHE). The conventional PRISM design uses a shell and tube design rated to the operating pressure of the steam generator, 14.7 MPa.[2, 16] This significantly increases the weight and complicates the design. Additionally, the heat exchanger requires special design to accommodate thermal expansion.[16] We examined PCHE, however, these are unsuitable for applications with sodium because of its high thermal conductivity can cause channel clogging.[1] Because the salt system is vented to atmosphere, the discharge pressure of the IHX under normal operations can at most be 60.9 kPa due to design pressure loss in the pipe, 5.5 kPa, and the static head of the pipe leading to the hot tank, 55.4 kPa. Assuming a blockage downstream of the IHX the peak pressure is the shut off head of the cold tank salt pumps, 1.24 MPa, well within the operating envelope for FPHE.[1]

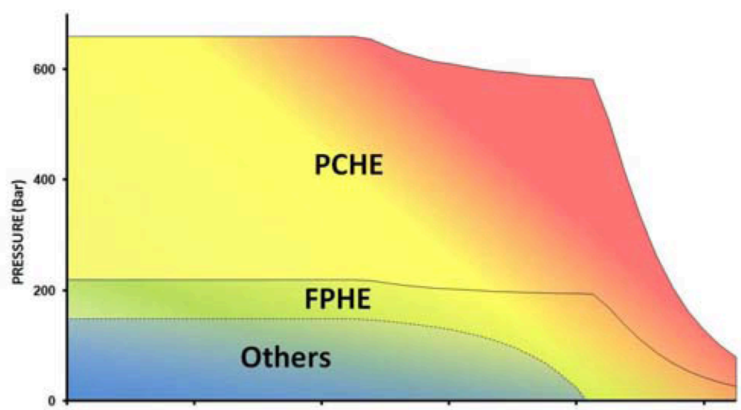

Figure 5 Heatric heat exchanger operational envelope from Southall and Dewson[1]

3.3.1.1 Regulatory Design Considerations

The NRC based the review characteristics of the IHX on GDC 15, 30, 31, and 32:[16]

- *GDC 15, "Reactor coolant system design": Design conditions of the PHTS [Primary Heat Transport System] shall not be exceeded under normal operation or anticipated operational occurrences.*

- *GDC 30, "Quality of reactor coolant pressure boundary": The PHTS shall be designed to the highest practical quality standards and shall provide a system for leak detection of sodium and cover gas.*
- *GDC-31, "Fracture prevention of reactor coolant pressure boundary": The reactor coolant pressure boundary shall be designed with sufficient margin to assure that when stressed under operating, maintenance, testing, and postulated accident conditions (1) the boundary behaves in a nonbrittle manner and (2) the probability of rapidly propagating fracture is minimized. The design shall reflect consideration of service temperatures and other conditions of the boundary material under operating, maintenance, testing, and postulated accident conditions and the uncertainties in determining (1) material properties, (2) the effects of irradiation on material properties, (3) residual, steady state and transient stresses, and (4) size of flaws.*
- *GDC-32, "Inspection of reactor coolant pressure boundary": The PHTS shall be designed to permit periodic inspection and testing of components to assess structural and functional integrity.[16, 28]*

Because of the reduced pressure requirements, GDC-31 is satisfied with a heat exchanger designed for lower operational pressures, allowing a reduction in mass and simplification in design. However much more detailed design analysis will be required to fully satisfy GDC-31. Verifying the IHX integrity through a pressure drop test or some other such test satisfies GDC-32. Using an approved high temperature nuclear code and placing a nuclide trace cover gas in the primary coolant and monitoring the cover gas of the hot salt tank for that isotope satisfies GDC-30. Designing the IHX to withstand pump shutoff head satisfies GDC-15. This is not an exhaustive analysis of the GDC, instead it is a prima facie analysis.

The separation of the primary system to the steam generator with a vented intermediate system creates an air gap. The air gap makes it physically impossible for the water to be introduced into the IHX. If any leakage occurs in the steam generator it will enter the cold salt tank (290°C, 1 atm) where it will evaporate and leave the tank vents.

3.3.1.2 Heat Exchanger Design

Taking into account the regulatory considerations of 2.2.1.1 and the limitations of sodium requiring larger channel sizes, we determined the FPHE would give the best performance characteristics. We settled on using the Kays and London's *plain plate-fin surface 12.00T*.[29] We examined various triangular, sinusoidal and plain fin geometries. We selected the triangular geometry because the relatively high Reynolds (13,000) and low Prandlt (0.005) numbers of the primary sodium were outside of the correlations of Kays and London.[29] We found a correlation for the friction factor of an isosceles triangular duct in Hesselgreaves:[30]

$$f = \frac{C}{\mathrm{Re}^{0.25}}$$

$$C = 0.060759 + 0.07863\phi - 0.078093\phi^2 - 0.20242\phi^3 + 0.28228\phi^4 \qquad (3.1)$$

ϕ is the minimum apex angle in radians.

Hesselgreaves suggested using the Nusslet number correlation for fully developed turbulent flow in a circular pipe.[30] However, the range of the lowest Prandlt number 0.5 of the correlations listed there did not adequately cover sodium in turbulent flow.

Using the logic of Hesselgreaves we used the constant heat flux approximation for cylindrical flow from El Wakil:[31]

$$Nu = 7 + 0.025 Pe^{0.8} \tag{3.2}$$

We accounted for the axial heat diffusion in sodium using El-Wakil:[31]

$$\frac{1}{Nu^*} = \frac{1}{Nu} + \frac{4}{Pe^2} \tag{3.3}$$

We also examined Kays and London wavy-fin plate-fin surface 17.8–3/8W [29] and found that the heat exchanger did not have a large enough frontal area to minimize the pressure drop for a reasonable channel length for the given configuration of a counter-flow heat exchanger core with cross flow entry and exits. It had such a high volumetric heat transfer area 1686 m^2/m^3 that the counter-flow core was too short to have the minimal exergy loss of counter-flow heat exchanger, because it was almost a cross flow

