Microreactor AGile Non-nuclear Experimental Testbed Aspen HYSYS Analysis

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Presented in Partial Fulfillment of the Requirements for the

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by

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Authorization to Submit Thesis

This thesis of Clayton Turner, submitted for the degree of Master of Science with a Major in Mechanical Engineering and titled “Microreactor AGile Non-nuclear Experimental Testbed Aspen HYSYS Analysis,” has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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Abstract

There is a lot of interest in modular nuclear microreactors and the benefits they bring for mobile power in remote areas and process heat applications (World Nuclear Association, 2020). Many companies in the nuclear power industry are developing various types of reactors, ranging from high temperature gas reactors (HTGRs), sodium-cooled fast reactors, molten salt reactors, light water reactors, and heat pipe cooled reactors. Each reactor type requires different thermal conditions to achieve their most efficient operations. Many of these miniaturized transportable reactor designs remain largely untested and unproven. To aid in the development of the miniaturized reactors, Idaho National Laboratory (INL) is developing a Microreactor AGile Non-nuclear Experimental Testbed (MAGNET). The MAGNET will be used to simulate the thermal conditions (pressures, temperatures, heat transfer fluids, etc.) that microreactors are expected to deliver. The MAGNET facility will accommodate various electrically heated microreactor prototypes. However, the first reactor type under consideration is a heat pipe cooled test article. The working fluid being considered to cool the heat pipes in the MAGNET system is nitrogen or helium with a max operating temperature of 600°C. To help in the development of the MAGNET facility, models were developed in Aspen HYSYS (Aspen Technology, Inc., 2016) to approximate the thermal conditions throughout the test loop.

The MAGNET models created could be used to simulate the experiments and potential experiments for the MAGNET. This could save time and money by reducing the number of costly experiments that provide little information. It could also be used to simulate off design conditions to determine safety parameters that could be potentially dangerous, like extreme pressures or temperatures. From the analyses, it was shown that the upper end temperature while using helium could reach close to 635°C. This approaches the upper limit of the piping at 650°C, making helium potentially dangerous unless changes are made to the mass flow rate or heat pipe power load. The models also showed a detailed pressure drop throughout the system showing that the MAGNET's compressor could handle the required pressure ratio. However, it also showed concern about the compressor handling the required mass flow rates. Another major application drawn from the HYSYS models was a representation of the heat loss and temperature loss throughout the piping. This showed that the heat loss from the piping was minimal when the power applied to the heat pipes was at least greater than 75 kW.

Modular nuclear microreactors generate power using various power conversion units (PCUs). Several common PCUs include steam Rankine cycles, air Brayton cycles, closed helium Brayton cycles, recuperated Brayton cycles, supercritical carbon dioxide cycles, and organic Rankine cycles. Combined power cycles can also be used to increase the thermal efficiency of the PCU. Combined cycles could include a Brayton cycle with a steam Rankine bottoming cycle. An advantage of the MAGNET is having the ability to easily attach a PCU to the MAGNET. Two options were considered for adding a PCU to the MAGNET. The first option was to find a physical PCU unit to attach to the test loop and the second option was to develop a PCU simulator.

The MAGNET HYSYS models were designed with a compressor and turbine to model a PCU. The configuration made was a recuperated Brayton cycle. The cycle was optimized by varying the outlet pressure of the turbine to achieve the highest thermal efficiency of 8.57% with nitrogen and 15.5% with helium. A PCU simulator was also designed from the research that Brayton cycles can be uniquely identified by three state points and knowing the pressure ratio. The PCU simulator simulates simple and recuperated Brayton cycles using a series of heat exchangers and valving. The major advantage of the PCU simulator was that it could simulate various Brayton cycles under various compressor and turbine efficiencies. However, the major disadvantage was that the system has be large capital cost estimated near 2.15 million dollars.

A simple Brayton cycle start up process was analyzed to provide understanding for the start-up process of a nuclear powered Brayton cycle. The data provided an upper limit for realistic compressor and turbine adiabatic efficiencies of 85% and 90%, respectively. From the analysis, the three key state points were collected which would allow the PCU simulator to simulate start up processes. An understanding for how a nuclear powered Brayton cycle could start up was also learned from the analysis. One could say that the nuclear powered PCU start up is similar to a conventional natural gas PCU except when the start up process begins. The nuclear reactor would be at operating temperatures before the PCU started. Then the heat could be applied to the PCU instantly instead of at conventional timing in natural gas PCU.

This thesis details the development of the Aspen HYSYS MAGNET model as well as the development of the PCU simulator, including cost estimates and start up analysis.

Acknowledgments

I would like to thank the University of Idaho for providing a great place to pursue my master’s degree. They have outstanding professors who have aided me in my educational goals. Specifically, Dr Michael McKellar for all the effort, time, and guidance in helping develop my engineering skills. His input was monumental in my success. I would like to thank my committee for their efforts with my learning and the development of this thesis, Dr John Crepeau and Dr David Arcilesi. I would also like to thank Donna Guillen and James O’Brien at the Idaho National Laboratory for providing great projects and funding for me.

Dedication

To my wife, Kali, for willingly supporting me and our kids through the busy extra years of graduate school and delaying our future plans.

To my dad, Terry, for answering hundreds of silly questions and for the extra time he has given to teach me.

To my mom, Nonalee, for always supporting and loving me and my family in our goals.

To God, our Heavenly Father, for the countless blessings to myself and my family which have helped us in our goals.

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Chapter 1: Introduction

1.1 Background

1.1.1 Modular Nuclear Microreactors

The idea of small modular nuclear power has reignited people's interest in nuclear power. This form of nuclear power adds a lot of versatility to what used to be a stagnant field. Instead of being a large, expensive, and stationary plant, small microreactors are transportable and reduce the impact of capital costs. This class of microreactors is new, which bring many new advantages and challenges (World Nuclear Association, 2020).

Modular nuclear microreactors are versatile reactors. This versatility comes from their factory fabrication, transportability, and self-adjustability. These reactors are simply designed so that many of the components are fabricated and assembled in a factory. This removes the need for large construction zones for assembling the micronuclear reactor. It removes large overhead and capital costs. It decreases the required time to set up and operate the unit. Once the units are assembled, they should be quick to install and allow for a "plug-and-play" setup (Office of Nuclear Energy, 2018; Vitali, Lamothe, Toomey, Peoples, & Mccabe, 2018). Customers can purchase these units without the worry of on-site construction zones and gain electrical access rapidly.

Once the units are assembled, they can be shipped directly from the factory to the desired location. Many of the current designed units are small and can fit within international standard organization (ISO) shipping containers. ISO containers are easily transportable by truck, train, boat, and airplane. An example rendering of a current reactor design being shipped is the HolosGen Holos Reactor, shown in Figure 1.1. Transportability is a desirable feature for many applications. Because the units are small, they require only a small amount of land, and can operate virtually anywhere.

A design consideration for microreactors is that they are designed to be self-adjusting and self-regulating. This is achieved by implementing passive cooling systems that are cooled by the ambient air. This prevents overheating and reactor meltdown, suggesting that the reactor would not require many specialized operators to be present continuously to monitor and operate the reactor (Office of Nuclear Energy, 2018). The use of passive cooling systems makes the reactors safe and require little maintenance while operating in public.

Figure 1.1 Rendering of the HolosGen Holos Reactor Shipping (HolosGen, 2017)

There are many reasons for the development of modular microreactors because of the large number of possible applicational uses for them. Some of the possible applications include providing power for military bases, military forward operations, remote areas, and for disaster areas. The Department of Defense (DoD) and Department of Energy (DOE) facilities have major interest in this technology and plan on operating these reactors by the end of 2027 (Charles, 2018). In 2016, the DoD was the largest consumer of energy using 21% of the total federal energy consumption. They used 201.4 billion BTUs which cost 3.7 billion dollars. Most of the energy demand was met by the use of electricity, natural gas, and other fuels like coal and oil. A remote domestic military airbase in Alaska is an example of a military facility that has a constant need of fuel. This airbase uses 800 tons of coal per day and consistently produces between 10-15 MWe. The use of a small modular microreactor could reduce or remove the constant need of coal for the airbase. One or two reactors could supply the needed power to this airbase (Nuclear Energy Institute, 2018).

Another major application of microreactors for the US military is for their forward operating bases. As designed, microreactors are easily transportable, robust, reliable, and quick to set up. An example for military use is the Westinghouse eVinci reactor, shown in Figure 1.2. Several major advantages for microreactors in forward operating bases are that they create energy independence, provide process heat applications, and remove the need for constant fuel resupplying which saves lives and money. Microreactors are being designed to operate 24/7 for several years without shutting down which provide energy resilience and independence. Power is generated by using the heat from the microreactor, while the excess heat is removed to cool the system. The excess heat from the reactor could be used in these forward bases to desalinate water and provide heating for the bases (Nuclear Energy Institute, 2018). Also, Juan A. Vitali et al showed in a report that energy independence would be beneficial since approximately 18,700 casualties (52%) of the approximately 36,000 total US casualties over the last nine years came from land transport missions. Removing the need for constant refueling caravans can save lives. Along with saving lives, it is estimated that there is an annual fuel cost of 256 million dollars to operate the 286 annual refueling convoys (Vitali, Lamothe, Toomey, Peoples, & Mccabe, 2018; Allen, Hartford, & Merkel, 2018).

Another use of the small reactors includes being transported to natural disaster areas to provide electricity for hospitals and other emergency responders. Since the microreactors are designed to be small, transportable, and quick to set up, use in a natural disaster area could provide power quickly and efficiently to critical infrastructure. (Vitali, Lamothe, Toomey, Peoples, & Mccabe, 2018). HolosGen, a microreactor company, showed that they have a model that can be airlifted into a disaster area and quickly provide power to emergency responders, water pump and sewage stations, water purification plants, ect. This would bring needed relief to cities hit by a disaster and could prevent further damage and provide necessities to the cities (HolosGen, 2017). A rendering of the HolosGen Holos reactor is shown in Figure 1.3.

Microreactors could also be used to supply power and heat to isolated communities and mining towns where it could be difficult or expensive to transport fuels to (Charles, 2018). The use cases in these locations are similar to that of the remote military bases and forward operating bases. These units could provide power, district heating, and heat process applications like desalinization of water to these areas. This allows these communities to thrive while not being tethered to the need of fuel. HolosGen provided data for their reactor in isolated communities. They detail that many of these areas receive their power from diesel generators costing around 34.5¢/kWh or more. The price per kWh depends on the difficulty of transporting fuel to the area. HolosGen estimated that they could produce electricity under similar conditions at a cost of 5.19¢/kWh with fuel that could last years (HolosGen, 2017). The heat from the microreactor could also be used for heating in the town and for cleaning water. A rendering of a possible application for the reactors in rural or mining towns is shown in Figure 1.4.

Figure 1.2 Rendering of Westinghouse eVinci Military Transportation (Charles, 2018)

Figure 1.3 HolosGen HOLOS Microreactor Deployed for Natural Disaster Aid (HolosGen, 2017)

Figure 1.4 Modular Nuclear Microreactor Application in Rural or Mining Town (Charles, 2018)

There are a wide variety of microreactors proposed by the nuclear power industry, including sodium-cooled fast reactors, molten salt reactors, high-temperature gas reactors (HTGRs), light water reactors, and heat pipe cooled reactors. Each reactor type has unique working fluid temperatures, which in turn have a profound effect on the efficiency of the PCU to produce power and provide process heat (McKellar, Boardman, Bragg-Sitton, & Sabharwall, 2018). Some examples of companies developing modular nuclear microreactors are X-energy, HolosGen LLC, General Atomics, NuScale, MicroNuclear LLC with INL and the University of Idaho, Westinghouse with Los Alamos National Laboratory (LANL) , and Oklo (Nuclear Energy Institute, 2018).

X-energy designed the Xe-Mobile which is a high temperature gas cooled reactor. Their design uses helium to cool the reactor which produces at least 1 MW of electrical power. The Xe-Mobile is an easily transportable design contained in an ISO container (X-Energy LLC, 2020) They also developed the X-battery, which is another high temperature gas cooled reactor with a thermal rating of 10 MW_{th}. Their reactor designs are designed to be operated autonomously and are capable of providing power, heat, and to support hydrogen production (Nuclear Energy Institute, 2018).

The Holos reactor by HolosGen LLC uses subcritical nuclear fuel cartridges in their reactor. This fuel is inserted into a large metal block with cooling channels and cooled by helium or carbon dioxide. Their design is mobile and quick to begin operating. Their design is also modular which makes it possibly to create large varying power ratings. The reactor can supply 3 MW_e and up to 81 MW_e using a closed recuperated Brayton cycle with a bottoming organic Rankine cycle to generate the power (Filippone & Jordan, 2018).

General Atomics is developing a mobile nuclear power supply that can supply 4-10 MW_e. Their design is transportable through shipping containers and can be operated autonomously. They estimate that their refueling period is greater than 10 years. From General Atomics expertise in advanced military products, their nuclear power supply is high performance with a high degree of safety (Nuclear Energy Institute, 2018; General Atomics, 2018).

NuScale's microreactors is their NuScale Power Module. This unit is a light-water microreactor and has a power range of 1 to 10 MW_e. Their design estimates that their plant can operate 10 or more years without the need for refuel and also have highly automated control room as they have These units are being considered to produce power, heat, desalination, and hydrogen production for DoD facilities, towns, and industry (Nuclear Energy Institute, 2018).

MicroNuclear, INL, and the University of Idaho are developing the Molten Salt Nuclear Battery. This microreactor is described as a battery as once the operational lifetime has expired, a new unit would be inserted. This microreactor operates of natural convection like heat pipes with the reactor core installed on the inside of the unit. The reactor core is cooled by molten salt and transfers heat to the desired process. This unit will produce 10 MW_{th} and have an expected operational lifetime of ten years (MicroNuclear LLC, 2020).

Westinghouse is developing a microreactor with LANL. This is a heat pipe cooled reactor and is a solid monolith which contains many holes to hold nuclear fuel and heat pipes. LANL developed a heat pipe reactor for space exploration that is currently under development to become a microreactor with Westinghouse. The reactor is known as the eVinci microreactor. This reactor operates within the range of 600°C to 700°C and can provide between 200 kW_e to 15 MW_e. They project that their reactor can operate up to 10 years without the need for refueling or maintenance since there is little moving parts in their design. (Kennedy, et al., January 2019; McClure, Poston, Rao, & Reid, 2015; Westinghouse, 2019; Nuclear Energy Institute, 2018).

Oklo is developing the Aurora reactor which is another heat pipe cooled reactor. Their design uses little moving parts and operates on natural physical forces. The reactor is a fast reactor and is not easily transportable as their design is meant to be installed underground. They project that their microreactor can produce 1.5 MW_e and have a refueling life span of more than 20 years (Nuclear Energy Institute, 2018; U.S. NRC, 2020).

1.1.2 Power Conversion Units

Power conversion units (PCU) are how modular nuclear microreactors generate power. PCUs can be structured in many ways to produce power, while the most common types for large power generation are Brayton cycles, recuperated Brayton cycles, and Rankine cycles. Combinations of those cycles are also used to create a combined thermal cycle, which have higher thermal efficiencies (Çengel & Boles, 2011).

Thermal efficiencies are an important factor when discussing power cycles. Thermal efficiency is a measure to determine how effective the system is at producing the desired product with the given input. In terms of power cycles, it is how much electrical power is produced from the given heat input from the heat source, as shown in Equation 1.1 (Çengel & Boles, 2011). This is a common method of comparing different power cycles. It is more desirable to have a higher thermal efficiency as it means the heat addition to the system is being utilized better. Companies search for higher thermal efficiencies because the heat input is generally the cost of fuel.

$$\eta_{th} = \frac{W_{out} - W_{in}}{Q_{in}}$$

Equation 1.1

Where:

W_{out} → net work out of the system

W_{in} → net work into the system

Q_{in} → heat into the system

Temperature and entropy (T-s) diagram and a pressure and specific volume (P-ν) diagram are often used to aid in understanding of power cycles. T-s diagrams detail how the temperature and entropy change throughout the power cycle with the addition and removal of heat (q) at varying pressures. P-ν diagrams show how the pressure specific volume of the working fluid change throughout the system. These two diagrams provide the same network produced by the cycle and is represented by the area enclosed, see Figure 1.5. These diagrams are useful to show how the power cycle operates, including where heat is added or removed (Çengel & Boles, 2011).

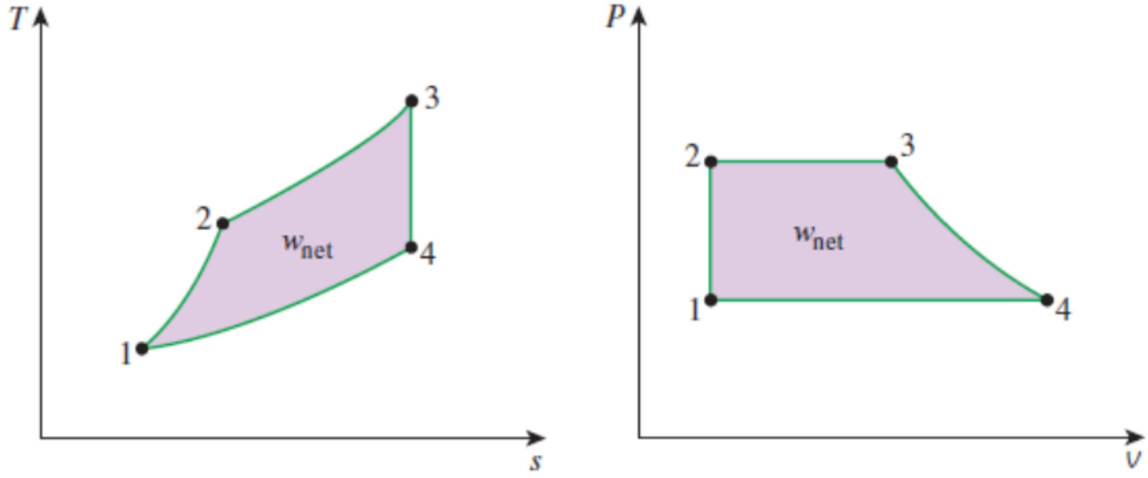


Figure 1.5 Example of a T-s and P-ν Diagram (Çengel & Boles, 2011)

Non-recuperated Brayton cycles are common power cycles to use when the working fluid is a gas. These cycles can either be "open" or "closed" which refer to the cycle either using ambient air or recirculating the same working fluid in a closed loop. In an open loop air Brayton cycle, ambient air would be drawn into the compressor and then exhausted back to the ambient air through the turbine. An example of an open air Brayton cycle is shown in Figure 1.6. This orientation is considered an open loop because the working fluid is not being recirculated throughout the system. A closed loop orientation would take the exhaust from the turbine, cool the working fluid, and then flow back into the compressor, as shown in Figure 1.7. The working fluid in a closed loop orientation could be helium (He), carbon dioxide (CO2), air, etc, since the working fluid remains within the loop. An example of the T-s and P-ν diagrams are shown in Figure 1.8.

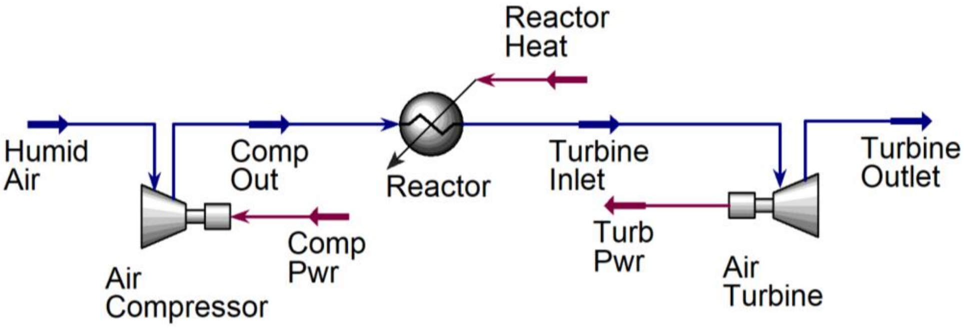


Figure 1.6 Open Air Brayton Cycle

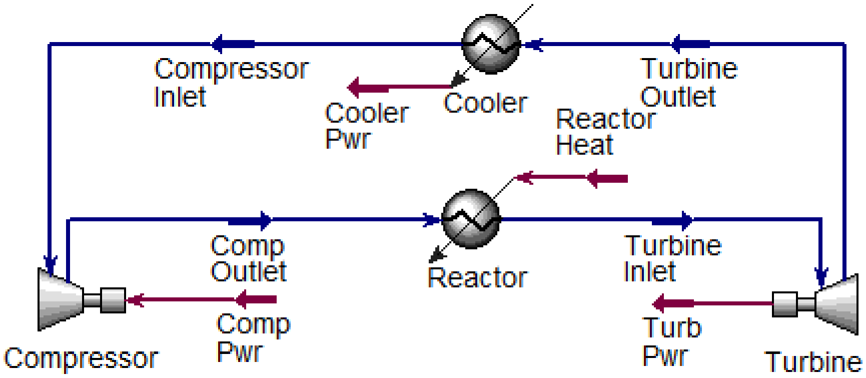


Figure 1.7 Closed Loop Brayton Cycle

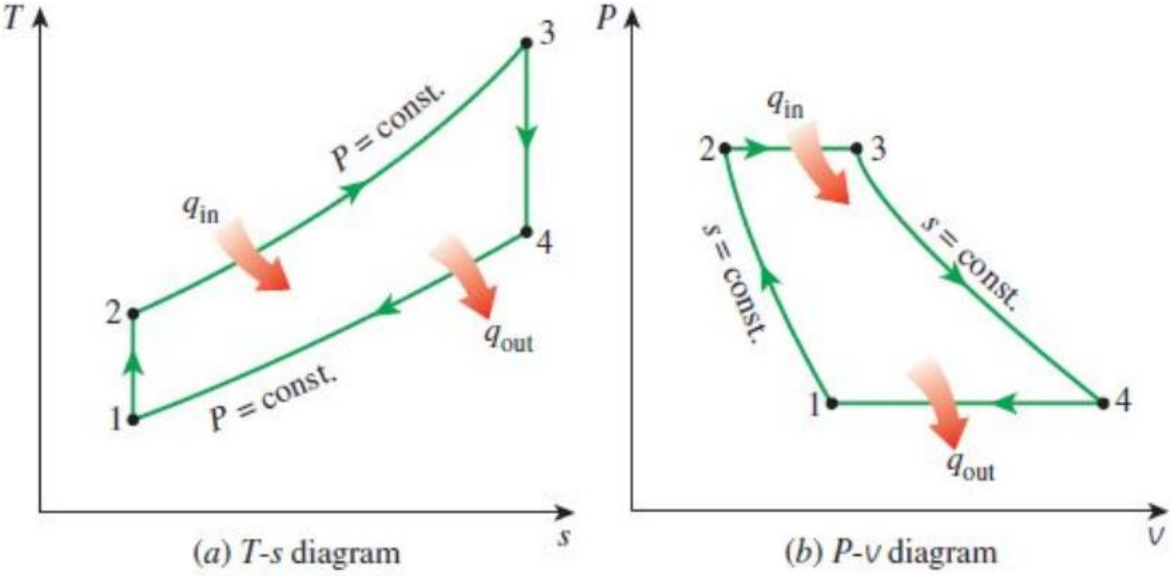


Figure 1.8 T-s and P-ν Diagrams for an Ideal Closed Loop Non-Recuperated Brayton Cycle (Çengel & Boles, 2011)

Recuperated Brayton cycles operate similarly to non-recuperated Brayton cycles, other than it operates with the addition of an intermediate heat exchanger, see Figure 1.9. In the heat exchanger, the compressor exhaust exchanges heat with the high temperature turbine exhaust. This decreases the required heat addition for the heat source and can greatly increase the thermal efficiency of the system (Çengel & Boles, 2011). For a closed loop recuperated Brayton cycle, the working fluid leaving the recuperating heat exchanger would then pass through a chiller and then flow back into the compressor. An example of a T-s diagram is shown in Figure 1.10. It is shown that recuperation increases the heat input which would lower the required heat input. This increases the thermal efficiency of this power cycle. These cycles have higher thermal efficiencies and operate at lower pressure ratios compared to their non-recuperated counter parts, as shown in Figure 1.11 where T_1/T_3 is the ratio between the lowest temperature and highest temperature in the cycle.

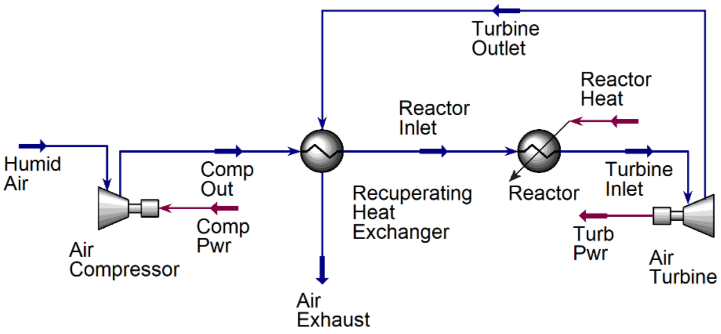


Figure 1.9 Recuperated Open Air Brayton Cycle

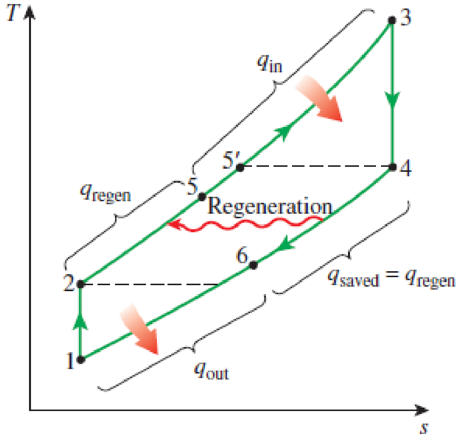


Figure 1.10 T-s Diagram of a Closed Loop Recuperated Brayton Cycle (Çengel & Boles, 2011)

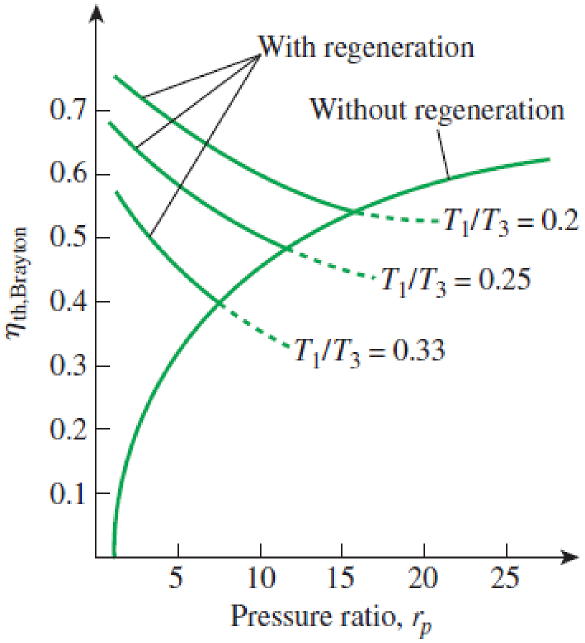


Figure 1.11 Pressure Ratios Compared Between Recuperated (Regeneration) and Non-Recuperated Brayton Cycles (Çengel & Boles, 2011)

A Rankine cycle is another possible power cycle that can be used with modular microreactors. Rankine cycles consist of four components: Gas turbine, pump, boiler, and a condenser. An example of a steam Rankine cycle is shown in Figure 1.12. This cycle is a closed loop cycle. As an example, water can be used as the working fluid for the power loop. Liquid water enters the pump and becomes pressurized. The water then passes through the boiler and vaporizes. The vapor passes through the gas turbine which converts mechanical energy into electrical energy. Once through the turbine, the water vapor passes through a condenser, condenses back into liquid water, and then reenters the pump. This process can be seen in the T-s diagram shown in Figure 1.13. The working fluids for this power loop are liquids that can vaporized. Refrigerants or other organic working fluids can also be used within this power cycle and are called Organic Rankine Cycles (ORC) (Çengel & Boles, 2011).

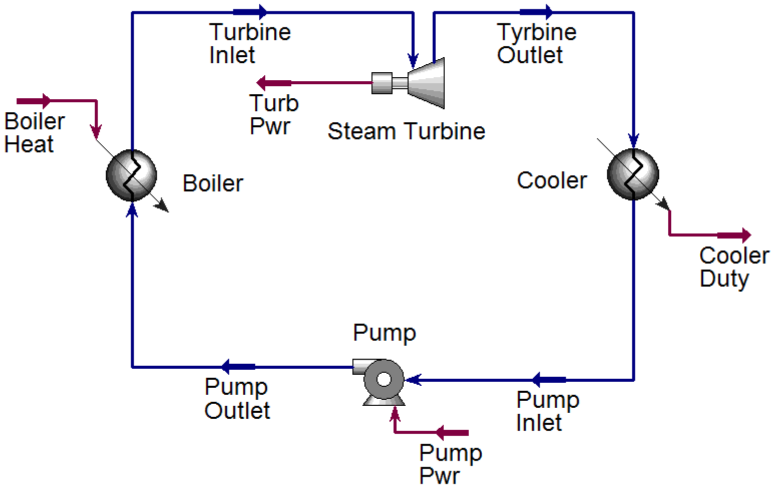


Figure 1.12 Steam Rankine Cycle

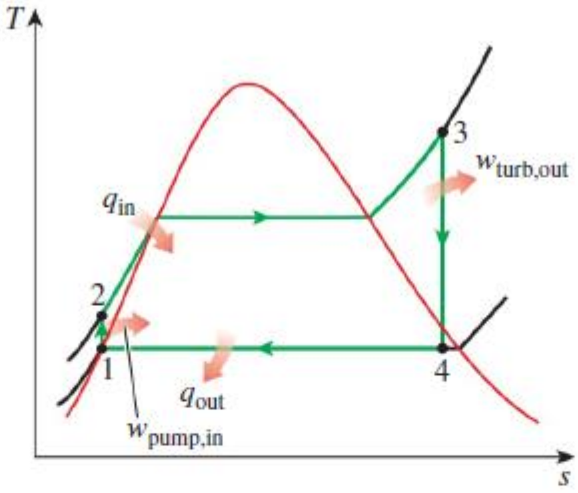


Figure 1.13 T-s Diagram for Steam Rankine Cycle (Çengel & Boles, 2011)

A common way to raise the thermal efficiency of power cycles is to create a combined cycle. Combined cycles have a main power cycle operating off the main heat source, as described above, and a secondary cycle connected to the cooler on the main cycle. The cooling section of the main power loop heats the secondary loop and then generates extra power. A common combined cycle would be a recuperated open air Brayton cycle with a bottoming steam Rankine cycle, an example is shown in Figure 1.14. The hot exhaust leaving the Brayton cycle would boil the water in the Rankine cycle. Typically, the Brayton topping cycle would use natural gas as the fuel, instead of a nuclear reactor, and have high inlet turbine temperatures. The hot air exhausted from this cycle would then boil the water in the steam Rankine cycle. A

T-s diagram of an open air Brayton cycle topping cycle with a bottoming steam Rankine cycle is shown in Figure 1.15. The state point numbers correlate with the state points in Figure 1.14. It is observed that the exhaust heat from the gas cycle heat provides the required heat for the steam cycle (Çengel & Boles, 2011). An example of an increase in thermal efficiencies from combined cycles is shown in a recent scoping study by Idaho National Laboratory (INL) and the University of Idaho (UI). They have shown that for a microreactor operating on a recuperated open air Brayton cycle with a reactor outlet temperature of 650°C (heat pipe or molten salt reactor), the thermal efficiency can increase from 36% to 40% with the addition of an ORC attached to a recuperated air Brayton cycle (Litrel, Guillen, & McKellar, 2018).

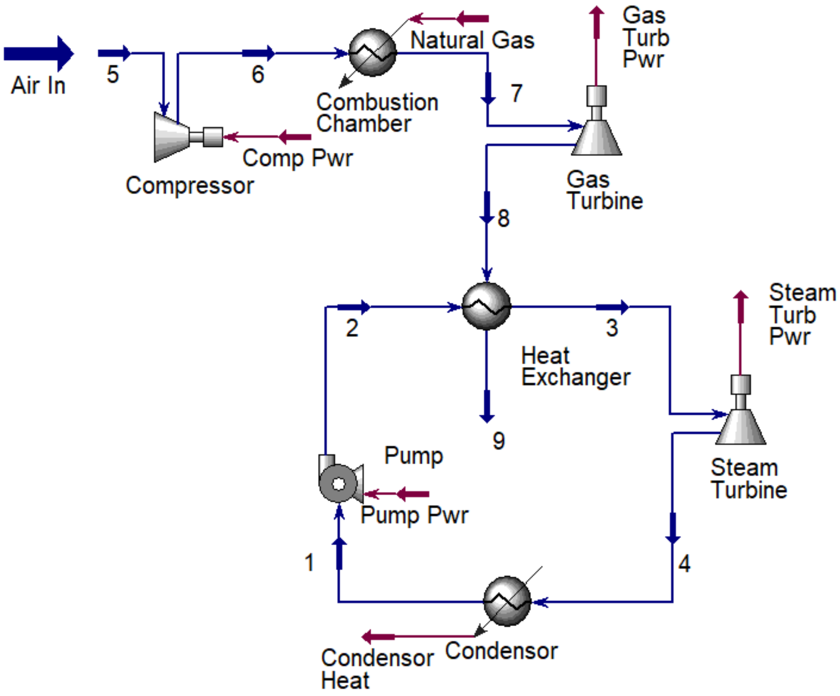


Figure 1.14 Combined Open Air Brayton Cycle with Bottoming Steam Rankine Cycle

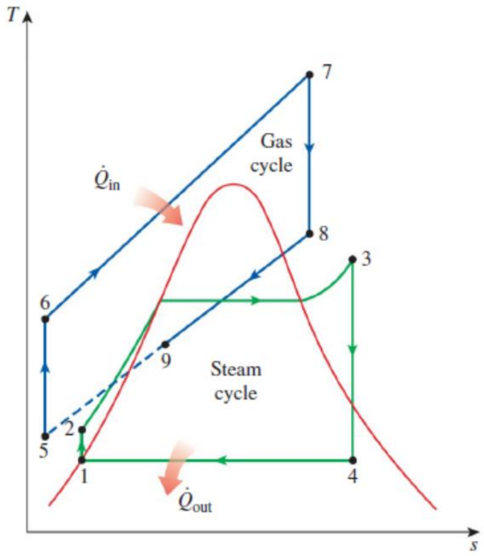


Figure 1.15 T-s Diagram for Combine Open Air Brayton Cycle with Bottoming Steam Rankine Cycle (Çengel & Boles, 2011)

1.2 Scope of Work

The new class of modular nuclear microreactors are largely untested and unproven. Thus, to aid in the development of the new class of modular nuclear microreactors, INL is developing the Microreactor AGile Non-nuclear Experimental Testbed (MAGNET) which will allow for the testing of various nuclear reactor types under safe conditions. The reactor types will be tested using electrically heated cartridges to mimic the heat produced from nuclear fission. This makes testing the reactor types safe from radiation and the article can be tested in steady state conditions, off design conditions, and safely tested to failure (Guillen, et al., 2019). Aspen HYSYS (Aspen Technology, Inc., 2016) has been used to develop the MAGNET and aid in its development. Aspen HYSYS models have been created for the MAGNET as well as PCU and a PCU simulator.

1.3 Thesis Outline

The course of discussion throughout this report begins in Chapter 2 with the development of the MAGNET Aspen HYSYS models. This entails detailed components and various process parameters at normal operations as well as off design conditions. Chapter 3 begins the Aspen HYSYS development of a physical PCU attached to the MAGNET as well as the development of a PCU simulator. The final chapter, Chapter 4, details the analysis of a simple Brayton cycle start up for off design simulations in the PCU simulator.

