# Diverting Steam Created in a Nuclear Reactor to Produce Electricity More Economically

by

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SUBMITTED TO THE DEPARTMENT OF NUCLEAR SCIENCE AND ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE IN NUCLEAR SCIENCE AND ENGINEERING

AT THE

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2017



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**Abstract**

Nuclear power is not as economically competitive as other electricity generation methods. To increase the use of nuclear power, nuclear power must become more profitable. A way to accomplish this is by storing superfluous energy during times of low energy prices to be used when the electricity price is greater. This could be done by varying the load to the turbine by diverting steam from before the turbine while the nuclear reactor runs at full power. In order to understand this project idea of diverting steam to a thermal storage to increase profit, literature on nuclear systems, steam turbines, and regulations was analyzed. It was found that between 40% and 75% of steam can be diverted from the secondary system of a pressurized water reactor. This number depends on the specific reactor and turbine system. The energy of the steam will be stored through a thermal storage method that can be directly or indirectly connected to the diverted steam. Each set-up comes with its advantages and disadvantages as adding a heat exchanger loses work, but would make regulatory considerations easier.

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# 1 Introduction

In 2014, 30% of greenhouse gases that were emitted in the United States came from the production of electricity [1]. This is because the burning of fossil fuels, coal, and natural gases make up the largest percent of electrical production. These greenhouse gases are causing global warming, a significant environmental challenge affecting today's climate by increasing global temperatures, sea levels, frequency and intensity of storms, and acidity of waters [2]. Nuclear power plants provide the ability to produce electricity without creating the harmful greenhouse gases. However, in the United States new nuclear power is not as economically competitive as other electricity generation methods—partly because of low-price natural gas and partly because of subsidized wind and solar. To increase the use of nuclear power, minimizing the production of greenhouse gases, nuclear power must become more profitable in its electricity production. A way to accomplish this, is to store superfluous energy during times of low electricity prices to be used when the electricity price is greater. This can be done through the thermal storage of heat from diverted steam from the secondary system of a pressurized water reactor and using the stored heat to produce electricity at times of higher electricity prices.

Electricity prices fluctuate based on time of day and year, but nuclear energy sources, such as nuclear reactors, optimally run at full capacity to minimize the cost of energy production. This means that the electricity produced by a nuclear power plant does not continuously make the same amount of money for a specific amount of electricity at different times of the day or year. To allow the nuclear reactors to continue to run at full capacity and maximize income, what is required is some type of heat storage to store energy when electricity prices are low and to turn the stored energy to electricity during high electricity price times, in addition to the nuclear power plants typical electricity production. There are multiple proposed ways of storing heat. Each has their own optimal conditions of the energy coming into its system. Many of the energy storing systems require steam to be diverted at high temperatures from the secondary loop of the nuclear reactor system [3]. The first step of determining which energy storage systems to be used, is to determine the amount and conditions of steam that can be diverted from the nuclear secondary systems. It needs to be determined where the steam will come from in the nuclear power plant, if a heat exchanger is necessary, how the energy will be stored, and how the stored energy will be used to create additional electricity.

When electricity prices are low it would be favorable to send all steam to storage, but in doing so the main turbines would shut down. This needs to be avoided so that the turbine does not need to restart, which takes a considerable amount of time, when the price of electricity increases and the plant should maximize output. The rate at which the nuclear plant attached to a thermal storage system increases to full electrical output is then limited by the ramping rate of the turbine. For these reasons, this study has the ground rule that the main turbine remains operating and the plant produces some minimum amount of electricity at times of low electricity prices. This leads to the major question to be addressed in this thesis—what fraction and how fast can steam be diverted to storage while keeping the main turbine online, producing electricity, with the capability to rapidly ramp up and down electrical output for the life of the plant.