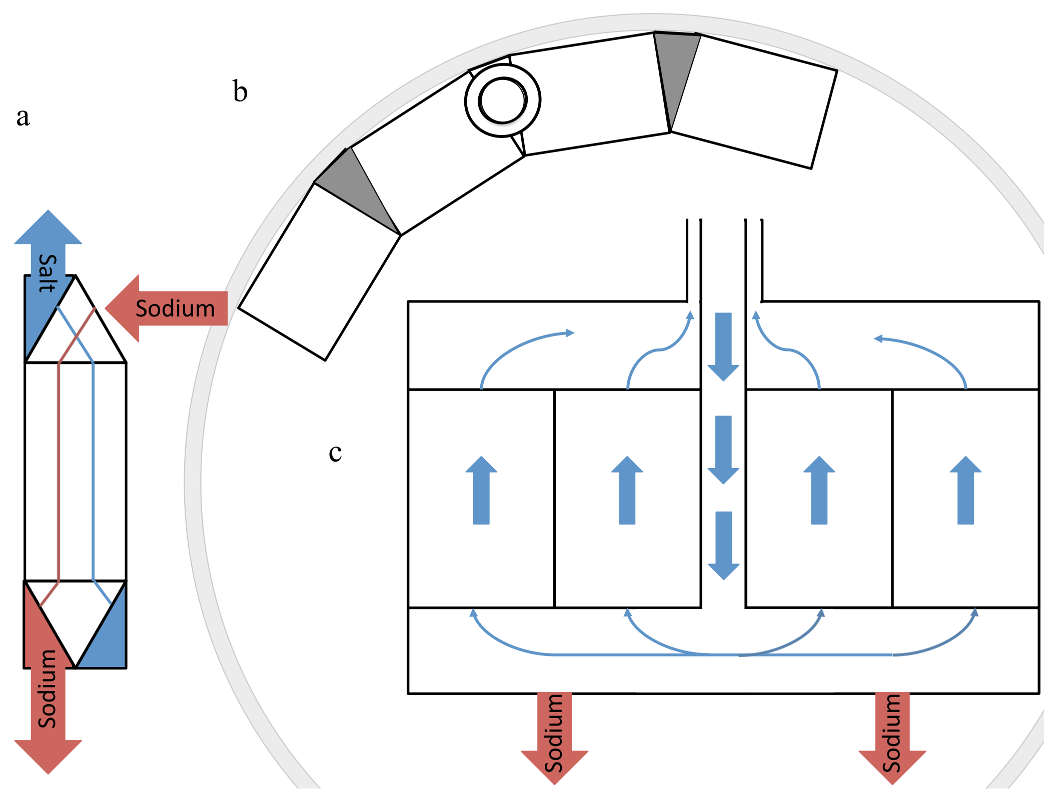

Figure 6 Intermediate Heat Exchanger (a) plate profile view (b) IHX top down view inside reactor vessel (c) IHX radial view showing salt flow path.

heat exchanger. Because of our sensitivity to pressure drop and our limited form factor working within the PRISM module we selected the straight fin FPHE.

Figure 6 shows the flow configuration of the IHX and how each IHX is assembled. Table 1 lists the pertinent design parameters for the IHX. Each IHX assembly consists of 4 counter-flow FPHE modules, two modules on either side of the salt supply pipe. We selected an approach temperature of 7°C between reactor core outlet and hot salt tank temperature as an initial reasonable guess. This resulted in each heat exchanger module being 1.405 m wide, 0.975 m thick, and 4.078 m long. Using the exact same IHX support structure as the conventional PRISM, the center of the IHX moved higher 1.3 m.

Table 1 Description of Intermediate Heat Exchanger

Reactor power [MW(t)]	840	
# IHX/Reactor	2	
# Modules/IHX	4	
Module Dimensions		
Length [mm]	4,078	
Width [mm]	1,405	
Thickness [mm]	975	
Surface Area Density [m^2/ m^3]	1,112	
	Salt	Sodium
Plate Type	plain fin plate 12.00T	
Fin Type	plain triangular	
Plate Divider Thickness [mm]	1	1
Plate Thickness [mm]	6.35	6.35
Fin Pitch [fins/m]	472	472
# Flow Channels/Plate	460	460
Plate Width [mm]	974.58	974.58
# Plates/Module	95	96
Re	516	13014
Pr	10.56	0.00544
Nu	9.033	7.707
Totals for Reactor		
Flow Area [m^2]	4.347	4.392
Total Heat Xfer Area [m^2]	24702	24962
ΔP @ 100% Flow [kPa]	35.07	0.6297
Flow [kg/s]	2745	4726
IHX inlet Density [kg/ m^3]	1775	835

We approximated the volume available in the PRISM vessel looking to maintain a nearly equivalent top down footprint. We estimated that the heat exchanger was 0.975 m thick and ran a circumferential arc that was 6.1 m of active heat exchanger width. We broke the entire IXH arc into 4 cords and adjusted the number of plates (flow area) to have a heat exchanger that was approximately 4 m long. This resulted in a heat exchanger of 5.6 m of active heat exchanger width. We felt that the thickness was the most important measure to keep constant, because changing the design of the core downcomer and flow control baffles would complicate the design change even further.

The original heat exchanger was 6.75 m long. While entirely possible to make the new design have the same length and have a much closer approach temperature, we would lose the benefit of the 1.3 m upward displacement of the IHX center of volume. This displacement will have a significant positive impact on the natural circulation and passive Decay Heat Removal (DHR) characteristics of the PRISM, higher elevation differences between the heat source and heat sink increases loop differential pressure, increasing natural circulation flow, which in turn increases DHR of the ACS, limiting plant temperature perturbations in various accident scenarios. This acts to increase the margin to sodium voiding improving plant overall safety especially for Anticipated Transient Without SCRAM (ATWS).

3.3.2 Auxiliary Cooling System Heat Exchanger

The ACS heat exchanger is a small heat exchanger that has two conflicting design goals. First, it must be able to remove enough decay heat to limit plant temperature transients in off normal situations. This is not for reactor safety. The Reactor Vessel Auxiliary Cooling System (RVACS) performs that function.[16] Instead, the ACS limits stress on the plant giving more margin to equipment damage over a wide range of plant casualties. Second, because initiation of the ACS must be done passively and it needing to be kept in a ready condition as a result of normal operations it will always have a small flow of salt through it, from the cold supply to the hot side, that under all flow configurations, must maintain an adequate margin to salt freezing within the ACS heat exchanger.

The heat exchanger is sized to allow adequate flow rate to limit off normal transient temperature excursions. Restricting airflow with louvers mitigates the heat loss during normal operations. There are two sets of louvers that require electricity to close. Their normal (deenergized) position is open.

Because of the time dependent nature of analyzing any of the critical accident scenarios (e.g. Unprotected Loss Of Flow, ULOF), the complexity of assessing the size of the ACS heat exchangers is not possible without using a transient system analysis code such as RELAP5-3D. Properly sizing the ACS heat exchangers is outstanding work that will be done as part of the thesis.