Chapter 2: Microreactor AGile Non-nuclear Experimental Testbed

2.1 Introduction

Experimental work will be performed at INL at the Microreactor AGile Non-nuclear Experimental Testbed (MAGNET) shown in Figure 2.1. The purpose of the MAGNET is to assists with the development, demonstration, and validation of microreactor components and systems. It will aid in moving the microreactor technology further by reducing the uncertainty and risk relative to the operation and deployment of these units. The MAGNET is being designed such that the systems and components can be safely tested in steady state operations, off design conditions, and to failure points. This will provide valuable information on failure mechanisms and limits. A goal of the MAGNET is to be diverse enough to test multiple microreactor concepts. The first test article the MAGNET is being designed for is a heat pipe cooled reactor prototype (Guillen, et al., 2019).

The MAGNET has the following specifications operating with a heat pipe cooled reactor (Guillen, et al., 2019):

- Power: nominal 250 kWth.
- Heat pipe working fluid: Sodium.
- Heat pipe operating temperature: 650°C.
- Heat pipes are cooled with a closed nitrogen or helium loop.
- Experiments may require up to 300 hours of continuous testing.
- Horizontally oriented heat pipes.

Aspen HYSYS v. 9 from AspenTech© (Aspen Technology, Inc., 2016) has been used to help aid in the development of the MAGNET. Aspen HYSYS is a chemical thermo-process modeling program that simulates process conditions throughout systems. Aspen HYSYS models of the MAGNET have been designed to estimate the process conditions throughout the testbed.

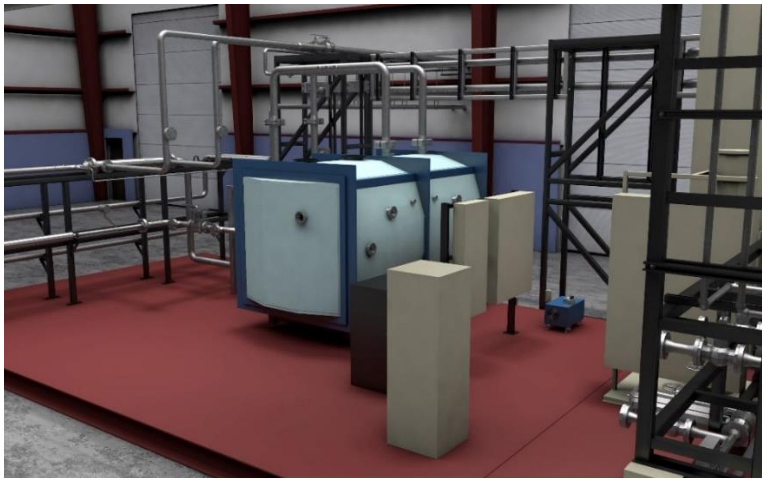


Figure 2.1 Rendering of the INL MAGNET Facility Design

2.2 MAGNET Aspen HYSYS Model Development with 250 kW of Heat Pipe Power

A process flow diagram of the INL MAGNET facility is shown in Figure 2.2 (O'Brien, 2019). The current testbed was designed to operate with a maximum gas coolant temperature of 600°C and a maximum design pressure of 2200 kPa. The working fluid within the loop will be either nitrogen or helium, depending on the tests. Aspen-HYSYS was utilized to create a process model for the test loop and is shown in Figure 2.3 with its accompanying process data sheet in Table 2.1. The process model estimates the pressure losses in the equipment and heat losses in the piping. Modeling approximations for the equipment found in the MAGNET have been made based on data sheets and assumptions which are described later in this chapter. The temperature and pressure values shown in the INL process diagram, Figure 2.2, and the Aspen HYSYS model, Figure 2.3, match closely.

The process data was based on a 250-kW heat pipe reactor with 600ºC exit temperature from the vacuum chamber. There are two similar models, one using nitrogen as the working fluid and the other using helium. Both models assume the same conditions but use different fluids. The process conditions and flow sheets for both the nitrogen and the helium models are found in Appendix A for comparison. The models and figures shown throughout the chapter are the nitrogen cycles unless specified otherwise. The conditions surrounding the heat exchangers were set as close as possible to the information found in their respective data sheets, found in Appendix E and Appendix F.

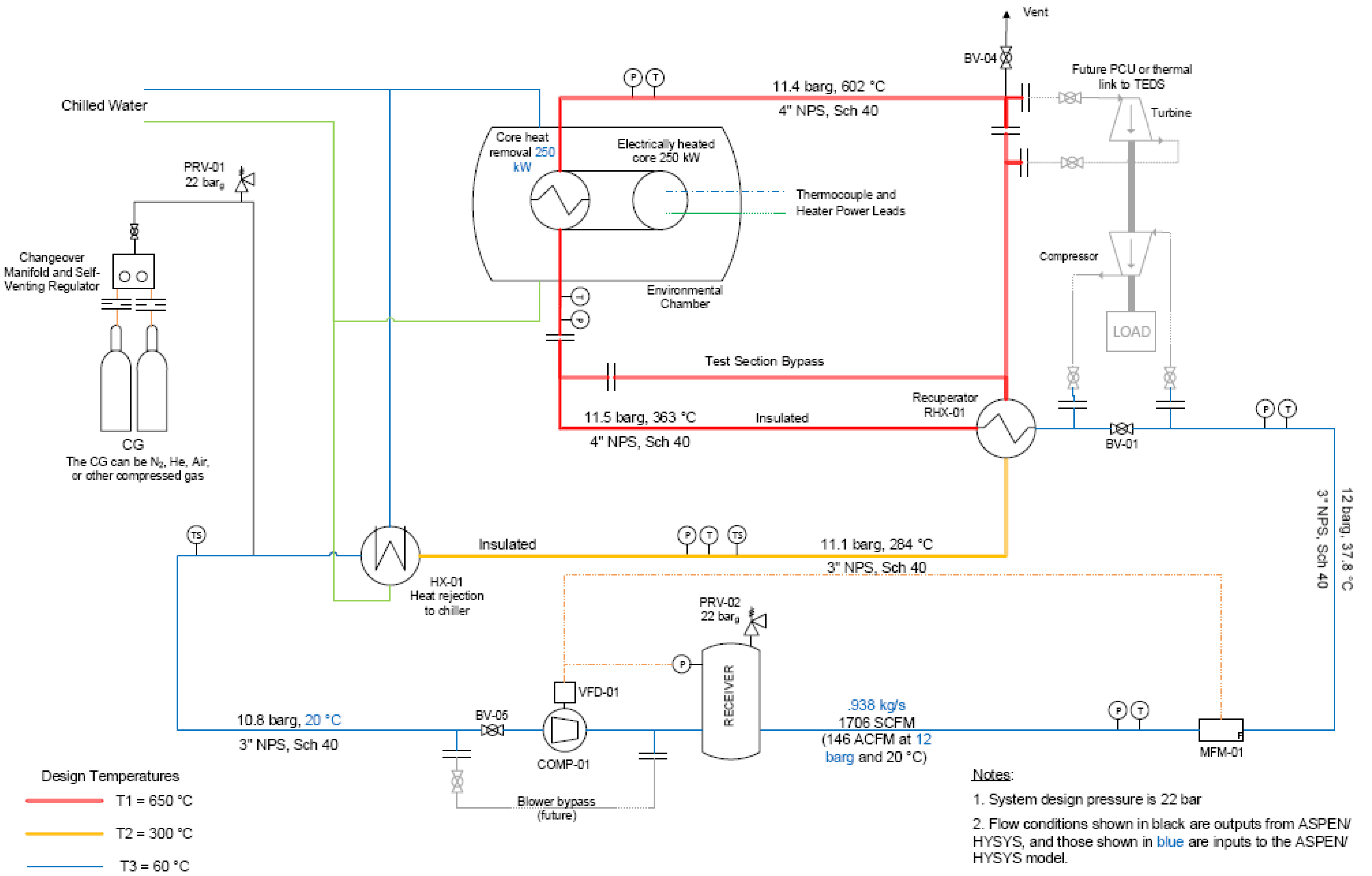


Figure 2.2 Nitrogen Process flow diagram of INL's Microreactor AGile Non-nuclear Experimental Testbed (O'Brien, 2019)

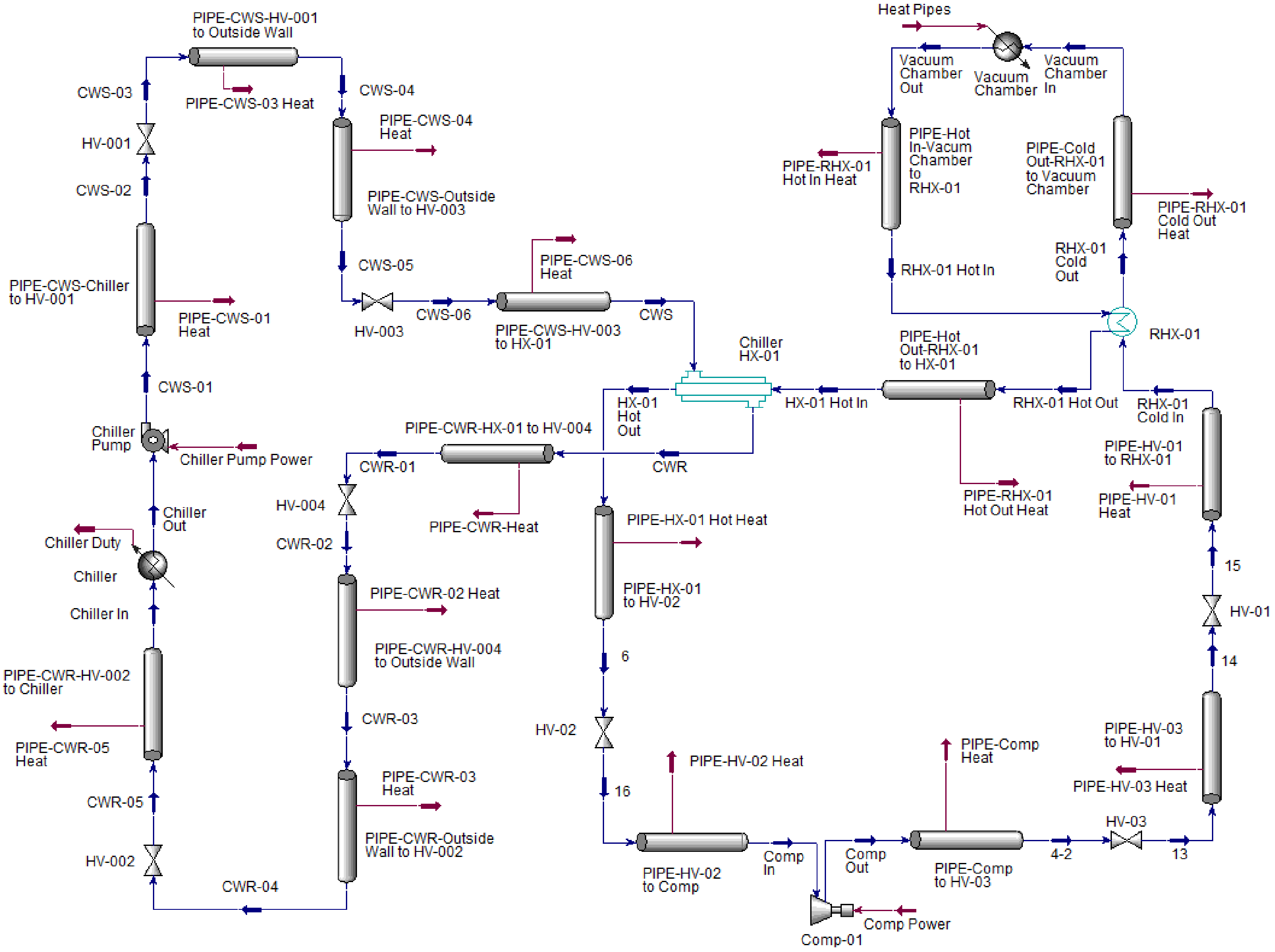


Figure 2.3 Aspen HYSYS Process Model of 250 kW Nitrogen Microreactor AGile Non-nuclear Experimental Testbed

Table 2.1 Aspen HYSYS Process Model of 250 kW Nitrogen Microreactor AGile Non-Nuclear Experimental Testbed Process Conditions

	Material Streams				
	HX-01 Hot In	**CWR**	**CWS**	**HX-01 Hot Out**	**RHX-01 Cold In**
Temperature (°C)	283.15	17.78	6.67	20.00	32.95
Pressure (kPa)	1222.01	473.89	500.01	1210.68	1285.14
Mass Flow (kg/s)	0.92	6.76	6.76	0.92	0.92
	RHX-01 Cold Out	**Vacuum Chamber In**	**6**	**Chiller In**	**Chiller Out**
Temperature (°C)	358.75	358.07	19.97	17.78	6.66
Pressure (kPa)	1274.36	1272.00	1194.00	483.36	473.69
Mass Flow (kg/s)	0.92	0.92	0.92	6.76	6.76
	CWS-04	**CWR-01**	**CWR-05**	**CWS-02**	**15**
Temperature (°C)	6.66	17.78	17.78	6.66	32.95
Pressure (kPa)	485.46	451.51	483.52	520.19	1286.02
Mass Flow (kg/s)	6.76	6.76	6.76	6.76	0.92
	16	**Comp Out**	**4-2**	**RHX Hot Avg**	**RHX Cold Avg**
Temperature (°C)	19.97	33.14	33.07	440.94	195.85
Pressure (kPa)	1193.41	1326.67	1302.91	1232.14	1279.75
Mass Flow (kg/s)	0.92	0.92	0.92	1.00	1.00
	2	**Vacuum Chamber Out**	**RHX-01 Hot In**	**RHX-01 Hot Out**	**Comp In**
Temperature (°C)	6.65	600.00	598.47	283.42	19.94
Pressure (kPa)	520.39	1246.93	1241.33	1222.96	1180.88
Mass Flow (kg/s)	6.76	0.92	0.92	0.92	0.92
	CWS-03	**CWS-06**	**13**	**14**	**CWR-02**
Temperature (°C)	6.66	6.67	33.07	32.95	17.78
Pressure (kPa)	519.99	484.84	1302.35	1286.59	451.31
Mass Flow (kg/s)	6.76	6.76	0.92	0.92	6.76
	CWR-03	**CWR-04**	**CWS-05**		
Temperature (°C)	17.78	17.78	6.67		
Pressure (kPa)	450.90	483.72	485.03		
Mass Flow (kg/s)	6.76	6.76	6.76		
	Energy Streams				
	Heat Pipes	**PIPE-RHX-01 Cold Out Heat**	**PIPE-RHX-01 Hot In Heat**	**PIPE-RHX-01 Hot Out Heat**	**PIPE-HV-03 Heat**
Heat Flow (MW)	2.50E-01	6.88E-04	1.62E-03	2.64E-04	7.91E-05

	PIPE-HX-01 Hot Heat	**PIPE-HV-02 Heat**	**Comp Power**	**Chiller Duty**	**PIPE-CWS-06 Heat**
Heat Flow (MW)	-6.77E-06	-6.67E-07	1.25E-02	2.60E-01	-5.76E-06
	PIPE-CWS-03 Heat	**PIPE-CWR-Heat**	**PIPE-CWR-05 Heat**	**PIPE-CWS-01 Heat**	**PIPE-HV-01 Heat**
Heat Flow (MW)	-2.03E-05	-7.01E-06	-2.42E-06	-1.03E-05	5.91E-06
	PIPE-Comp Heat	**Chiller Pump Power**	**PIPE-CWR-02 Heat**	**PIPE-CWR-03 Heat**	**PIPE-CWS-04 Heat**
Heat Flow (MW)	9.53E-06	3.91E-04	-6.12E-06	-4.83E-06	-2.61E-05

	Heat Exchangers	
	RHX-01	**Chiller HX-01**
Duty (MW)	0.324	0.260
LMTD (°C)	245.17	84.80
UA (W/°C)	1320.68	3065.07
Minimum Approach (°C)	239.72	13.33

2.2.1 MAGNET Piping and Valves

The MAGNET model is used to estimate the expected conditions of the testbed. This detailed model incorporates the piping and fittings found within the system. The piping components model the length of the pipe, the pipe size, the pipe insulation, pipe fittings, and the change in height for each pipe segment. The piping data was obtained from INL documentation and AutoCAD *.dwg files detailing exact pipe lengths and elevation changes. The pipe segment lengths, heights, and fittings were constructed as described in Aspen HYSYS Operations Guide. An example of the configuration is shown in Figure 2.4. The reference height for all the pipes is 10 inches from the ground, as that is the height of the skid the MAGNET is mounted on.

Each pipe segment includes all the piping and fittings between the components in their names. For example, “Pipe-CWS-HV-003 to HX-01” is the cold-water service pipeline from the valve HV-003 to chiller HX-01. It includes the piping, lengths, elevation changes, and the fittings. Figure 2.5 shows the first 5 elements out of the 14 total elements for “Pipe-CWS-HV-003 to HX-01.” These elements represent different pipe fittings: such as pipes, reducers, tees, and elbows. Pipe unions were also modeled as piping with an equivalent length to approximate the correct pressure drop. These elements are used to calculate the pressure loss due to friction and minor losses throughout the piping section.

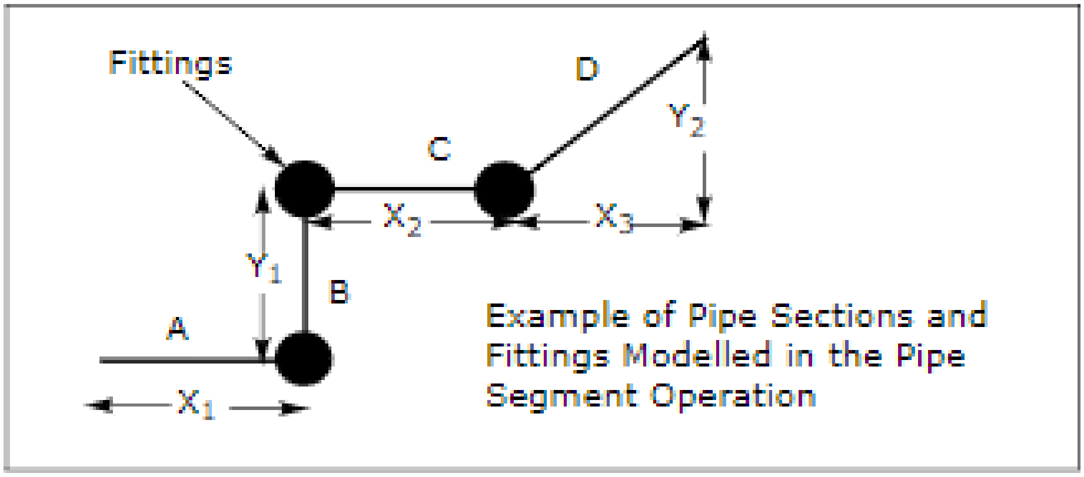
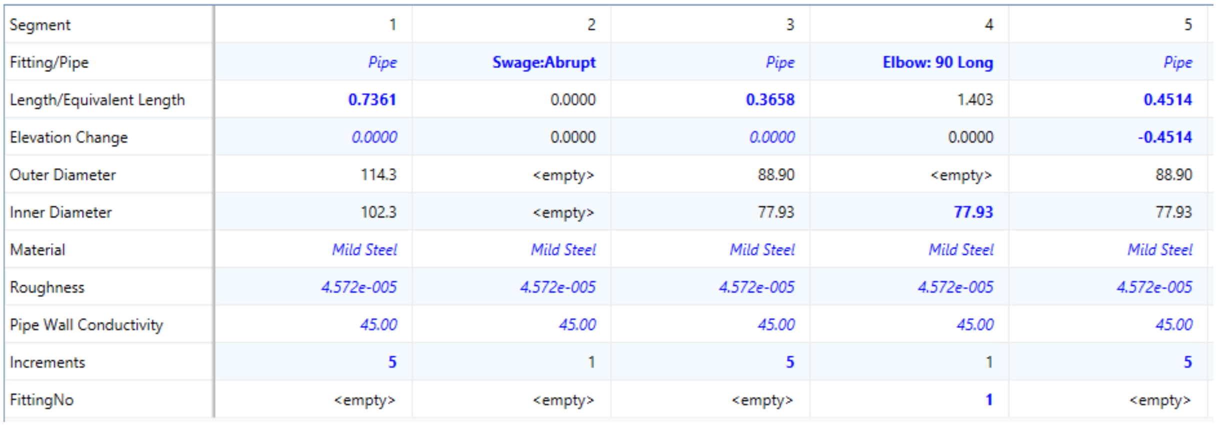


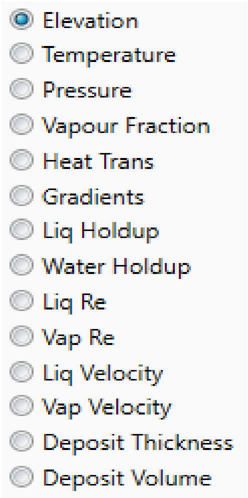
Figure 2.4 AspenTech HYSYS Operations Guide for Pipe Sections (Aspen Technology, 2005)



Segment	1	2	3	4	5
Fitting/Pipe	*Pipe*	**Swage:Abrupt**	*Pipe*	**Elbow: 90 Long**	*Pipe*
Length/Equivalent Length	**0.7361**	0.0000	**0.3658**	1.403	**0.4514**
Elevation Change	*0.0000*	0.0000	*0.0000*	0.0000	**-0.4514**
Outer Diameter	114.3	<empty>	88.90	<empty>	88.90
Inner Diameter	102.3	<empty>	77.93	**77.93**	77.93
Material	*Mild Steel*	*Mild Steel*	*Mild Steel*	*Mild Steel*	*Mild Steel*
Roughness	*4.572e-005*	*4.572e-005*	*4.572e-005*	*4.572e-005*	*4.572e-005*
Pipe Wall Conductivity	*45.00*	*45.00*	*45.00*	*45.00*	*45.00*
Increments	**5**	1	**5**	1	**5**
FittingNo	<empty>	<empty>	<empty>	**1**	<empty>

Figure 2.5 Pipe-CWS-HV-003 to HX-01 Piping Elements

Various data can be obtained for each pipe segment found within the Aspen HYSYS model. Examples of the information that can be gathered from the pipe segments are shown in Figure 2.6. This information can be turned into useful plots and broken down across the length of the pipe segment. This allows for graphical representations to determine the effects of fittings, pipe length, and elevation change. Using the pipe segment "Pipe-CWS-HV-003 to HX-01," the same as above, the elevation change and pressure in the pipe have been plotted and shown in Figure 2.7. The pressure is shown to decrease across the pipe segment from the CWS 4-inch Ball Valve and 4-inch to 3-inch reducer. The pressure makes a sharp drop at the reducer, around 1.1 m along the length of the pipe, then decreases to the elbow. The pressure is shown to increase between ~1.1 m to ~3 m along the length of the pipe due to a decrease in elevation. After this change, the pipe is then kept at a constant elevation and the pressure gradually drops. The piping modeled only incorporates vertical or horizontal piping and the profile is shown in Figure 2.8. It should be noted that the pipe length is slightly longer than physically present due to the estimation of the union pressure drops using equivalent pipe lengths. It should also be noted that the fluid being used for the chilled water loop is EG50, which is a water and ethylene glycol mixture. The mass composition used is about 55% of water to 45% of ethylene glycol. The percentages were determined to match the given properties from the chiller HX-01 data sheet supplied by the manufacturer.



● Elevation
○ Temperature
○ Pressure
○ Vapour Fraction
○ Heat Trans
○ Gradients
○ Liq Holdup
○ Water Holdup
○ Liq Re
○ Vap Re
○ Liq Velocity
○ Vap Velocity
○ Deposit Thickness
○ Deposit Volume

Figure 2.6 Pipe Segment Information

Figure 2.9 shows similar plots for the pipe "Pipe-HV-03 to HV-01" which has a working fluid of pure nitrogen. This pipe segment has 32 different piping elements. Figure 2.10 shows the pressure and elevation changes compared to the total pipe length of the MAGNET. The graph starts at the exhaust of the compressor and terminates at the inlet to the compressor.

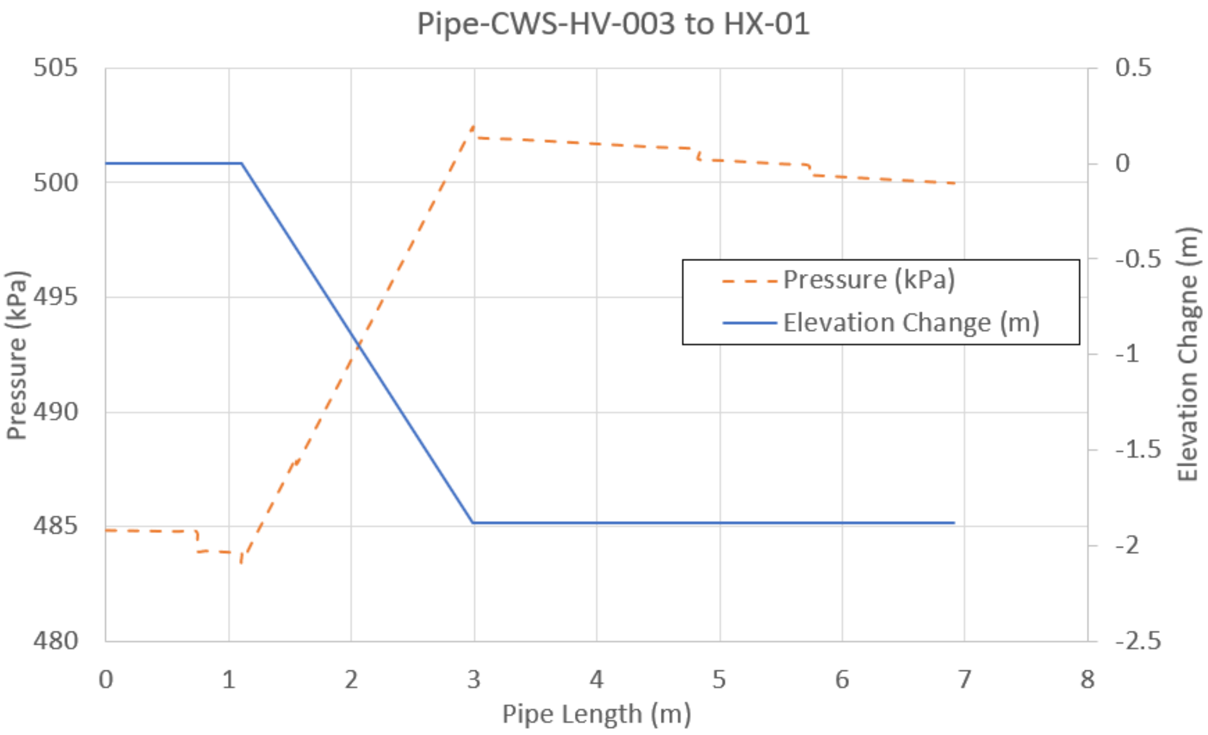


Figure 2.7 Pipe-CWS-HV-003 to HX-01 Elevation and Pressure Verse Pipe Length Plot

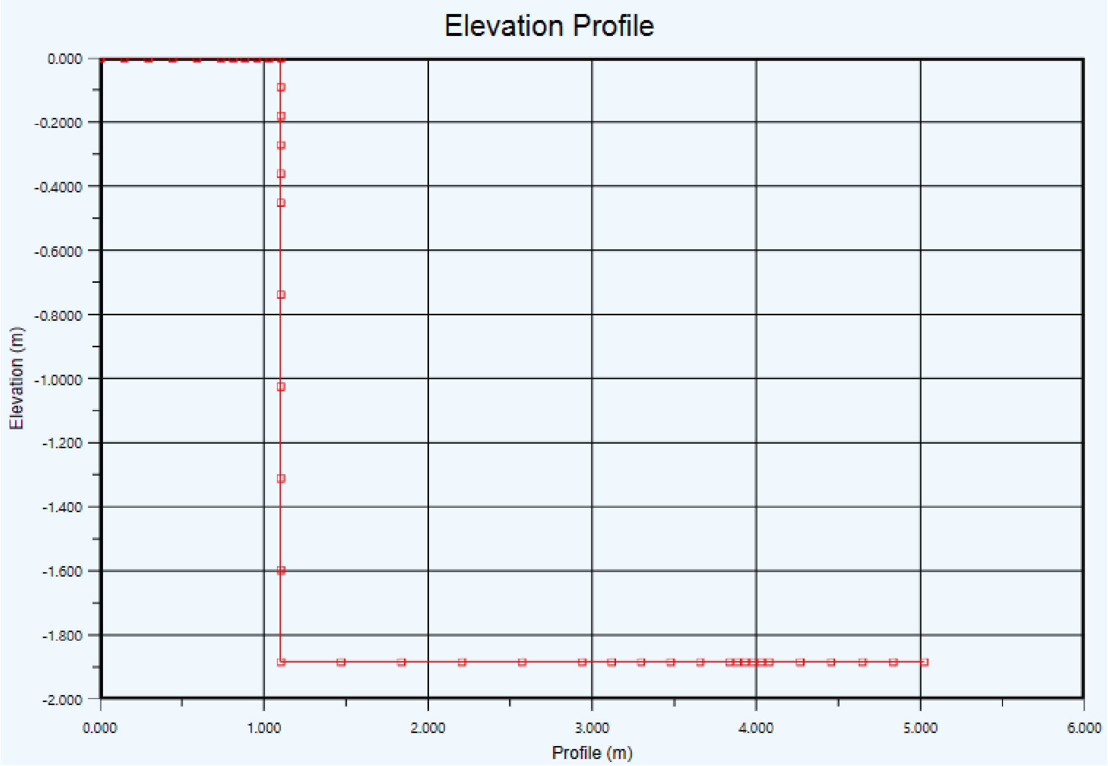


Figure 2.8 Pipe-CWS-HV-003 to HX-01 Elevation Profile

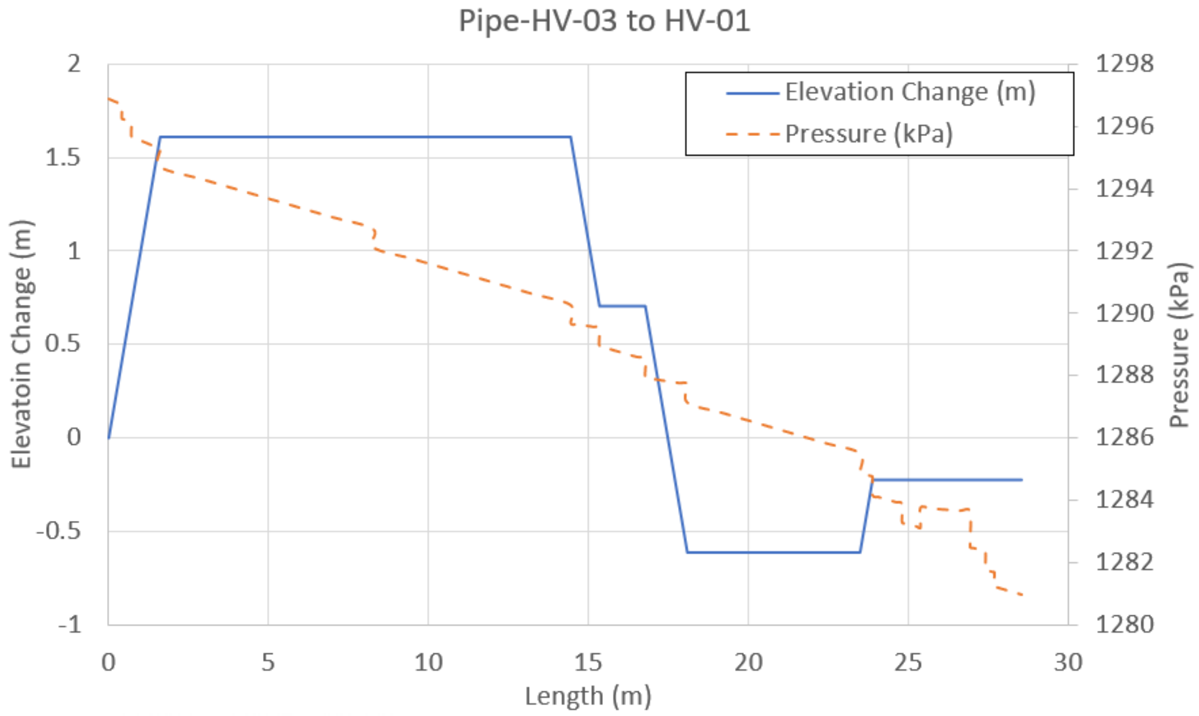


Figure 2.9 Pipe-HV-03 to HV-01 Elevation and Pressure Verse Pipe Length Plot

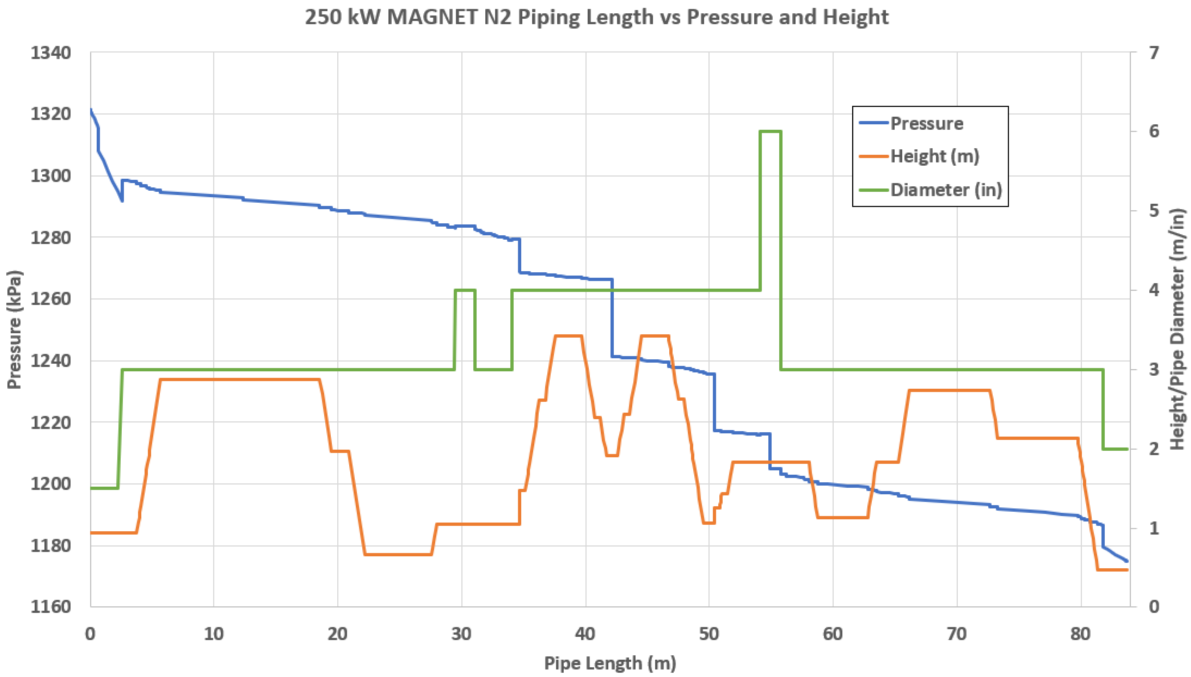


Figure 2.10 MAGNET Piping Pressure Drop and Height Profile using Nitrogen at 250 kW of Heat Pipe Power

The valving is located between the physical pipe segments in the MAGNET. The valves are all isolation valves of varying sizes and will either be fully opened or fully closed during operation. Aspen HYSYS calculated the pressure drop across the valves using the Cv supplied by the manufacturer. The gas valves are three-inch valves and the chilled water valves are four-inch valves. The Cv values used are shown in Table 2.2. The pressure drop varies for each Aspen HYSYS model depending on flow rates and fluid conditions.