A second question is whether reactor steam should go directly to the storage system or use a heat exchanger and generate steam in a secondary loop that goes to the storage system. When steam is sent off-site to industrial customers, there is typically an intermediate heat exchanger that isolates the reactor steam from the steam sent off-site. However, the storage system is controlled by the utility and in most cases, will be located on site. Under such circumstances there may be no need for an isolation heat exchanger but a need to monitor for radioactivity that could be transported to the storage system. Key inputs to answering this question include and regulatory considerations and what are the costs (dollars, temperature loss, and work loss) of such a heat exchanger. Understanding these costs are required before any decisions on whether such a system should be used or compensating mechanisms such as monitoring primary steam supply for radioactivity.

The electricity output to the grid for this coupled system of nuclear power plant and thermal storage varies from the minimum electricity generated by the reactor plant to keep the turbine on-line to the full output of the reactor plant and the maximum additional electricity generation from the thermal storage system. While these are not new ideas, the putting it together with a nuclear reactor is.

# 2 Background

## 2.1 Electricity Price Variation

The price of electricity varies by time of year and time of day. It depends on demands and is affected by electricity generation methods such as wind and solar power that fluctuate at varying rates [4]. For nuclear power to be more profitable, it must produce electricity when electricity prices are higher matching the price variations.

## 2.2 Load Following Nuclear Power Plants

Nuclear power plants are typically run as base load electricity sources, producing a constant amount of electricity. For nuclear power plants to produce electricity to match electricity prices they must run as load following. Load following will allow for more use of nuclear power in electricity generation. For example, France is able to use nuclear power plants for 75% of their electricity generation because some of their reactors are able to vary their electrical output to match electricity demand [5]. The rate of the change in power levels may be limited by the reactor or turbine, with most limits coming from the variability of the reactor power. By storing thermal energy from the secondary loop of the reactor the limitation on variation rate of the reactor will no longer be a factor because the reactor core runs at a constant full load.

## 2.3 Thermal Storage Methods

Using a thermal storage system attached to a nuclear reactor will allow the reactor to continue operating at constant power while varying the electrical output to the grid by varying the amount of steam that goes to the main turbines. The remainder of the steam would go to the thermal storage system. There are six current heat storage methods that are compatible with light-water reactors [6].

### *2.3.1 Steam Accumulators*

A steam accumulator is a vessel that would store steam from a high-pressure source as hot condensed water at a high pressure. When the valve is opened, the hot pressurized water flashes to steam. There is much experience with steam accumulators at low pressures and there is military experience with steam accumulators in high performance systems for launching aircraft off aircraft carriers [6].

### *2.3.2 Packed Bed Thermal Storage*

For packed-bed thermal storage, steam would be injected into a pebble bed that is heated as the steam is condensed and exits the bottom of the vessel as water. The process is then reversed to produce steam for peak power production. There is limited experimental data for this storage method, but is similar to chemical reactors that have extensive data [6].

### *2.3.3 Sensible Heat Fluid Systems*

This thermal storage system has heat from the steam from the reactor stored in a hot fluid such as salt or oil at low pressures. This hot fluid would then be used to create steam when needed. This system requires a heat exchanger between the reactor steam and the storage system unlike steam accumulators and packed bed thermal storage. There is no research for this storage method associated with nuclear reactors, but it is similar to some solar thermal power systems [6].

### *2.3.4 Cryogenic Air Systems*

For thermal energy storage with a cryogenic air system, during low energy price times air would be liquefied and stored. To produce electricity the liquid air is compressed, heated with steam and sent through a gas turbine to produce electricity. This method has a round-trip efficiency of 71%. There is a limited experience base for this thermal storage method [6].

### *2.3.5 Hot Rock Systems*

A hot rock thermal energy system would use the steam to heat an enclosure of crushed rock with circulating hot air which could then be used to produce steam to be used for electricity. This also can be co-located with industrial furnaces because it will have hot air [6].

### *2.3.6 Geologic Heat Storage Systems*

Geologic heat storage systems would take a preferred geology and inject hot steam and works similar to the packed bed thermal system. Heat is recovered by a traditional geothermal power plant. This system is an option for seasonal storage of electricity. Also, relevant to this system, is extensive experience in well drilling and fracking [6].