3.3.3 PCS Heat Exchanger

As noted previously the PCS heat exchanger can not have an impact on the primary system because of the air gap between the two. Additionally, the compatibility of Solar Salt with potential working fluids, water, S-CO_2, and He, eliminates any concern over adverse chemical reactions. Combining these two features means that conventional non-nuclear design, manufacture, and construction can be used outside of the regulatory consideration of the NRC. This greatly reduces the cost and regulatory liability in building the PCS. It is conceivable that even the EPA can become irrelevant once the reactors are sited. As the PCS can be designed to use air-cooling for heat rejection, a common feature of combined cycle plants.

It is not important to consider the PCS beyond the capacity for it to accept the heat from the nTES. There is no credible way for the PCS to impact the operation of the reactor. This more than satisfies the concerns the NRC raised in NUREG-1368 about using conventional industrial standards in the Balance of Plant (BOP).[16]

For the purpose of thermodynamic modeling, we assumed the steam generator would have similar performance characteristics as that of the conventional PRISM. The hot Solar Salt is 15°C hotter than the conventional sodium hotleg. The salt return temperature is 36°C colder than the conventional sodium cold leg. In the final design of the PCS steam generator this will require careful pinch point analysis. For the purpose of crude modeling we will assume turbine throttle conditions of 14.7 MPa/467°C and a feedwater temperature of 216°C.

3.4 Piping Systems

Initial design configurations relied upon using the PRISM modules as is, only replacing the steam generator with the sodium salt heat exchanger. This approach, while simpler from a safety analysis standpoint, made the plant more expensive. It maintained the In Service Inspections (ISI) requirement of the intermediate loop as it still contained sodium, kept the material cost of the IHX with entirely unnecessary design margins, and necessitated the need for guard pipes and sodium leak detection equipment for the intermediate loop. When these assumptions were inserted into a LCOE model, the market impact of the system, and potential for future sales was minimal as there would be very little market demand based on pure business considerations.

We sought to resolve the cost problem by eliminating as many systems and components as possible. The design had to be made as simple as possible. We began by eliminating any sodium outside of the primary containment vessel. Initial design consideration was just given to directly coupling the IHX with the hot and cold tanks with nothing else in between. This eliminated the original ACS entirely. While the salt could still provide cooling, it could not do so passively. While possible for the RVACS to be able to reject an adequate amount of heat, the temperature rise impacted the ability of the reactor to function again after the accident without significant capital expense. Operational reliability and resiliency is not a specific NRC charter as it does not impact safety. It is, however, a key issue for utilities who would rather not walk away from a $2 billion dollar investment. We needed to provide a low cost physical insurance policy.

3.4.1 Reactor Vessel Internals

The lower portion of the IHX is located 3 m above the bottom portion of the nominal PRISM IHX. This increases the distance and shielding between the core and the IHX further reducing any potential activation of the Solar Salt. The IHX bottom seal plate and shielding will need to be relocated upward in order to better function. However, this is not possible without a major design revision of the primary EM pumps, which share the same seal plate. (The seal plate is used to separate the hot plenum from the cold plenum.)[16] To resolve this the only configuration change inside the primary structure is to extend the discharge pipes of the IHX down to the IHX discharge/EM pump suction manifold. There is no foreseeable need to redesign the Inconel 718 piston rings and stellite seal plate surface interface [16] used to seal the IHX discharge piping and EM pump suctions from the hot plenum.

Because there is no sodium outside of the reactor vessel and primary containment there is no need to have any additional leak detection/ leak mitigation other than that needed to satisfy the GDC for the reactor vessel.

The removal of more dense steel with the smaller IHX lowers the weight of the reactor vessel and increases the sodium coolant inventory. This should have a positive impact on the accident response and normal operations of the PRISM module. A more detailed and thorough review is needed once a final design configuration is established. For the purpose of this study the positive impact is taken as no impact on accident response. Some of this may be apparent with the RELAP5-3D model that will be developed in support of our study, but will not be specifically examined.

3.4.2 ACS/Primary Interface Salt

We wanted to keep the design of the portion of the nTES extending from and including the cold tank salt pumps to the discharge at the top of the hot salt tank as close to the configuration of a hot and cold pipe as possible. We also wanted to limit the design changes of to the nuclear island. In the baseline PRISM design, the ACS/steam generator was located on the same seismically isolated plane as the reactor vessel. In the redesigned PRISM, there was a significant reduction in the amount of material on the seismically isolated plane. The entire Intermediate Heat Transport System (IHTS) was removed and replaced with a small compact ACS heat exchanger and IHX supply and discharge piping.

The salt cold leg is 290°C which is 74°C above the feedwater temperature for the conventional PRISM steam generator. Because of the similarities of heat capacity of the water and the salt at these temperatures, the reactivity feedback from perturbations in salt flow rate will be less severe than in the case of feedwater transients. This represents a design improvement for the nTES over a conventional PRISM.

Because of the NRC's regulations over the control of reactivity the reactor operators are the only individuals who can have control of the cold salt pump speed. Because the cold salt tank and hot salt tanks act as "infinite thermal reservoirs" under normal operations, we treat normal plant operations of the nTES as an open system. For this reason we restrict the NRC's consideration of plant design from the suction of the cold tank pump to the discharge into the hot tank. The reactor operators have one restriction, that the cold tank has adequate salt level to maintain NPSH for the reactors. As long as this condition is met and adequate electrical power is available, reactor operations above the point of adding heat are permitted. A loss of the cold salt tank for whatever reason would not impact reactor safety.

The purpose of modifying the ACS is not for reactor safety. It is for plant reliability, so to protect the plant from pipe breaks and tank ruptures the ACS needs to be properly configured. It must passively maintain thermal coupling of the ACS heat exchanger and the IHX. For this purpose, there is a loop seal with a siphon break. This allows establishing a liquid salt level above the top of the ACS heat exchanger in the loop seal–the loop seal acting as a standpipe. Passively creating a standpipe allows extended operations of the ACS until the plant cools down such that the ACS can be drained to prevent solidification.

The ACS is defined formally from the top of the loop seals and portions of piping that include the IHX. The ACS is made entirely of SS321 or SS347 for temperature and corrosion resistance.