Table 2.2 Valve Flow Coefficients (Keckley Company)

Valve Flow Coefficients					
Size	C_v	Size	C_v	Size	C_v
1-1/2"	100	2-1/2"	285	4"	610
2"	145	3"	425	6"	920

The MAGNET is using Thermo 1200 for the piping insulation and is four inches thick. The insulation was assumed to be placed on all pipe segments. To accurately describe the pipe segments, the thermal conductivity of the insulation was considered for each pipe segment. According to the manufacturer, the thermal conductivity of the insulation is dependent on the mean temperature (Johns Manville, 2019). The manufacture's insulation information is shown in Appendix D. The mean insulation temperature was based on the average of the pipe inlet and outlet temperatures of the working fluid and the ambient temperature. The ambient air temperature surrounding the piping is assumed to be 21.11°C for all piping, both the indoors and outdoors. The MAGNET gas piping has an insulation thickness of 4 inches. The chilled water piping uses a different type of insulation with a thickness of 1.5 inches. An example of the inlet temperature, outlet temperature, mean temperature, and thermal conductivity for the nitrogen loop with the heat pipes operating at 250 kW are shown in Table 2.3. The thermal conductivity values vary for each model as the inlet temperatures differ due to the working fluid and heat pipe power load. The insulation's thermal conductivity for the chilled water loop was also adjusted for each model. The exact values for the thermal conductivities of the insulation can be seen in Appendix A through Appendix C under the Piping Segments section in the tables.

Aspen HYSYS also estimates the outside heat transfer coefficient surrounding the piping using the ambient temperature and the airflow across the pipes. The ambient air temperature is the same as above, 21.11°C, and the airflow is assumed to be 1 ft/sec (0.31 m/s). Both the ambient temperature and the airflow across the pipes can easily be adjusted. The airflow was estimated for the conditions found in the testing facility and the velocity is within the expected air speed range for thermal comfort, as shown in Figure 2.11. This figure was created from the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 55 parameters (Jenkins, 2019).

Table 2.3 Piping Thermal Conductivity Values

	Pipe Inlet Temperature (°C)	Pipe Outlet Temperature (°C)	Average Pipe Temperature (°C)	Mean Temperature (°C)	Thermal Conductivity (W/m°C)
RHX-01 Hot in Piping	600	598.5	599.2	310	0.0844
RHX-01 Hot out Piping	283.5	283.2	283.3	152	0.0635
RHX-01 Cold in Piping	33.06	33.05	33.05	27	0.0486
RHX-01 Cold out Piping	358.8	358.1	358.5	190	0.0683

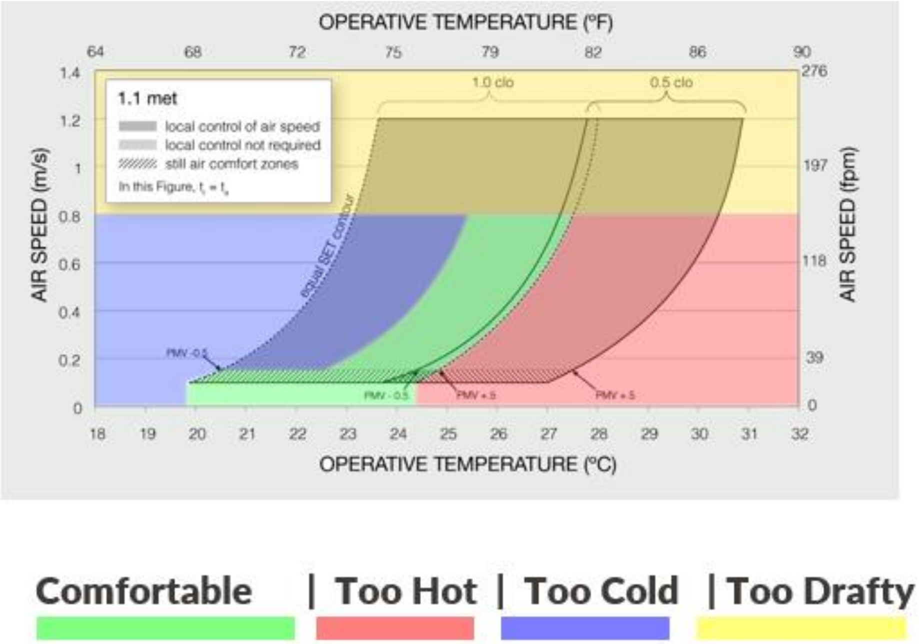


Figure 2.11 Thermal Comfort Chart using ASHRAE 55 Parameters (Jenkins, 2019)

2.2.2 Heat Exchangers

2.2.2.1 Recuperating Heat Exchanger

A recuperating heat exchanger is in the design of the MAGNET. These types of heat exchangers are generally used to preheat the working fluid before entering the process. Preheating the gas reduces the required heat addition to the working fluid from the heater. It can also increase the mass flow rate of the system at a constant heat load which can increase production (Çengel & Boles, 2011). The recuperating heat exchanger used in the MAGNET is a printed circuit heat exchanger (PCHE) and is used to preheat the gas before it enters the vacuum chamber containing the heat pipes. This lowers the electrical energy used to power the electric heaters to activate the heat pipes. INL specified the desired process conditions of the recuperating heat exchanger, shown in Table 2.4.

Table 2.4 MAGNET Recuperating Heat Exchanger Design Conditions

	Cold Side Parameters	Hot Side Parameters
Mass Flow Rate	0.938 kg/s	0.938 kg/s
Nominal Inlet Pressure	12 bar_g	10.625 bar_g
Nominal Pressure Difference	0.375 bar_g	0.375 bar_g
Nominal T_{in}	38 °C	600 °C
Nominal T_{out}	360 °C	290 °C

An approximation for the MAGNET recuperated heat exchanger was modeled in Aspen HYSYS to approximate its performance in the Aspen HYSYS models. This allowed the recuperating heat exchanger to be operated at off design conditions, where the design conditions are nitrogen at 250 kW of heat pipe power. The heat transfer and pressure drop correlations were found in the Physical Model Development and Optimal Design of PCHE for Intermediate Heat Exchangers in HTGRs (Kim & No, 2012). The correlations shown in Kim and No’s paper for pressure drop are shown in Equation 2.1 and Equation 2.2. Their Nusselt number correlation is shown in Equation 2.3. They did not include the Prandtl number in their correlations and their justification was that the Prandtl numbers remained nearly constant. In the MAGNET models for both helium and nitrogen, the Prandtl numbers also remain nearly constant. The model may be a better approximation for helium compared to nitrogen as there is little variation in the helium Prandtl number. The Prandtl numbers are shown in Table 2.5. The “Hot Avg” and “Cold

Avg" Prandtl numbers are based off the average temperature across the heat exchanger, not the averages of the Prandtl numbers.

$$f \cdot Re = 15.78 + a \cdot Re^{b}$$

Equation 2.1

$$f = \frac{\triangle P \, D_h}{2 L_p \rho v^2}$$

Equation 2.2

$$Nu = 4.089 + c \cdot Re^{d}$$

Equation 2.3

Where: f → Fanning Factor
Re → Reynolds Number
Nu → Nusselt Number
$\triangle P$ → Pressure Drop
D_h → Hydraulic Diameter
L_p → Actual Channel Length in a Pitch
v → Velocity
ρ → Fluid Density
a, b, c, d → Fitting Constants for Geometry

a	b	c	d
0.009126	0.9913	0.001255	1.058

NOTE: a, b, c, and d were interpolated between the listed values

Table 2.5 Recuperating Heat Exchanger Prandtl Number Comparison

Recuperating Heat Exchanger Prandtl Number Comparison						
	Hot In	Hot Out	Hot Avg	Cold In	Cold Out	Cold Avg
Pr (N2)	0.8112	0.7469	0.7747	0.7461	0.7584	0.7395
Pr (He)	0.6722	0.6729	0.6728	0.6714	0.6727	0.6729

A PCHE was sized and designed to meet the conditions set by INL by following Kim and No's approach. This heat exchanger approximates how the MAGNET PCHE could perform.

The manufacture has not provided details on the performance or internal structure for a more accurate model. However, this is a good approximation and starting point for the heat exchanger. The design was set to match Kim and No's heat exchanger found in their report. They assumed that the flow channels are half circles and are counter current that are oriented parallel to each other, but the channels could be zig-zagged, as shown in Figure 2.12. The physical dimensions of the recuperating heat exchanger were approximated to fit within the manifold manufacturing drawings, shown in Appendix E. With the estimated outer dimensions, the PCHE was designed in Dassault SolidWorks to develop a reasonable sized PCHE with an appropriate plate count, channel count, channel size, channel angle, and heat transfer surface area. This ensured a design that could physically be made. The parameters were adjusted to match the UA from the MAGNET design specifications, which was approximately 1332 W/^{o}C. The overall heat transfer coefficient (U) was found using the correlation found in Equation 2.3, which produced a distinct heat transfer area (A). The flow channel parameters and number of plates were adjusted to match the needed U and A. The found area was held constant for every Aspen HYSYS model. The exit temperatures were also adjusted to match the calculated UA from the known U and A from the correlation. The resulting heat exchanger design is shown in Figure 2.13. The accompanying table detailing the internal structure of the heat exchanger is shown in Table 2.6. It should be noted, again, that this could approximate the MAGNET recuperating heat exchanger and is not the exact heat exchanger being supplied.

The advantage of having a designed heat exchanger in the model is that it can simulate results when off design conditions are used. The recuperated heat exchanger design functions from an imbedded spread sheet found within Aspen HYSYS. The process variables are adjusted to match the heat exchanger's UA and pressure drop calculated in the spread sheet. The heat transfer area remains constant and the overall heat transfer coefficient and pressure drops are calculated using the correlations. A comparison between the inlet and outlet conditions using helium and nitrogen compared to the MAGNET design conditions are shown in Table 2.7. From the table, the nitrogen cycle matches closely to the MAGNET design conditions. The text in red shows the difference in the temperatures coming out of the heat exchanger. The nitrogen and helium temperatures vary greatly from each other, but it is also seen that the nitrogen has a much larger mass flow rate.

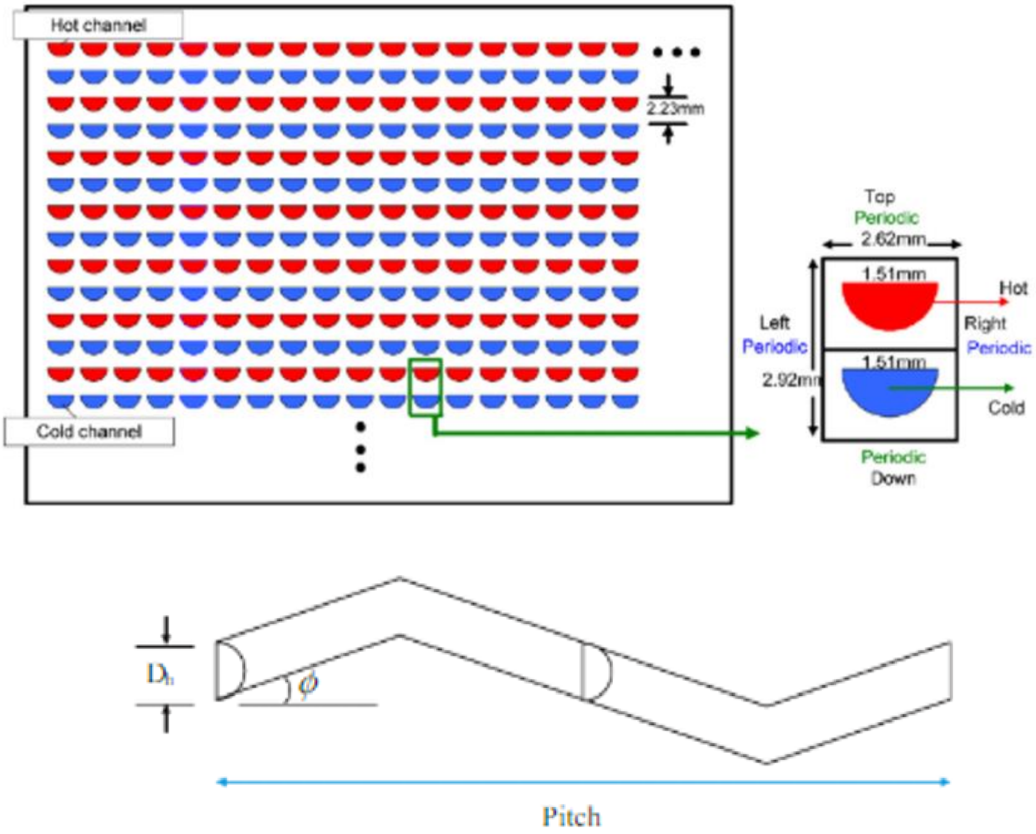


Figure 2.12 Kim and No’s PCHE Design (Kim & No, 2012)

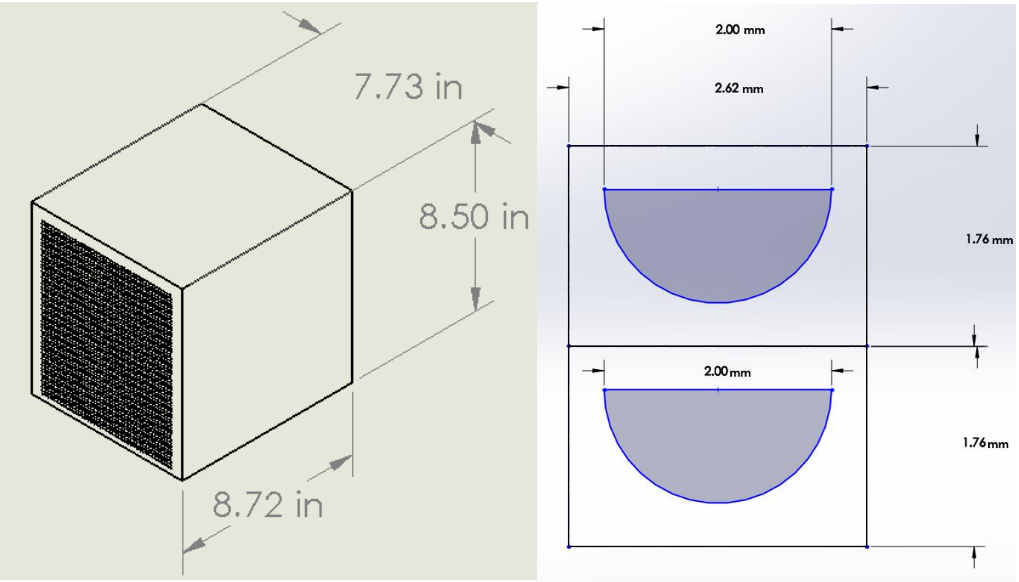


Figure 2.13 MAGNET Recuperating Heat Exchanger Design

Table 2.6 MAGNET Recuperating Heat Exchanger Interal Parameters

Recuperating Heat Exchanger Internal Parameters		
Diameter (D)	2.00 mm	0.002 m
Hydraulic Diameter (Dh)	1.22 mm	0.00122 m
Pitch (P)	24.60 mm	0.0246 m
Theta (Degrees)	6.43	
Theta (Rad)	0.112	
Length per Pitch (Lp)	24.76 mm	0.02476 m
Flow Area per Channel (Af)	1.571 mm^2	1.57 E-6 m^2
Channels per Sheet	65	
Number of Sheets	112	
Number of Pitches	9	
Af for Cold Channel	5.718 E-3 m^2	
Af for Hot Channel	5.718 E-3 m^2	
Perimeter	5.142 E-3 m	
Surface Area per Pitch (As)	1.273 E-4 m^2	
As Cold per Channel	1.146 E-3 m^2	
As Hot per Channel	1.146 E-3 m^2	
Total As Cold	4.170 m^2	
Total As Hot	4.170 m^2	

Table 2.7 Recuperating Heat Exchanger Performance Comparison at 250 kW of Heat Pipe Power

RHX-01 Comparison at 250 kW Heat Pipe Power			
	Nitrogen	Helium	MAGNET Design
Temperature [°C]			
Hot In	598.5	598.9	600
Hot Out	283.5	208.5	~290
Cold In	33.05	34.88	38
Cold Out	358.8	425.1	360
Hot Side Pressure Drop (kPa)	18.45	17.28	37.5
Cold Side Pressure Drop (kPa)	10.83	11.16	37.5
Duty (kW)	323.8	556.1	326.95
U (W/m^2C)	316.8	767.7	--
UA (W/C)	1321	3201	1332
A (m^2)	4.170	4.170	--
Mass Flow Rate (kg/s)	0.919	0.274	0.938

It should be noted, for all heat exchangers shown in this report, that there is a smaller difference in temperature when helium is used compared to nitrogen. This is due to a difference in the specific heat (C_p) values for the two fluids. Since both fluids in these operating ranges can be assumed to be ideal gases, the governing equation can be simplified and is shown in Equation 2.4. The equation shows that helium has the same amount of heat transfer for a smaller change in temperature compared to nitrogen as helium's C_p is approximately 5 times large than nitrogen at room temperature (Çengel & Boles, 2011).

$$\dot{Q} = \dot{m} C_p \Delta T \qquad \textbf{\textit{Equation 2.4}}$$

2.2.2.2 Heat Pipe Heat Exchanger Approximation

Los Alamos National Laboratory (LANL) is currently developing a heat pipe heat exchanger using a plenum to distribute flow to the tubes surrounding the heat pipes. These tubes perform like many tube-in-tube heat exchangers that are connected in parallel. Figure 2.14 shows a general schematic of LANL's heat pipe cooled reactor with attached heat exchanger (McClure, Poston, Rao, & Reid, 2015). A double tubed heat exchanger was designed in an Aspen HYSYS spread sheet to approximate the performance of the heat pipe heat exchanger under varying process parameters. This heat exchanger was designed assuming a pure double tubed heat exchanger in parallel. It is not LANL's heat exchanger design as their information is unknown. The design in Aspen HYSYS is only an approximation to give a general idea of how different conditions affect the performance of MAGNET. This is, however, a good approximation. The double tubed heat exchanger was sized to heat nitrogen to 600°C assuming the full power load of 250 kW at 2 kW per heat pipe. This means there are 125 heat pipes in the system, and they are assumed to operate at 650°C (Guillen, et al., 2019). Figure 2.15 shows the configuration of the heat exchanger attached to the heat pipes in the MAGNET Aspen HYSYS model. The heat exchanger is a bunch of double tubes in parallel which increases the total heat transfer area, illustrated in Figure 2.16. It is assumed that the total MAGNET flow is split evenly across each heat pipe. The heat pipes are filled with sodium and sodium's properties have been estimated using "Thermodynamic and Transport Properties of Sodium Liquid and Vapor" (Fink & Leibowitz, 1995). This allows for an approximation for the outlet temperature of the working fluid.

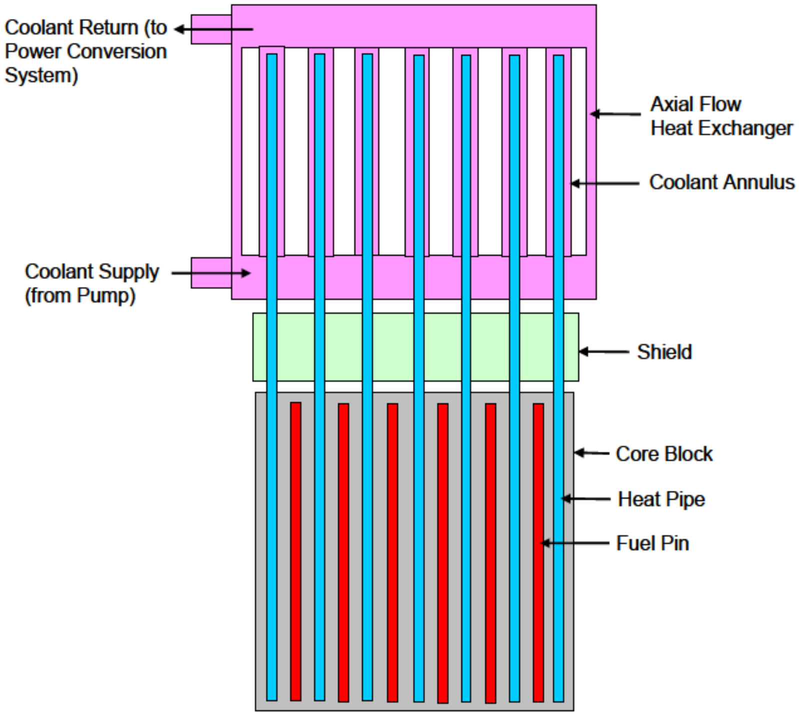


Figure 2.14 LANL's Sample Schematic of Heat Pipe Reactor with Heat Exchanger Attached (McClure, Poston, Rao, & Reid, 2015)

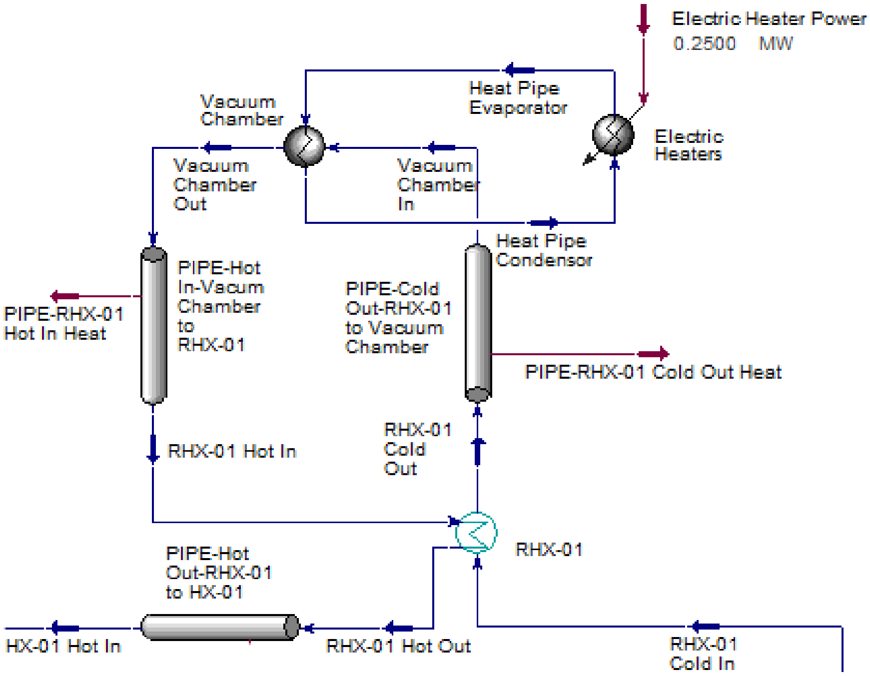


Figure 2.15 Heat Pipe Heat Exchanger Model

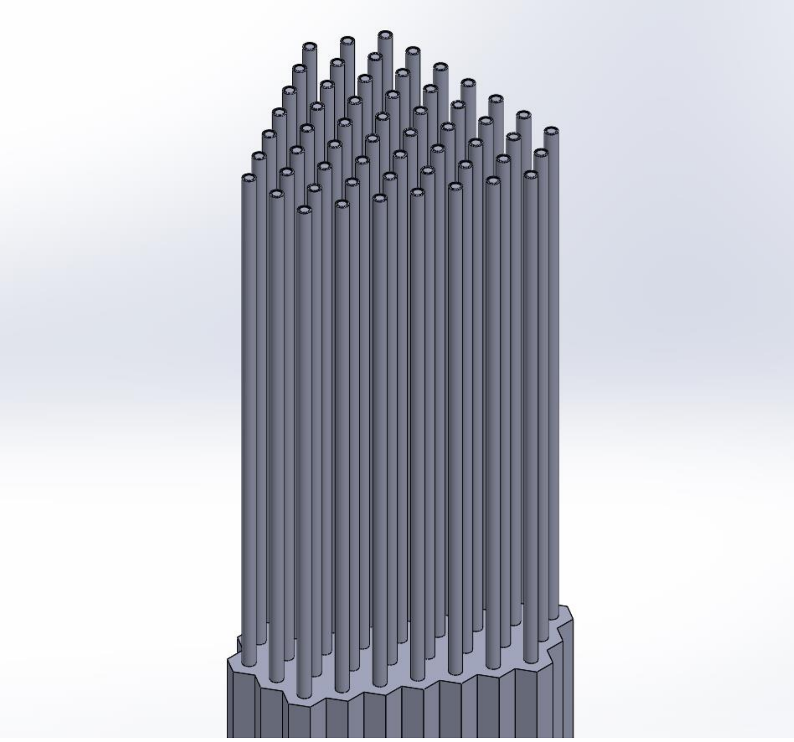


Figure 2.16 MAGNET Double Tubed Heat Pipe Heat Exchanger Illustration

The heat exchanger was designed from standard double tubed heat exchanger correlations. The equations used were obtained in *Design of Fluid Thermal Systems* by William Janna. To solve for this type of heat exchanger, it was assumed that the heat pipes were isothermal. This is a fair assumption as heat pipes only vary by a small amount across the condenser (Advanced Cooling Technologies, 2020; Meseguer, Perez-Greande, & Sanz-Andres, 2012). Therefore, the process of finding the required heat transfer coefficient was done by finding the heat exchanger effectiveness and number of transfer units (NTU) at the design conditions. Since the heat pipe is isothermal and condensing, the equations for the solution simplify greatly. From the correlations, U was found and then the inner diameter of the outer pipe was adjusted to match the required UA. The diameters were held constant after the correct area was found.

$$Nu = \frac{hD}{k_f} = 0.023(Re)^{\frac{4}{5}}Pr^{0.4}$$ **Equation 2.5**

The double tubed heat exchanger was sized around heat pipes that have condenser lengths of 3.28 ft (1 m) and diameters of 5/8 in. The outside tube's inner diameter for the heat exchanger is 0.7772 in. This allows for an accurate approximation of the outlet temperature of the working fluid in the MAGNET during varying process parameters. The heat exchanger is designed in an Aspen HYSYS embedded spread sheet. The sizing of the double tubed heat exchanger is shown in Table 2.8 with an single tube illustration in Figure 2.17.

Table 2.8 Double Tubed Heat Pipe Heat Exchanger Design

Double Tubed Heat Pipe Heat Exchanger Design	
Heat Pipe Outer Diameter	1.59 e-2 m
Outer Pipe Inner Diameter	1.97 e-2 m
Length of Heat Pipe	1.00 m
Heat Transfer Surface Area	4.99 E-2 m^2
Heat Pipe Power	250 kW
Single Heat Pipe Power Load	2 kW
Number of Heat Pipes	125

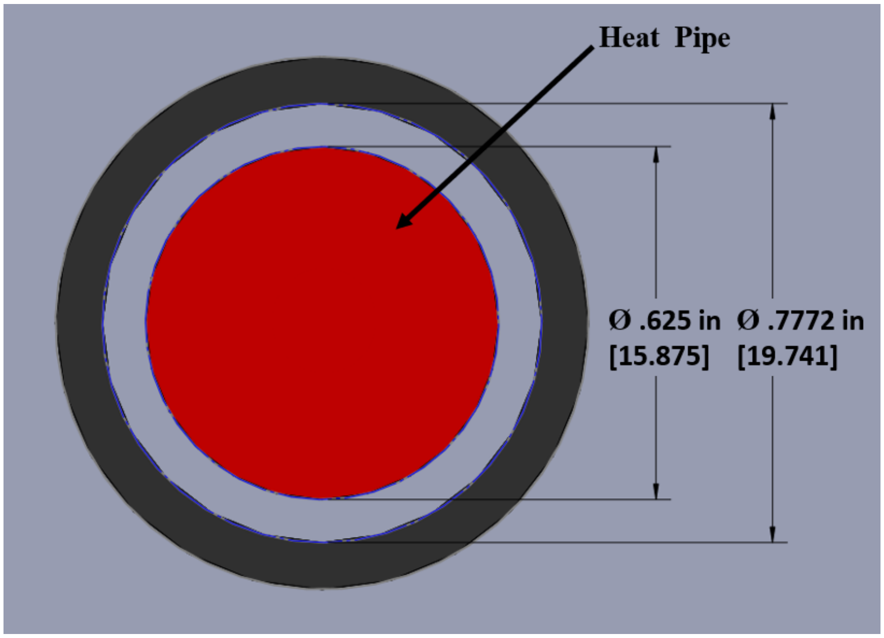


Figure 2.17 MAGNET Double Tubed Heat Exchanger Single Tube Sizing

The described double tubed heat exchanger was created in an Aspen HYSYS heat exchanger model to compare the spread sheet results. The Aspen HYSYS heat exchanger used the same design parameters and tube sizes as was designed in the Aspen HYSYS spread sheet. The Aspen HYSYS heat exchanger model was a single double tubed heat exchanger. The model could not simulate a duty load of 250 kW since it could only have 9 heat exchangers in parallel. This limited the comparison and validation to 9 heat pipes at 3 kW each. Thus, the models were compared to a heat pipe power load of 27 kW. The resulting temperatures were similar to each other, as shown in Table 2.9. The Aspen HYSYS heat exchanger shows that the heat pipe temperature decreased slightly while still undergoing a near complete phase change. The fluid's phase changes from 1 (pure vapor) down to 0.0553 (near liquid). The pressure drop on the cold side (MAGNET gas) calculated by Aspen HYSYS is approximately 2% of the vacuum chamber's inlet pressure. Since the actual geometry of the real heat exchanger is not known, an assumption of a 2% pressure drop from 1266 kPa has been made across the spread sheet heat exchanger. This assumed pressure drop is held constant for each of the different variations in the process conditions.

Table 2.9 Heat Pipe Heat Exchanger 27 kW Aspen HYSYS Comparison

Heat Pipe Heat Exchanger at 27 kW		
	Aspen HYSYS Spread Sheet	Aspen HYSYS Heat Exchanger
Number of Heat Pipes	9	9
Temperature [°C]		
Hot In	650.00	650.00
Hot Out	650.00	649.9
Cold In	442.3	442.3
Cold Out	604.1	595.2
Hot Side Pressure Drop (kPa)	0.00	0.011
Cold Side Pressure Drop (kPa)	25.03	20.70
Duty (kW)	27.00	25.51
U (W/m^2°C)	562.5	---
UA (W/°C)	252.5	222.3
A (m^2)	0.449	---
Cold Fluid Mass Flow Rate (kg/s)	0.147	0.147

The use of an approximated heat pipe heat exchanger has allowed for the comparison of the heat pipe performance between nitrogen and helium. Using nitrogen as the working fluid, the vacuum chamber outlet is approximately 600°C, while the helium loop temperature is closer to 634°C. The pipe insulation, thermo 1200, is rated to 650°C and the design operating temperature of the test loop is 600°C. The comparison between nitrogen and helium are in Table 2.10. The models using the heat pipe heat exchanger are found in Appendix B.

Table 2.10 Heat Pipe Heat Exchanger Comparison for 250 kW

Heat Pipe Heat Exchanger		
	250 kW	
	Nitrogen	Helium
Number of Heat Pipes	125 @ 2 kW	
Temperature [°C]		
Hot In	650	650
Hot Out	650	650
Cold In	358.1	451.7
Cold Out	600.0	634.3
Hot Side Pressure Drop (kPa)	0	0
Cold Side Pressure Drop (kPa)	25.33	25.0
Duty (kW)	250.0	250.0
U (W/m^2°C)	293.9	556.8
UA (W/°C)	1832	3471
A (m^2)	6.234	6.234
Cold Fluid Mass Flow Rate (kg/s)	0.919	0.264

2.2.2.3 Chiller Heat Exchanger

Modelling the chiller heat exchanger, HX-01, was attempted; however, it was determined that critical information of the internal structure was lacking. This heat exchanger uses corrugated tubes, which enhance the heat transfer and increase the pressure drop considerably. Two separate shell and tube heat exchangers were modeled in an attempt to simulate the MAGNET chiller heat exchanger: one was modeled with the Aspen HYSYS heat exchanger component and the other was with standard equations. These heat exchanger models were built using the specifications provided by the manufacturer but used smooth tubes instead of corrugated tubes. This was done since the heat transfer correlations were known. The results were vastly different from the manufacturer's data, as shown in Table 2.11 to Table 2.13. The cold side is the chilled water entering the chiller heat exchanger and the hot side is the nitrogen in the MAGNET. The manufacturer's datasheet is found in Appendix F.

The exit temperatures shown in Table 2.12 and Table 2.13 are very comparable. The two varied slightly from each other because Aspen HYSYS used the current process fluid properties at the current temperatures while the book calculations used average properties between the large ranges set by the manufacture.

Table 2.11 Chiller HX-01 Manufacturers Data

	Manufacturer			
	Cold In	Cold Out	Hot In	Hot Out
Temp (ºF)	44	**64**	527	**68**
Pressure Drop (Psi)	3.79		1.64	
Log Mean Temp Difference (ºF)	148.3			
Fitted Heat Transfer Area (ft^2)	24.09			
Duty (BTU/hr)	9.13 E5			
UA (BTU/hr ºF)	6.15 E3			
U (BTU/hr ft^2 ºF)	255.4			

Table 2.12 Chiller HX-01 Book Calculations using Equations and Correlations Found in Design of Fluid Thermal Systems 4th ed (Janna, 2015)

	Book Calculations			
	Cold In	Cold Out	Hot In	Hot Out
Temp (ºF)	44	**53.72**	527	**303.8**
Pressure Drop (Psi)	2.38		0.73	
Log Mean Temp Difference (ºF)	355.9			
Fitted Heat Transfer Area (ft^2)	23.98			
Duty (BTU/hr)	4.55 E5			
UA (BTU/hr ºF)	1.28 E3			
U (BTU/hr ft^2 ºF)	53.48			

Table 2.13 Chiller HX-01 Aspen HYSYS Model using the Heat Exchanger Design Module

	HYSYS Calculations			
	Cold In	Cold Out	Hot In	Hot Out
Temp (ºF)	44	**53.11**	527	**320**
Pressure Drop (Psi)	1.60		0.70	
Log Mean Temp Difference (ºF)	366.3			
Fitted Heat Transfer Area (ft^2)	-			
Duty (BTU/hr)	4.260 E5			
UA (BTU/hr ºF)	1.16 E3			
U (BTU/hr ft^2 ºF)	-			

Several different attempts were used to obtain the exit temperatures the manufacturer showed. First, the lengths of the designed heat exchangers were adjusted while the rest was held constant. The lengths needed to be around 30.5 ft long (up from 4.92 ft) to obtain similar outlet temperatures. This made the UA similar between the manufacturer's specifications, but the heat transfer area was about 6 times larger than what the manufacturer showed. This is most likely not an effective design. Second, Richard Christensen, The Nuclear Engineering Program Director at the University of Idaho and heat exchanger expert, said that the fluted tubes could enhance heat transfer between 2 to 5 times (Christensen, 2020). Using this idea, the heat transfer coefficients were scaled by about 5.7 on the tube side and about 5.2 on the shell side. This was done while keeping the original length and design. This produced an appropriate exit temperature that matched the manufacturer's data. However, simply scaling the heat transfer coefficient might not accurately describe the effects of flow, fluid mixing, pressure drop, and heat transfer. Lastly, other heat transfer correlations were found and tested. Some had many values, like the Reynolds number, that were way out of the expected ranges while other correlations produced decent values, but the exit temperatures were still too high. It may be necessary to perform tests on the chiller HX-01 and collect data to build an accurate Aspen HYSYS heat exchanger model. The performance data could be used to create heat transfer correlations and could be simulated within Aspen HYSYS. The current values found within the nitrogen and helium MAGNET models are shown in Table 2.14. An approximation applied to adjust the chiller unit's mass flow rate to maintain a chilled water outlet temperature of 64°F (17.77°C). This makes the inlet and exit temperature of the chilled water and the MAGNET gas exit temperature to remain constant, which matches the chiller HX-01 manufacture's data sheet.