## 2.4 Ramping Limitations

Nuclear reactors do not ramp as quickly as the steam turbines that they are connected to in the reactor plant. As a result, ramping the electricity production up and down by controlling the turbine production is quicker than controlling the power output of the reactor. The limitations on the ramping of the steam turbines then become the limitations on the change in electricity production by the reactor plant when steam starts being diverted from the secondary system of the reactor, or the steam stops being diverted.

## 2.5 Use of an Intermediate Heat Exchanger

When steam is diverted from the secondary system of the nuclear reactor, the steam could go directly to the thermal storage, or the thermal storage may pair better with the steam first going through an intermediate hear exchanger. An intermediate heat exchanger includes new variables that can affect regulations and will affect the work of the system.

# 3 Methodology

A literature review and analysis was done to find the necessary information to determine the methods of diverting and storing steam, producing electricity from the thermal storage, finding limitations, determining the usefulness of an intermediate heat exchanger, and finding possible regulatory limitations.

## 3.1 Determining Turbine Load Limits

Research to determine the possible minimum turbine load was done through a literature review of design specifications so as to find the limiting factors to minimum turbine load [7]. Possible load percentage values can also be seen from articles that analyze the steam capacity of the secondary loops of pressurized water reactors [8].

## 3.2 Determining Load Following Capabilities

To find the load following capabilities of nuclear power plant systems a literature review of material on the French load following nuclear power plants was done. This includes scientific articles and research done by the Organization for Economic Co-operation and Development's Nuclear Energy Agency into the economics of load following nuclear reactors [9]. Other sources of information include turbine suppliers.

## 3.3 Determining Steam State Values

The conditions of the steam that is being diverted needs to be known in the consideration for thermal storage types. The steam states at varying locations of secondary system of the reactor and the thermal storage system are found as well from reported values. These values are determined through a mix of literature review and thermodynamic analysis.

## 3.4 Determining Systems

Values determined will vary based on the specific reactor systems, the thermal energy storage system, the system to create electricity from the stored thermal energy, and the systems that would have to be added to make the reactor and thermal storage fit together. Therefore, research was done into the different systems. This is done through a literature review of articles and design specifications. Specific attention was paid to the Westinghouse AP-1000 because several such plants are being built in the United States and China.

## 3.5 Identifying Regulatory and Other Institutional Constraints

There may be regulatory or other constraints associated with diverting steam from the power plant to storage systems. These are explored to determine if there are limits that might impact retrofit into existing plants or coupling to new plants. The recent experience with the Fort Calhoun plant was examined as the plant was to sell steam to Cargill.

## 3.6 Boiling Water Reactor Possibilities

There is the possibility of diverting steam from a boiling water reactor (BWR) as well as a PWR. A paper from the proceeding of ICAAP 2017 discussed a study into this possibility [10]. This paper was analyzed for the capability of BWR's sending secondary steam offsite.

# 4 Results and Discussion

## 4.1 Turbine Load Limits

The minimum turbine load was found from multiple sources and the limits came from the minimum loads tested, maximum steam that could be sent through the bypass system that allows steam created in the steam generator to not go through the main turbines, and from turbine plateau limits. The minimum loads on different turbines were found to be between 25% and 60% [7, 8, 11, and 12]. The 60% minimum load comes from design regulations of the AP1000 and is limited by the condenser in the amount of steam that it can take from the bypass before the main turbine. The 25% comes from the plateau of the turbine in the ATMEA1 reactor system which has its first units planned to begin operation in 2023 [11].

Turbine's also have maximum limits that cause the turbine to trip and shutdown. Because of these maximum limits the turbine cannot produce more that 110% of its rated maximum electricity output [12]. For that reason, it would make sense for the thermal storage to have its own turbine and generator system to produce its electricity. This also allows for a simpler design where the steam is diverted from the nuclear reactor at one junction before the turbines and the cooler water sent back to another junction after the turbines and no additional breaks in the nuclear system to allow for steam to be added before the turbine from the thermal storage.