Draining the ACS and the supply piping is a needed maintenance evolution and the plant configuration needs to be able to support both evolutions. The ACS would use the conventional PRISM intermediate loop salt tank for draining. This is a dual purpose tank and can be used to drain both reactors' ACS. Similarly the salt hot and cold legs outside of the loop seal need to have the capability of draining to a common tank. Both tanks are used in maintenance and accident scenarios to put the plant into various conditions.

For a loss of a salt tank or a rupture in a supply return line outside of the loop seal, the nuclear island would reach a configuration where the affected piping is drained outside of the loop seal and the ACS is on service in natural circulation operations. This would be a configuration used in maintenance to affect repairs on the salt tank and can last indefinitely from any power history. A break inside the ACS is equivalent to the design consideration for the conventional PRISM in the event of a loss of the IHTS as an unprotected event, Unprotected Loss of Heat Sink (ULOHS), which PRISM shows satisfactory response.[16] With the removal of the sodium/water interface from the IHTS, the probability of a loss of the ACS is reduced. Under a Probabilistic Risk Assessment (PRA) this will improve the safety characteristics of PRISM. The details of a PRA are well beyond the scope of this study as a full PRA analysis requires detailed design information about the system configuration.

In any accident scenario that does not affect the salt tanks or associated ACS piping, the storage system acts as an infinite heat well lengthening the time before the reactor operators need to act before placing the plant in a safe condition.

The ACS siphon break is a pipe with a fluidic diode providing reverse bias in the direction from the normally higher pressure cold leg to lower pressure hot leg.[32] This minimizes the exergetic payment to the environment to maintain the siphon break warm and continuously in service.

The ACS heat exchanger has a fluidic diode that is similarly biased and for the same reasons. In this system the louvers, mentioned earlier are used to minimize heat losses to the environment under normal and low flow conditions to prevent a salt freeze in the heat exchanger. There are two sets of louvers on the exhaust stack, each opening is large enough to accommodate design cooling if the other set fails to open. The louvers will open automatically on a loss of electrical power, initiating ACS operation. The heat exchanger attaches to low points in the system to minimize the likelihood of gas binding during cooling operations.

If for some reason the ACS fails to initiate properly there are three relief valves at the top of the IHX piping on the reactor vessel head. These relief valves serve a reactor safety purpose by preventing an over pressurization of IHX. This could only occur if operators fail to drain the ACS at an appropriate time. The only other valves in the ACS are the vent/drain valves. Because of the few number of small valves, valve packing is not exposed to high temperature salt on a routine basis, this reduces the requirements maintenance for these valves, and allows the use of less expensive valves due to fewer design requirements. The only other valves in the salt system are located at the top of the salt tanks to regulate, isolate, and recirculate pump flow. There is also an ability to cross-connect the pump discharge manifolds between the two reactors. This is a low cost means of increasing operational flexibility, this allows putting the spare pump in service to either unit in the event of a forced outage from any one pump. This allows both reactors to operate at 100% power with one pump out of service for maintenance.

Because the system is intended to be drained under maintenance conditions, and the near continual duty cycle (>95% availability) normal operations ensures freeze protection. Additionally, when the system is offline it only needs to be drained under specific maintenance conditions to prevent the salt from freezing and rupturing pipes. Heat trace would not see a high enough duty cycle to pre-warm the piping in order to justify its cost. Pre-warming is necessary to prevent salt freezing during refill operations and minimize thermal stresses. Pre-warming is accomplished by recirculating a dry nitrogen cover-gas through a heater.

RELAP5-3D will be used to verify design operations, and sizing of the piping and ACS heat exchanger. The proposed design change affects reactor safety features under a PRA framework, thus it is important to demonstrate the system operations through dynamic modeling in RELAP.

4 Combustion Turbines

nTES includes a novel feature with the inclusion of combustion turbines with the reactor. Traditional reactors require back up diesel generators that very rarely run and are required for reactor safety. PRISM does not require back up electrical power to ensure reactor safety.[16] It can however take credit for multiple redundant and independent power supplies under PRA. This will allow the reactor to maintain criticality in the event of a loss of offsite power.

To improve the capital recovery of the assets used to provide back up power, they need to provide a normal service. nTES uses the combustion turbines as rapid response peaking units, 253 MW(e), and as an additional means of refilling the hot salt tank, 238 MW(t). These combustion turbines operate with a 6% capacity factor providing 3% of the total electricity provided by the entire system. The design uses 3 General Electric PG7121EA 84.4MW(e) combustion turbines. They have a nominal heat rate of 11,054 kJ/kW-hr and exhaust gas temperature of 536°C. Conventional combined cycle exhaust gas coolers have an approach temperature of 22°C. which equates to a steam temperature of 514°C. In our application, we are only dealing with sensible heat, and without any pinch points due to a phase transition, can achieve closer approach temperatures from the Heat Recovery Heat Exchangers (HRHX), or even use compact cross flow heat exchangers and achieve similar performance.

Developing the heat exchanger and a closed loop control model for the combustion turbines needs to be done. Time permitting these may be included in the thesis. Regardless, these two issues require further exposition, just not necessarily here.

5 Power Conversion System

The PCS is nominally a Rankine cycle. The installed configuration is of (10) General Electric S207EA units in various turbine configurations. The number of cycles allows scaled addition of generating capacity and allows the units which are the most efficient to operate at the highest capacity factor–baseload, while the less expensive and less efficient units operate at a lower capacity factor–load following. This allows plants to be shut down for periods of low demand and then restarted when needed, in the same exact duty cycle they were designed for. Instead of having one big plant run flat out we have a number of entirely automated plants operate in various portions of the load profile at consistent power levels. Consistent plant operation minimizes the O&M costs, which in nTES are a significant portion of the LCOE.