Table 2.14 Current Chiller HX-01 Values for the Nitrogen and Helium MAGNET Cycles using 250 kW of Heat Pipe Power without the Heat Pipe Heat Exchanger

Current Chiller HX-01 Values		
	Nitrogen	Helium
Duty (kW)/(BTU/hr)	260 (887200)	269 (916200)
UA (W/°C)/(BTU/hr °F)	3065 (5810)	4611 (8740)
Min. Approach (°C)/(°F)	13.33 (24.00)	13.33 (24.00)
LMTD (°C)/(°F)	84.81 (152.7)	58.26 (104.9)

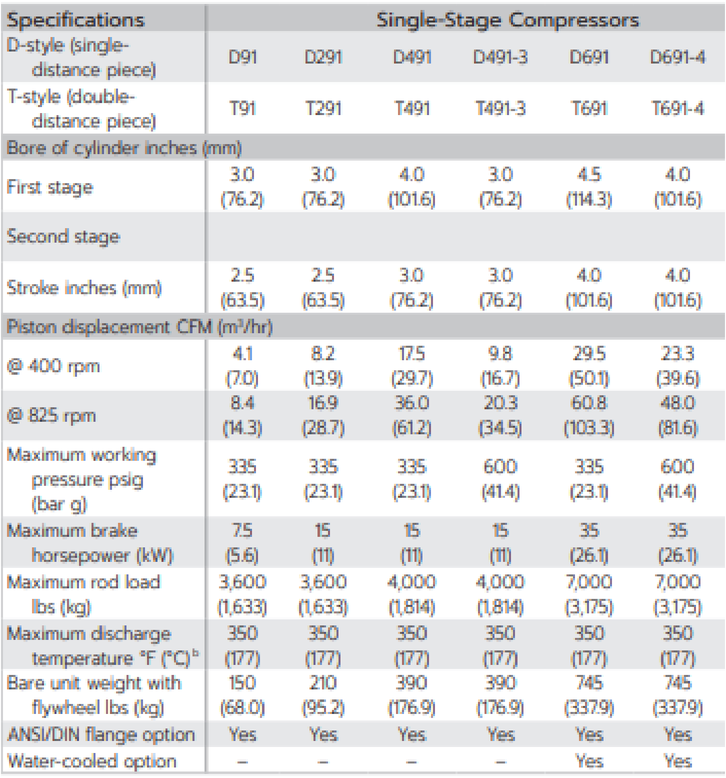
2.2.3 Compressor

The compressor in the MAGNET is used to drive the flow and control the pressure of the MAGNET working fluid. A Corken Inc compressor, model FD691-4, has been purchased for the MAGNET. It is a 25 hp reciprocating compressor. The compressor is single staged with a variable speed drive. An attempt was made in Aspen HYSYS to model the compressor making it function from the rotational speed of the unit. However, the results from Aspen HYSYS did not match the manufacture's data; therefore, the unit does not operate off the compressor specifications.

Aspen HYSYS has an option to model reciprocating compressors and requires internal information about the compressor to function. This information lets Aspen HYSYS simulate the compressor using the rotational speed. The needed data required for the compressor model is shown Table 2.15. To accurately model the compressor, the bore size, stroke size, cylinder type, and the speed are needed. The Corken compressor specification sheet is shown in Figure 2.18 and provides the needed information for Aspen HYSYS. A performance sheet was also obtained from INL and is shown in Figure 2.19. The pressures and temperatures in the performance sheet were used to determine the default fixed clearance volume to match the volumetric efficiency listed. For some of the conditions in the performance sheet to be met, the adiabatic efficiency of the compressor needed to be 100% to match the outlet temperature of 126°F. It was also determined that the default fixed clearance volume needed to be 24.25%. Though the exhaust temperature and volumetric efficiency were met, the flow rate of the gas was incorrect. The performance sheet showed a piston displacement of 48 CFM and Aspen HYSYS calculated 22.08 ACFM or 363.19 SCFM. This model was also used to check the compressor performance at the MAGNET conditions.

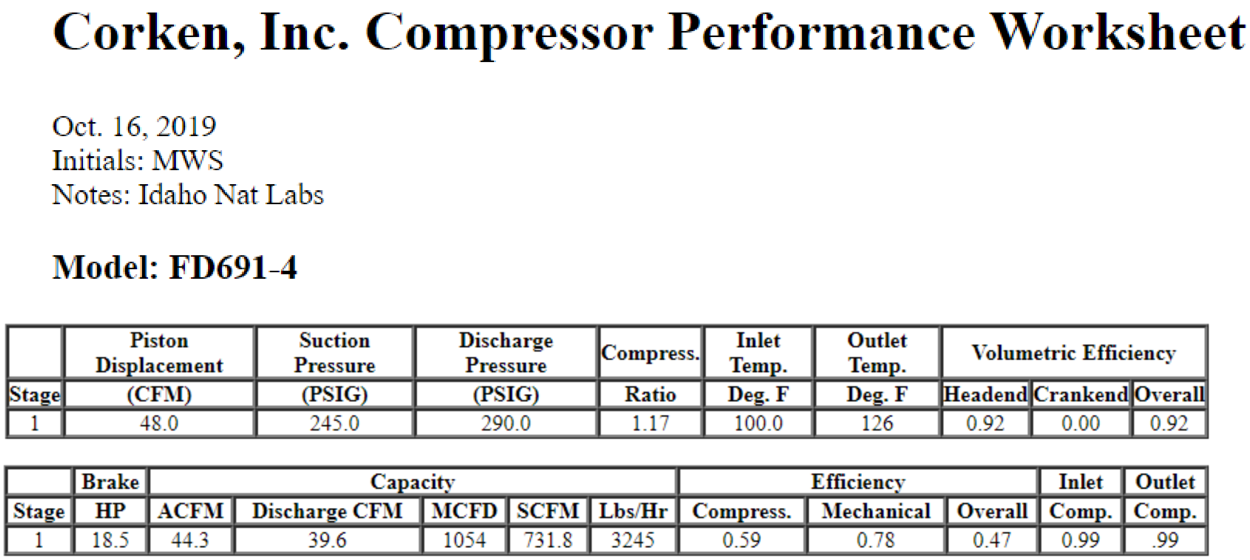
Table 2.15 Aspen HYSYS Reciprocating Compressor Input Data

HYSYS Reciprocating Compressor Input Data	
Number of Cylinders	1
Cylinder Type	Single-Acting, Outer End
Bore (ft)	0.333
Stroke (ft)	0.333
Piston Rod Diameter (ft)	8.202 E-2
Const. Vol. Efficiency Loss (%)	4.00
Default Fixed Clearance Vol. (%)	24.25
Zero Speed Flow Resistance (k)	0.0 lb/hr/sqrt(psia-lb/ft^3)
Typical Design Speed (RPM)	825
Volumetric Efficiency (%)	92
Speed (RPM)	825



Specifications	Single-Stage Compressors					
D-style (single-distance piece)	D91	D291	D491	D491-3	D691	D691-4
T-style (double-distance piece)	T91	T291	T491	T491-3	T691	T691-4
Bore of cylinder inches (mm)						
First stage	3.0 (76.2)	3.0 (76.2)	4.0 (101.6)	3.0 (76.2)	4.5 (114.3)	4.0 (101.6)
Second stage						
Stroke inches (mm)	2.5 (63.5)	2.5 (63.5)	3.0 (76.2)	3.0 (76.2)	4.0 (101.6)	4.0 (101.6)
Piston displacement CFM (m^3/hr)						
@ 400 rpm	4.1 (7.0)	8.2 (13.9)	17.5 (29.7)	9.8 (16.7)	29.5 (50.1)	23.3 (39.6)
@ 825 rpm	8.4 (14.3)	16.9 (28.7)	36.0 (61.2)	20.3 (34.5)	60.8 (103.3)	48.0 (81.6)
Maximum working pressure psig (bar g)	335 (23.1)	335 (23.1)	335 (23.1)	600 (41.4)	335 (23.1)	600 (41.4)
Maximum brake horsepower (kW)	7.5 (5.6)	15 (11)	15 (11)	15 (11)	35 (26.1)	35 (26.1)
Maximum rod load lbs (kg)	3,600 (1,633)	3,600 (1,633)	4,000 (1,814)	4,000 (1,814)	7,000 (3,175)	7,000 (3,175)
Maximum discharge temperature °F (°C)^{b}	350 (177)	350 (177)	350 (177)	350 (177)	350 (177)	350 (177)
Bare unit weight with flywheel lbs (kg)	150 (68.0)	210 (95.2)	390 (176.9)	390 (176.9)	745 (337.9)	745 (337.9)
ANSI/DIN flange option	Yes	Yes	Yes	Yes	Yes	Yes
Water-cooled option	–	–	–	–	Yes	Yes

Figure 2.18 Corken Compressors Data Sheet for D691-4 Industrial Series Compressors (Corken Inc, 2018)



Corken, Inc. Compressor Performance Worksheet

Oct. 16, 2019
Initials: MWS
Notes: Idaho Nat Labs

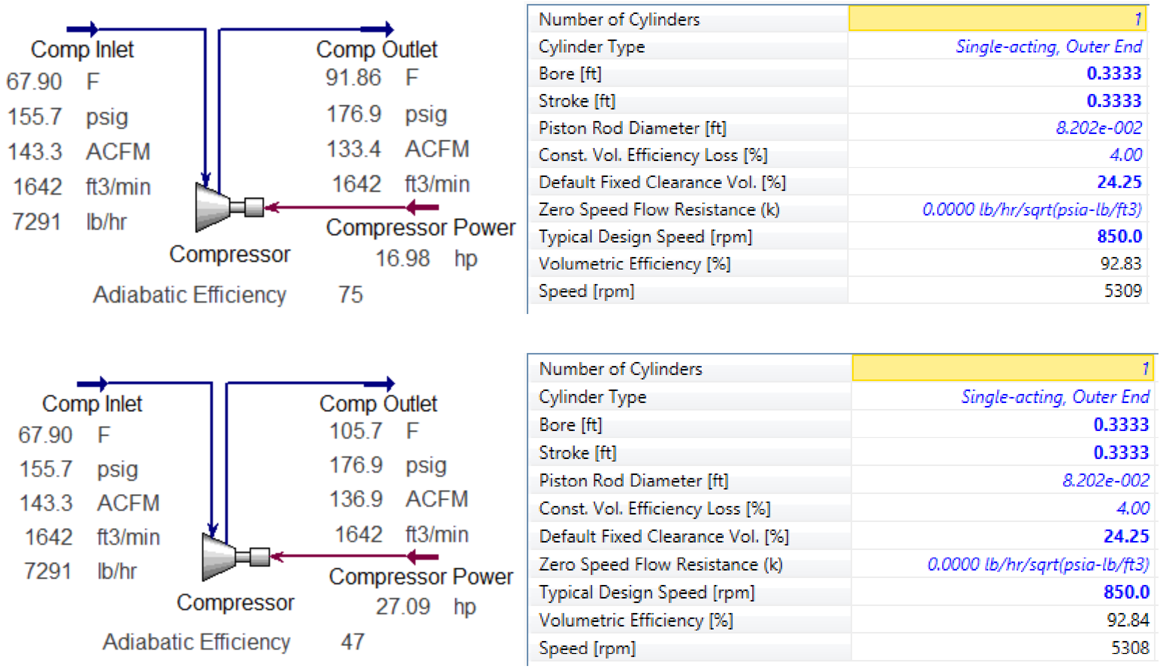
Model: FD691-4

	Piston Displacement	Suction Pressure	Discharge Pressure	Compress.	Inlet Temp.	Outlet Temp.	Volumetric Efficiency		
Stage	(CFM)	(PSIG)	(PSIG)	Ratio	Deg. F	Deg. F	Headend	Crankend	Overall
1	48.0	245.0	290.0	1.17	100.0	126	0.92	0.00	0.92

	Brake	Capacity					Efficiency			Inlet	Outlet
Stage	HP	ACFM	Discharge CFM	MCFD	SCFM	Lbs/Hr	Compress.	Mechanical	Overall	Comp.	Comp.
1	18.5	44.3	39.6	1054	731.8	3245	0.59	0.78	0.47	0.99	.99

Figure 2.19 MAGNET Compressor Performance Worksheet Calculator using Nitrogen

Several attempts were done to simulate the compressor from the given data but were unsuccessful. To perform these simulations, the found "default fixed clearance volume" was kept constant for the compressor at MAGNET conditions using nitrogen at 250 kW of heat pipe power. As a 100% adiabatic efficiency is unrealistic, an upper end compressor efficiency of 75% was used for one study and 47% for another study. The efficiency of 47% was shown in the performance sheet in Figure 2.19. The two tests consisted of defining the needed flow rate and having Aspen HYSYS calculate the needed compressor speed. For both tests, the calculated compressor speed was around 5308 rpm. The manufacture’s data show an operating speed of 850 rpm. The two case studies are shown in Figure 2.20. These values are extremely large; therefore, the compressor models are not estimating the performance of the compressor using the compressor information.



Number of Cylinders	1
Cylinder Type	Single-acting, Outer End
Bore [ft]	0.3333
Stroke [ft]	0.3333
Piston Rod Diameter [ft]	8.202e-002
Const. Vol. Efficiency Loss [%]	4.00
Default Fixed Clearance Vol. [%]	24.25
Zero Speed Flow Resistance (k)	0.0000 lb/hr/sqrt(psia-lb/ft3)
Typical Design Speed [rpm]	850.0
Volumetric Efficiency [%]	92.83
Speed [rpm]	5309

Number of Cylinders	1
Cylinder Type	Single-acting, Outer End
Bore [ft]	0.3333
Stroke [ft]	0.3333
Piston Rod Diameter [ft]	8.202e-002
Const. Vol. Efficiency Loss [%]	4.00
Default Fixed Clearance Vol. [%]	24.25
Zero Speed Flow Resistance (k)	0.0000 lb/hr/sqrt(psia-lb/ft3)
Typical Design Speed [rpm]	850.0
Volumetric Efficiency [%]	92.84
Speed [rpm]	5308

Figure 2.20 Aspen HYSYS Compressor Case Studies at MAGNET Conditions using Nitrogen at 250 kW without the Heat Pipe Heat Exchanger

The compressors for the Aspen HYSYS models were assumed to have a 75% adiabatic efficiency. This value is on the upper end of compressor efficiencies and may represent the best possible scenario. The units are not dynamically solved from the compressor’s specifications and rotational speed. Table 2.16 shows a comparison between the duty, horsepower, and compression ratio between the nitrogen and the helium cycle. The current compressor operates from a 25 hp motor. To maintain the pressures using helium, the compressor uses 29 hp. There was also a slight difference in pressure ratios due to differences in the pressure losses across the MAGNET equipment.

Table 2.16 Compressor Comparison Between Nitrogen and Helium MAGNET Cycles using 250 kW of Heat Pipe Power without the Heat Pipe Heat Exchanger

Compressor		
	N2	He
Horse Power (hp)	16.83	28.90
Duty (kW)	12.55	21.55
Pressure Ratio	1.123	1.100
Mass Flow (kg/s)	0.919	0.274
Actual Volumetric Flow Rate (m3/h)	243.5	505.3

2.2.4 Chiller Unit

A 200-ton chiller unit is used to cool the MAGNET loop. The loop is connected to the chiller heat exchanger HX-01. The fluid being used in the chilled water loop is EG50, which is a combination of water and ethylene glycol. The piping between the heat exchanger HX-01 and chiller unit has been modeled and provides the required duty from the physical chiller unit, shown in Figure 2.21. There is a difference in chiller duties between the helium and nitrogen loops, as shown in Table 2.17. The flow rate is also different due to maintaining a constant chilled water outlet temperature from the chiller HX-01.

Table 2.17 Chiller Duty Comparison Between Nitrogen and Helium MAGNET Cycles using 250 kW of Heat Pipe Power without the Heat Pipe Heat Exchanger

Chiller		
	N2	He
Duty (kW)	260.5	269.1
Mass Flow (kg/s)	6.76	6.98

Another Aspen HYSYS model being considered to attach to the MAGNET is the 200-ton chiller unit. This model includes the pump for the EG50 fluid. The EG50 is chilled by R-410a in the refrigeration loop, which is air-cooled. This model is lacking expected conditions of the refrigeration loop. The model is shown in Figure 2.22 and would be attached to the “Chiller In” and “Chiller Out” streams found in the MAGNET model. The chiller pump in the MAGNET model would also be removed.

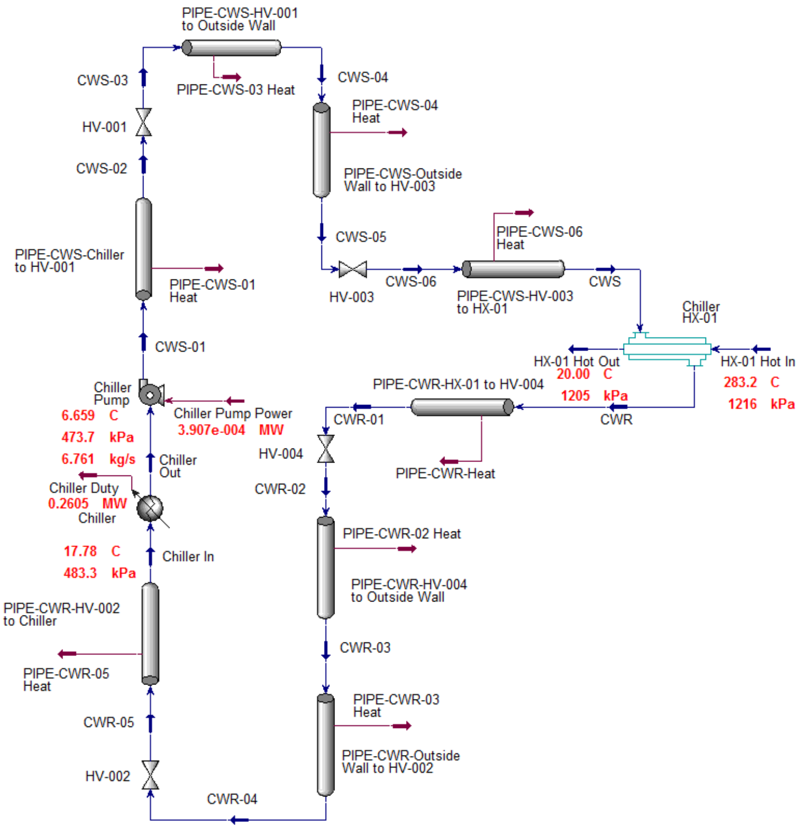


Figure 2.21 MAGNET Chilled Water Loop using Nitrogen at 250 kW Heat Pipe Power without the Heat Pipe Heat Exchanger

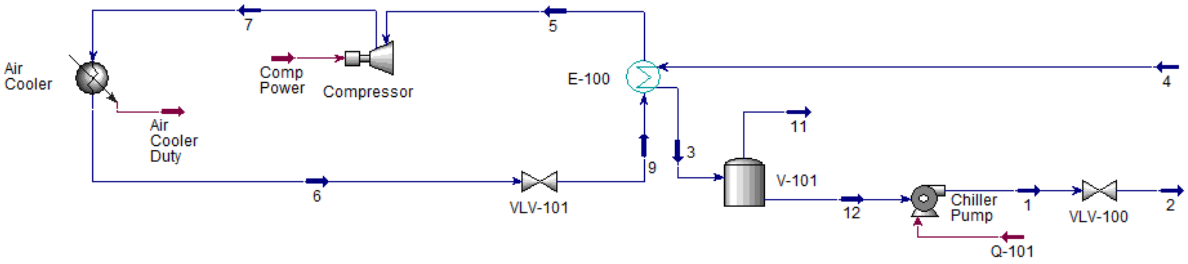


Figure 2.22 Chiller Unit Model

2.3 MAGNET Aspen HYSYS Model Development Operating at Off-Design Heat Pipe Power

2.3.1 MAGNET Operating at 75 kW of Heat Pipe Power

One of the initial tests the MAGNET will operate at is 75 kW of power to the heat pipes. The Aspen HYSYS process flow diagram for nitrogen is shown in Figure 2.23 with its process data in Table 2.18. This test loop condition has a flow rate of 0.324 kg/s compared to full scale flow of 0.919 kg/s. The recuperating heat exchanger also has slightly different conditions with the slower flow rate. Detailed process conditions for nitrogen and helium are found in Appendix A.

Comparison tables between the helium and nitrogen loops operating at 75 kW and 250 kW of heat pipe power are shown below in Table 2.19 to Table 2.21 for the compressor, chiller, and the recuperating heat exchanger. The heat pipe heat exchanger was also compared between helium and nitrogen at 75 kW and 250 kW of heat pipe power. The mass flow rates were adjusted to obtain the desired duty from the heat exchanger. This produced the vacuum chamber outlet temperatures for nitrogen to be approximately 600°C, while the helium loop temperatures were closer to 634°C. It is also shown that the inlet temperatures on the cold side vary greatly between the cycles. The comparisons between nitrogen and helium are in Table 2.22.

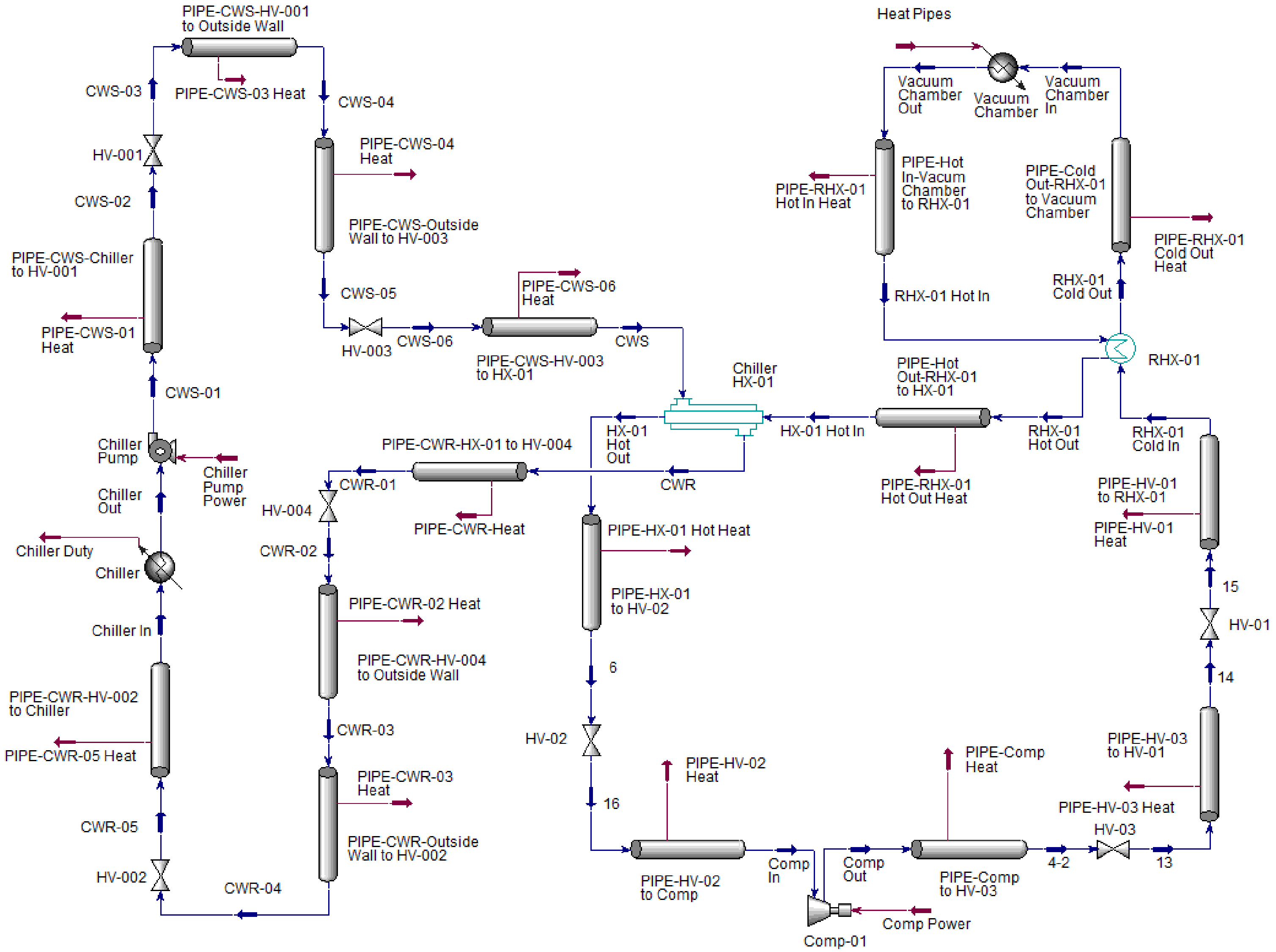


Figure 2.23 MAGNET Operating with Nitrogen at 75 kW of Power without the Heat Pipe Heat Exchanger

Table 2.18 MAGNET Operating with Nitrogen at 75 kW of Power Process Conditions without the Heat Pipe Heat Exchanger

	Material Streams				
	HX-01 Hot In	**CWR**	**CWS**	**HX-01 Hot Out**	**RHX-01 Cold In**
Temperature (°C)	232.97	17.78	6.67	20.00	24.55
Pressure (kPa)	1237.32	473.89	500.00	1225.99	1268.60
Mass Flow (kg/s)	0.324	1.923	1.923	0.324	0.324
	RHX-01 Cold Out	**Vacuum Chamber In**	**Vacuum Chamber Out**	**RHX-01 Hot In**	**RHX-01 Hot Out**
Temperature (°C)	396.85	394.67	600.00	595.67	233.56
Pressure (kPa)	1266.68	1266.33	1241.33	1240.64	1237.48
Mass Flow (kg/s)	0.324	0.324	0.324	0.324	0.324
	Comp In	**6**	**Chiller In**	**Chiller Out**	**CWS-04**
Temperature (°C)	20.02	20.02	17.78	6.65	6.66
Pressure (kPa)	1222.48	1223.99	487.26	477.52	480.61
Mass Flow (kg/s)	0.324	0.324	1.923	1.923	1.923
	CWR-01	**CWR-05**	**CWS-02**	**CWS-03**	**CWS-06**
Temperature (°C)	17.78	17.78	6.66	6.66	6.67
Pressure (kPa)	453.89	487.28	514.49	514.47	480.54
Mass Flow (kg/s)	1.923	1.923	1.923	1.923	1.923
	13	**14**	**15**	**16**	**Comp Out**
Temperature (°C)	24.63	24.56	24.56	20.02	24.65
Pressure (kPa)	1270.74	1268.78	1268.71	1223.92	1273.88
Mass Flow (kg/s)	0.324	0.324	0.324	0.324	0.324
	4-2	**CWR-02**	**CWR-03**	**CWR-04**	**CWS-05**
Temperature (°C)	24.63	17.78	17.78	17.78	6.67
Pressure (kPa)	1270.81	453.88	453.83	487.29	480.56
Mass Flow (kg/s)	0.324	1.923	1.923	1.923	1.923
	CWS-01				
Temperature (°C)	6.66				
Pressure (kPa)	514.51				
Mass Flow (kg/s)	1.92				
	Energy Streams				
	Heat Pipes	**PIPE-RHX-01 Cold Out Heat**	**PIPE-RHX-01 Hot In Heat**	**PIPE-RHX-01 Hot Out Heat**	**PIPE-HV-03 Heat**
Heat Flow (kW)	75.00	0.783	1.61	0.204	0.023

	PIPE-HX-01 Hot Heat	**PIPE-HV-02 Heat**	**Comp Power**	**Chiller Duty**	**PIPE-CWS-06 Heat**
Heat Flow (kW)	-6.62E-03	-6.51E-04	1.55	74.11	-5.73E-03
	PIPE-CWS-03 Heat	**PIPE-CWR-Heat**	**PIPE-CWR-05 Heat**	**PIPE-CWS-01 Heat**	**PIPE-HV-01 Heat**
Heat Flow (kW)	-2.08E-02	-7.17E-03	-2.42E-03	-1.03E-02	1.70E-03
	PIPE-Comp Heat	**Chiller Pump Power**	**PIPE-CWR-02 Heat**	**PIPE-CWR-03 Heat**	**PIPE-CWS-04 Heat**
Heat Flow (kW)	2.77E-03	8.81E-02	-6.11E-03	-4.60E-03	-2.60E-02

Heat Exchangers		
	RHX-01	**Chiller HX-01**
Duty (kW)	130.70	73.94
LMTD (°C)	640.71	1014.34
UA (W/°C)	198.82	13.33
Minimum Approach (°C)	204.00	72.89

Table 2.19 MAGNET Compressor Comparison for 75 kW and 250 kW of Heat Pipe Power without the Heat Pipe Heat Exchanger

Compressor				
	75 kW		**250 kW**	
	Nitrogen	Helium	Nitrogen	Helium
HP	2.076	5.629	16.830	28.900
kW	1.548	4.198	12.550	21.550
Pressure Ratio	1.046	1.049	1.123	1.100
Mass Flow (kg/s)	0.324	0.117	0.919	0.274
Actual Volumetric Flow Rate (m3/h)	82.51	210.10	243.50	505.30

Table 2.20 MAGNET Chiller Comparison for 75 kW and 250 kW of Heat Pipe Power without the Heat Pipe Heat Exchanger

Chiller				
	75 kW		**250 kW**	
	Nitrogen	Helium	Nitrogen	Helium
Duty (kW)	74.110	76.610	260.500	269.100
Mass Flow Rate (kg/s)	1.923	1.986	6.760	6.980

Table 2.21 MAGNET RHX-01 Comparison for 75 kW and 250 kW of Heat Pipe Power without the Heat Pipe Heat Exchanger

RHX-01 Comparison	75 kW		250 kW	
	Nitrogen	Helium	Nitrogen	Helium
Temperature [°C]				
Hot In	595.7	597.3	598.5	598.9
Hot Out	233.6	145.8	283.5	208.5
Cold In	24.55	26.84	33.05	34.88
Cold Out	396.9	478.3	358.8	425.1
Hot Side Pressure Drop (kPa)	3.159	4.962	18.45	17.28
Cold Side Pressure Drop (kPa)	1.923	3.573	10.83	11.16
Duty (kW)	130.7	274.6	323.8	556.1
U (W/m^2°C)	153.7	553.3	316.8	767.7
UA (W/°C)	640.7	2307	1321	3201
A (m^2)	4.17	4.17	4.17	4.17
Mass Flow Rate (kg/s)	0.3238	0.117	0.919	0.274

Table 2.22 Heat Pipe Heat Exchanger Comparison for 75 kW and 250 kW

	Heat Pipe Heat Exchanger			
	75 kW		250 kW	
	Nitrogen	Helium	Nitrogen	Helium
Number of Heat Pipes	25 @ 3 kW		125 @ 2 kW	
Temperature [°C]				
Hot In	650	650	650	650
Hot Out	650	650	650	650
Cold In	392.2	506.6	358.1	451.7
Cold Out	596.7	633.9	600.0	634.3
Hot Side Pressure Drop (kPa)	0	0	0	0
Cold Side Pressure Drop (kPa)	25.0	25.0	25.33	25.0
Duty (kW)	75.0	75.0	250.0	250.0
U (W/m^2°C)	465.3	1033	293.9	556.8
UA (W/°C)	580.2	1288	1832	3471
A (m^2)	1.247	1.247	6.234	6.234
Cold Fluid Mass Flow Rate (kg/s)	0.325	0.113	0.919	0.264

2.3.2 MAGNET Operating at 2 kW of Heat Pipe Power

An initial test is planned for the MAGNET to operate using one heat pipe at 2 to 3 kW. The Aspen HYSYS process flow diagram and process conditions are shown in Appendix A. Is has been assumed that the equipment in the MAGNET will remain the same as currently designed for the higher flow rates and numbers of heat pipes. For this test, however, the PCHE recuperating heat exchanger was replaced by a Sentry tube in tube heat exchanger and a low flow mass flow meter. The heat pipe heat exchanger would also be adjusted to accommodate only one heat pipe, but it is assumed in the Aspen HYSYS model that the dimensions of the tube is the same as discussed earlier in the chapter. The Sentry tube-in-tube heat exchanger model being used is the DTC-IN7/SSD-8-1-1. This uses an Inconel inner tube with a stainless-steel outer tube. The tube in tube heat exchanger was modeled using double tubed heat exchanger equations found in *Design of Fluid Thermal Systems* by William Janna. The sizing of the heat exchanger in Aspen HYSYS can be seen in Table 2.23 and the manufacture’s data sheet is in Appendix E. The wall thickness for both the inner tube (0.065 inches) and outer tube (0.083 inches) were obtained by contacting the manufacturer (Sentry, 2020). A double tubed Aspen HYSYS heat exchanger model was created to compare results to the standard equations, a similar process for validating the heat pipe heat exchanger discussed earlier. The results are similar and are shown in Table 2.24.

It was assumed that the exhaust temperature of the vacuum chamber was 600^{o}C. This assumption was made for both the Aspen HYSYS models with and without the heat pipe heat exchanger. To obtain this temperature, the flow rate needed to be near 0.0045 kg/s. Since the flow rate is smaller than what the compressor could operate at, the flow will be driven by the compressor receiver tank. Once the pressure in the receiver tank drops below a certain threshold, the compressor will turn on and pressurize the tank to a set value and then turn off. This will allow the current compressor to be used for this low flow case.

The low flow within the system and the large pipe sizes create a lot of residence time in the piping. The piping throughout the MAGNET is mostly 3 inches in diameter, with a few sections of 4-inch pipe around the vacuum chamber. The velocity within the 3-inch pipes are near 0.068 m/s. The volumetric flow rates are also shown in Table 2.25, where the values were provided by Aspen HYSYS. This low velocity and low volumetric flow rate allow for a large amount of heat transfer from the pipes to the ambient air. This resulted in the fluid within most pipes to be at ambient temperatures. Where the temperatures are elevated, a lot of heat is lost due to the small flow.

Performance of the compressor, chiller, recuperated heat exchanger and the heat pipe heat exchanger are shown between Table 2.26 to Table 2.29. The heat pipe heat exchanger showed that the exhaust temperature is 583°C. This value could be increased to 600°C if the flow rate were decreased and the heat pipe power were increased. A smaller outer tubed diameter could also be placed over the heat pipe beside the one designed in the previous sections (0.7772-inch inner diameter).