Because the AP1000 and the ATMEA1 are the newest reactor designs that will be built, they are being focused on. The AP1000 has the ability to bypass 40% of the steam from the turbine to the condenser through the steam bypass system. That means that the load limit to the turbine will be at 60%. The ATMEA1 has the ability to limit the load to the turbine to 25% which is considerably lower than the 60% of the AP1000.

When the load to the turbine changes, the efficiency also changes. Figure 1 shows a 2011 accumulation of sources of relative thermal efficiency versus percentage of partial load and the line of best fit for these curves. Equation 1 shows the line of best fit and is given by the solid line in Figure 1. As seen in Figure 1, the efficiency is affected by the load percentage and at lower load percentages, the relative efficiency is also lower. This means that lowering the load percentage by diverting steam before the turbines will decrease the efficiency of the turbine.

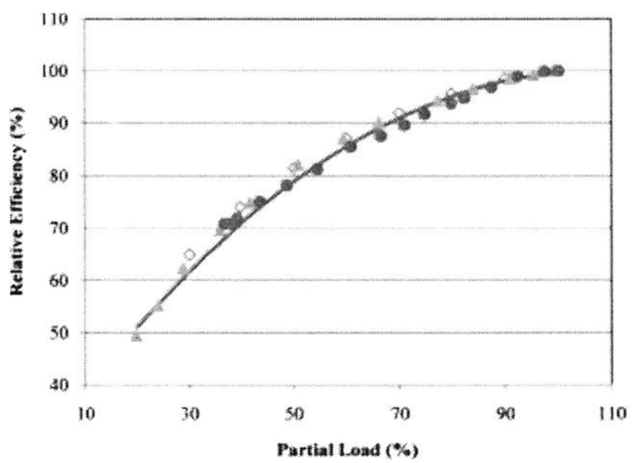


**Figure 1:** Relative efficiency for partial loads of a turbine. This figure shows how for lower partial loads in the turbine, the relative efficiency is also lower. So, if some of the load is diverted to another system and does not go through the turbine, then the efficiency of the turbine will decrease. The line of best fit for the data is seen by the solid blue line in the figure [13].

$$\frac{\eta_{th,PL}}{\eta_{th,Nom}} = -0.00006343(PL)^2 + 0.2626 \quad [13] \tag{1}$$

Varying the load to the turbine by diverting steam will affect the temperature of the load going to the turbine [14]. Figure 2 shows how the Δ heat rate is affected by the load percentage to the turbine. Δ heat rate is the reciprocal of heat efficiency [14]. This means that the efficiency of the plant increases as the load percentage gets closer to the design point.

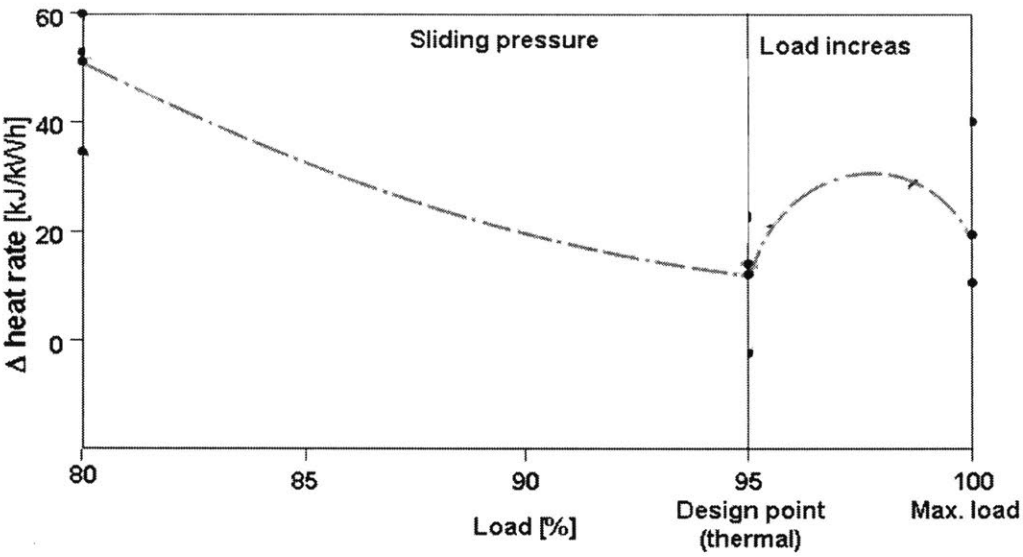


**Figure 2:** Delta Heat Rate versus Load Percentage. Delta heat rate is the reciprocal of plant efficiency, so this shows how plant efficiency improves as the load percentage gets closer to the design point from lower than or greater than the design point [14].