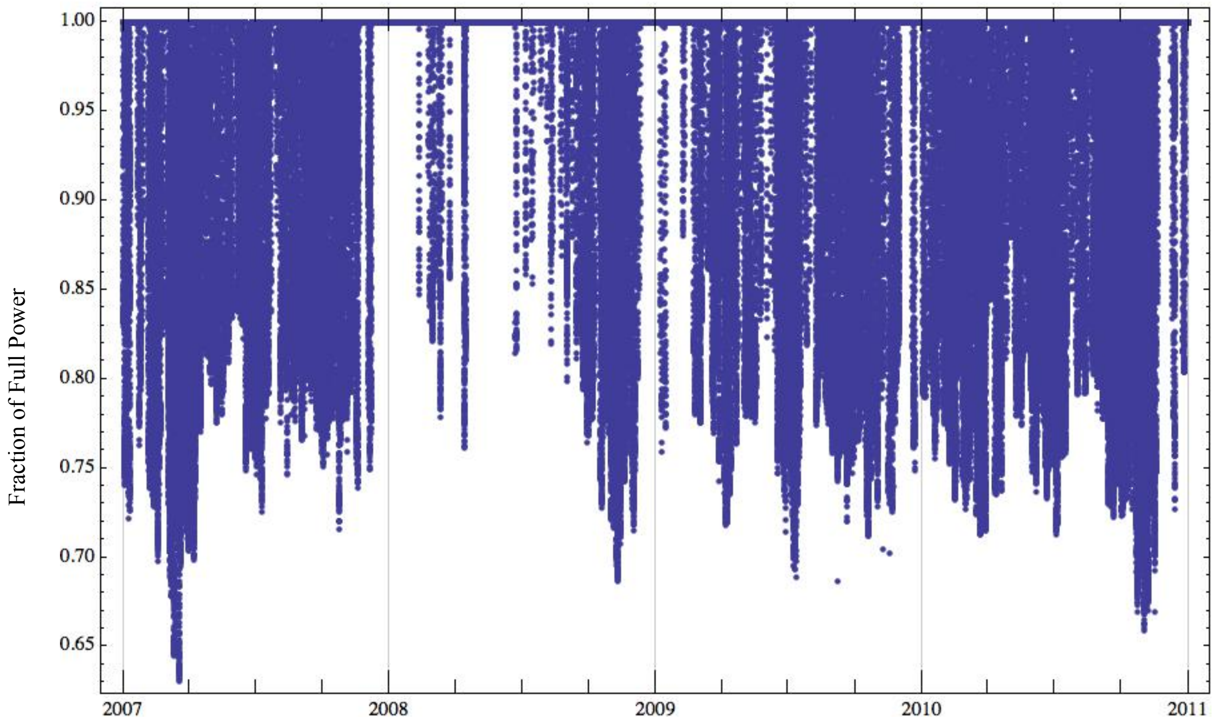

Figure 7 Load profile of online nTES reactors in the Bonneville Power Administration

6 Reactor Kinetics

Our evaluation of the reactor focused entirely on establishing a reasonable design and identifying some key points that require more careful evaluation. We have so far avoided any discussion of how the reactor is controlled during normal operations. Through the IHX, the reactor sees a constant cold salt supply temperature with varying salt flow rates. The reactor needs to be able to accommodate a change in salt flow rate while maintaining a constant steady-state-to-steady-state salt return temperature. Power changes need to occur quickly and are restricted by reactivity addition rate and by power level (<100% and > 5%). Figure 7 shows the reactor power of the online reactors (those not in refueling outage) attached into the Bonneville Power Administration's grid if nTES were to supply the entire load profile. The grid data was taken from the BPA's online database of power history in 5-minute averages.[33]

Based upon the nTES design there are three things that control reactivity: control rod position, primary coolant flow, and salt flow. In commercial nuclear power plants the plant operators are procedurally restricted to applying only one reactivity insertion at a time. These large and complex systems develop an amount of inertia where an action that is taken too quickly, can initiate a complex string of problems complicating what could have been a simple evolution. Additionally, the large LWR's use oxide fuel that if heated up too quickly can crack leading to fuel cladding failure. For this reason operators must condition the fuel, which is a slow rate of power increase to gradually heat the fuel pins. Fuel conditioning rate of power change is about 2% per hour.

Such an approach to reactivity control and power changes with nTES will not meet our operational needs. We need to rely upon a different operational model. Here we turn to the marine propulsion plants aboard United States Navy ships. These reactors have a different fuel, smaller cores (sizes on the order of PRISM), and a simple balance of plant. These three things allow Navy cores to have design rates of power change three orders of magnitude faster than monolithic commercial plants. These plants are small dynamic and extremely responsive. Part of a watch team's core competency is to simultaneously cause three independent reactivity insertions, outward shim, increasing primary coolant flow, and drastically increasing feed water flow. It is possible to execute such a complex evolution on a routine basis. Thus we use a Naval approach to controlling our small reactor. There is one critical difference in the reactor dynamics between the Navy cores and PRISM. Navy cores are highly enriched uranium thermal spectrum reactors having effective delayed neutron precursor concentrations of about 0.0070. PRISM is plutonium fueled fast reactor and has an effective delayed neutron precursor concentration of about 0.0035, half that of the Navy cores. This means smaller reactivity changes have a larger impact on power in PRISM.

PRISM's metallic fuel has a very high thermal conductivity compared to oxide fuels and as a result a much lower fuel pin radial temperature gradient. "Metal fuel has excellent transient capabilities. The metal fuel itself does not impose any restrictions on transient operations or load following capabilities."[34]

6.1 State Space Control

Our primary goal is to develop a control strategy for the three control variables that affect core reactivity: control rod height, primary pump flow, and salt flow. To achieve this goal we will use a state space representation. In this representation, we define the reactor as a vector of orthogonal parameters, these vectors form an intensive state space defining the condition of the reactor. Intensive parameters are variables that are not necessarily measurable outside of the system but yet impact the operation of the system. One example in our application are the delayed neutron precursors. The state vectors are related by system of differential equations that describe how perturbations in one affect the output of the entire system.[35]

Our interest is in first establishing an optimal control law. This requires a closed loop solution. The approach Weaver takes uses the Hamilton-Jacobi method. He states,

"[T]he Hamilton-Jacobi approach gave a closed-loop control, referred to as the optimum –control-law, which minimized a given performance index. Unfortunately the determination of the optimum-control law requires the solution of a nonlinear partial

differential equation that is difficult to solve except for elementary problems or for the linear case with a performance index of the quadratic form."[35]

PRISM is smaller core than large LWR's. Additionally, it has a hard fast neutron spectrum. The fast spectrum and moderately sized core ensure that there is strong buckling. The buckling acts to provide a stable neutron spatial distribution that is independent of reactor power, satisfying one assumption of the point kinetic reactor approximation.[36] However, the distribution in phase of the neutrons carries a strong energy dependence that is a function of core power.[36] When we assume the distribution in phase of neutrons is separable from time we take that it has a constant shape that only differs by the average density of neutrons in the core. Referring to Gibbs, a constant distribution in phase of the neutrons results in constant information entropy of the distribution in phase.[37]

$$\begin{aligned}
\langle S\rangle &= -N\int_0^\infty \mathrm{d}E\int_{4\pi}\mathrm{d}\hat{\Omega}\int_V \mathrm{d}\vec{r}p\left(\vec{r},\hat{\Omega},E\right)\ln\left[p\left(\vec{r},\hat{\Omega},E\right)\right]\\
s &= -\int_0^\infty \mathrm{d}E\int_{4\pi}\mathrm{d}\hat{\Omega}\int_V \mathrm{d}\vec{r}p\left(\vec{r},\hat{\Omega},E\right)\ln\left[p\left(\vec{r},\hat{\Omega},E\right)\right]\\
\langle S\rangle &= Ns
\end{aligned} \tag{6.1}$$