Table 2.23 Sentry's Double Tubed RHX-01 Sizing

Sentry's Double Tubed RHX-01 Sizing			
Tube Sizing			
ID Tube (ID p) (m)	9.40 E-3	ID Annulus (ID a) (m)	2.12 E-2
OD p (m)	1.27 E-2	OD a (m)	2.54 E-2
Tube Thickness (m)	1.65 E-3	Annulus Thickness (m)	2.11 E-3
Flow Areas			
A p (m^2)	6.94 E-5	A a (m^2)	2.26 E-4
Fluid Velocities			
V p (m/s)	8.47 m/s	V a (m/s)	1.43
Hydraulic Diameter (Dh) (m)	8.48 E-3	Equivalent Diameter (De) (m)	2.26 E-2
Reynolds Numbers			
Re p	2.22 E-4	Re a	1.41 E4
Nusselt Numbers			
Nu p	63.7	Nu a	43.6
Convection Coefficients			
h inner (W/m^2-C)	275.6	h a (W/m^2-C)	65.80
h p (W/m^2-C)	204.0		
Overall Heat Transfer Coefficient (Uo) (W/m^2-C)	49.75		
Outlet Temperatures			
R	0.987	Length (m)	5.79
E	0.971	Outer Surface Area of Pipe (Ao) (m^2)	0.231
Hot Out (°C)	133.5	Cold Out (°C)	271.9

Table 2.24 Sentry Double Tubed RHX-01 Comparison between Spread Sheet Equations and Aspen HYSYS Heat Exchanger Model without Heat Pipe Heat Exchanger

Double Tubed RHX-01 Comparison (2 kW) without Heat Pipe Heat Exchanger		
	Spread Sheet without Heat Pipe Heat Exchanger	Aspen HYSYS
Number of Heat Pipes	1	1
Temperature [C]		
Hot In	381.1	381.1
Hot Out	133.0	121.8
Cold In	21.95	21.95
Cold Out	273.4	284.4
Hot Side Pressure Drop (kPa)	5.440	4.034
Cold Side Pressure Drop (kPa)	0.019	0.572
Duty (kW)	1.21	1.26
U (W/m^2C)	47.66	---
UA (W/C)	11.01	12.8
A (m^2)	0.231	---
Mass Flow Rate (kg/s)	4.46 E-03	4.46 E-03

Table 2.25 MAGNET 2 kW of Heat Pipe Power Working Fluid Residence Time without Heat Pipe Heat Exchanger

Residence Time of Nitrogen in MAGNET operating heat pipes at 2 kW without Heat Pipe Heat Exchanger					
	Pipe following Compressor (3-inch pipe)	Pipe following RHX cold side (3-inch pipe)	Pipe following Vacuum Chamber (4-inch pipe)	Pipe following RHX hot side (4-inch pipe)	Pipe following Chiller HX hot side (3-inch pipe)
Volumetric Flow Rate (m^3/hr)	1.114	2.065	3.364	1.569	1.134
Time per Volume (hr/m^3)	0.898	0.484	0.297	0.637	0.882

Table 2.26 Compressor Performance at 2 kW with the Heat Pipe Heat Exchanger

Compressor (2 kW) Loop with Heat Pipe Heat Exchanger	
	N2
HP	0.025
kW	0.0187
Pressure Ratio	1.04
Actual Volumetric Flow (m3/h)	1.199

Table 2.27 Chiller Performance at 2 kW with the Heat Pipe Heat Exchanger

Chiller (2 kW) Loop with Heat Pipe Heat Exchanger	
	N2
Duty (kW)	0.586
Mass Flow (kg/s)	0.012

Table 2.28 Double Tubed Sentry RHX-01 with the Heat Pipe Heat Exchanger

Double Tubed RHX-01 Comparison (2 kW) with Heat Pipe Heat Exchanger		
	Spread Sheet with Heat Pipe Heat Exchanger	Aspen HYSYS RHX-01 Heat Exchanger
Number of Heat Pipes	1	1
Temperature [C]		
Hot In	380.2	380.2
Hot Out	133.5	122.4
Cold In	22.02	22.02
Cold Out	272.0	283.0
Hot Side Pressure Drop (kPa)	6.009	4.421
Cold Side Pressure Drop (kPa)	0.018	0.626
Duty (kW)	1.26	1.32
U (W/m^2C)	49.75	---
UA (W/C)	11.50	13.4
A (m^2)	0.231	---
Mass Flow Rate (kg/s)	4.70 E-03	4.70 E-03

Table 2.29 Heat Pipe Heat Exchanger Performance at 2 kW

Double Tubed Heat Pipe Heat Exchanger (2 kW)		
	Aspen HYSYS Spread Sheet	Aspen HYSYS Heat Exchanger
Number of Heat Pipes	1	1
Temperature [C]		
Hot In	650.0	650.0
Hot Out	650.0	649.7
Cold In	200.5	200.5
Cold Out	583.5	561.4
Hot Side Pressure Drop (kPa)	0.00	0.0246
Cold Side Pressure Drop (kPa)	25.33	1.952
Duty (kW)	2.00	1.882
U (W/m^2C)	201.6	---
UA (W/C)	10.10	8.46
A (m^2)	0.050	---
Mass Flow Rate (kg/s)	4.70 E-03	4.70 E-03

Chapter 3: Power Conversion Unit for MAGNET

3.1 Introduction

There has been new interest in modular nuclear microreactors for power generation and process heat applications over the past few years. These nuclear microreactors typically operate between 1 megawatt of thermal energy (MW_{th}) to 20 MW_{th}. Current designs are modular, allowing them to be easily transported by truck, train, or boat. Another key feature of microreactors is that their components would be able to be assembled in a factory and shipped out. The last key feature is that they are to be self-adjusting to minimize the need for a large number of operators by utilizing passive safety systems that reduce the possibility of reactor failure (Office of Nuclear Energy, 2018). These nuclear reactors are designed to provide heat and energy. They are often connected to a power conversion unit (PCU) which in turn generates power.

Power conversion units can come in many forms with different working fluids. The general process of a PCU is to increase the thermal energy of the working fluid and convert it into electrical energy. The thermal energy of the working fluid is increased by raising the pressure and temperature. The pressure is increased by using pumps for liquids in a Rankine cycle or by using compressors when vapors and gases are used, commonly found in Brayton cycles. The heat addition to the working fluid is traditionally supplied through a combustion process but could also be supplied from nuclear reactors through heat exchangers. The high energy fluid then passes through a turbine which converts mechanical energy into electrical energy (Çengel & Boles, 2011). Common working fluids for different PCUs include air, helium, carbon dioxide (CO_2), water, and organic fluids such as refrigerants. Examples of PCUs attached to a microreactor include HolosGen’s Holos Reactor and Westinghouse’s eVinci. Both reactors are cooled differently, but both utilize a high temperature Brayton cycle. The eVinci uses a microreactor that is cooled by heat pipes where the heat is then transferred to the PCU by the use of a heat exchanger-heat pipe interface (Westinghouse, 2019). The Holos reactor is cooled using helium or CO_2 which are directly integrated into the PCU (Filippone & Jordan, 2018).

This new class of microreactors provide many benefits but lack needed data to show that they are safe and effective. For this purpose, Idaho National Laboratory (INL) is developing the Microreactor AGile Non-nuclear Experimental Testbed (MAGNET) to aid in the development of new microreactor designs and concepts. The MAGNET is being designed to test many different reactor types in a safe environment that allows for testing of steady state conditions, transient conditions, and failure modes (Guillen, et al., 2019). The design allows for a broad range of reactor types as well as auxiliary systems, such as PCUs and process heat applications. These auxiliary systems add real loads to the system and can provide critical information regarding the impact to the reactor, such as response time to change. The first reactor type the MAGNET is being designed for is a heat pipe cooled reactor. The working fluid for this application is pure nitrogen. This is a safety feature to avoid possible reactions with the sodium in the heat pipes if failure was to be tested (Guillen, et al., 2019). The system will operate at a temperature of 600°C, which is a typical heat range for heat pipe reactors, and a pressure range of 1051 kPa to 1241 kPa following the reactor (Westinghouse, 2019). The auxiliary systems being considered in this chapter are a physical PCU attached to the MAGNET and a newly design PCU simulator unit.

Throughout this chapter there is talk of optimized cycles and the general process will be detailed here. The optimization process for Brayton cycles involves parametric studies to vary the main process variable, pressure. The type of nuclear reactor being concidered in here were heat pipe cooled reactors. The MAGNET reactor will be cooled by sodium cooled heat pipes which have an operating range between 600°C to 1100°C (Advanced Cooling Technologies, 2020). From this range, it was determined that the desire operating temperature range of the heat pipes in the MAGNET would be between 600°C to 700°C (Guillen, et al., 2019; Turner & Guillen, 2020). Since the desired reactor outlet temperature was known, 600°C for the MAGNET, the main variables to be changed were the pressure ratio, the compressor adiabatic efficiency, and the turbine adiabatic efficiency. The pressure ratio affects how much work the compressor requires as well as how much work the turine generates. The adiabatic efficiencies refer to how the unit operates to a reversable work unit. These three parameters greatly affect the maximum thermal efficiency achievable by the PCU. The optimization occured by holding the adiabatic efficiencies constant and varying the pressure ratios. This process produced thermal efficiency curves for the cycles. Two examples of optimized cycles for varying adiabatic efficiencies for this report are shown in Figure 3.1 to Figure 3.4.

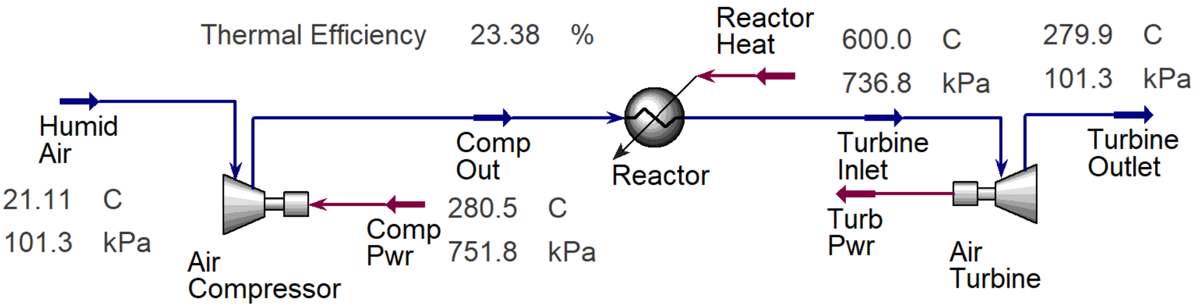


Figure 3.1 Simple Brayton Cycle with 85% Compressor and 90% Turbine Adiabatic Efficiencies with Air at 50% Relative Humidity

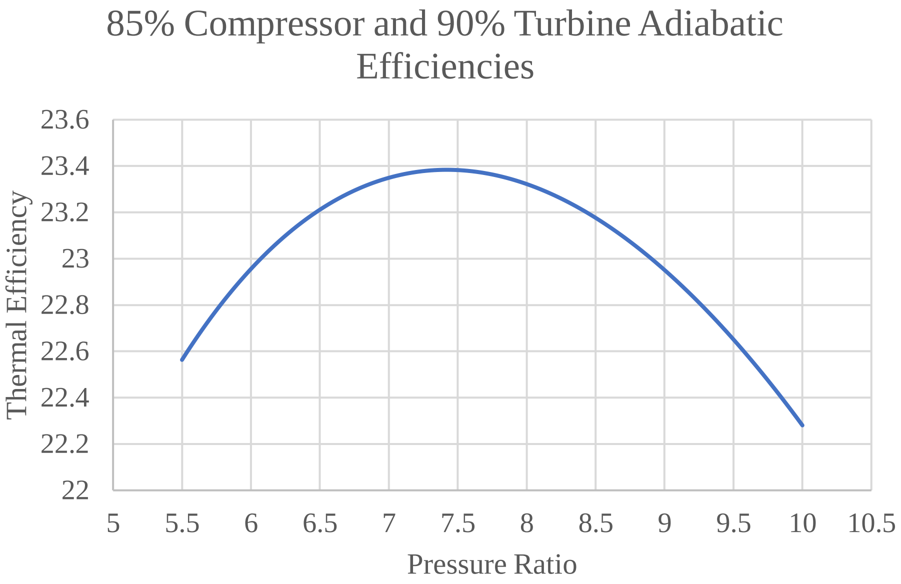


Figure 3.2 Pressure Ratio vs Thermal Efficiency Curve for the Simple Brayton Cycle with 85% Compressor and 90% Turbine Adiabatic Efficiencies with Air at 50% Relative Humidity

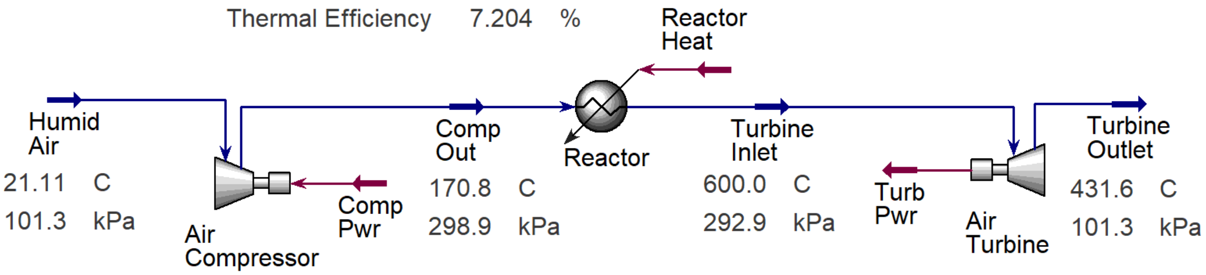


Figure 3.3 Simple Brayton Cycle with 70% Compressor and 80% Turbine Adiabatic Efficiencies with Air at 50% Relative Humidity

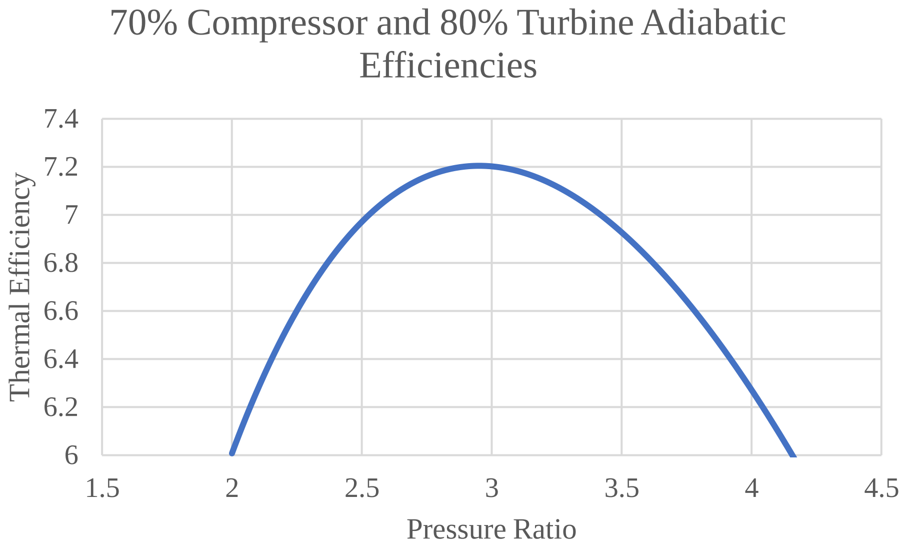


Figure 3.4 Pressure Ratio vs Thermal Efficiency Curve for the Simple Brayton Cycle with 70% Compressor and 80% Turbine Adiabatic Efficiencies with Air at 50% Relative Humidity

3.2 Physical PCU Connected to MAGNET

An auxiliary system being considered for the MAGNET is to demonstrate electrical power generation by coupling it to an appropriately sized power conversion unit (PCU). This configuration would apply a prototypical load to the system and could test the response of the heat pipe cooled reactor under a range of conditions. The current configuration of the MAGNET lends itself to the use of a recuperated Brayton cycle. Brayton cycles are common PCU cycles. A basic recuperated air Brayton cycle is shown in Figure 3.5 and this cycle draws in ambient air and compresses it. The compressed air then exchanges heat with the hot exhaust of the turbine through the recuperating heat exchanger. Recuperation reduces the temperature difference across the reactor which increases the mass flow rate of the air for a given heat load. The hot gas then expands through the turbine and is exhausted to the ambient air after traveling through the recuperating heat exchanger. This cycle more efficiently uses the hot gases leaving the turbine and has a higher mass flow rate, which increases the PCU's thermal efficiency.

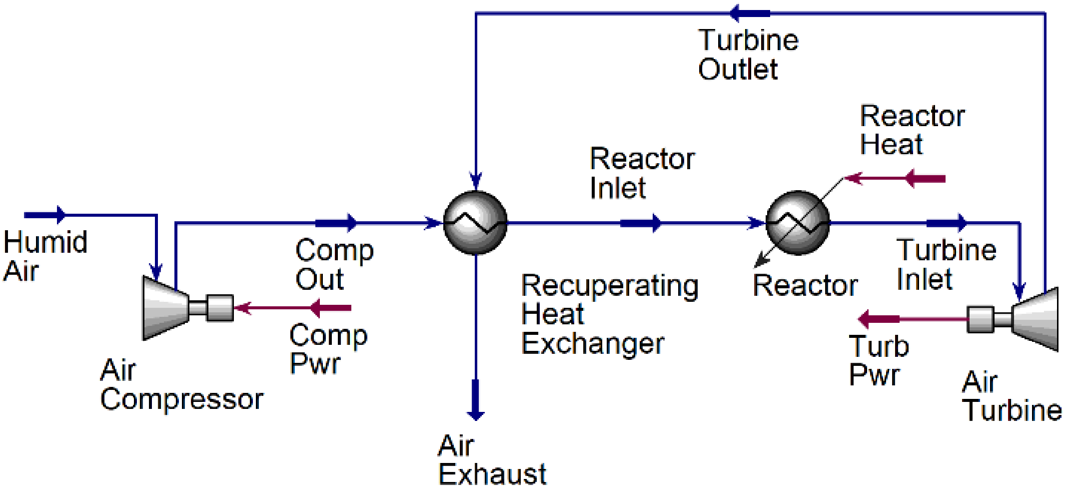


Figure 3.5 Basic Open-Air Recuperated Brayton Cycle

A similar PCU loop uses a closed loop Brayton cycle. The difference is that the turbine exhaust, once it leaves the recuperating heat exchanger, goes through a cooling unit, and then re-enters the compressor. Closed loop cycles are needed when inert gases are used, such as in the MAGNET. It can be seen in the process flow diagram of the MAGNET in Figure 2.2 that there are connections for a PCU unit. The PCU unit attached to the MAGNET would be a compressor and a turbine and it would complete a closed-loop Brayton cycle. The cycle would utilize the recuperating heat exchanger, vacuum chamber containing the heat pipes, the chiller heat exchanger, and by-pass the MAGNET compressor. The proposed configuration is shown in Figure 3.6 with the process conditions shown in Table 3.1. If the piping models and valving were removed in Figure 3.6, it would be seen that it is a standard closed loop Brayton cycle.

The PCU is assuming a compressor efficiency of 75% and a turbine efficiency of 90%. This was the same for both the helium and nitrogen models. More detailed information for both the nitrogen and helium loops are in Appendix C. Rough optimizations of the pressure, ± 50 kPa, in the MAGNET PCU loop have been performed to obtain the highest thermal efficiency. The results are in Table 3.2.

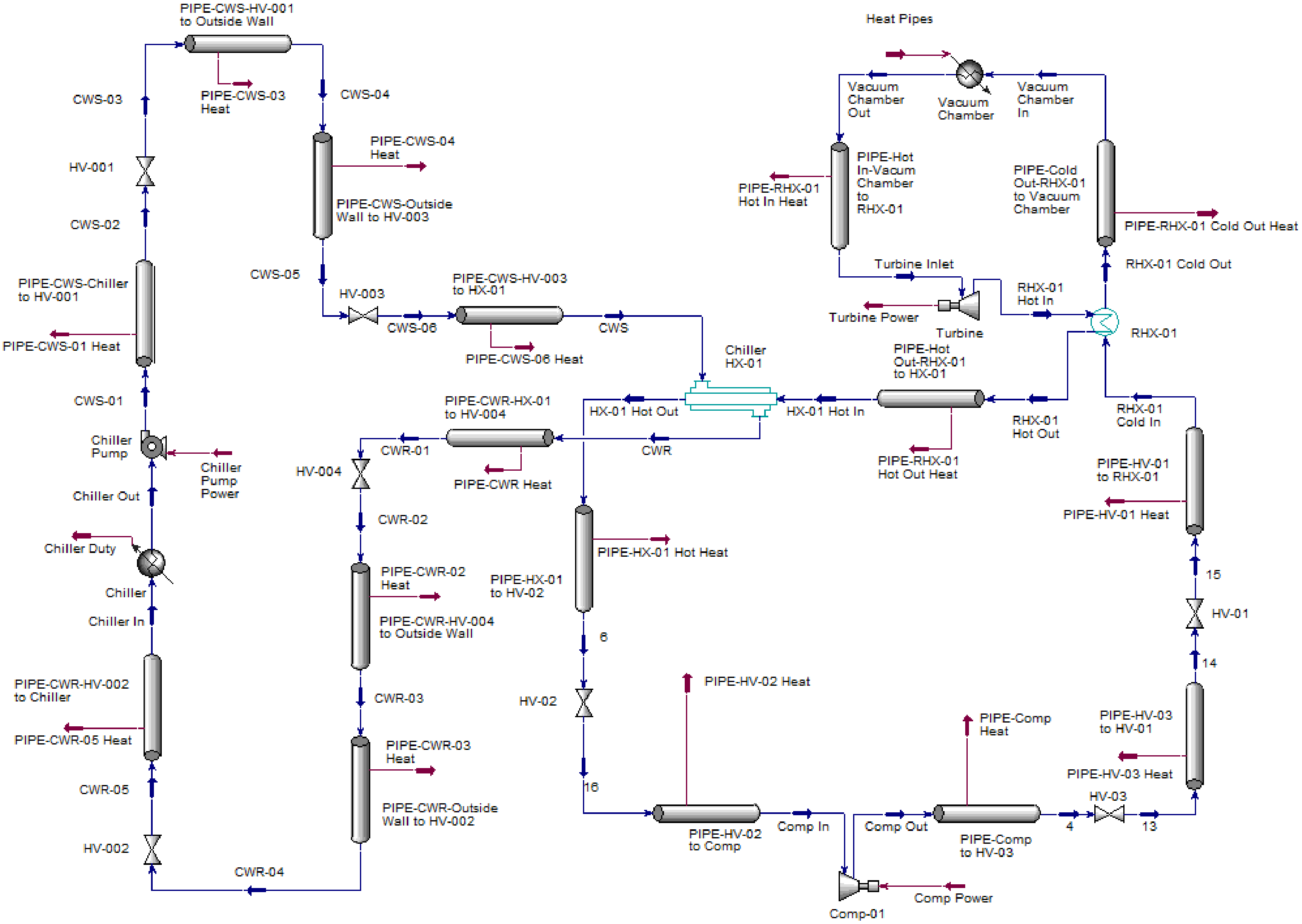


Figure 3.6 MAGNET as a Closed Loop Brayton Cycle using Nitrogen as the Working Fluid

Table 3.1 MAGNET as Closed Loop Brayton Cycle using Nitrogen as the Working Fluid Process Conditions

	Material Streams				
	HX-01 Hot In	**CWR**	**CWS**	**HX-01 Hot Out**	**RHX-01 Cold In**
Temperature (°C)	277.23	17.78	6.67	20.00	125.68
Pressure (kPa)	622.69	473.89	500.01	611.36	1277.64
Mass Flow (kg/s)	0.819	5.855	5.855	0.819	0.819
	RHX-01 Cold Out	**Vacuum Chamber In**	**Vacuum Chamber Out**	**RHX-01 Hot In**	**RHX-01 Hot Out**
Temperature (°C)	328.68	328.00	600.00	476.63	277.53
Pressure (kPa)	1268.13	1266.33	1241.00	650.00	624.11
Mass Flow (kg/s)	0.819	0.819	0.819	0.819	0.819
	Comp In	**6**	**Chiller In**	**Chiller Out**	**CWR-01**
Temperature (°C)	19.89	19.94	17.78	6.66	17.78
Pressure (kPa)	562.62	584.50	484.38	474.69	452.13
Mass Flow (kg/s)	0.819	0.819	5.855	5.855	5.855
	CWR-05	**CWR-03**	**CWR-02**	**CWS-02**	**CWS-03**
Temperature (°C)	17.78	17.78	17.78	6.66	6.66
Pressure (kPa)	484.51	451.67	451.98	518.68	518.53
Mass Flow (kg/s)	5.855	5.855	5.855	5.855	5.855
	CWS-06	**13**	**14**	**15**	**16**
Temperature (°C)	6.66	126.64	125.74	125.74	19.94
Pressure (kPa)	483.70	1295.78	1279.16	1278.57	583.54
Mass Flow (kg/s)	5.855	0.819	0.819	0.819	0.819
	Comp Out	**4**	**Turbine Inlet**	**CWS-01**	**CWS-05**
Temperature (°C)	126.77	126.64	598.28	6.66	6.66
Pressure (kPa)	1321.37	1296.38	1236.53	518.81	483.85
Mass Flow (kg/s)	0.819	0.819	0.819	5.855	5.855
	CWR-04	**CWS-04**			
Temperature (°C)	17.78	6.66			
Pressure (kPa)	484.65	484.18			
Mass Flow (kg/s)	5.855	5.855			
	Energy Streams				
	Heat Pipes	**PIPE-RHX-01 Cold Out Heat**	**PIPE-RHX-01 Hot In Heat**	**PIPE-RHX-01 Hot Out Heat**	**PIPE-HV-03 Heat**
Heat Flow (kW)	250.005997	0.6111156	1.6198487	0.256712	0.7671721

	PIPE-HX-01 Hot Heat	**PIPE-HV-02 Heat**	**Comp Power**	**Chiller Duty**	**PIPE-CWS-06 Heat**
Heat Flow (kW)	-0.0068914	-0.0006879	91.707707	225.63514	-0.028819
	PIPE-CWS-03 Heat	**PIPE-CWR-02 Heat**	**PIPE-CWR Heat**	**PIPE-CWR-05 Heat**	**PIPE-CWS-01 Heat**
Heat Flow (kW)	-0.0200234	-0.0061239	-0.0069015	-0.0114666	-0.01032
	PIPE-HV-01 Heat	**PIPE-Comp Heat**	**Turbine Power**	**Chiller Pump Power**	**PIPE-CWS-04 Heat**
Heat Flow (kW)	0.05734303	0.09239585	113.14103	0.319839	-0.02605
	PIPE-CWR-03 Heat				
Heat Flow (kW)	-0.0227997				

	Heat Exchangers	
	RHX-01	**Chiller HX-01**
Duty (kW)	180.41	225.18
LMTD (°C)	1203.27	2694.30
UA (W/°C)	147.94	13.33
Minimum Approach (°C)	149.93	83.58

Table 3.2 MAGNET PCU Nitrogen and Helium Comparison

	Compressor Power (kW)	Turbine Power (kW)	Total Power (kW)	Compressor Pressure Ratio	Turbine Pressure In (kPa)	Turbine Pressure Out (kPa)	Mass Flow (kg/s)	Heat Pipe (kW)	Thermal Efficiency
N2	91.7	113	21.3	2.35	1237	650	0.819	250	8.57%
He	132	171	39	2.06	1239	675	0.194	250	15.50%

3.3 Power Conversion Unit Simulator

The MAGNET has a goal to provide a testbed that is broadly applicable to multiple microreactor concepts. Keeping that in mind, the second auxiliary system for the MAGNET is a PCU simulator. An advantage of using a PCU simulator over a physical PCU is that the simulator can simulate many different PCU cycles at varying process parameters. The main parameter that could be changed are the adiabatic efficiencies of the compressors and the turbines. The simulator can also simulate various transient conditions as well as start up and shut down state points. This is advantageous as it can show how these various cycles could influence the performance of the tested reactor type.

To reiterate, the first microreactor to be studied within the MAGNET is a heat-pipe cooled reactor. The MAGNET has the following specification (Guillen, et al., 2019):

- Power: nominal 250 kWth.

Figure 3.7 shows an iteration of a process flow diagram of INL's MAGNET that the PCU simulator's design was based on (O'Brien, 2019). This iteration of the testbed was designed to reach a temperature of 600°C and a pressure of 1050 kPa, instead of 1241 kPa as discussed in earlier chapters. The working fluid within the loop is currently designed to operate with nitrogen; while in the future, designs may change to use helium operating at a temperature of 850°C. A simplified MAGNET Aspen HYSYS process model designed around Figure 3.7 is shown in Figure 3.8. The Aspen HYSYS model estimates the pressure loss in the equipment as well as the heat loss from the piping. The values within INL's process diagram and those within the Aspen HYSYS model match closely.

A PCU simulator has been designed. The design accounts for air Brayton, recuperated air Brayton, and recuperated helium cycles. Currently, the MAGNET is not designed to operate at the higher helium cycle temperatures because the equipment for the simulator was not specified to handle the higher temperatures. The super critical CO2 cycle was not considered because the MAGNET will not operate at sufficient pressures to test the cycle. Bottoming cycles like organic Rankine cycles (ORC) are also not being considered as they do not interface directly with the microreactor. However, an ORC could be simulated from process conditions of a Brayton cycle model that is connected to a bottoming ORC. These conditions could show additional impact on the MAGNET. The layout of the PCU simulator is shown in Figure 3.9. The theory and process of design are discussed in further sections.

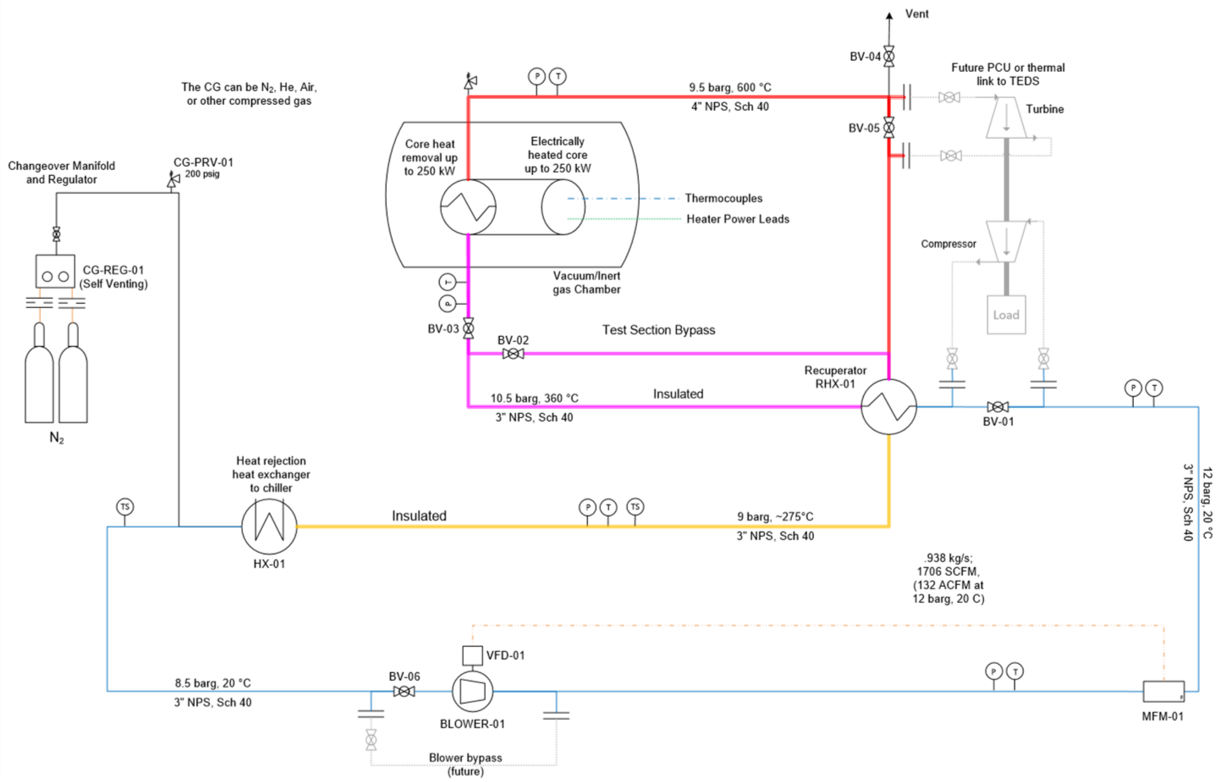


Figure 3.7 Process Flow diagram of INL's Microreactor AGile Non-nuclear Experimental Testbed for PCU Simulator (O'Brien, 2019)

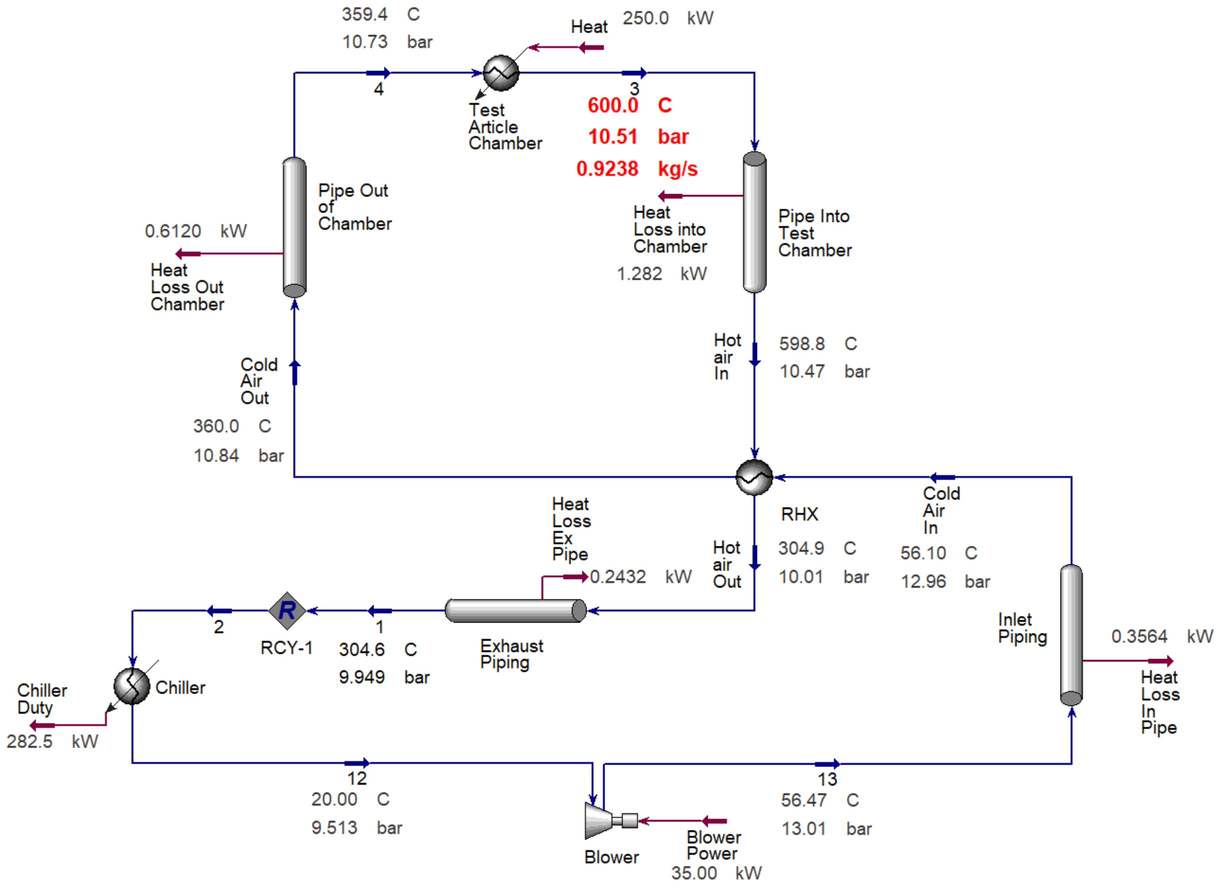


Figure 3.8 Aspen HYSYS Process Model of Microreactor AGile Non-nuclear Experimental Testbed for PCU Simulator

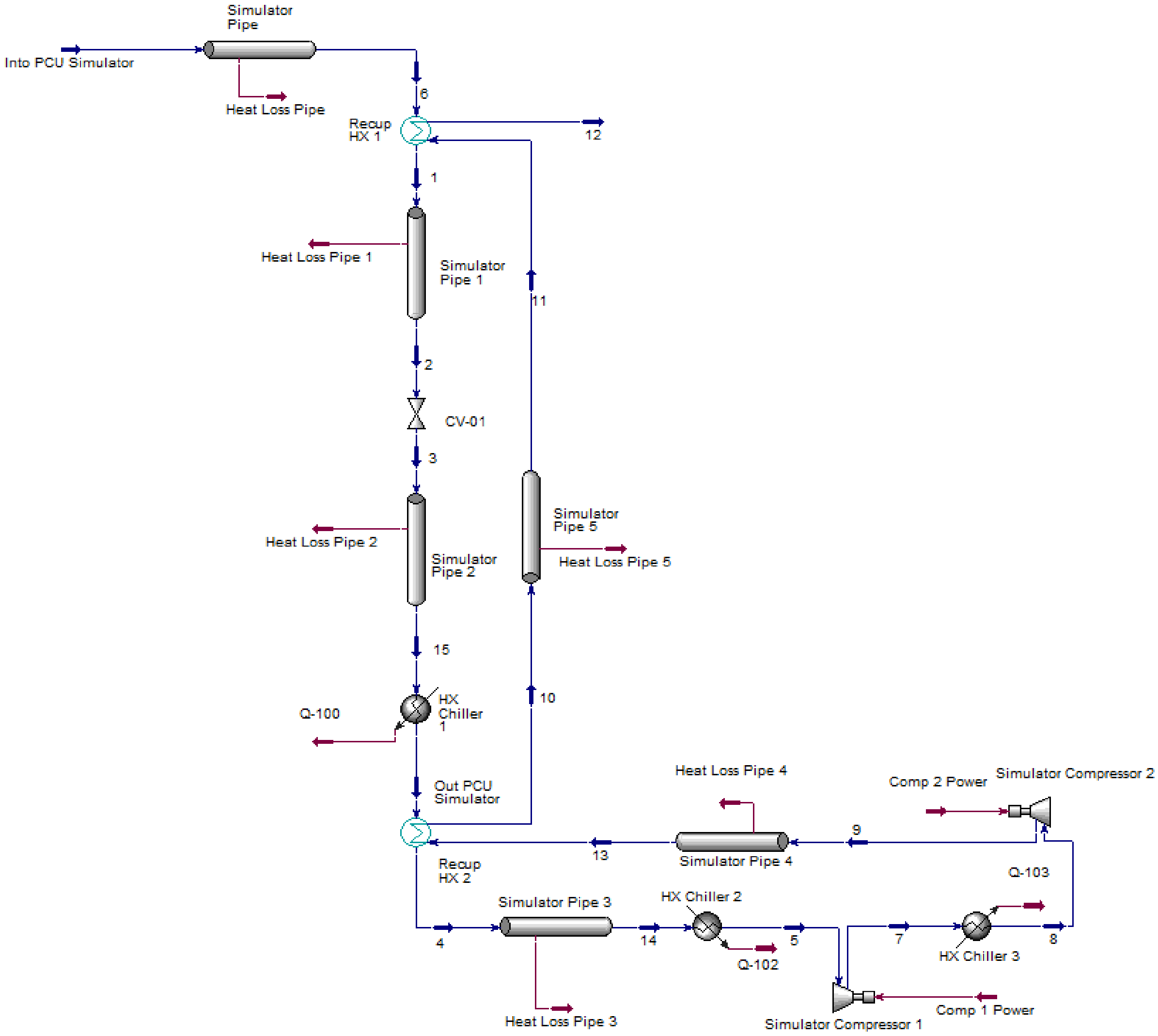


Figure 3.9 Power Conversion Unit Simulator Layout

3.3.1 Power Conversion Unit Simulator Theory

A PCU simulator has been designed to attach to the MAGNET as a plug-and-play system as shown in Figure 3.9. The simulator's design is drawn from optimized open Brayton cycles, both recuperative and non-recuperative. First, some theory is needed to understand how the PCU simulator was designed to mimic the conditions of an actual PCU.

