Multi-Use High-Technology Testbed

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***Abstract*— The efficient use of energy is one method of potentially reducing the amount of fossil fuels that are used world-wide to generate electricity. Nuclear energy presents a promising sustainable energy source for the future that generates few to no greenhouse gases. While it creates energy that can be used for electricity it also has many byproducts that are treated as waste or not utilized to their full potential. Waste heat is a major product of nuclear energy that should be harnessed and applied to other processes. These include water desalination/water purification hydrogen production, use in industrial chemical operations, or electricity production. Nuclear energy is most often base load following power and very inflexible. One way to address this is to use Hybrid Energy Systems (HES). By doing this the system can be load following and hence more efficient and sustainable. Therefore, the goal of this project is to create a system that mimics the waste heat from a reactor, demonstrate how to utilize that heat, and show that when energy demand is low the reactor does not need to reduce power; the energy can be directed elsewhere to create goods. This paper presents the details of the Energy Conversion Loop (ECL) that was developed to act as a test bed for experimentation of the aforementioned processes and test the possibility of nuclear HES. Further, the paper presents a proposed intelligent control system that can adapt to the system requirements for the ECL. In addition, the system has great potential for education on critical infrastructure protection and testing of future control logic systems and mechanical systems.**

Keywords—Advanced Control Systems, Hybrid Energy Systems, Multi-use Testbed

I. INTRODUCTION

The debate continues on the magnitude and validity of climate change caused by human activities [1]. However, there is no debate about the need to make buildings, modes of transportation, factories, and homes as energy efficient as possible. Energy costs plummeted during the latter half of 2015 and the first quarter of 2016. The cost of fossil energy has varied widely in the last four decades. Within a year prices might once again be at a record level if some man-made or natural disaster occurs or they could plummet below where they are now. Given that climate change could occur with the wasteful use of fossil fuel and the fact that fossil energy costs could and will swing wildly it is imperative that every effort be made to utilize energy sources to their fullest.

Nuclear energy has offered a reliable and efficient source of electricity for many parts of the world for decades. Its attractiveness has only increased with the demand for “green” technologies. It produces low to no greenhouse gases requires no fossil fuels to operate on a daily basis. While it is a viable source of energy it has its own shortcomings, such as the unresolved issue of the disposal of nuclear waste and the high cost of building a new nuclear power plant. Another problem is most nuclear power plants produce only the base load of all the energy demand of a system, near 60% of demand [2]. These reactors cannot easily or efficiently follow the demand made on the grid. In some places, France for example, a few nuclear power plants have been designed to ramp up and down the power output to follow the highs and lows of energy demand [3]. While this is great from the standpoint of those using the energy, it decreases reactor efficiency and is not conducive to the longevity of said reactor [3]. Ideally, a system that follows the energy demands as they occur is desired or is “load following”. Hybrid energy systems have been proposed to address the load following issue [4], [5].

Hybrid energy systems (HES) are two or more separate energy producers used together to produce energy commodities [2], [4], [6]. The HES this paper focuses on is the use of nuclear reactor waste heat as a source of further energy utilization. Nuclear reactors use a fluid to cool the core and produce the steam needed for the production of electricity. Traditionally this steam, or coolant, is used to convert the energy then cooled elsewhere. The heat is released into the environment without being used further. By adding technologies to nuclear reactors to use the wasted heat, a system can be developed to make more than just electricity and allow for loading following capabilities [5].For example, if demand is low the heat and power of the reactor and be diverted to a process heat application, like fuel refining, and when energy demand is high the resources can be diverted to just producing energy for the grid. Combining this with highly variable renewable energy sources, solar or wind energy, can create a flexible, stable, and load following system [4].