We can see that if we affect the leakage of the core, e.g. changing flow affects the level of the Gas Expansion Modules (GEM), that this will cause a perturbation of δs_0 which to the first order and for the sake of our analysis is small thus:

$$\begin{aligned}
s_f &= s_0 + \delta s_0\\
s_f &\approx s_0
\end{aligned} \tag{6.2}$$

We now can use the point kinetic equation as the constant specific entropy of the neutron flux is constant. Our analysis will start with a one-group model for the delayed neutron precursors. From there, we will incorporate various reactivity feedback mechanisms. We may consider adding mixing effects in the hot and cold plenums.

The difficulty remains for a time dependent model of the IHX. Roetzel and Xuan note that the time dependent differential equations are non linear in situations of changing flow.[38] To simply this problem, we establish the boundary conditions. First is that the salt supply temperature to the hot tank remains constant. Second, the hot plenum temperature is constant. This is a non fixed boundary condition used in the state space model that applies here as well. The state space model uses the deviation of the core outlet temperature from the hot plenum as the condition to be minimized. Third, the salt cold tank supply remains constant. The final boundary condition is that we desire a constant inlet temperature in the core. This will act as a boundary condition for the control problem. From these boundary conditions we are left with a trivial relationship:

$$\begin{aligned} m_{Na} c_{p,Na} \left(T_h - T_c\right)_{Na} &= m_{Salt} c_{p,Salt} \left(T_h - T_c\right)_{Salt} \\ m_{Na} &= m_{Salt} \frac{c_{p,Salt} \left(T_h - T_c\right)_{Salt}}{c_{p,Na} \left(T_h - T_c\right)_{Na}} \end{aligned} \tag{6.3}$$

Deviations from this relationship or significant temperature fluctuations will induce nonlinearities into the system. A more complete analysis would use the fully non linear equations for the IHX. This does not mean that the system of equations is necessarily unstable, just that the linear approximation no longer possesses a valid set of assumptions/boundary conditions.

Sumner notes the GEMs provide a significant flow reactivity.[39]

$$\rho_{flow} = \frac{\dot{m}_{100\%} - \dot{m}}{\dot{m}_{100\%}} \left(-\$1.4\right) \tag{6.4}$$

Because the core inlet and outlet conditions are relatively fixed steady-state-to-steady-state.

$$\dot{Q}_{Rx} = \dot{m}_{Rx} c_{p,Na} \left(T_h - T_c\right)_{Rx}$$
$$\dot{m}_{Rx} = \frac{\dot{Q}_{Rx}}{c_{p,Na}\left(T_h - T_c\right)_{Rx}} \tag{6.5}$$

flow is linearly proportional to reactor power, but has an exponential feedback effect on power, that requires operator control to compensate. This is a simultaneous control scenario with control rod motion in the opposite direction of pump speed, a pump speed increase is an inward rod shim. Additionally, the magnitude of the potential reactivity insertion from pump speed changes requires limits on the possible speed change of the pump. The pumps are EM pumps, so the speed that is being referred to here is the flow velocity of the coolant, which is directly proportional to the armature current in the pump. Because the pumps output can be controlled in a continuous manner, it is possible to tune the pump speed to precisely compensate for a rod shim in order to maintain the plant temperatures constant.

There is an additional problem, on a longer time scale the composition of the core changes due to breeding in the blanket, this changes the density in phase of the neutron flux and the average values used to calculate the delayed neutron precursors. The kinetics of the core change as a function of burnup.[36] This requires careful consideration for how the control code automatically adjusts for changes in core composition and changes in neutron detector efficiency as a function of the detector age and gain.

Three things need to be determined in control of the reactor.

1. Determine impact of hot plenum temperature fluctuations have on heat exchanger performance.

2. Determine envelope of stability for the reactor and determine where in the operational envelope the proposed control is located, and see if there is a way for operators to visualize location in the operational envelope.
3. Build a model for updating the reactivity constants based upon observed data.

7 Policy and Economics

The design considerations for nTES assumed that utilities would face a large number of coal plants being retired, a non-trivial price on carbon/stringent regulations, and a desire to work within existing infrastructure. Because of these considerations, nTES needed to supply the traditional duty cycle of coal plants, nuclear plants, combined cycle plants, and some of the role of combustion turbines. It needed to do this while having the reactor operate at greater than a 90% capacity factor to allow capital recovery. It needs to have the ability to operate independently of the grid, and be able to bootstrap the grid in the event of a station blackout and/or loss of offsite power. The policy and economic forces utilities face today represent a tremendous market opportunity for any technology that can fulfill that gap. nTES storage capacity was iteratively adjusted until it satisfied the above criteria. The system was able to supply 97% of electricity demand for the BPA, with the reactors operating at a 92% capacity factor (23 month cycle length plus 1 month for refueling outages) using similarly sized energy storage system that was already built.

While entirely possible to size the storage system and PCS to handle the entire load profile, a mixture of fuel sources provided the greatest operational flexibility. If a reactor were to have a forced outage, the combustion turbines could handle a significant portion of the lost load. We felt that it was important for the site to have a “rolling reserve” capacity on its own, and to not rely upon outside generation sources. This flexibility comes at a cost, however, the increased reliability allows the utility to forgo continued investment in long distance transmission, as nTES is ideal for maintaining smaller independent service areas with increased reliability.