A simplified open Brayton cycle consists of three or four components, depending if the cycle is recuperated or not; a compressor, turbine, heat source, and a heat exchanger (Çengel & Boles, 2011). The heat source could be combustion, nuclear power, or electrical heaters (this is the case in the MAGNET). The working fluid, typically air, in an open Brayton cycle follows this process:

1. Air is drawn from ambient conditions and pressurized through the compressor.
2. The compressed air is pre-heated through a recuperating heat exchanger (if recuperation is used).
3. The compressed air is fully heated through the heat source.
4. It is then expanded through the turbine which lowers the pressure and temperature of the air.
5. The hot air then exchanges heat with the compressed air in a recuperating heat exchanger (if recuperation is used).
6. The air is then exhausted out of the system.

Simplified process flow diagrams for both non-recuperated and recuperated open Brayton cycles are shown in Figure 3.10 and Figure 3.11, respectively.

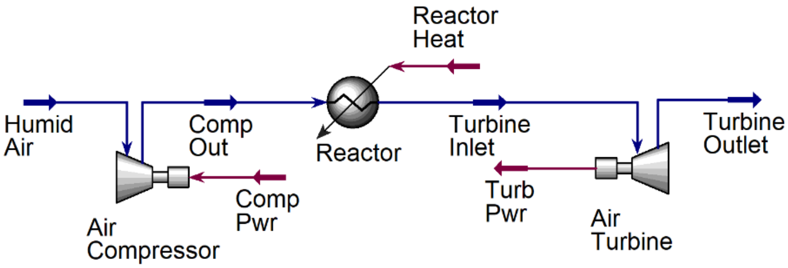


Figure 3.10 Process Flow Diagram of Open Brayton Cycle

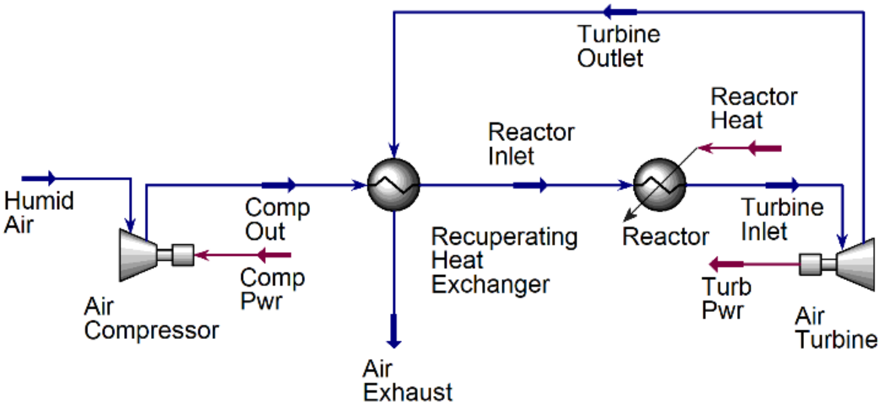


Figure 3.11 Process Flow Diagram of Open Recuperated Brayton Cycle

Simulating the open Brayton cycle requires certain conditions to be mimicked. The equations that govern the compressor and the turbine are derived from the first and second laws of thermodynamics. Equation 3.1 show the first law. Simplifications of neglecting potential and kinetic energy, steady-state and steady flow conditions, conservation of mass, and an adiabatic process are applied to Equation 3.1 to obtain Equation 3.2. For the cycles under consideration, the working fluids are ideal gases. Therefore, ideal gas relations, such as Equation 3.3 and Equation 3.4, may be used to clarify how the cycles can be simulated within the test loop. This is a valid assumption for nitrogen, air, and helium since they behave like ideal gases at the operating conditions found within the MAGNET. The final governing equations for the compressor and turbine are shown in Equation 3.9 and Equation 3.10.

$$\dot{Q} - \dot{W} = \sum \dot{m}(h + PE + KE)_e - \sum \dot{m}(h + PE + KE)_i$$ ***Equation 3.1***

$$-\dot{W}_{act} = \dot{m}(h_e - h_i)$$ ***Equation 3.2***

$$(h_e - h_i) = C_p(T_e - T_i)$$ ***Equation 3.3***

$$T_{e,s} = T_i \left(\frac{P_e}{P_i}\right)^{\frac{\gamma-1}{\gamma}}$$ ***Equation 3.4***

$$\dot{W}_{rev} = \dot{m}C_p\left(T_i - T_{e,s}\right) = \dot{m}C_p\left(T_i - T_i\left(\frac{P_e}{P_i}\right)^{\frac{\gamma-1}{\gamma}}\right)$$ ***Equation 3.5***

$$= \dot{m}C_pT_i\left(1 - \left(\frac{P_e}{P_i}\right)^{\frac{\gamma-1}{\gamma}}\right)$$

$$\dot{W}_{turb,act} = \eta_{turb}\dot{W}_{turb,rev}$$ ***Equation 3.6***

$$\dot{W}_{comp,act} = \frac{\dot{W}_{comp,rev}}{\eta_{comp}}$$ ***Equation 3.7***

$$\frac{C_p}{R} = \frac{\gamma}{\gamma - 1}$$ ***Equation 3.8***

$$\dot{W}_{turb,act} = \dot{m}RT_i\eta_{turb}\left(\frac{\gamma}{\gamma - 1}\right)\left[1 - \left(\frac{P_e}{P_i}\right)^{\frac{\gamma-1}{\gamma}}\right]$$ ***Equation 3.9***

$$\dot{W}_{comp,act} = \frac{\dot{m}RT_i}{\eta_{comp}}\left(\frac{\gamma}{\gamma - 1}\right)\left[1 - \left(\frac{P_e}{P_i}\right)^{\frac{\gamma-1}{\gamma}}\right]$$ ***Equation 3.10***

Where:

$\dot{W}_{act}$ → Actual Power for Turbine/Compressor

$\dot{m}$ → Mass Flow Rate

R → Individual Gas Constant

T_i → Inlet Temperature

η → Adiabatic Efficiency of Turbine/Compressor

γ → Specific Heat Ratio

P_i → Inlet Pressure

P_e → Outlet Pressure

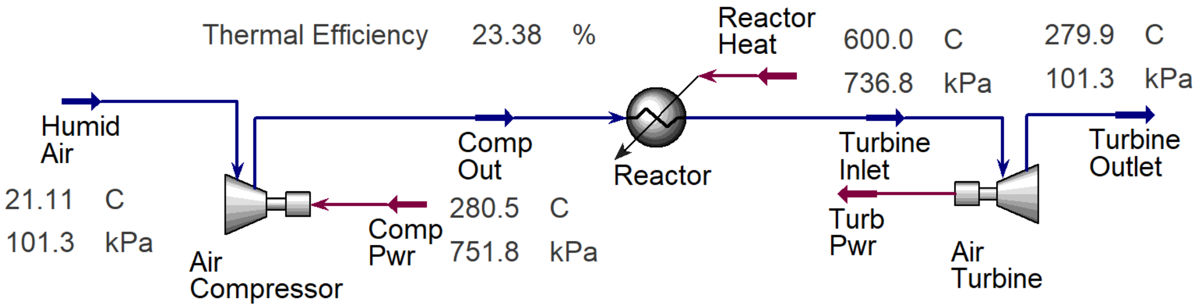
The relationships shown in Equation 3.4 and Equation 3.9 reveal that the working fluid in a turbine undergo two major changes for positive work: a drop in temperature and pressure. Therefore, simulating a turbine must include a pressure and temperature drop. Equation 3.9 also shows that the work done is a strong function of the pressure ratio. By maintaining the pressure ratio, the PCU simulator can simulate an actual field PCU while maintaining the conditions provided by the MAGNET. This also agrees with McKellar et al’s finding that Brayton cycles have an optimal pressure ratio for a given set of inlet turbine conditions. Keeping the optimal pressure ratio with the same turbine inlet conditions maintains the optimal cycle (McKellar, Boardman, Bragg-Sitton, & Sabharwall, 2018). To show this is the case, standard optimized Brayton cycles were compared to modified Brayton cycles using the desired outlet conditions of the MAGNET vacuum chamber. This analysis is shown in the next section.

3.3.2 Modified Power Conversion Units for the MAGNET

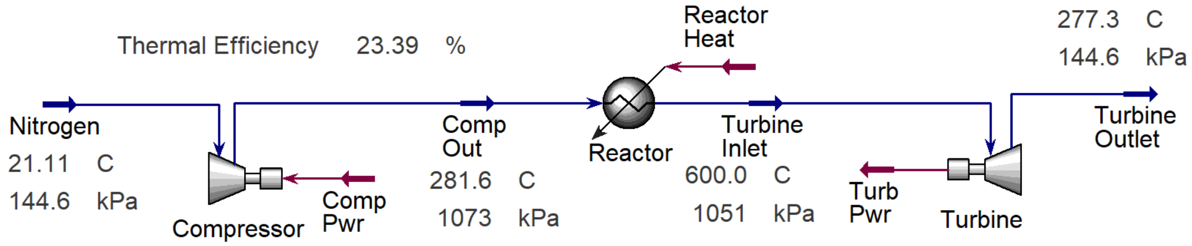
The work in the section was performed primarily by Dr Michael McKellar with assistance from Clayton Turner. It is, however, needed for the development of the power conversion unit simulator.

Analyses have been performed on optimized power cycles using expected operating conditions for a heat pipe cooled nuclear reactor. The optimized power cycles were then compared to MAGNET conditions using the same working fluid. During the optimization process, the power cycles used 600°C as the turbine inlet temperature. Two cases of the air Brayton cycle were analyzed, and their thermal efficiencies were optimized by adjusting the compressor outlet pressure. The first case used compressor and turbine efficiencies of 70% and 80%, respectively; the second used compressor and turbine efficiencies of 85% and 90%, respectively. Both cases used ambient air for the compressor inlet at 21.1°C, 1 atmosphere, and 50% humidity for the field PCUs. The modified PCU used nitrogen and MAGNET conditions at the test chamber outlet. When the helium PCUs were compared, both the field and the modified PCUs used helium. As shown in Figure 3.12 and Figure 3.13, the pressures do not match but the pressure ratios do. The temperatures throughout the cycles and the thermal efficiencies are very close. The pressure ratio has a stronger influence on the efficiency of the cycles than the magnitudes of the absolute pressures or pressure differences. Also, because air is 78% nitrogen by mole fraction, using nitrogen instead of air has little effect on the performance of the cycle. The case studies with the recuperated air Brayton cycles had the same conclusions about the pressure ratio, see Figure 3.14 and Figure 3.15.

The recuperated helium Brayton cycle was also analyzed. A new Aspen HYSYS model of the MAGNET was developed to estimate the performance of the testbed with a high temperature of 850°C, keeping the pressure at 1051 kPa, see Figure 3.16. As with the air cases, the helium Brayton cycles have temperatures and thermal efficiencies close to one another regardless of the pressure magnitudes if the pressure ratios remain the same. This is shown in Figure 3.17 and Figure 3.18. All the models shown in this section are found in Appendix G: Aspen HYSYS Power Cycle Models for the Development of PCU Test Loop for Micro-Reactor Testbed.

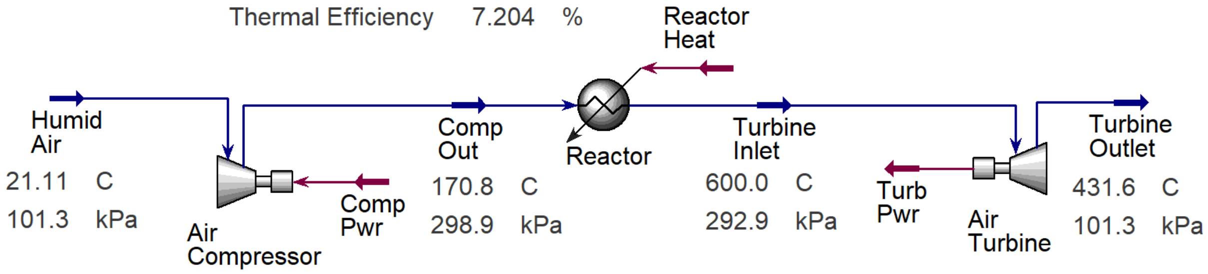


a. Open Air Brayton Cycle

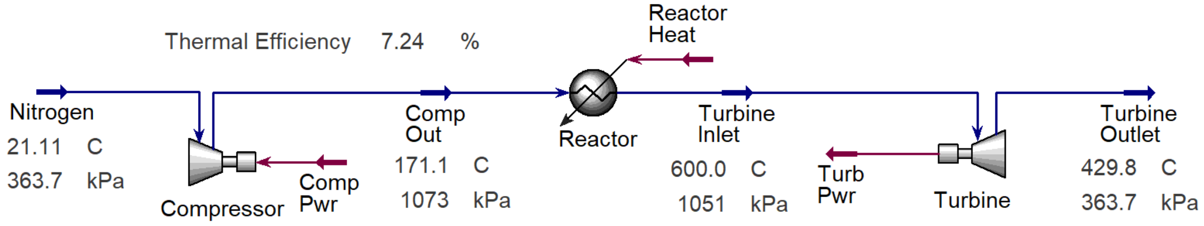


b. Open Nitrogen Brayton Cycle

Figure 3.12 Comparison of Open Brayton Cycles: One with Air at Expected Operating Conditions, the Other with Nitrogen using MAGNET Conditions into the Turbine. Turbine and Compressor Adiabatic Efficiencies are 85% and 90%, Respectively

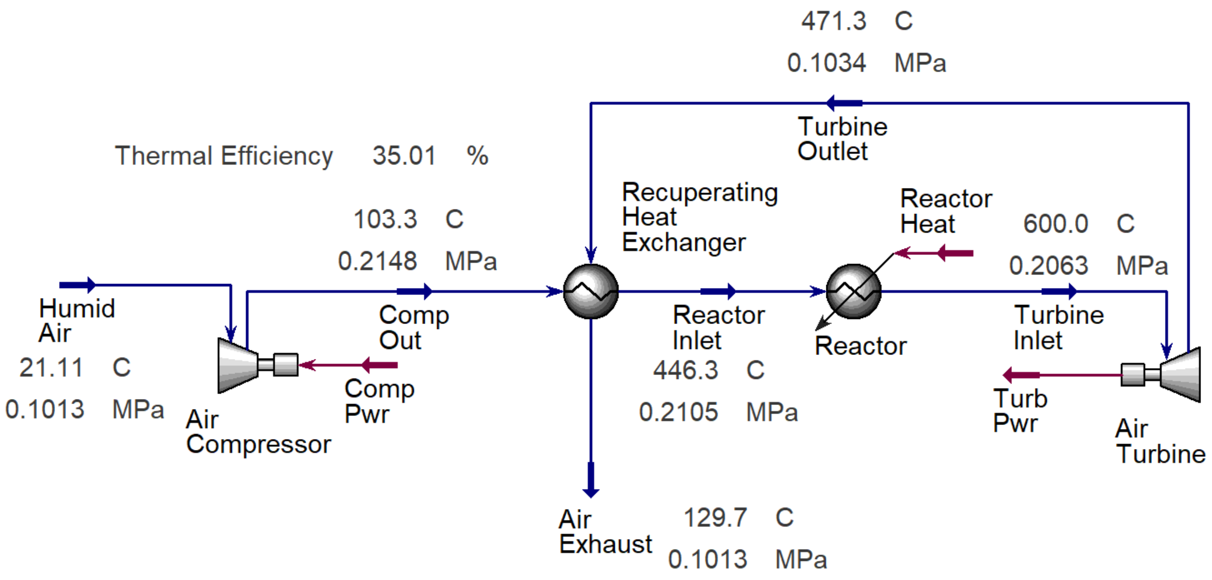


a. Open Air Brayton Cycle

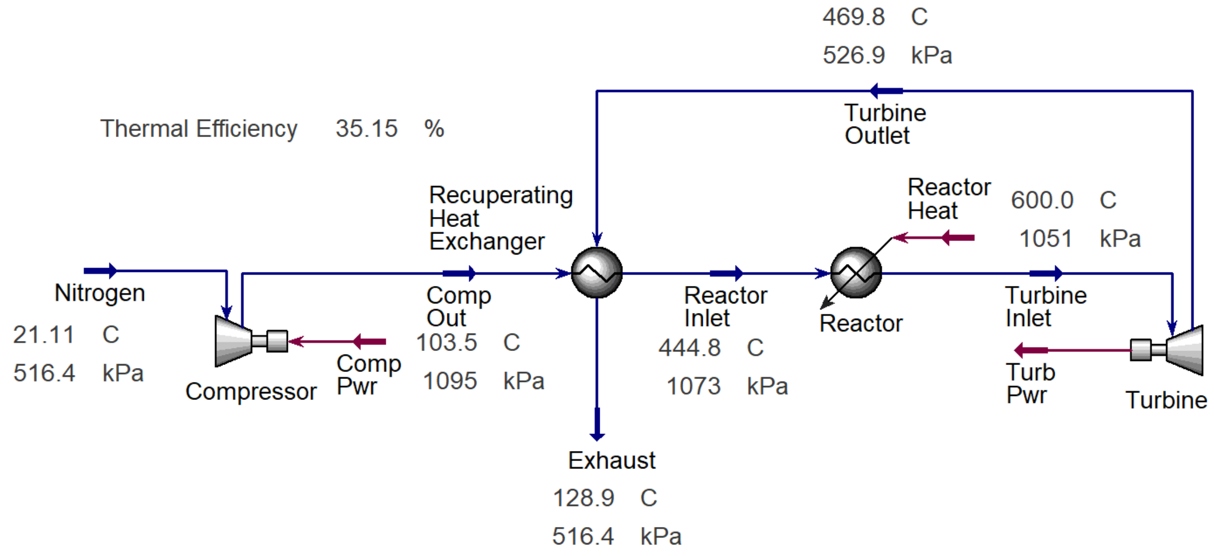


b. Open Nitrogen Brayton Cycle

Figure 3.13 Comparison of Open Brayton Cycles: One with Air at Expected Operating Conditions, the Other with Nitrogen using MAGNET Conditions into the Turbine. Turbine and Compressor Adiabatic Efficiencies are 70% and 80%, Respectively

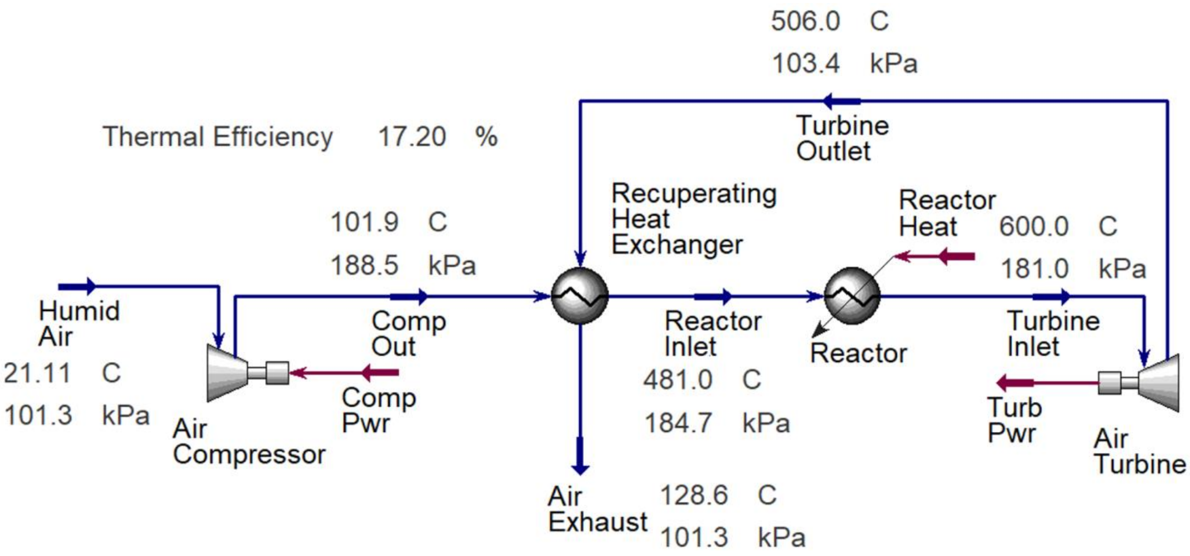


a. Open Recuperated Air Brayton Cycle

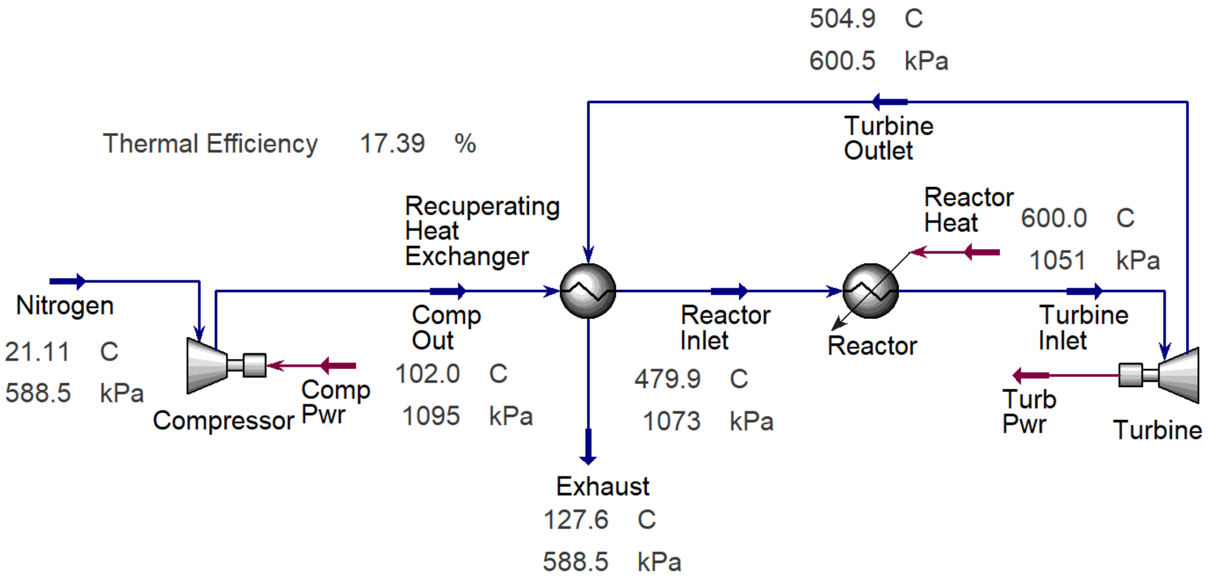


b. Open Recuperated Nitrogen Brayton Cycle

Figure 3.14 Comparison of Recuperated Open Brayton Cycles: One with Air at Expected Operating Conditions, the Other with Nitrogen using MAGNET Conditions into the Turbine. Turbine and Compressor Adiabatic Efficiencies are 85% and 90%, Respectively



a. Open Recuperated Air Brayton Cycle



b. Open Recuperated Nitrogen Brayton Cycle

Figure 3.15 Comparison of Open Recuperated Brayton Cycles: One with Air at Expected Operating Conditions, the Other with Nitrogen using MAGNET Conditions into the Turbine. Turbine and Compressor Adiabatic Efficiencies are 70% and 80%, Respectively

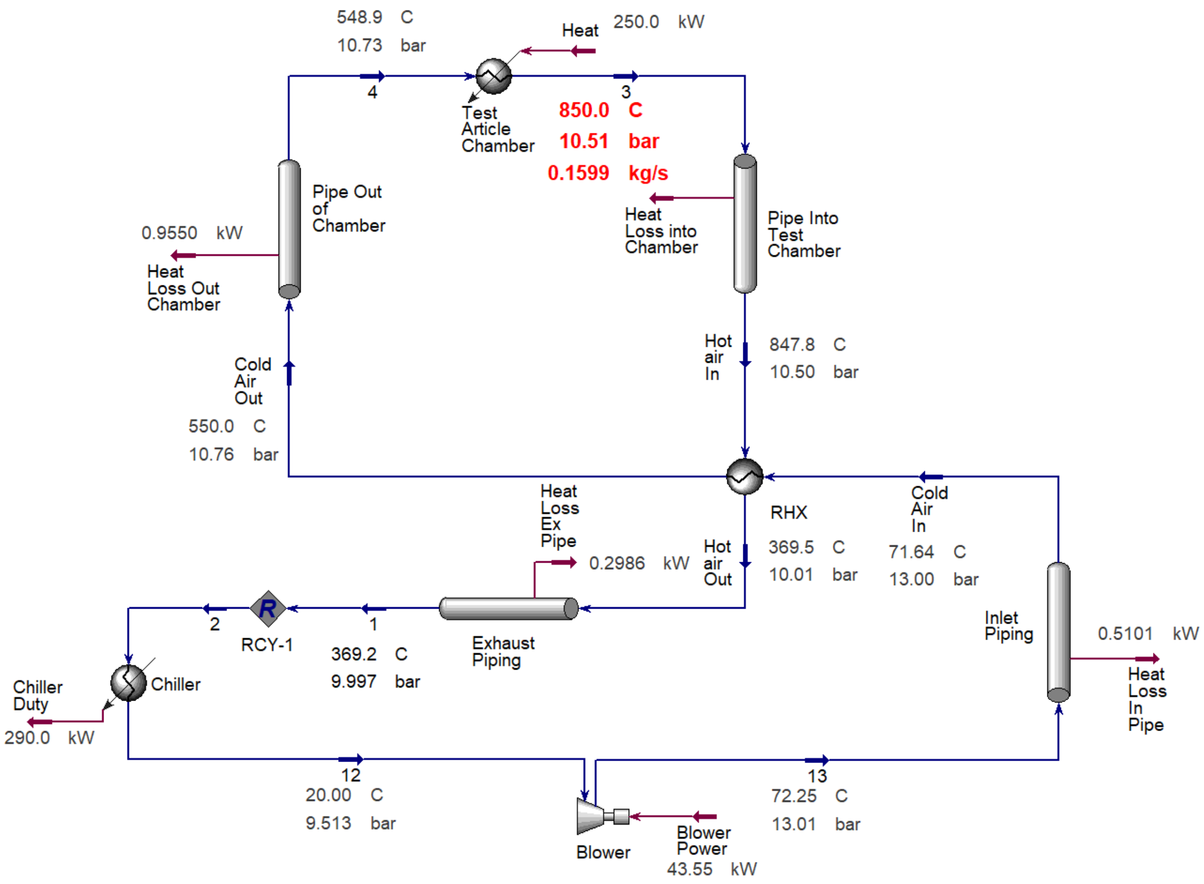
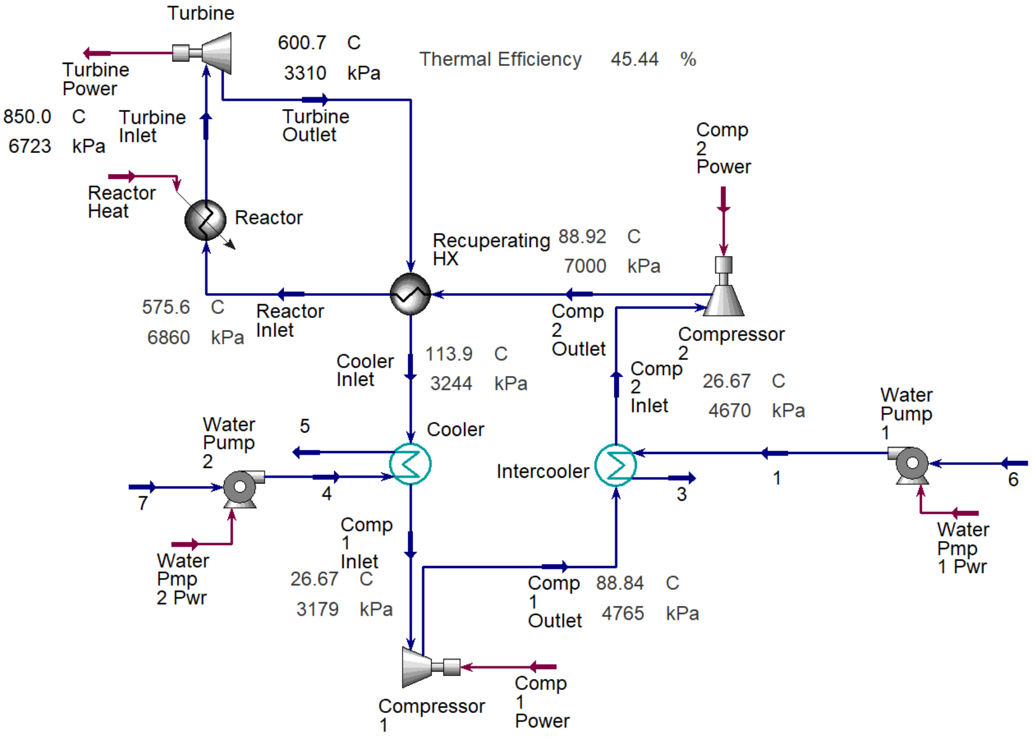
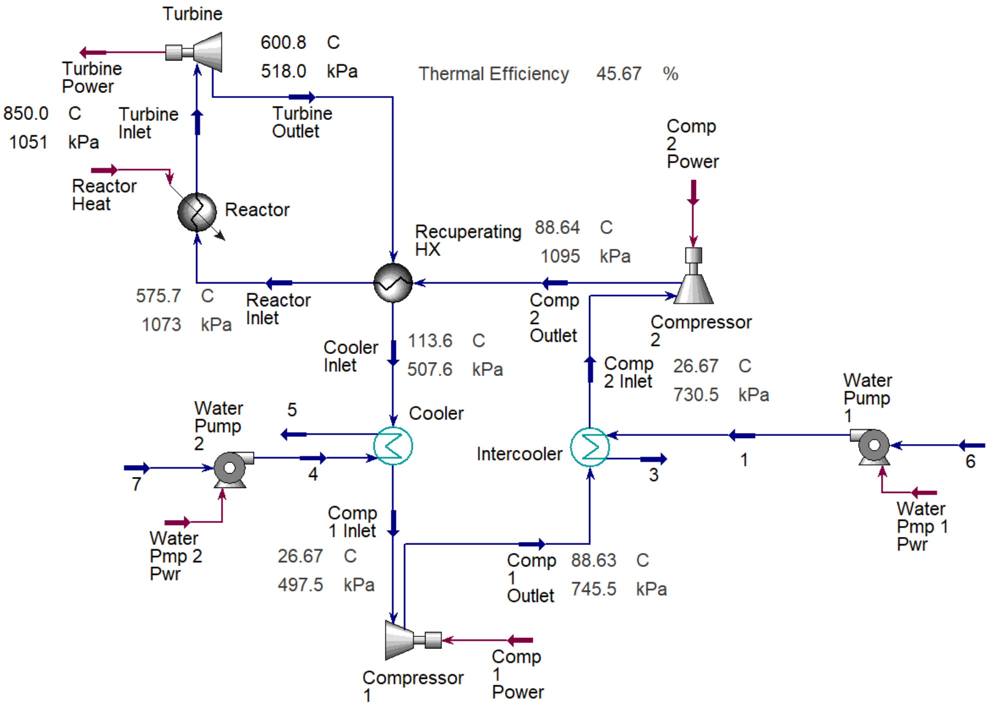


Figure 3.16 Aspen HYSYS Process Model of Microreactor AGile Non-nuclear Experimental Testbed with Helium

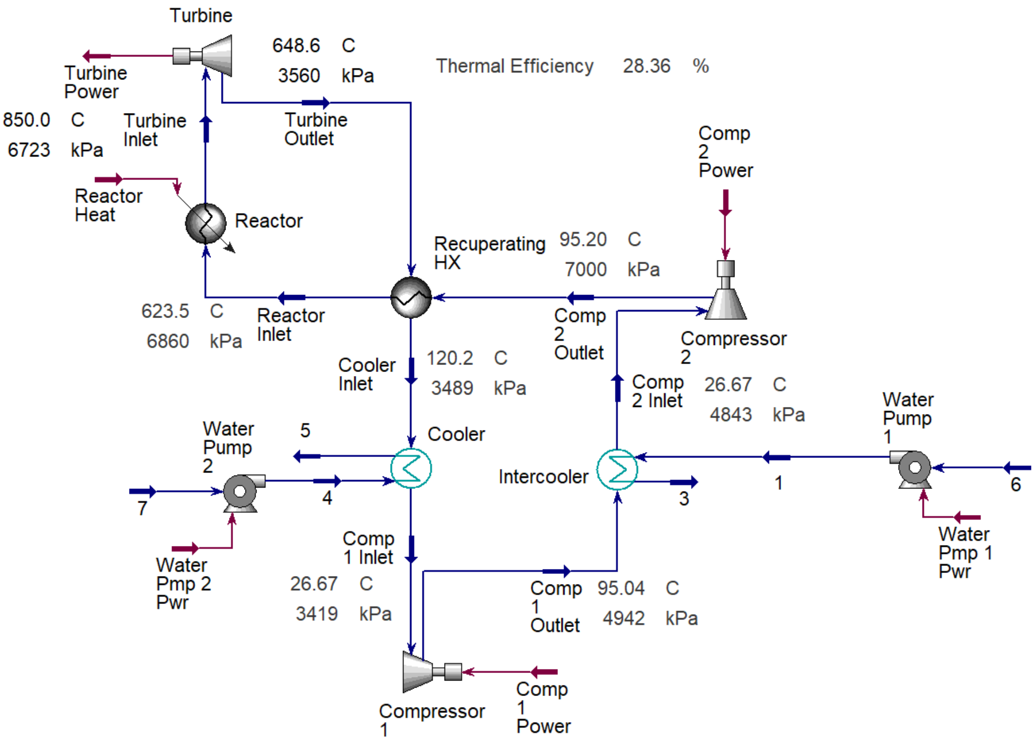


a. Helium Recuperated Closed Brayton Cycle at Operating Conditions

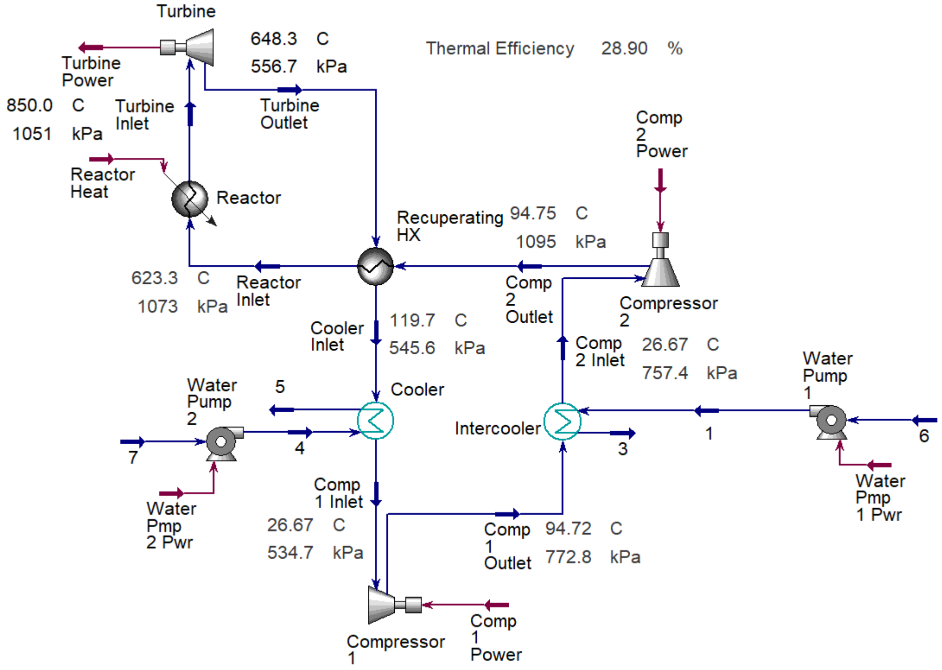


b. Helium Recuperated Close Brayton Cycle at MAGNET Conditions

Figure 3.17 Comparison of Recuperated Helium Brayton Cycles: One at Expected Operating Conditions, the Other using MAGNET Conditions into the Turbine. Turbine and Compressor Adiabatic Efficiencies are 85% and 90%, Respectively



a. Helium Recuperated Closed Brayton Cycle at Operating Conditions



b. Helium Recuperated Close Brayton Cycle at MAGNET Conditions

Figure 3.18 Comparison of Recuperated Helium Brayton Cycles: One at Expected Operating Conditions, the Other using MAGNET Conditions into the Turbine. Turbine and Compressor Adiabatic Efficiencies are 70% and 80%, Respectively

3.3.3 Power Conversion Unit Simulator Design

To simulate a power conversion unit within the MAGNET, the simulator needs to undergo a pressure drop and heat exchange. It is assumed that the gas turbine and compressor unit simulated were axial. A process model of the PCU simulator without temperature control ability was developed in Aspen HYSYS, see Figure 3.19. The process of this PCU simulator is described as follows: the model uses a high temperature recuperating heat exchanger to simulate the temperature drop. A control valve was used to simulate the pressure drop. A low temperature recuperating heat exchanger was used to lower the temperature more before the entering a chiller unit. The chiller unit controls the temperature entering the compressor. The use of recuperating heat exchangers instead of chiller units was to reduce the required duty of the chiller and to recover lost heat. The fluid is then compressed back to the pressure of the MAGNET and travels back through recuperating heat exchangers. The gas then reenters the MAGNET.