Nuclear waste heat has many proposed uses, such as desalination, hydrogen production, pyrolysis, and thermal energy storage, but few have been put into practice or thoroughly experimented [2], [5], [7]-[10]. The goal of this project is to create a way to mimic waste heat utilization and test the uses of the remaining water heat energy in a system. The design would become a test bed for examining the best ways of using waste process heat

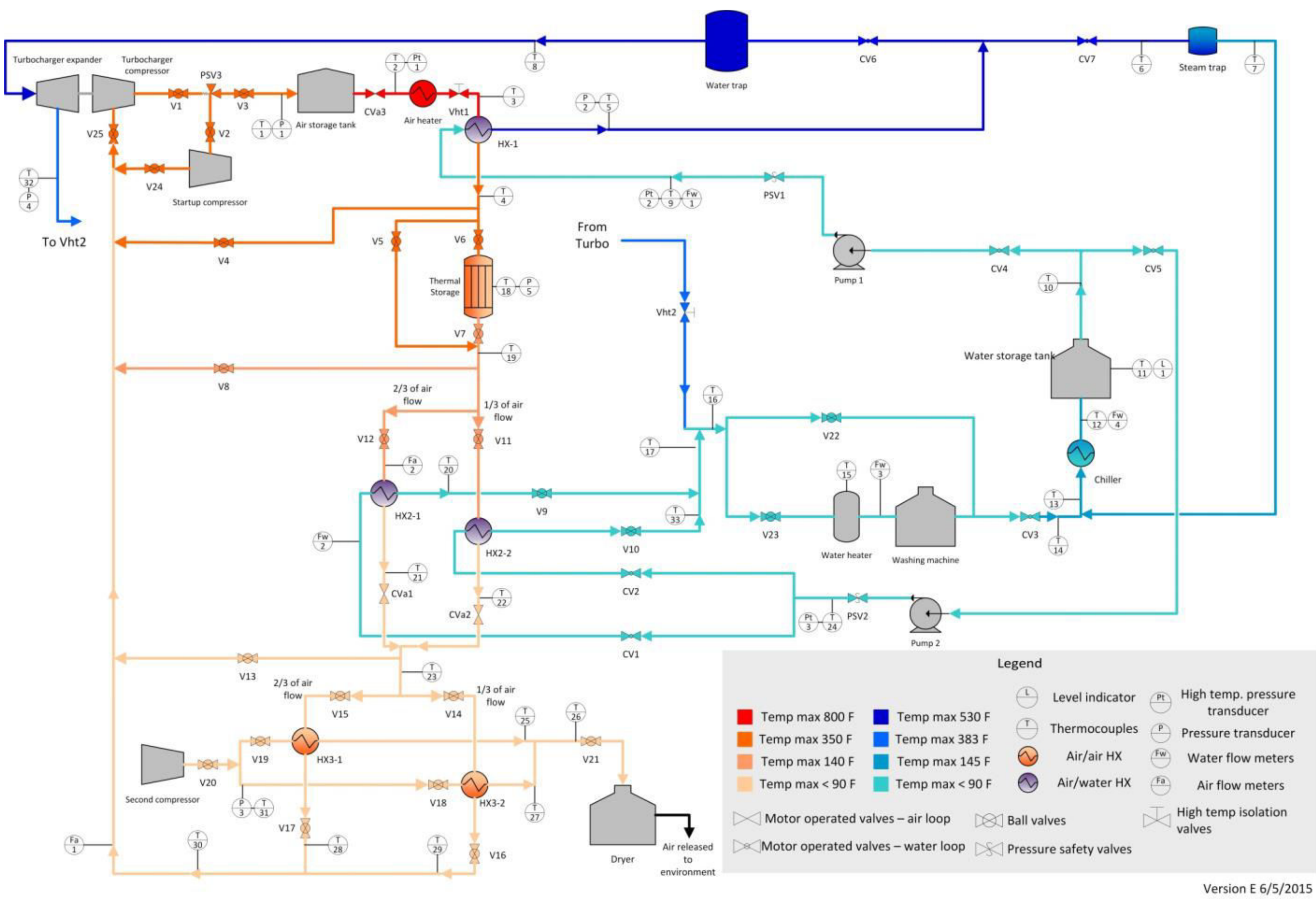

Figure 1: Piping and Instrumentation Diagram.

The rest of the paper is organized as follows. Section II presents the details of the system design. Section III describes the proposed control system. Section IV presents an analysis on the possibilities for usage of the presented system and finally, Section V concludes the paper.

II. System Design

This section presents details the design of the mechanical aspects of the system.The system consists of several loops that water or air flow through to be used. Each demonstrates the use of waste heat from the reactor.

The steam from the reactor can either be used to heat air or water. Figure 1 is a piping and instrumentation diagram illustrating the system connections and flow.