For nTES to be built it must be competitive in the market. Therefore it is critical to understand the market conditions, policy affecting the market, capital constraints of utilities, existing infrastructure, and commercially available technologies. The economic analysis done here is reported in constant 2011 dollars using the United States Consumer Price Index as reported by the Bureau of Labor Statistics.[40] The levelized cost methodology is from a model reported by the Congressional Budget Office.[5]

Table 2 Summary of cost estimates used in economic analysis

	t^{const} [yr]	C^{overn} [$/kW]	c^{varOM} [$/MW-hr]	$C^{fixedOM}$ [$/MW]	HR [Btu/ kW-hr]	C^{incap} <30 yrs [$/MW]	C^{incap} ≥30 yrs [$/MW]	e^{cap}	Fuel	MACRS
PRISM‡	3	1480	0.18	11.1	3412	7030	9000	0.923	Nuclear	49.12
Rankine	3	333	3.37	14.22	9749	6000	12000	0.6	Heat	49.13
CT	2	973	7.34	15.45	10480	6000	12000	0.0633	Natural Gas	49.15
Repowered	3	0	3.37	14.22	9749	15000	19000	0.6	Heat	49.13

‡ costs are reported in terms of output, using a HR of 3,412 Btu/kW-hr means the PRISM output is heat.

In the cost models for nTES, direct subsidy was excluded from consideration. Standard business deductions, e.g. depreciation, fuel, and O&M, are included at the rates for the particular component mandated by 26 CFR §168. PRISM used an asset class of 49.12, Rankine PCS used 49.13, and the combustion turbine used 49.15. Depreciation of the nuclear fuel assemblies, 49.121, was not considered.

Because the nTES is not producing electricity, the unit of account is in thermal energy produced. In a sense, it sells heat on demand to the PCS. Over the nTES life it must recover its cost and make sufficient equity payments to attract investment. This cost is averaged over a 40-year cost recovery period. PRISM's operational life is 60-years.[16] the 20-year difference does not appreciably affect the Levelized Value Of Heat (LVOH). Table 2 provides the assumptions used to determine the LVOH. For baseline comparisons, a default financing of 8% debt rate and 14% equity IRR financed 45% by debt. The cost of the FOAK reactor is based on having an equivalent cost of construction as a large LWR, roughly \$6,000/kW(e), of which \$1,000/kW(e) is assumed to come from the balance of plant. PRISM has a nominal thermal output of 840 MW(t) and 311MW(e). The resulting cost per unit is \$1,851/kW(t). The storage cost is \$8/kW(t) in this particular nTES configuration. Because of the other uncertainties in the overnight cost of the reactor, the cost of storage can be neglected as it impacts the LVOH by only \$0.16/MW-hr(t). The N^{th} Of A Kind (NOAK) cost of a modular reactor is 80% of the FOAK, \$1,480/kW(t) for PRISM.[41] Using inflation adjusted costs of thermal storage with solar salt \$6.1/kW-hr(t) the installed cost of 1.96 GW-hr storage capacity is \$12 million. Divided by the thermal output from both reactors, this is \$7.1/kW(t). When incorporated in the cost of the site the cost impact was lost in the rounding error. The LVOH for the first reactors is \$36.0/MW-hr(t), \$10.6/MMBtu for a regulated utility and \$42.1/MW-hr(t), \$12.3/MMBtu. Based on these results it is apparent that there is a 20% cost premium on heat for nTES to be viable as a merchant generator. The remaining focus of analysis is on regulated utilities as these are the most likely place to see initial development.

To determine the impact of financing costs a 6% rate for debt and 9.75% was used. This resulted in a cost of \$24.3/MW-hr(t) or \$7.12/MMBtu. Under this financing structure, use of the PTC under the Energy Policy Act of 2005 was considered. This had a negligible impact on the cost of heat. $23.9/MW-hr(t), $6.99/MMBtu, 2% reduction.

There are two main drivers of cost, financing and O&M. For a utility to consider development, nTES must be competitive with other fuel sources. For comparison historic EIA average monthly price (real 2011 dollars) is $4.5/MMBtu at Henry Hub. Delivery charges are $1.1/MMBtu for electric utilities. These are considered firm contracts and represent a delivered cost of $5.6/MMBtu. However, the firm contracts carry significant *force majeure* clauses that the utility will not indemnify the supplier unless if there is negligence on the part of the supplier. Unlike a coal pile there is no onsite storage of fuel in natural gas plants. Hurricane Sandy showed just how vulnerable those supply lines are to disruption with many natural gas fired plants unable to operate for several days because there was no power to drive the pipeline compressors. FOAK nTES provides several years worth of heat onsite to allow the PCS to restore the grid, at a 27% premium over natural gas.

The price point target for the reactor vendor is to supply a reactor that delivers a LVOH of $5.6/MMBtu. Even if this goal is not met, the reliability of nTES over natural gas will be a significant selling point. The work here proposes one way of simplifying PRISM to reduce costs and make the technology more competitive. However, if the social cost of carbon is considered, $38/metric ton CO_2,[42] the cost of natural gas becomes $8.7/MMBtu. If the EPA enforces such a cost structure under the 2007 endangerment finding, natural gas will be priced almost completely out of the market.

Using a repowered coal plant (fully depreciated and with costs completely recovered), the competitively financed FOAK nTES provides carbon free electricity at $77/MW-hr(e). This is for the average cost of electricity produced and represents 97% of a utility's entire load profile. The national average cost of production according to the Energy Information Agency is $54/MW-hr, ranging form $38/MW-hr to $64/MW-hr.[43] Figure 8 shows the reference scenario trend of the cost of producing electricity. Figure 9 shows the cost of producing electricity using the social cost of carbon projected to 2050.[42]

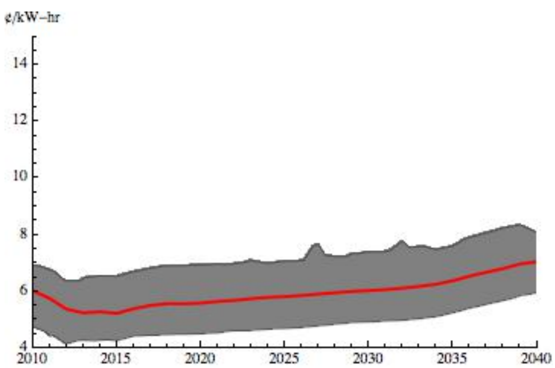

Figure 9 EIA AEO 2013 range of cost of producing electricity

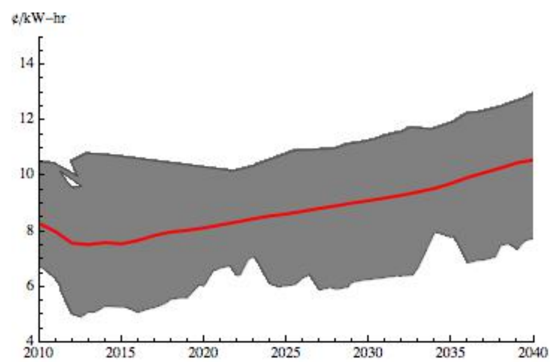

Figure 9 EIA AEO 2013 range of cost of producing electricity including social cost of carbon.