Each PCU case was considered independently from the others to determine the sizes of the heat exchangers, compressors, and valves unique to each simulated PCU. An assumption was made for each model that each recuperating heat exchanger had a minimum approach near 25°C. This made the results comparable. By comparing the cases, sizes of the components were selected so that all the PCUs considered could be simulated with the PCU simulator. The simulation of the six Brayton cycle cases are shown in Figure 3.19 through Figure 3.24. Detailed process information about sizing of the PCU Simulator can be found in Appendix H. The PCU simulator was designed to simulate the PCU turbine. However, by also specifying the inlet temperature into the MAGNET vacuum chamber, the cycle's compression side may also be simulated. Thus, by knowing the pressures and temperatures at the three key points (the inlet and outlet of the turbine simulator and into the MAGNET test chamber) will uniquely identify the cycle under consideration. Therefore, the simulator can simulate not only the design conditions but also the key state points of transient operations such as the start up and shutdown of a PCU. A start up analyses of a non-recuperated heat pipe Brayton cycles and their key state points are discussed in Chapter 4.

It should be noted that the nitrogen Brayton cycle at high turbine and compressor efficiencies uses two identical compressors. This splits the pressure ratio from 7.65 down to

2.79 for each compressor, which put the pressure ratio more in line with the other PCU cycles. Two compressors also reduce the size and cost of a single compressor and makes the compressor more realistic. Table 3.3 shows the compression ratios needed to achieve an accurate simulation of the PCU cycles.

The valves, compressors, and heat exchanger sizing information for each case analyzed for the PCU simulator are given in Table 3.4 through Table 3.6. These tables show the maximum and minimum conditions for the valves, compressors, and heat exchangers. The critical information is shown in red. It is shown that the largest required pressure ratio and the largest duty for HX chiller 2 occur when simulating the nitrogen Brayton cycle at high turbine and compressor efficiencies. When simulating the nitrogen Brayton cycle at low turbine and compressor efficiencies, the simulator compressor requires the most power and HX chiller 1 has the largest duty. The lowest duty for Recup HX1 and the highest duty for Recup HX2 are found simulating the recuperated nitrogen Brayton cycle with low compressor and turbine efficiencies. The desired sizing of each component is discussed in the next section.

Table 3.3 Compressor Ratios of PCU Cycle and PCU Simulator

	Compression Ratio	2 Compressor Pressure Ratio
Air Brayton Cycle with η_{comp} = 85% and η_{turb} = 90%	7.65	2.79
Air Brayton Cycle with η_{comp} = 70% and η_{turb} = 80%	3.14	3.14
Recuperated Air Brayton Cycle with η_{comp} = 85% and η_{turb} = 90%	2.55	2.55
Recuperated Air Brayton Cycle with η_{comp} = 70% and η_{turb} = 80%	1.85	1.85

Table 3.4 Valve Sizing for PCU Simulator Pressure Drop

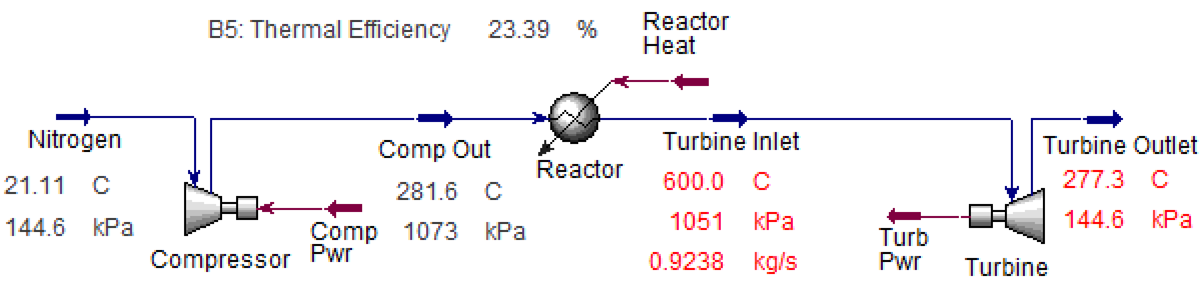
Simulated Cycle	Turbine Efficiency	Compressor Efficiency	Cg	Cv (USGPM: 60F, 1 psi)	Pressure Drop (kPa)
Nitrogen Brayton Cycle	85%	90%	1832	54.7	881
	70%	80%	2096	62.3	665
Recuperated Nitrogen Brayton Cycle	85%	90%	2220	66.3	501
	70%	80%	2353	70.3	427
Modified Recuperated Helium Brayton Cycle	85%	90%	2200	66.3	507
	70%	80%	2220	66.3	467

Table 3.5 Sizing of PCU Simulator Compressor

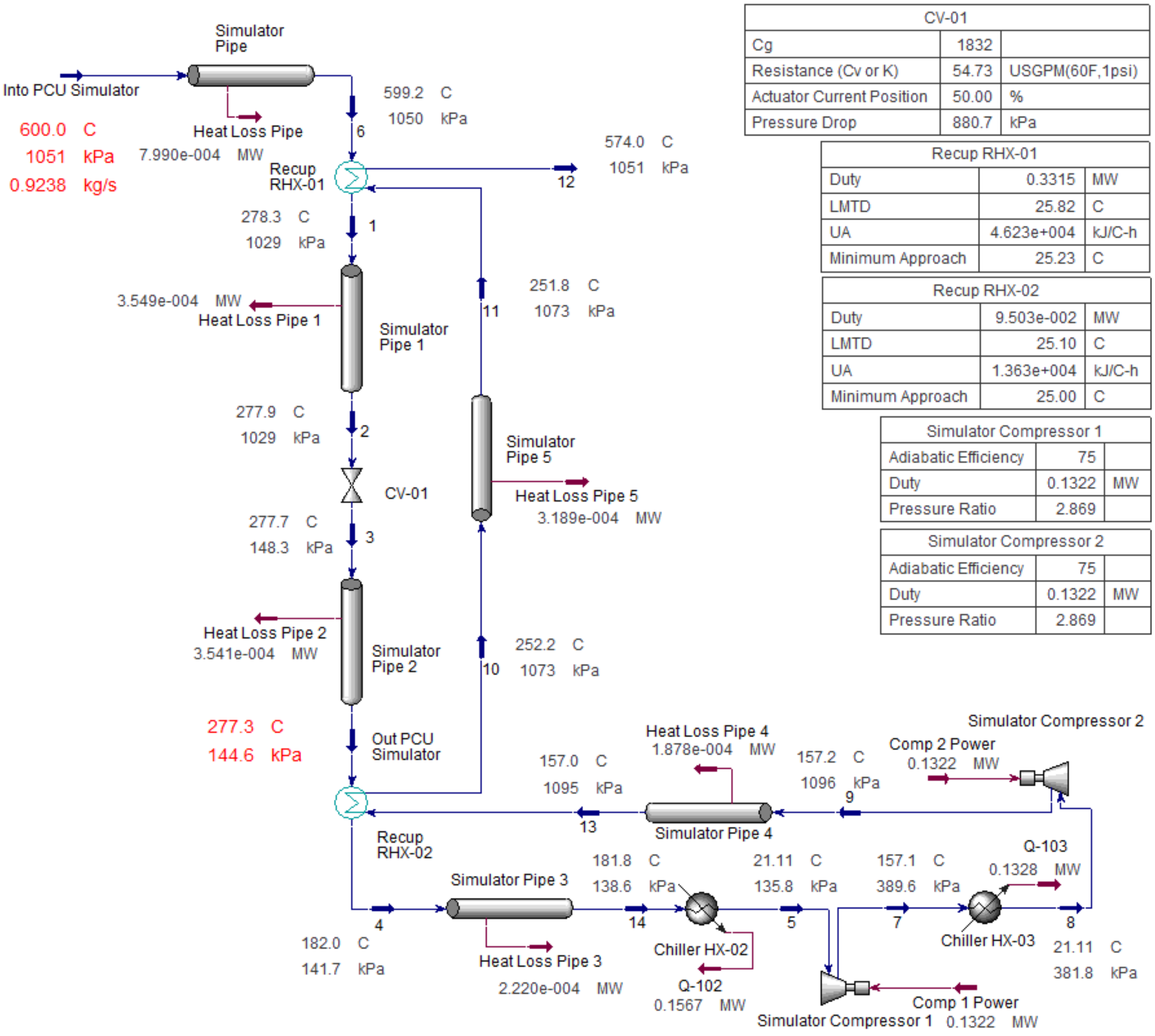
Simulated Cycle	Turbine Efficiency	Compressor Efficiency	Simulator Compressor		Simulator Compressor 2	
			Power (MW)	Pressure Ratio	Power (MW)	Pressure Ratio
Nitrogen Brayton Cycle	85%	90%	0.132	2.87	0.132	2.87
	70%	80%	0.145	3.14	0	0
Recuperated Nitrogen Brayton Cycle	85%	90%	.00931	2.17	0	0
	70%	80%	.00758	1.90	0	0
Modified Recuperated Helium Brayton Cycle	85%	90%	0.121	2.20	0	0
	70%	80%	0.108	2.05	0	0

Table 3.6 Sizing of Chiller and Recuperating Heat Exchangers for PCU Simulator

Simulated Cycle	Turbine Efficiency	Compressor Efficiency	Recup RHX1 (MW)	Recup RHX2 (MW)	Chiller HX-02 (MW)	Chiller HX-03 (MW)
Nitrogen Brayton Cycle	85%	90%	0.332	0.0095	0.157	0.133
	70%	80%	0.176	0.237	0.170	0
Recuperated Nitrogen Brayton Cycle	85%	90%	0.135	0.331	0.119	0
	70%	80%	0.00979	0.385	0.101	0
Modified Recuperated Helium Brayton Cycle	85%	90%	0.205	0.34	0.142	0
	70%	80%	0.165	0.392	0.129	0



a. Open Nitrogen Brayton Cycle



CV-01		
Cg	1832	
Resistance (Cv or K)	54.73	USGPM(60F,1psi)
Actuator Current Position	50.00	%
Pressure Drop	880.7	kPa

Recup RHX-01		
Duty	0.3315	MW
LMTD	25.82	C
UA	4.623e+004	kJ/C-h
Minimum Approach	25.23	C

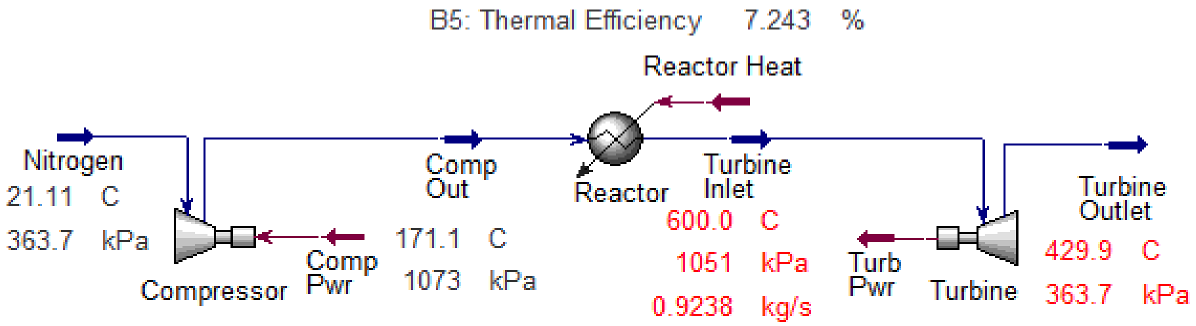
Recup RHX-02		
Duty	9.503e-002	MW
LMTD	25.10	C
UA	1.363e+004	kJ/C-h
Minimum Approach	25.00	C

Simulator Compressor 1		
Adiabatic Efficiency	75	
Duty	0.1322	MW
Pressure Ratio	2.869	

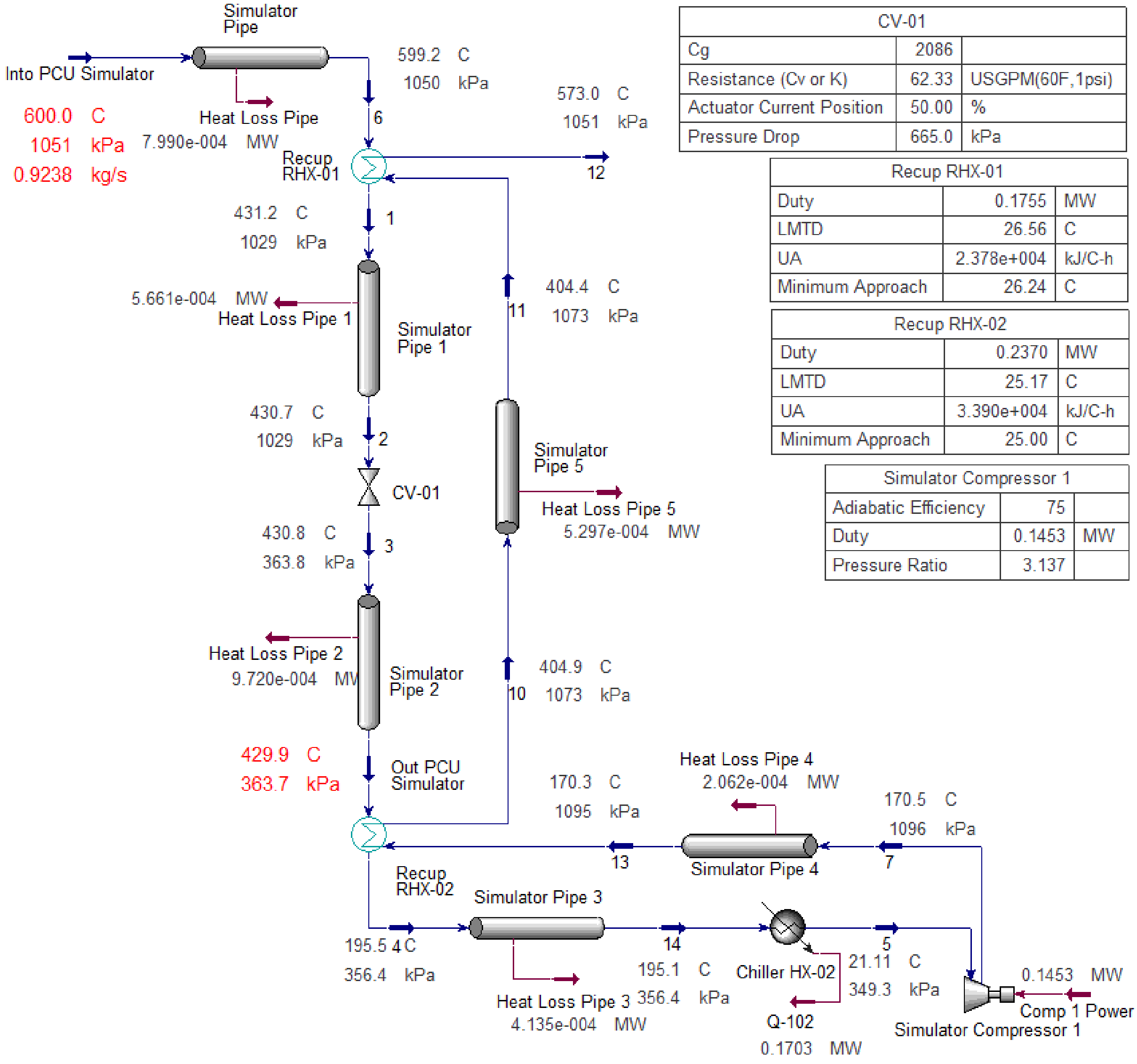
Simulator Compressor 2		
Adiabatic Efficiency	75	
Duty	0.1322	MW
Pressure Ratio	2.869	

b. PCU Simulation of Open Nitrogen Brayton Cycle

Figure 3.19 MAGNET PCU Simulation Loop for Nitrogen Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 85% and 90%



a. Open Nitrogen Brayton Cycle



CV-01		
Cg	2086	
Resistance (Cv or K)	62.33	USGPM(60F,1psi)
Actuator Current Position	50.00	%
Pressure Drop	665.0	kPa

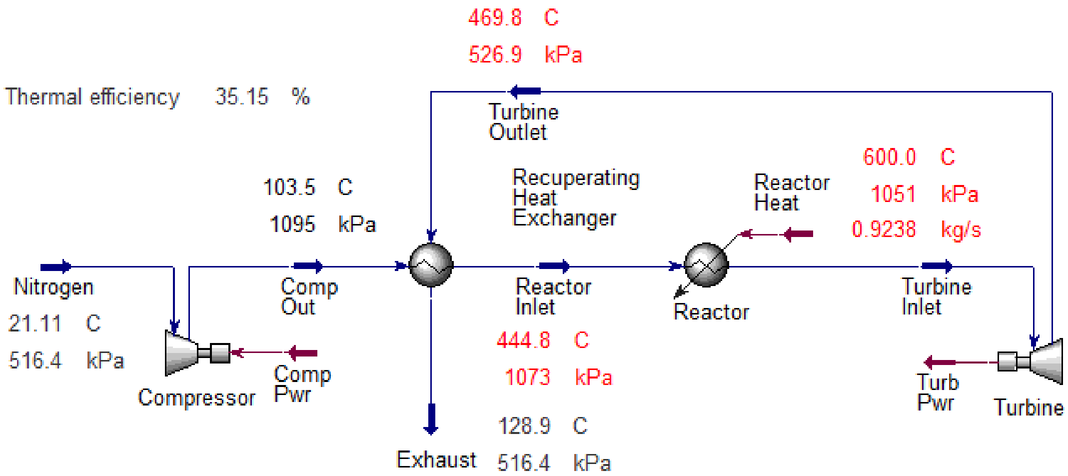
Recup RHX-01		
Duty	0.1755	MW
LMTD	26.56	C
UA	2.378e+004	kJ/C-h
Minimum Approach	26.24	C

Recup RHX-02		
Duty	0.2370	MW
LMTD	25.17	C
UA	3.390e+004	kJ/C-h
Minimum Approach	25.00	C

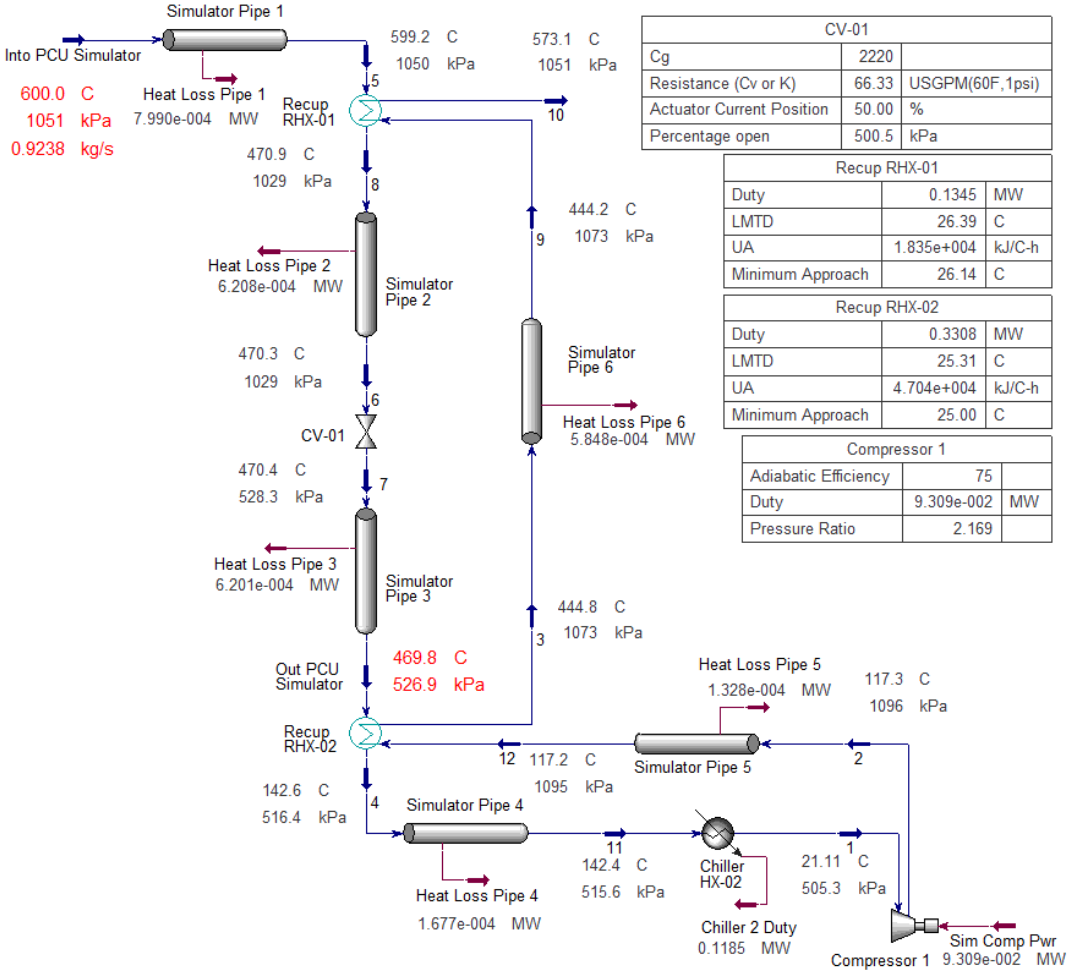
Simulator Compressor 1		
Adiabatic Efficiency	75	
Duty	0.1453	MW
Pressure Ratio	3.137	

b. PCU Simulation of Open Nitrogen Brayton Cycle

Figure 3.20 MAGNET PCU Simulation Loop for Nitrogen Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 70% and 80%



a. Open Recuperated Nitrogen Brayton Cycle



CV-01		
Cg	2220	
Resistance (Cv or K)	66.33	USGPM(60F,1psi)
Actuator Current Position	50.00	%
Percentage open	500.5	kPa

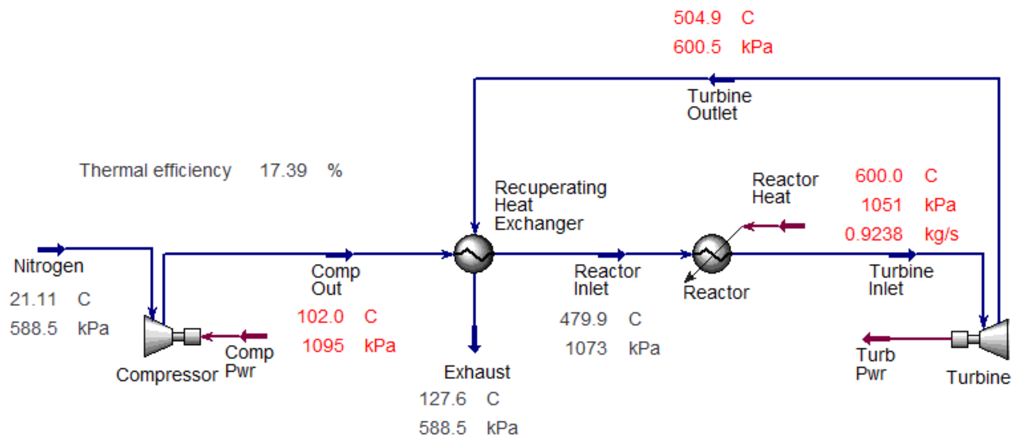
Recup RHX-01		
Duty	0.1345	MW
LMTD	26.39	C
UA	1.835e+004	kJ/C-h
Minimum Approach	26.14	C

Recup RHX-02		
Duty	0.3308	MW
LMTD	25.31	C
UA	4.704e+004	kJ/C-h
Minimum Approach	25.00	C

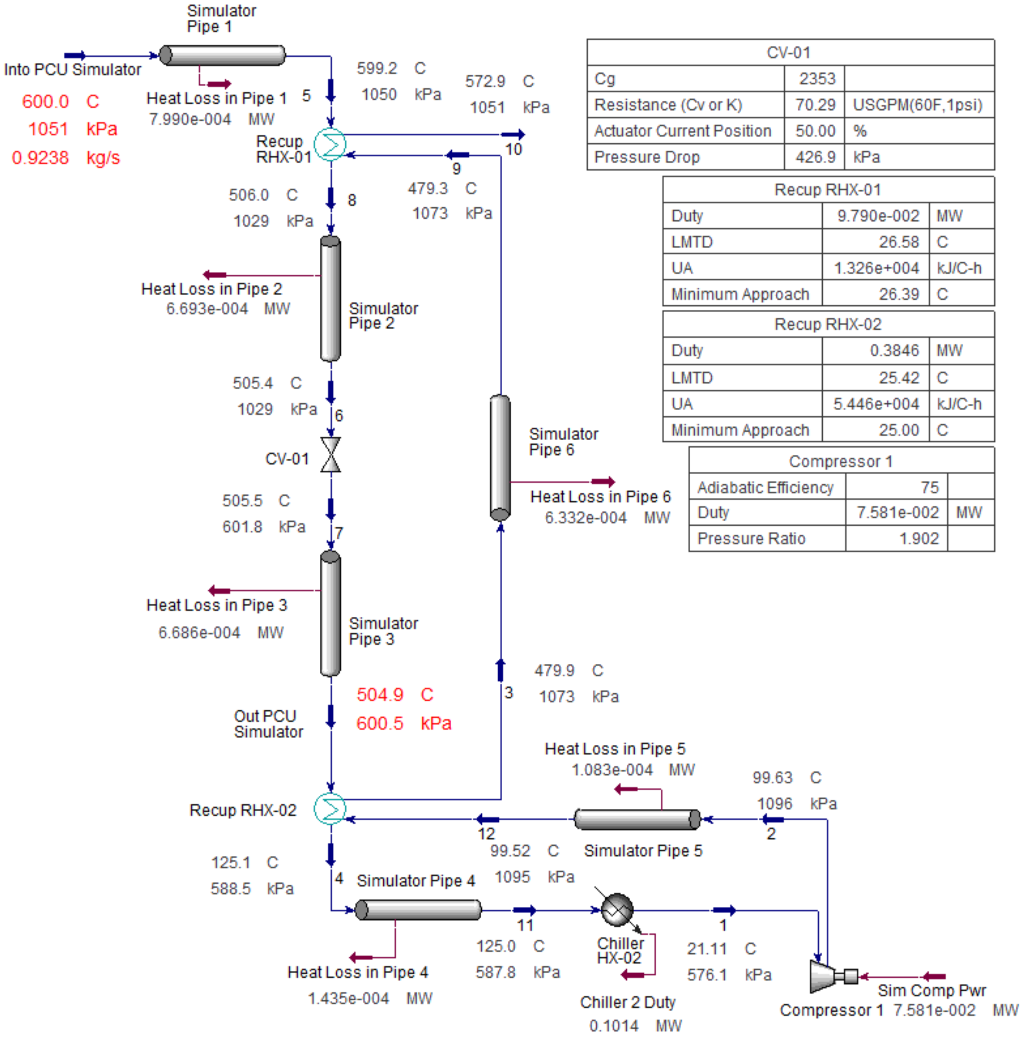
Compressor 1		
Adiabatic Efficiency	75	
Duty	9.309e-002	MW
Pressure Ratio	2.169	

b. PCU Simulation of Open Recuperated Nitrogen Brayton Cycle

Figure 3.21 MAGNET PCU Simulation Loop for Recuperated Nitrogen Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 85% and 90%



a. Open Recuperated Nitrogen Brayton Cycle



CV-01		
Cg	2353	
Resistance (Cv or K)	70.29	USGPM(60F,1psi)
Actuator Current Position	50.00	%
Pressure Drop	426.9	kPa

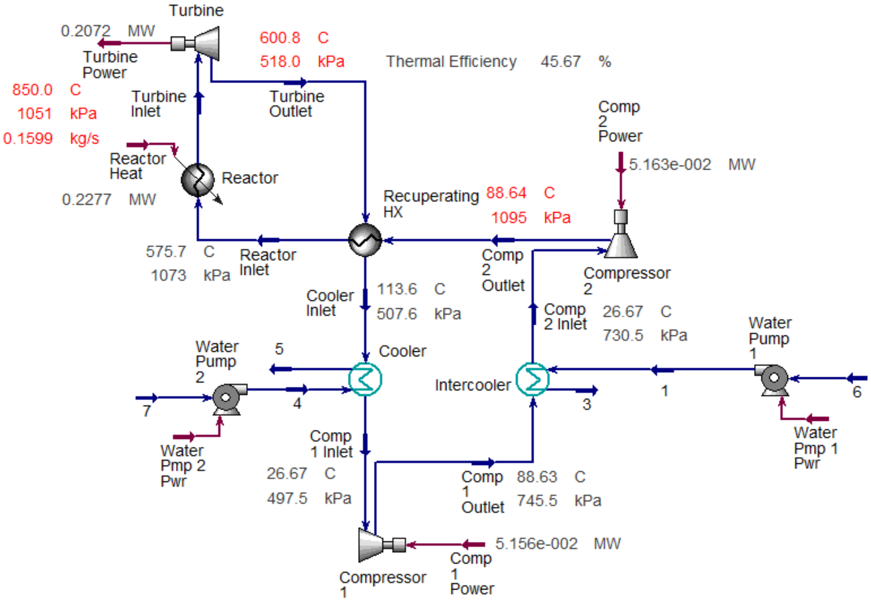
Recup RHX-01		
Duty	9.790e-002	MW
LMTD	26.58	C
UA	1.326e+004	kJ/C-h
Minimum Approach	26.39	C

Recup RHX-02		
Duty	0.3846	MW
LMTD	25.42	C
UA	5.446e+004	kJ/C-h
Minimum Approach	25.00	C

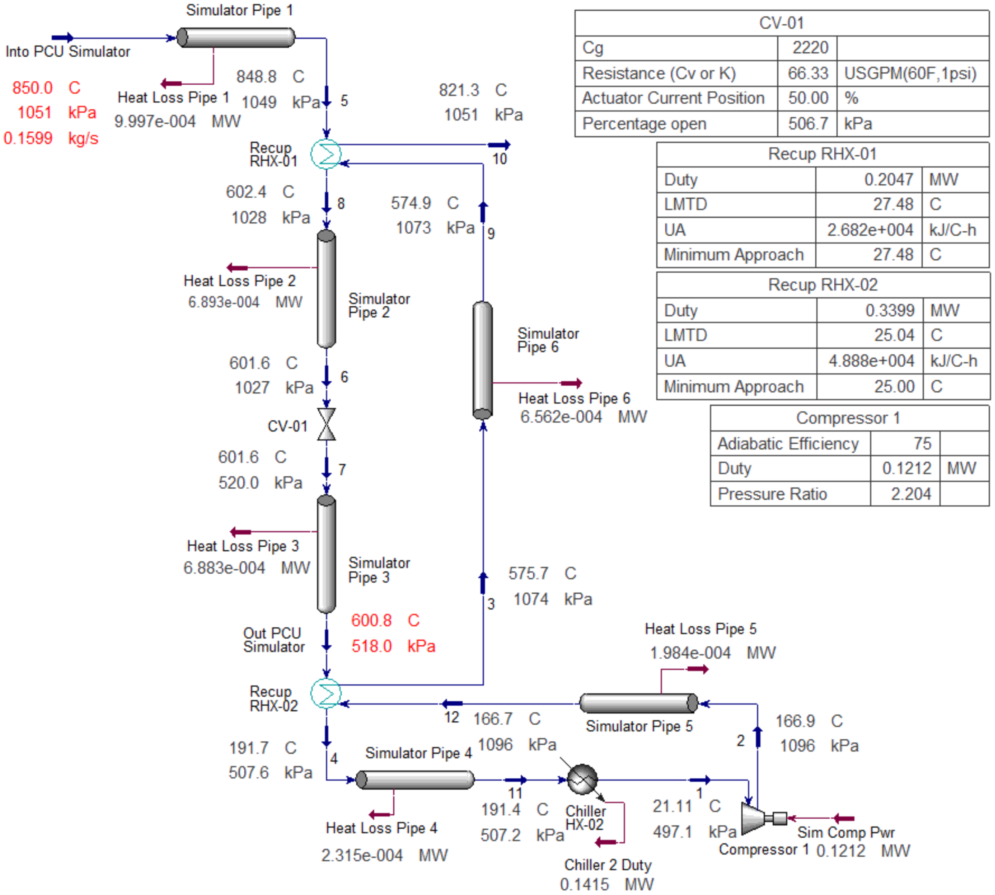
Compressor 1		
Adiabatic Efficiency	75	
Duty	7.581e-002	MW
Pressure Ratio	1.902	

b. PCU Simulation of Open Recuperated Nitrogen Brayton Cycle

Figure 3.22 MAGNET PCU Simulation Loop for Recuperated Nitrogen Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 70% and 80%



a. Helium Brayton Cycle



CV-01		
Cg	2220	
Resistance (Cv or K)	66.33	USGPM(60F,1psi)
Actuator Current Position	50.00	%
Percentage open	506.7	kPa