In Figure 2 the delta heat rate, and therefore the efficiency, does not change linearly with the load percentage. Looking at load percentages lower than the design point, the delta heat rate and efficiency changes more at lower load percentages. This means that the efficiency increasingly gets worse as the load percentage is lowered.

Figure 1 encompasses the minimum turbine loads that were found for the AP1000 and ATMEA1 reactor plant turbines and Equation 1 comes from the values presented in Figure 1, so it would be acceptable to use Equation 1 to estimate the relative efficiency for minimum loads for those systems turbines. Using Equation 1, the efficiency of the AP1000 turbine can be estimated as 86% relative efficiency for the minimum turbine load of 60%, and 57% relative efficiency for the ATMEA1 minimum turbine load of 25%. Because the efficiency changes considerably at the minimum turbine loads, the power created by the turbine is significantly affected as well.

## 4.2 Load Following Capabilities

Different nuclear power plants have different capabilities when it comes to changing their electrical output to the grid. Table I below shows typical output rate of changes for nuclear power plants from the United States, France, Germany, and the ATMEA1 plant that is a cooperation between France and Japan.

Table I. Electrical Output Change by Country [11, 15]

| Country | Output Rate of Change per Minute |
|---|---|
| United States | 0.25% - 1% |
| France | 3% - 5% |
| Germany | 5% - 10% |
| ATMEA1 | 1% - 3% |

These rates of change are limited by the reactor capabilities. By not changing the primary loop of a PWR and taking steam from the secondary loop, the rate of change will be limited by the ramp rates of the main turbine. This will allow for quicker ramping up and down. France is currently able to run 75% of their electrical grid off nuclear power because they have the ability to ramp their reactors. If the ramping ability was increases then theoretically the percentage of total electricity production by nuclear power would also increase.

The ramping of the power output of the current reactor systems ramp not only the turbine, but also the reactor. By diverting steam from the secondary system of a PWR, and designing the change so that the primary loop of the reactor is not affected the nuclear reactor will not notice the ramping of the turbine and will continue to operate at full power.

## 4.3 Steam State Values

Nuclear reactors run on a Rankine cycle. The flow going into the turbine is at the high temperature and high pressure phase and if steam is diverted before the turbine, then the diverted steam will be coming from this flow at high temperature and pressure of the system. The steam will go to either a heat exchanger or directly to the thermal storage where the heat will be transferred. The steam will lose enough heat to become water again and then can go back into the secondary system of the PWR after the turbines and condenser to keep water levels in the steam generator.

The turbine that is used for the AP1000 nuclear power plant is the Hitachi TC6F 52-inch last-stage blade unit [16]. This turbine has rated steam temperatures of 543°F and pressure of 970 psia for main steam and 487°F for reheat [17].

A Chinese large scale advanced PWR turbine has inlet values of pressure at 5.95 kPa, temperature around 550 K, and mass flow of 2249 kg/s [8].

In 1967 work began on the Midland nuclear power plant that consisted of two units that would both produce electricity and send steam to the DOW chemical plant a mile away. The steam sent to the DOW chemical plant was a tertiary loop connected to the secondary loop of the PWR. The plant was never finished, but the plan was to sell 20% of the steam output [18]. The majority of the steam would come from Unit 1 at 460 kg/s at 1200 kPa and 50 kg/s at 4100 kPa [19]. The preliminary safety analysis report for the Midland plant was done in 1968 and is referenced in a 2011 NRC project [20], but could not be found to access more details. Similarly, the details are not known for the 2006 Cargill-OPPD Steam Supply Project as it did not reach the regulatory phase.