A. Air Loop

The system begins with an air storage tank and air heater with capabilities of heating air up to 800^{o}C (1472 ^{o}F). Due to the limitations of the system piping our testing will not reach this level for safety purposes. Air is heated gradually in the air heater then flows to a shell and tube heat exchanger, HX-1. The air flowing through the tube side heats water flowing through the shell side. From here the air is directed to a bypass loop back to a turbo charger that mimics a turbine attached to the system or the air is directed to a thermal storage device. This thermal storage device currently uses soy wax as the heat storage medium. However, other media are being considered. The air then flows to two air-water heat exchangers. These two heat exchangers provide hot water used in the washing machine. Next the air flows to two air-air heat exchangers and heats air from a compressor to be used by the clothes dryer then released into the environment.

B. Water Loop

The water loop is heated by the air loop as previously explained. In the first heat exchanger the water is heated to 260oC (500oF) and sent to either a water trap or steam trap. The water trap path sends the steam to a control valve where conditions will be monitored. Then it is sent to the water heater and washing machine. The steam trap loop sends liquid water to the chiller where the water is cooled and stored in a large tank where the process begins again or the water is pumped to the second set of heat exchangers to be heated by the air exiting the thermal storage device. Using a process modeling software, Aspen Hysys, a model (see Figure 2) was created to test the temperature and pressures of the system prior to physical testing [10]. This model was run as if the thermal energy storage (TES) was bypassed and the two heat exchangers for HX2 and HX3 were one