Further work in the policy and economic analysis will clarify the role and provide a more detailed cost sensitivity analysis of the final design. Further research will be done to more accurately determine the price of nTES. There will be some discussion of the safety improvements on the impact for plant siting next to population centers, leaving the Emergency Planning Zone (EPZ) at the nuclear island's security barrier. Initial research shows that the viability of repowering existing coal plants can be done at 77% of currently operating facilities under the existing 10 mile EPZ.[44] Thus consideration of collapsing the EPZ is not a regulatory concern that must be resolved for nTES to become established in the market.

Additional work needs to be done to assess the impact of being able to meet demand without straining interconnection lines. This is closer to the model of the electric grid prior to the 1970's where smaller generators were located closer to the population centers. At the time the grid interconnections were not as large so the utility had to manage forced outages on a smaller scale and with less outside assistance. There is potential here to reduce the transmission and distribution cost, by reducing the capital needed–maintaining a smaller and more isolated grid, and increasing the capital utilization of local grids. Such an approach would act to increase the overall grid stability limiting common mode faults such as the 2003 Northeast blackout, by establishing a network of smaller networks that are able to function independently of each other. EIA estimates the average transmission cost of $10/MW-hr and distribution costs of $30/MW-hr.[43] Using an integrated systems approach, nTES may be able to provide a more reliable lower overall cost of electricity to consumers by reducing transmission and distribution costs over other alternative sources .

8 Conclusion

This work develops a coupled nuclear and thermal energy storage system designed to repower existing fossil fueled infrastructure. The nTES represents a set of technologies that have not previously been brought together: nuclear reactors, thermal energy storage, and combined cycle plants. Coupling nuclear reactors with some form of energy storage is not new, e.g. pumped hydro. Using nuclear sensible heat storage was first considered in the 1970's.[45] Other work in this area focused on describing the system and at a very generic level.[46] Denholm et al. stated "A thermal block… coupled directly to the reactor core, can have a direct impact on the reactor's thermal feedbacks and kinetics. Identifying all of the relevant design changes will require the development and analysis of a conceptual coupled nuclear/TES system, which is a proposed area of future work."[46]

We found no exposition to-date of the impact to reactor kinetics energy storage needs. Such an exposition requires a fairly detailed physical model and conceptual design. This detailed design here is, to a large extent, finished. Additionally, any proposed system must consider market needs and identify any unfilled gaps. A previous study focused on integrating the nTES with renewable energy systems.[46] While entirely possible, this is not considered in this work because the load balancing of grid renewables reduces the capacity factor of the nuclear plant and increases the energy storage requirements/costs. However, current regulations mandating a level of renewable production make accounting for this design need a reality.

The work described here is novel because it proposes a specific conceptual design to be evaluated. A design constrained by existing materials, existing technology, market considerations, and policy restrictions. These constraints served to define the operational role of the facility, and represent, in our opinion, choices that a utility has to make. The evaluation approach of the proposed design is novel as well.

By fulfilling a set of perceived needs, we are able to identify a time series of reactor power. With this information the next tasks are to identify the necessary operational and design constraints to satisfy reactor safety and mission needs. Here the biggest difficulty will be in accounting for all of the different reactivity feedback mechanisms in the closed loop control model and in the detailed computer simulation.

Once this is complete, the next task is to exercise the system through a set of accidents and transients to further refine/justify the design.

Initial work on this topic, was to rough out a workable design that was modular and scalable in design, construction, and operation. The goal was to deliver electricity at current market prices of production with increased reliability using mostly nuclear energy.

nTES cannot be designed in a vacuum and must meet customers needs and satisfy existing policy constraints. By changing only the components of the existing infrastructure, nTES provides an opportunity for utilities to avoid the loss of use on much of their existing capital assets.

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10 Terminilogy

°C	degree Celsius
(e)	electric energy
(t)	thermal energy
ACS	Auxiliary Cooling System
ASME	American Society of Mechanical Engineers
ATWS	Anticipated Transient Without SCRAM
BOP	Balance of Plant
$Ca(NO_3)_2$	calcium nitrate
CFR	Code of Federal Regulations
CO_2	carbon dioxide
Cr	chromium
C^{overn}	overnight cost
c^{varOM}	variable O&M cost
$C^{fixedOM}$	fixed O&M cost
C^{incap}	incremental capital cost
DHR	Decay Heat Removal System
e^{cap}	capacity factor
EM	Electro Motive
EPA	Environmental Protection Agency
FOAK	First of a Kind
FPHE	Fin Plate Heat Exchanger
GDC	General Design Criteria
GE	General Electric
GE-H	General Electric–Hitachi
GEM	Gas Expansion Module
η_{th}	thermodynamic efficiency
He	helium
HR	Heat Rate
HRHX	Heat Recovery Heat Exchanger
IHTS	Intermediate Heat Transport System
IHX	Intermediate Heat Exchanger
IRR	Internal Rate of Return
ISI	In Service Inspection
kg	kilogram
kJ	kilojoule
kPa	kilopascal
kW	kilowatt
KNO_3	potassium nitrate
LCOE	Levelized Cost of Electricity
LVOH	Levelized Value of Heat
$LiNO_3$	lithium nitrate
LWR	Light Water Reactor
m	meter
mm	millimeter

MACRS	Modified Accelerated Cost Recovery System
mils	thousandth of an inch
Mo	molybdenum
MMBtu	million British thermal units
MPa	Megapascal
MW	Megawatt
$NaNO_3$	sodium nitrate
NOAK	n^{th} of a Kind
NPSH	Net Positive Suction Head
NRC	Nuclear Regulatory Commission
nTES	nuclear Thermal Energy Storage System
NTU	Number of Transfer Units
Nu	Nusselt Number
O&M	Operations & Maintenance
PCHE	Printed Circuit Heat Exchanger
PCS	Power Conversion System
Pe	Peclet Number
PHTS	Primary Heat Transport System
PRA	Probabilistic Risk Analysis
PRISM	Power Reactor Innovative Small Module
Re	Reynolds Number
RVACS	Reactor Vessel Auxiliary Cooling System
s	second
$S\text{-}CO_2$	Super critical carbon dioxide
SFR	Sodium Fast Reactor
SS	stainless steel
t^{const}	length of construction
ULOF	Unprotected Loss of Flow
ULOHS	Unprotected Loss of Heat Sink
yr	year