## 4.4 Direct or Indirect Heat Storage

Diverting steam before the turbine in the secondary system of a PWR could allow for this steam to be directly used in the thermal storage, or indirectly. It would indirectly be used by going through a heat exchanger and having an additional flow loop that flows between this heat exchanger and the thermal storage.

The Cargill-OPPD Steam Supply Project in 2006 created a plan to divert steam from the Fort Calhoun OPPD nuclear power plant from a connection after the steam generator and before the turbine and use an additional flow loop connected by a reboiler to send heated steam to the Cargill plant. Figure 3 shows the set-up of these connections [21]. In Figure 3, 1 shows the primary loop that goes through the reactor, 2a shows the typical secondary loop that goes from the steam generator to the turbine, to the condenser, and back to the steam generator, 2b shows the new loop that goes from the secondary system before the turbine to the reboiler and back to the steam generator, and 3 shows the loop that takes heated steam from the reboiler to Cargill and then back from Cargill to the reboiler.

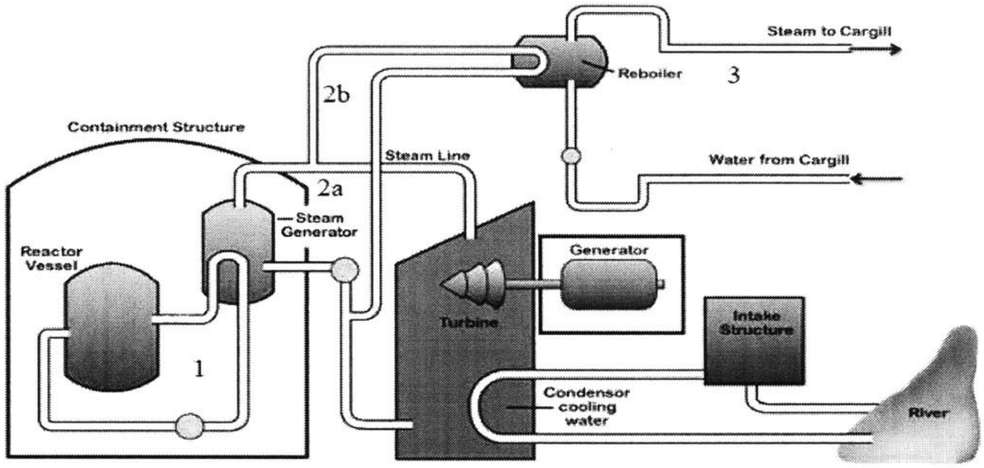


**Figure 3:** Cargill-OPPD Steam Supply Project design. This figure shows the design set-up for sending diverted steam from the Fort Calhoun OPPD nuclear reactor to the Cargill plant. The interesting parts of this design are shown by flow loops 2b and 3. 2b shows the diverted steam flow to a reboiler. Loop 3 shows how steam is sent to Cargill by heating water through the heat exchange with the 2b loop [21].

Using a heat exchanger like the Cargill-OPPD steam supply project is the indirect method of sending steam to a thermal storage method. The thermal storage would connect in a similar design where Cargill is connected in Figure 3. This issue with heat exchangers is that they are not 100% efficient with real world conditions. There are many types of heat exchangers and they tend to work more efficiently under different conditions. Figure 3 shows that the Cargill-OPPD project made use of a reboiler.

The Midland nuclear power plant that consisted of two units was designed to both produce electricity and send steam to the DOW chemical plant. The steam sent to the DOW chemical plant was a tertiary loop connected to the secondary loop of the PWR through a heat exchanger. The system was designed to run in three different modes that varied the units sending heating steam to high and low pressure evaporators [22].