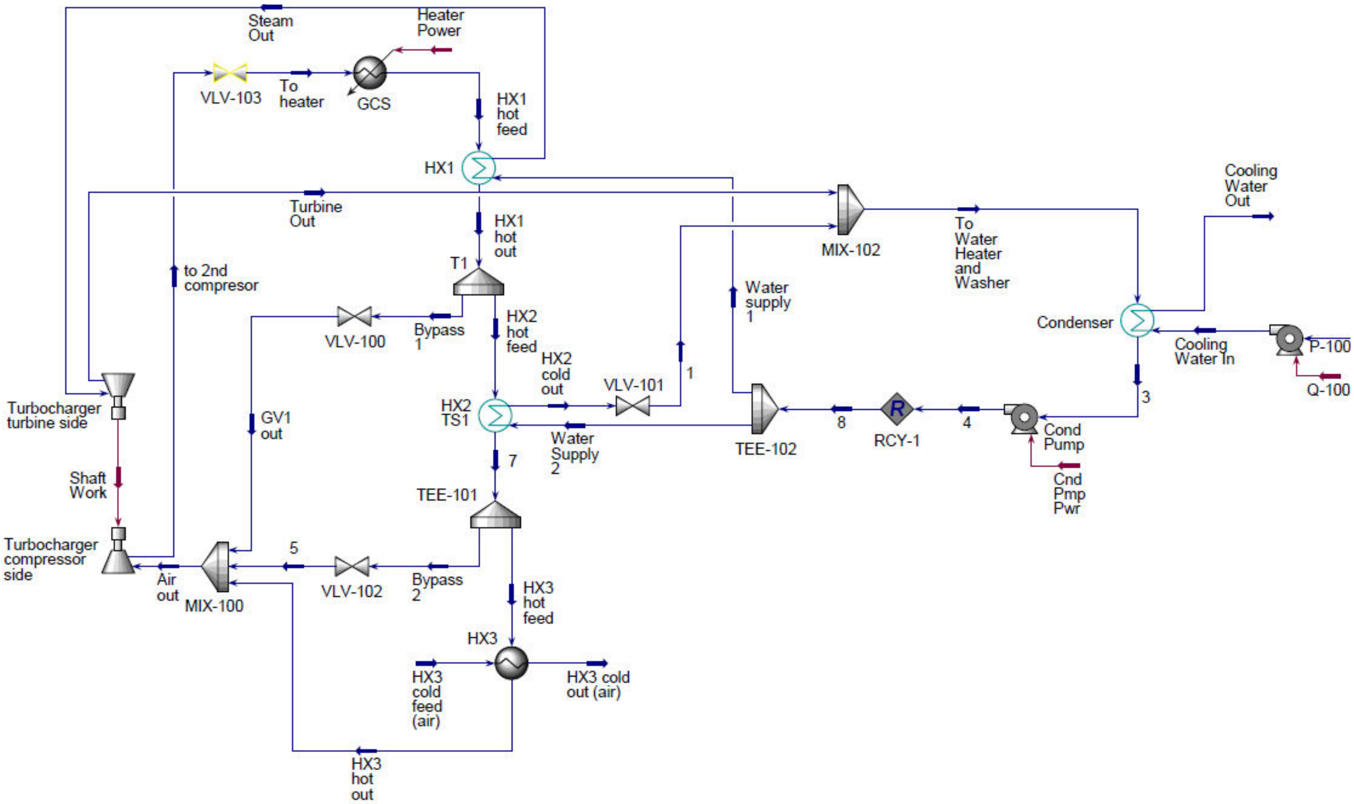

Figure 2: HYSYS model of ECL system

large heat exchanger. Table 1 gives the temperature and pressure maximums for key portions of the system. A maximum of 420^{o} C (800^{o}F) is the highest temperature in the system due to mechanical limitations of system components.

TABLE 1 OPERATING CONDITION RESULTS FROM ASPEN HSYS FOR ECL

Heat Exchanger	Operating temp (^{o}C)		Max Pressure (KPa)	
	In	Out	In	Out
HX1(**air**/*water*)	**425**	**154**	**675**	**662**
	30	*170*	*689*	*675*
HX2s(**air**/*water*)	**154**	**55**	**662**	**648**
	30	*36*	*689*	*675*
HX3s(air/air) (**shell**/*tube*)	**55**	**47**	**648**	**636**
	25	*50*	*172*	*169*
To the washing machine	*52*		*276*	
To the dryer	*52*		*169*	
To chiller	*30*		*275*	

By monitoring these sections of the system possible processes can be proposed to incorporate at this point in the system an exchanger with more storage capacity, or a heat exchanger that needs testing.

The values obtained from testing the dryer will indicate what type of future experiments can be run with it as well. There is a possibility of experimental food drying or industrial drying processes. Another option is to use the air as heat for buildings. This can also be applied to the water loop.

III. Intelligent Control System

This section discusses the control framework for the ECL. The section first, briefly introduces Artificial Neural Networks (ANN) and then, elaborates the overall Intelligent Control System (ICS) and its components.

A. *Artificial Neural Networks*

ANNs are Computational Intelligence (CI) architectures which are a proven methodology for optimization, forecasting, data mining, multidimensional nonlinear function approximation and many other areas [11]-[13]. The basic unit of an ANN is a neuron. Each neuron has a set of inputs and produces an output based on the inputs. In addition, it is able to differently weigh each input according to the priority of the input.

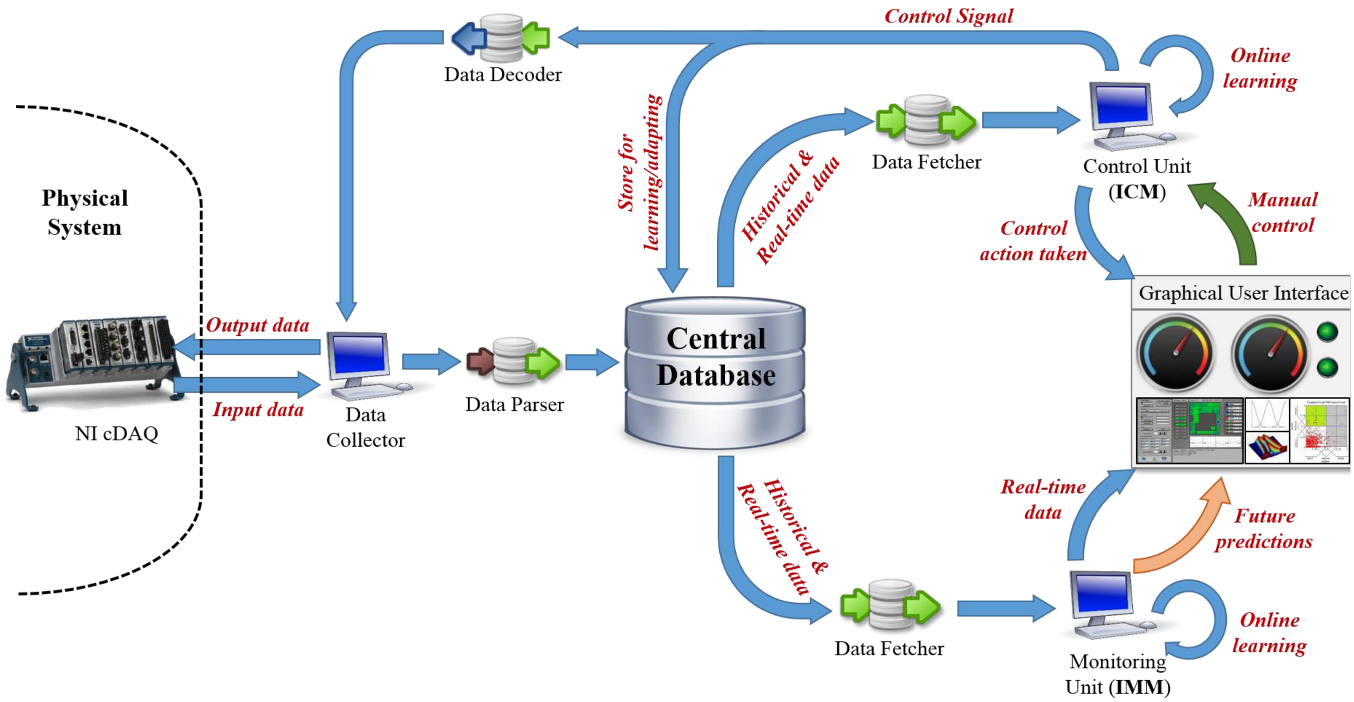

Figure 3: Presented Intelligent Control System

An artificial neuron achieves that by using input vectors, weights, a threshold value and output vectors. For each input x_q there is a weight w_q assigned. The weighted sum of a neuron can be given as,

$$z = \sum_{q=1}^{n} w_q x_q \tag{1}$$

where, n is the number of inputs.

The output of the neuron is controlled by the activation function, value of which, act as a threshold.

The output of the neuron a is given by:

$$a = f_s\left(\sum_{q=1}^{n} w_q x_q\right) \tag{2}$$

where, $f_s(x)$ is called the activation function.

A neural network comprises of multiple interconnected neurons, arranged in several layers. There are one input and one output layer and multiple hidden layers. For a given layer L we can calculate the error if the desired output is known using:

$$E = \sum_{p=1}^{P} \sum_{m=1}^{M} (d_{pm} - x_{pm}^{L})^2 \tag{3}$$

where, P is the number of patterns, M is the number of outputs and d_{pm} is the desired output pattern p and output m.

B. *Presented Intelligent Control System*

The Intelligent Control System (ICS) is responsible for managing the electronically controllable components of theECL and overall monitoring of the entire system. In order to accomplish the task, ICS performs two main subtasks, 1) Intelligent control of the system and 2) Intelligent monitoring of the system. The presented ICS leverages the capabilities of ANNs. The modelling and learning of the system is entirely data driven. The ICS contains main component types: 1) Intelligent Control Module (ICM), 2) Intelligent monitoring module (IMM), and 3) Additional components. Figure. 3 shows the presented ICS framework.

The ICS connects to the physical system through the NI cDAQ shown in the figure. The input data are acquired from the cDAQ and fed to the control and monitoring units after performing the necessary parsing and converting. Similarly, the output control signals are sent back to the control unit using the cDAQ. These control signals include automated intelligent control as well manual control by the user. Before sending the control signals to the cDAQ, control data are sent though decoders. A central database is used for recording input data; for training ICM and IMM with historical data, and output data; which contains the control decision history and predictive modelling history.

Intelligent Control Module

The intelligent control for the ICS is carried out using ANNs. The objective of the ICM is to provide outputs to the electrically controllable modules. The ICM learns from both historic and real time data. Initial training for control strategy is carried out using historic data. Real time data are used to perform online training thus enabling the ICM to be more