These two plants that proposed sending steam offsite both used heat exchangers to do so, but used two different types of heat exchangers. Equation 2 shows how the percentage of work, W%, can be calculated for a heat exchanger [23]. Work percentage is the percentage of work that is not lost, so a heat exchanger that has no loses would have a work percentage of 100%. Both the Chinese large scale advanced PWR and AP1000 have load temperatures of about 550K that go to the main turbine. Using this temperature for the hot inlet temperature, $T_{a1}$, and assuming the cold temperatures, $T_{a2}$ and $T_{b1}$, are the same on both sides of the heat exchanger and equal to the condenser temperature, 200K, Equation 2 gives the work lost percentages in Table II [8, 12].

$$\frac{(T_{b1}-T_{b2})}{(T_{a1}-T_{a2})} = W\% \qquad [23] \tag{2}$$

| Table II: Work percentage calculated from difference in hot temperatures from Equation 2 | |
|---|---|
| Difference in Hot Temperatures | Work Percentage |
| 25 | 90% |
| 50 | 80% |
| 75 | 70% |

Table II shows that the efficiency which is equal to the work percentage decreases linearly with the difference in hot temperatures.

## 4.5 Regulatory Considerations

Depending on the final setup of the system for diverting steam and how the energy goes to thermal storage there will be varying regulatory considerations. Having the thermal storage on the same site as the nuclear reactor power plant would limit additional environmental concerns. Using a heat exchanger would limit regulatory considerations as well because the storage system would have two areas of discontinuity from the primary system of the nuclear reactor. No matter what is done, a full plan would have to be drawn up for NRC review with the proposal for the plant.

The Midland nuclear power plant that began being built in 1967, but was never completed, proposed selling steam to the DOW chemical plant a mile away. This steam was to be produced from a heat exchanger connected to the secondary loops of the PWR's. The NRC reviewed the Midland nuclear plant units in 1982 for environmental considerations and the chemical plant was also included in the environmental information provided, but the DOW chemical plant itself was not reviewed by the NRC [24]. This means that for diverting steam to a thermal storage system the thermal storage system may not need to be reviewed by the NRC, but its connection to the nuclear plant would need to be reviewed.

## 4.6 Boiling Water Reactor Considerations

It is also possible to send steam offsite from a boiling water reactor (BWR) through the use of a two-loop intermediate heat exchanger [10]. Where the steam from the BWR primary loop connects to the intermediate heat exchanger changes the input temperature which changes the heat exchanger output temperature. This means the system can be designed differently with different steam destinations in mind.

# 5 Conclusions

Depending on the reactor that steam is diverted from, there will be different limits on the amount of steam that can be diverted from before the turbine in the secondary system of a PWR. The AP1000 shows a minimum load to the turbine to be 60%, while the ATMEA1 can have a minimum load of 25%. This means the steam diversion system will have to be designed for a specific reactor and not for PWR's in general because 60% to 25% is a lot of variation. The specific reactor will also affect the load following capability, which will affect the rate at which the load to the turbine is changed.

If a heat exchanger was used connected to the tertiary system of the thermal storage, the heat exchanger would have some work loss and therefore economic losses, but the use of a heat exchanger creates another boundary between the thermal storage and the radioactive primary loop of the reactor. This will help with regulatory considerations. Also, having the thermal storage on site will take away additional regulatory considerations that would arise if the storage was offsite.

# 6 Future Work

Looking to the future, more work would have to be done before a final design for this idea could be designed and implemented. The main aspects that need to be worked on include the specifics of which reactor this will be paired with, the design for the steam diversion, pairing it to a thermal storage method, and going through the regulation process to make this a reality. It would make the most sense to pair this with one of the newer designs of reactors that are still to be built. Looking at the AP1000, further study is required to know the turbine limits on minimum load as the current limitations to minimum load come from the condenser limitations for steam bypass.

If the load percentage of steam that will be diverted is within the limits for the steam bypass system, it would make sense that the steam diversion system could be designed very similarly, but with the ability to regulate the exact percentage of steam that is being diverted. The turbine system could also be modified to lessen the lowering of efficiency as the load to the turbine decreases. The final decisions made will affect the thermal storage method selected and how the plant would run. The NRC regulates the safety of nuclear power plants and this modification will also have to be reviewed.

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