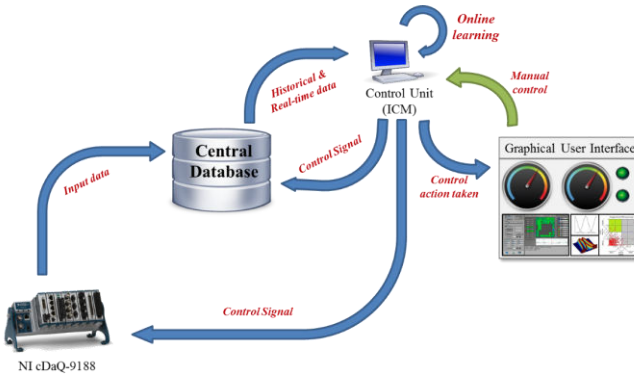

Figure 4: Intelligent Control Module (ICM)

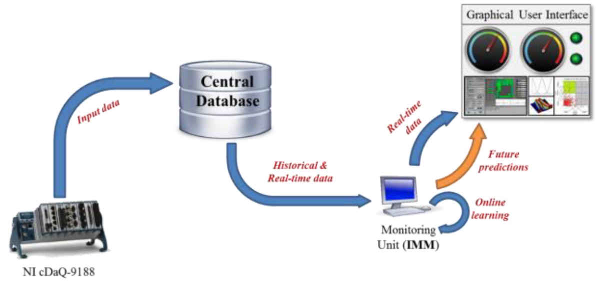

Figure 5: Intelligent Monitoring Module

adaptable in previously unseen behavior. For the ICM, supervised learning techniques are used. In supervised learning, the inputs and the desired outputs of for those inputs are fed to the neural network [13]. The ANN performs the nonlinear input-output mapping to model the desired behavior of the system. Once this initial training is carried out using historic data, online learning can be done during operations. The ICM will learn from manual controls and from new system behavior as they occur.

ICM is fed with historic and real time sensory data from the system (see Figure. 4). Further, historic data from different control scenarios are presented to the ICM with the desired provided by the ICM. Fig 5 shows the framework for the presented ICM.

Intelligent Monitoring Module

Similarly to the ICM, the monitoring is carried out ANNs based on supervised leaning. The objective of the ICM is to perform intelligent predictions for the system states. These predictions are calculated based on historic and real time data from multiple sensors. The IMM provides improved state awareness to the system to add to the control of the ICM. The IMM is used for detecting previously unseen behavior of the system which can be potentially anomalous.

Similar to the ICM, IMM is fed with sensory inputs acquired through the cDAQs . The outputs of the IMM are predictions for each sensor. These predictions are displayed to the user through a developed graphical user interface (GUI). Figure 5 shows the framework for the presented IMM.

Additional Components

In addition to the ICM and the IMM, the ICS contains several other components that are essential to the correct operation of the ECL. Three such essential components are 1) Heat exchanger (HX) modeling, 2) GUI and 3) Database.

Modelling HX is important for increasing accuracy of other predictions of the system. Thus, accurate HX modelling improves state awareness. However, HX modeling has been shown to be a difficult task to be carried out with traditional methods. Further, it has been shown that ANNs are capable of accurately accomplishing this task [14]. Therefore, ANNs will be utilized to carry out HX modeling.

A GUI is used to provide a rolled-up view of the entire system to the human operator. The GUI provides the state information to the user which includes system control state from ICM, current system behavior state, future predictions from the IMU and current/ predicted alarm states. In addition to providing the operator with current state information, the GUI is used to provide manual control signals to the ICM. This functionality is used to override the ICM in occasions such as emergency shutdowns. Further, the GUI is used to acquire user feedback about control actions and predictions. The feedback is used for online training.

A central database is used to incrementally store historic sensory values, control decisions from the ICM, sensory predictions from the IMM and manual controls and user feedback. In addition to the database, data parsers and decoders are used to convert data from DAQ values to measurements and convert control signals to DAQ interpretable values respectively. Further, a data fetcher acts as the connector between the modules; ICM and IMM and the database. Fetcher fetches required data for the ICM and IMM from the database.

IV. Analysis

This section analyzes the potential use cases of the presented ECL. The washer, dryer, and chiller are used to mimic a more complex system that could be used with the design. New experiments would not only occur at the current locations of the washer and dryer in the system. These experiments can be used anywhere in the piping system if the temperatures, pressures, and flows align with the needs of the experiment. Process heat can be used in many applications; three applications of interest are desalination, hydrogen production, and fast pyrolysis.

By using the HYSYS calculated values we can determine possible replacements for the washer, dryer, and chiller or additional components can be incorporated to facilitate testing.

A. Desalination

Desalination is the removal of salt and harmful contents of sea water for the purpose of creating fresh water. Desalination can be done through usage of nuclear heat or electrical means [6]. The system will work with processes such as multi-effect distillation (MED) or multi-stage flash distillation (MSF). MED requires temperatures around 71^{o} C(160 ^{o}F) and MSF requires 90-110^{o}C (194-230 ^{o}F) [15]. This is feasible with the HYSYS values in our system. On the left is steam from a boiler. If a proposed system were connected to the ECL near the first heat exchanger steam can be used similarly.

Another option for desalination is reverse osmosis (RO). This could be done by connecting a turbine to the system and creating the electricity needed for RO. After testing of the system is complete the energy possibility can be calculated where the turbocharger is on Fig. 1.

B. Hydrogen production

Nuclear energy use for hydrogen production has been proposed but has not been heavily tested [9], [16]. High temperature gas reactors can be easily used for hydrogen production with an output temperature of 900^{o}C [16]. This uses steam for the production of the hydrogen in thermochemical splitting. Our system does not reach these temperatures and would be unadvisable to do so because of components limitations. Some studies have shown temperatures from 400 to 3000^{o}C can be used. With such a broad range of temperatures, specific hydrogen production technologies can be tested with the system. Another option is to create the energy required for electrolysis for hydrogen creation [17]. A 1kg hydrogen/day unit requires 3kW of power for electrolysis [19]. By using the values created by the system after testing we can determine the capabilities of the ECL to produce this much energy with a small turbine or battery.

C. Pyrolysis

Pyrolysis is the decomposition of biomass caused by heating the substance in the absence of oxygen. The biomass is decomposed into a gas, liquid, or solid (char) substance. All of these components can be used in further processes; liquid as a bio-oil or fuel, char as a fuel source, and gas can be recycled back into the pyrolysis process. The liquid product, pyrolysis-oil, is the most practical product to collect due to its ease of transport and storage and use in several applications. Pyrolysis oil can be used as a fuel source for boilers, turbines, or furnaces; it can be further refined to make transportation fuel, or can be used in chemical processes. Anytime pyrolysis is preformed the three products are created but the process can be manipulated to create more of one type of product. Fast pyrolysis allows for the highest pyrolysis oil production. The requirements for fast pyrolysis are a <2 sec. vapor retention time at 500^{o}C (932 ^{o}F) of the biomass. At these conditions vapor is created from the biomass that must be quickly quenched to condense into the pyrolysis oil [19]-[22]. Below is a diagram illustrating the set-up of a fluidized bed pyrolysis apparatus. The recycle gas and air are what would be heated through a heat exchanger with the heat from the ECL. This process can easily be accomplished with the ECL. A heat exchanger of the steam or hot air from the ECL heating nitrogen for the pyrolysis process can be attached after the heater, or replace HX-1 possibly. Temperature here is 426^{o}C (800^{o}F) and could easily transfer the energy to nitrogen for pyrolysis use. The temperature would be below the common 500 ^{o}C (932 ^{o}F) needed for optimal bio oil yield, but would be able to prove the idea that nuclear process heat can be used for pyrolysis purposes.

D. Education and Training

The ECL has one other major potential and that is in the area of education and training. Because this device is a semi-scale industrial piece of equipment with very sophisticated mechanical, electrical and a very advanced control system it is a perfect piece of equipment for assisting with education and training on control system design, critical infrastructure protection, mechanical systems, heat exchanger design, and heat storage and utilization. The ECL has both the digital electronic control system; along with hardwired system protection devices and mechanical pressure relieve devices.

In one possible scenario the ECL could be made visible on the internet and allowed to be attacked. The ECL could be brought down by attackers, but because the device has hardwired thermal and pressure protection devices it would be protected from catastrophic failure. The attack could then be studied to see how the intruders found the device and how they plotted their attack. Another scenario is that the device be made visible on a local network and students could play attackers and defenders of the system.

Other potential uses we have discussed are for testing advanced control console and control room designs, and non-destructive testing of the piping and valves.

V. CONCLUSIONS

The ECL test bed will allow us to develop a way of testing possible nuclear hybrid processes, along with testing various control system logic and educational possibilities. What processes can be tested will depend on the results of future testing to be completed in the Spring of 2016.

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