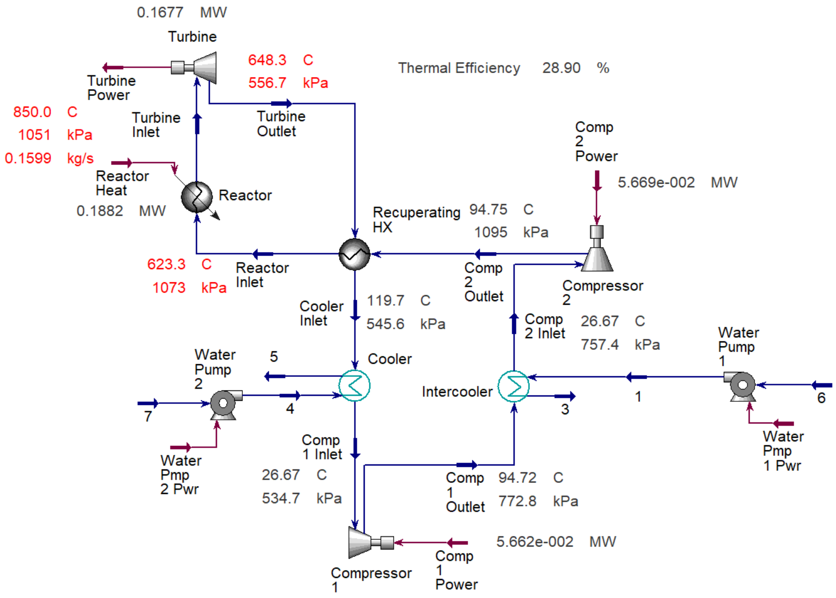
Recup RHX-01		
Duty	0.2047	MW
LMTD	27.48	C
UA	2.682e+004	kJ/C-h
Minimum Approach	27.48	C

Recup RHX-02		
Duty	0.3399	MW
LMTD	25.04	C
UA	4.888e+004	kJ/C-h
Minimum Approach	25.00	C

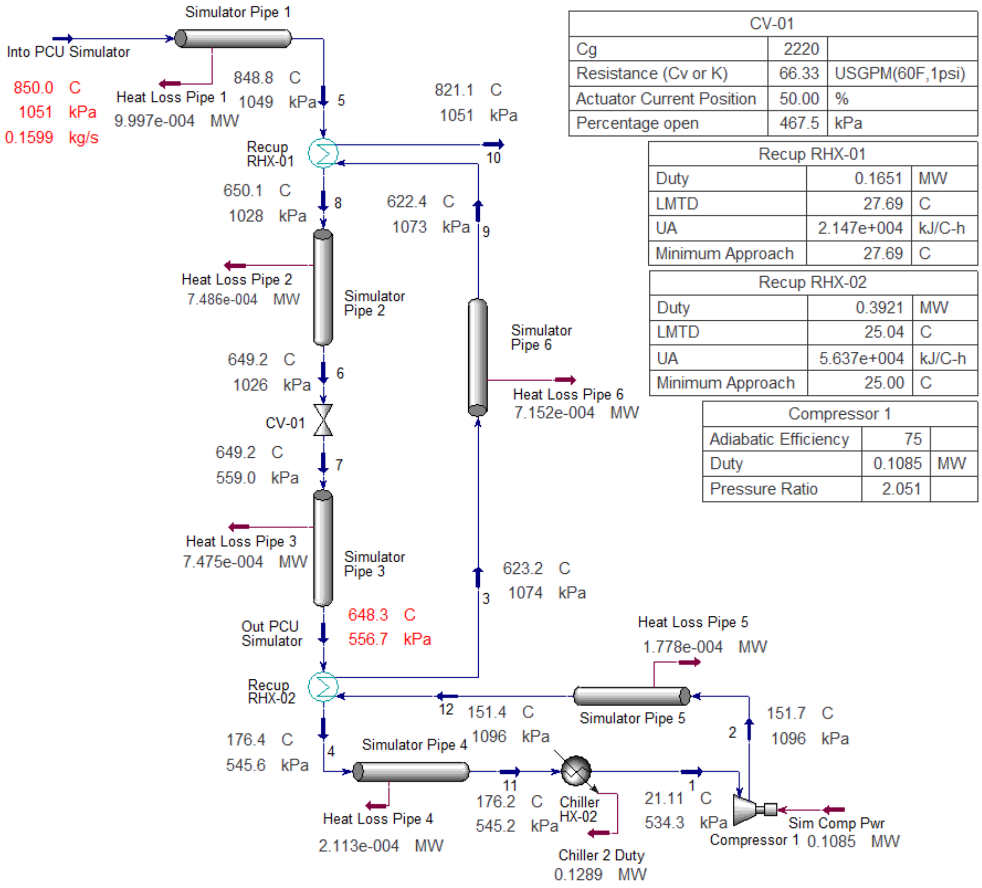
Compressor 1		
Adiabatic Efficiency	75	
Duty	0.1212	MW
Pressure Ratio	2.204	

b. PCU Simulation of Helium Brayton Cycle

Figure 3.23 MAGNET PCU Simulation Loop for Recuperated Helium Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 85% and 90%



a. Helium Brayton Cycle



CV-01		
Cg	2220	
Resistance (Cv or K)	66.33	USGPM(60F,1psi)
Actuator Current Position	50.00	%
Percentage open	467.5	kPa

Recup RHX-01		
Duty	0.1651	MW
LMTD	27.69	C
UA	2.147e+004	kJ/C-h
Minimum Approach	27.69	C

Recup RHX-02		
Duty	0.3921	MW
LMTD	25.04	C
UA	5.637e+004	kJ/C-h
Minimum Approach	25.00	C

Compressor 1		
Adiabatic Efficiency	75	
Duty	0.1085	MW
Pressure Ratio	2.051	

b. PCU Simulation of Helium Brayton Cycle

Figure 3.24 MAGNET PCU Simulation Loop for Recuperated Helium Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 70% and 80%.

3.3.4 Component Specifications of the Power Conversion Unit Simulator

A piping and instrumentation diagram (P&ID), shown in Figure 3.25, has been created. Each valve, compressor, and heat exchangers have unique labels. In addition, thermocouples, pressure transducers, and flow meters are labeled. The equipment was sized from similar loops for the varying power cycles, shown in the previous section. The major difference between the PCU simulator and the case studies in the previous section is that a chiller heat exchanger HX-01 has been added. Its location is between the recuperating heat exchanger RHX-02 and the control valve, as shown in Figure 3.26. Detailed process information regarding the PCU simulator with the chiller are found in Appendix I. This is an important feature as it allows for the temperature control of T3 of different simulations, shown in the P&ID in Figure 3.25. This allows for the different PCU cycles to be simulated with constant physical recuperating heat exchangers. In the previous section, the chiller heat exchanger HX-01 was not included because an assumption that the high temperature recuperating heat exchanger, RHX-01, was used to achieve the desired simulated temperature. The chiller heat exchanger HX-01 has been sized to the largest duty found in the simulations to ensure enough cooling capacity for every cycle.

The recuperating heat exchangers have been sized from Table 3.6 in the red text. The sizing was performed differently for the recuperating heat exchangers than just selecting the largest size. The recuperating heat exchanger RHX-01 was sized to the smallest duty and the recuperating heat exchanger RHX-02 was sized to the largest duty. The chosen duties determined the UA for both the recuperating heat exchangers. This combination for the recuperating heat exchangers were chosen to ensure that cooling was always required for the chiller HX-01. If RHX-01 was sized to the largest UA found, then the chiller HX-01 would require either cooling or heating depending on the simulated cycle. The PCU simulator model assumed a constant UA for each recuperating heat exchangers to determine their performance. Assuming a constant UA is a reasonable initial assumption as the conditions surrounding the recuperating heat exchangers in the different models remain within a similar range of temperatures; though it is noted that the UA would not remain constant between each case.

The other components were sized depending on their functions. The compressors were sized by determining the minimum and maximum pressure ratio range and the control valve CV-01 was sized to meet the desired range of pressure drops. The chiller heat exchangers were sized by the largest duty.

The current PCU simulator allows for different physical PCUs to be simulated. This process is accomplished by controlling the state points in the simulator to the desired PCU turbine outlet conditions. The thermocouple, T3, maintains the correct temperature by adjusting the mass flow rate of the chilled water at $\dot{m}2$. The desired simulation pressure at P2 is determined from the pressure transducer which is controlled by CV-01. This makes obtaining the desired temperature and pressure obtainable by the system. Also, by knowing the conditions entering the vacuum chamber, a unique PCU can be simulated.

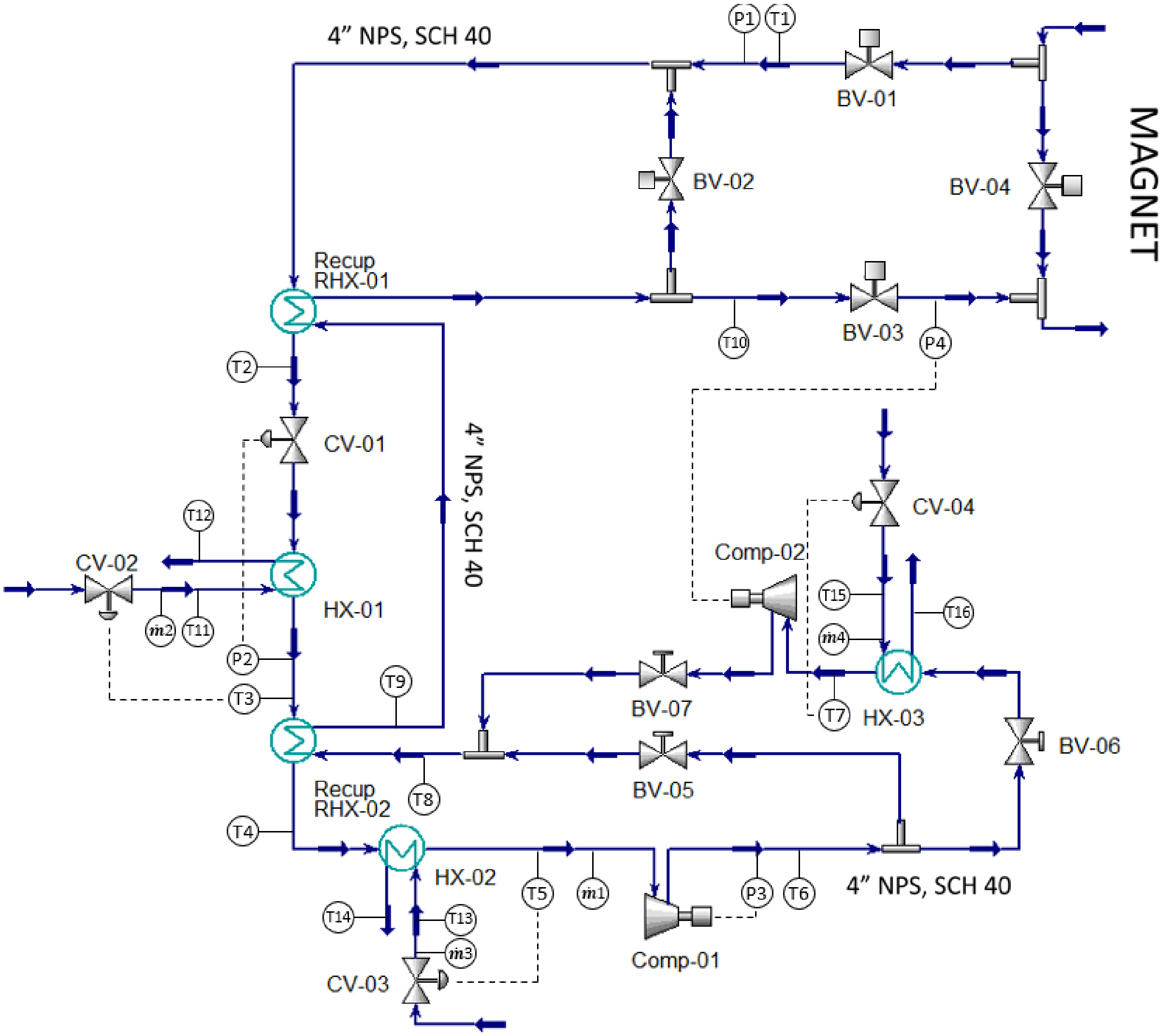
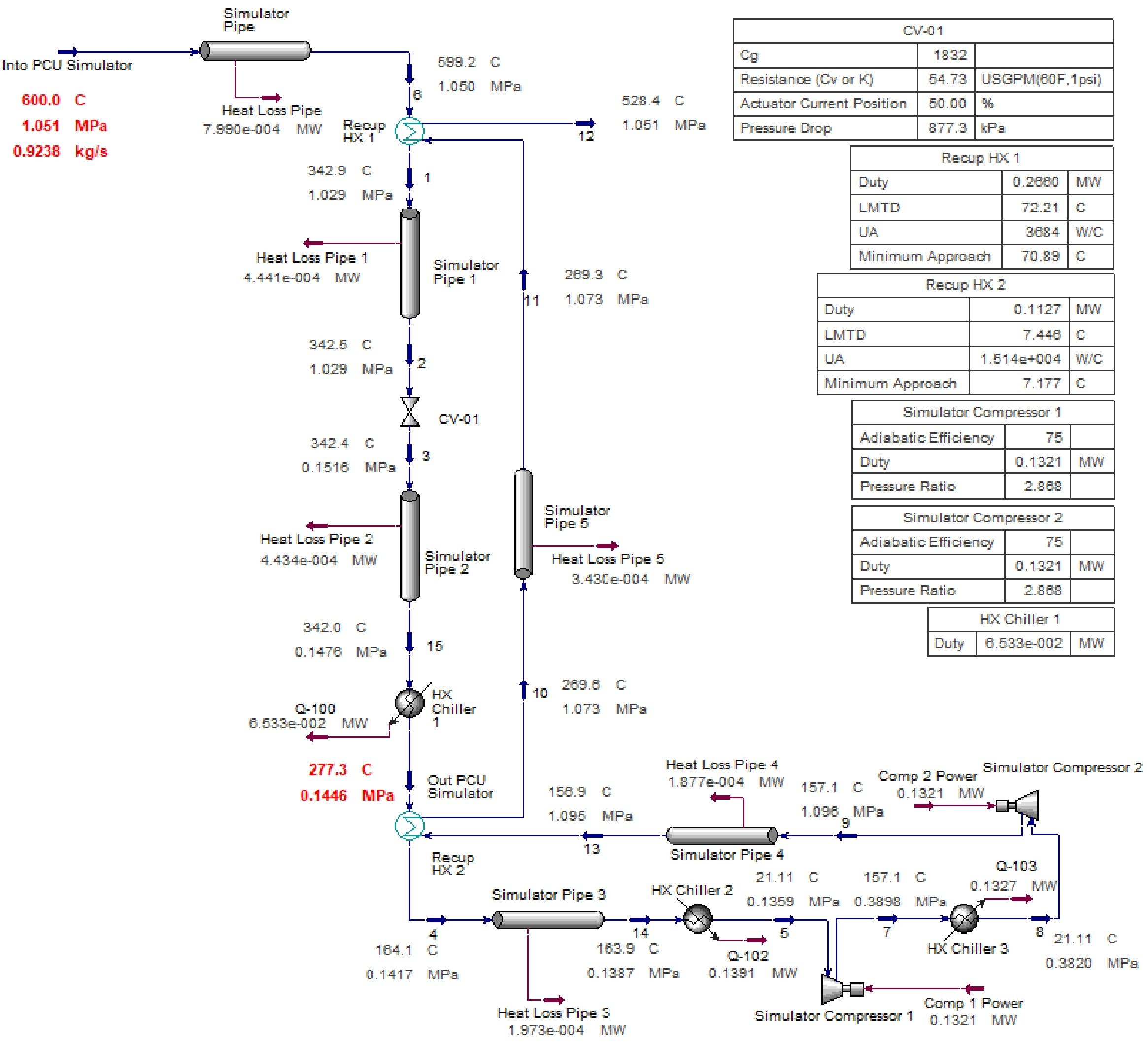


Figure 3.25 Piping and Instrumentation Diagram



CV-01		
Cg	1832	
Resistance (Cv or K)	54.73	USGPM(60F,1psi)
Actuator Current Position	50.00	%
Pressure Drop	877.3	kPa

Recup HX 1		
Duty	0.2660	MW
LMTD	72.21	C
UA	3684	W/C
Minimum Approach	70.89	C

Recup HX 2		
Duty	0.1127	MW
LMTD	7.446	C
UA	1.514e+004	W/C
Minimum Approach	7.177	C

Simulator Compressor 1		
Adiabatic Efficiency	75	
Duty	0.1321	MW
Pressure Ratio	2.868	

Simulator Compressor 2		
Adiabatic Efficiency	75	
Duty	0.1321	MW
Pressure Ratio	2.868	

HX Chiller 1		
Duty	6.533e-002	MW

Figure 3.26 Power Conversion Unit Simulator

3.3.4.1 PCU Simulator Company Inquiries and Detailed Component Specifications

Many companies were approached to obtain quotes for feasible component designs for the PCU simulator. The companies include Flowserve Valves, Kobelco Compressors, Corken, Root Systems Inc, Barber-Nichols, HEXCES, Vacuum Process Engineering, Heatric, and Exergy Heat Transfer Solutions. It should be noted that some of the companies were initially approached on older iterations of the PCU simulator and did not respond to the updated information.

Kobelco industries was approached to size a feasible compressor that would meet the system requirements. They determined that a screw compressor would be best suited for the component Comp-01. Kobelco gave an estimated price range of 1 to 1.5 million dollars but determined after some analysis that their company could not meet the system requirements (Kobelco). Roots System Inc was also approached about a feasible compressor design and they responded that they were able to manufacture a compressor that could handle the desired conditions of the PCU simulator. Their estimate was for one compressor including a skid that would be approximately 18 ft x 12 ft that housed the controls, piping, and intercooler, and it would cost 1 to 2 million dollars. This estimate was approximated closer to 2 million dollars during a phone conversation with the Roots System Inc representative. The proposed compressor was a 12-inch piping, two stage rotary lobe compressor with a nominal 350 HP driver motor. The compressor is also API 619 compliant. The lead time was approximated to be 40 weeks (Root Systems Inc, 2020).

Exergy Heat Transfer Solutions was approached to size the two chiller units and the recuperated heat exchanger. The company respectfully declined sizing due to challenges of high flow rates for tube-in-tube heat exchanger and the large temperature differences for shell and tubes. The other heat exchanger companies did not reply.

Flowserve was approached to size component CV-01 and BV-01/02. CB-Pacific and Flowserve fulfilled the request and these units have been fully specified. Their performance data sheets can be found in Appendix J and Appendix K.

All the component specifications are shown below between Table 3.7 to Table 3.10. The component names were determined from the P&ID shown in Figure 3.25. Some tables include condition 1 and condition 2. These are different conditions that the equipment will be exposed to and would need to be sized to handle both conditions. In the cases of the valves, many are exposed to high heat and pressures while they are closed and not in operation.

Table 3.7 PCU Simulator Control Valve Specifications

	CV-01	
Process Information	Condition 1	Condition 2
Temperature [C]	277	506
Inlet pressure [MPa]	1.03	1.03
Outlet pressure [MPa]	0.143	0.601
Flow rate [kg/s]	0.924	0.924
Fluid	Nitrogen	Nitrogen

Table 3.8 PCU Simulator Compressor Specifications

	Comp-01			Comp-02
Process Information	Condition 1	Condition 2*	Condition 3	Condition 1*
Temperature in [C]	21.1	21.1	21.1	21.1
Pressure In [MPa]	0.577	0.137	0.356	0.384
Pressure Out [MPa]	1.1	0.392	1.1	1.1
Mass Flow Rate [kg/s]	0.924	0.924	0.924	0.924
Fluid Type	Nitrogen	Nitrogen	Nitrogen	Nitrogen
Pressure Ratio	1.9	2.85	3.08	2.85

* **NOTE:** Comp-01 Condition 2 and Comp-02 Condition 1 is for the nitrogen Brayton cycle at high turbine and compressor efficiency. This cycle required two identical compressors to lower the pressure ratio into a feasible pressure range.

Table 3.9 PCU Simulator Isolation Valve Specifications

	BV-01	BV-02		BV-03	BV-04	BV-05	BV-06		BV-07	
Process Information	Condition 1	Condition 1	Condition 2	Condition 1	Condition 1	Condition 1	Condition 1	Condition 2	Condition 1	Condition 2
Temperature [C]	600	154	600	574	600	168	156	168	156	168
Inlet Pressure [MPa]	1.05	1.05	1.05	1.06	1.05	1.1	0.392	1.1	1.1	1.1
Outlet Pressure [MPa]	1.04	1.04	---	1.05	1.04	1.09	0.385	---	1.09	---
Mass Flow Rate [kg/s]	0.924	0.924	---	0.924	0.924	0.924	0.924	---	0.924	---
Fluid	Nitrogen	Nitrogen	Nitrogen	Nitrogen	Nitrogen	Nitrogen	Nitrogen	Nitrogen	Nitrogen	Nitrogen
Cv (USGPM)	232	323	---	227	232	161	267	---	318	---
Percentage open [%]	100	100	0	100	100	100	100	0	100	0

Table 3.10 PCU Simulator Heat Exchangers and Chillers Specifications

	Chiller HX-01		Chiller HX-02		Chiller HX-03		Recuperator RHX-01		Recuperator RHX-02	
	Hot Fluid	**Cold Fluid**	**Hot Fluid**	**Cold Fluid**	**Hot Fluid**	**Cold Fluid**	**Hot Fluid**	**Cold Fluid**	**Hot Fluid**	**Cold Fluid**
Fluid Type	Nitrogen	Water	Nitrogen	Water	Nitrogen	Water	Nitrogen	Nitrogen	Nitrogen	Nitrogen
Flow Rate [kg/s]	0.924		0.924		0.924		0.924	0.924	0.924	0.924
Temperature In [C]	344		195		156		599	479	505	99.3
Temperature Out [C]	276		21.1		21.1		506	573	125	480
Pressure In [MPa]	0.146		0.356		0.392		1.05	1.07	0.589	1.1
Allowable Pressure Drop [MPa]	0.0689		0.0689		0.0689		0.0689	0.0689	0.0689	0.0689
UA [W/C]	---		---		---		3680		15100	
Heat Transfer Rate [kW]	69		170		132		97.9		385	

A computer aided design (CAD) drawing is shown in Figure 3.27. This is a general representation of the P&ID but is not accurate of the actual sized component. Since the physical components are not known, only one compressor has been shown. Other considerations that the CAD does not account for are thermal expansion joints in various areas that would be needed to protect components against thermal expansion of the piping. The system may fail if expansion joints are not included in the final design. More figures of the simulator loop are included in the Appendix L.

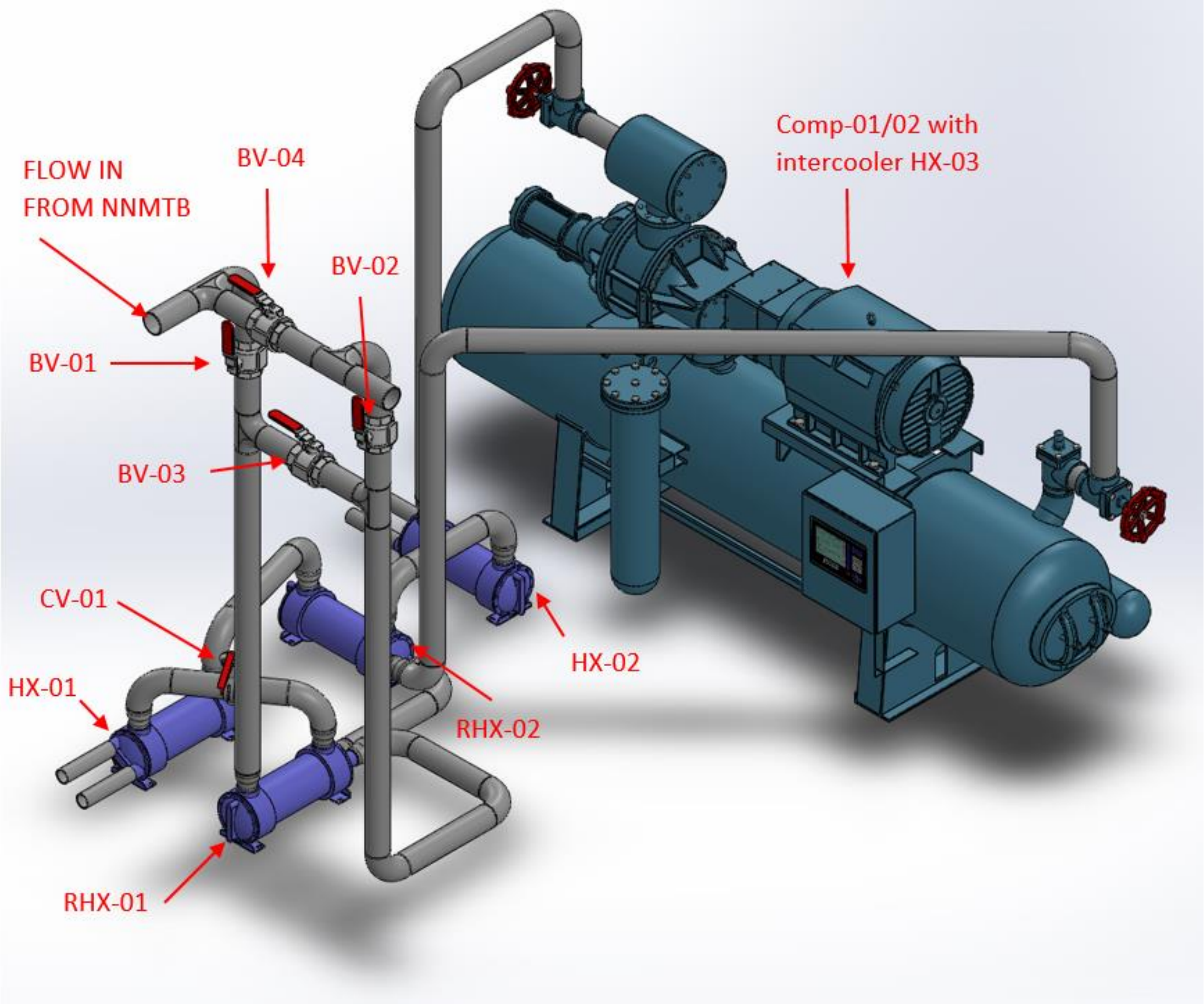


Figure 3.27 Computer Aided Design (CAD) Concept of PCU Simulator

3.3.4.2 Design Consideration for Fluid Velocity and Pipe Noise

Concerns were raised when using 4” NPS pipe, especially after the gas was expanded following the CV-01 valve. The velocities after the expansion may reach up to 420 ft/sec.

Velocities at this rate may cause choked flow within the valves and cause them to be uncontrollable. However, the CV-01 data sheet show that the max mach number for the largest pressure drop in the valve is 0.477. It also shows that the pipe mach number is 0.265 (Flowserve, 2020). The CV-01 data sheet is shown in Appendix J. Another concern with the high velocities is the large piping noises. Table 3.11 shows the velocities and the estimated pipe noise for the different cycles. At these velocities, the pipe noise could be uncomfortably loud. It would be recommended to increase the pipe size which would decrease the gas velocity to ensure that the pipe noise falls within code. Equation 3.11 shows the "pipe noise generated in air ducts" calculation from Engineering Toolbox (Engineering Toolbox, n.d.). This calculation, however, does not include insulation around the pipes. Pipe insulation in the PCU simulator would be kept consistent with the MAGNET and therefore would have 4 inches of insulation surrounding the piping.

$$L_N = 10 + 50\log\left(\frac{v}{197}\right) + 10\log\left(\frac{A_{cs}}{1550}\right)\ [dB]$$ ***Equation 3.11***

Where:

$L_N \rightarrow Sound\ power\ level\ (dB)$
$v \rightarrow Fluid\ velocity\ \left(\frac{ft}{min}\right)$
$A_{cs} \rightarrow Cross\ section\ flow\ area\ (in^2)$

Table 3.11 Pipe Noise in Duct Calculations for 4 inch Piping in the PCU Simulator for Flow Rates for MAGNET Test Chamber at 250 kW

	Velocity after CV-01 [ft/sec] (m/s)	Cross Section Flow Area [in^2]	Pipe Noise [dB]
Air Brayton Cycle at η_{comp}=85% and η_{turb}=90%	420 (128)	12.7	94.5
Air Brayton Cycle at η_{comp}=70% and η_{turb}=80%	215 (65.5)	12.7	80
Recuperated Air Brayton Cycle at η_{comp}=85% and η_{turb}=90%	178 (54.3)	12.7	75.9
Recuperated Air Brayton Cycle at η_{comp}=70% and η_{turb}=80%	141 (43.0)	12.7	70.8

The pipe insulation would reduce the noise of the piping. Also, the fluid velocity can be reduced to decrease the noise. The fluid velocity can be decreased by increasing the pipe diameter. Table 3.12 shows the velocities and pipe noises compared to different pipe diameters. The pipe segment length was assumed to be 9.84 ft (3 m) and all schedule 40 mild steel piping. The pipe was also considered at the highest velocity site right after CV-01 after the fluid is expanded. It would be recommended to decrease the flow through the PCU simulator or to increase the pipe size to a minimum of 8 inches to reduce the fluid velocity to a more acceptable range. The American Society of Mechanical Engineers state in ASME B31.8-2018, “Gas velocities should not exceed 100 ft/sec (30 m/s) at peak conditions… High gas velocities in piping increase turbulence and pressure drop and contribute to excessive sound pressure levels (aerodynamic noise)…” (The American Society of Mechanical Engineers, 2018).

Table 3.12 Fluid Velocity and Pipe Noise Compared to Various Standard Pipe Sizes

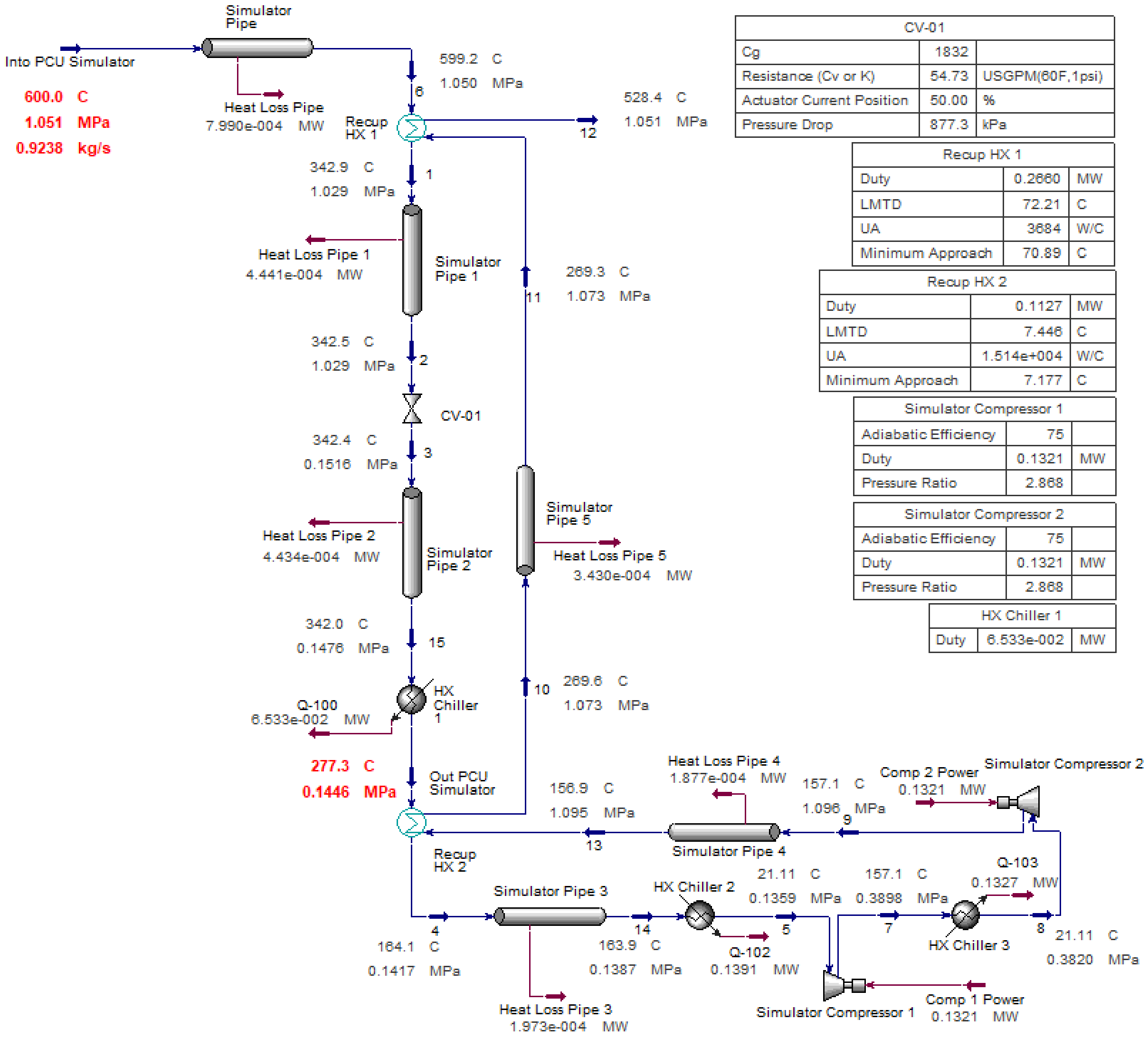
Pipe Size	Pipe Inner Diameter [in]	Cross-Sectional Area [in^2]	Averaged Fluid Velocity [ft/s] (m/s)	Pipe Noise [dB]
4-inch sch 40	4.026	12.7	416 (127)	94.3
5-inch sch 40	5.047	20	262 (79.9)	86.2
6-inch sch 40	6.065	28.9	181 (55.2)	79.8
8-inch sch 40	7.981	50	104 (31.8)	70.2
10-inch sch 40	10.02	78.9	66.3 (20.2)	62.3
12-inch sch 40	11.938	112	46.7 (14.2)	56.2
14-inch sch 40	13.124	135	38.6 (11.8)	52.9

3.3.5 Test Plan for Power Conversion Unit Simulator

Test plans were developed to perform shakedown tests for the PCU simulator to simulate the start up of the simple nitrogen Brayton cycles and to simulate the recuperated nitrogen Brayton cycles. The test plans for different cycles have varying turbine and compressor efficiencies. To develop the test plans, a process model of the PCU simulator was developed that kept specifications of the design constant, see Figure 3.28. The specifications for the recuperating heat exchangers, valves, chillers, and compressors were held constant. The design conditions for the high temperature recuperating heat exchanger was set to the lowest duty design specifications while the low temperature recuperating heat exchanger used the highest duty design specifications of the nitrogen cycles. This allowed a chiller to be put in place to control the desired simulated turbine outlet temperature for each case considered. Figure 3.29 shows the piping and instrumentation diagram of the PCU simulator. Each valve, compressor, and heat exchangers have unique labels. In addition, thermocouples, pressure transducers, and flow meters are labeled.

A procedure was developed to run shakedown tests on the PCU simulator. The shakedown tests have no heat from the MAGNET. After purging of gases and charging the PCU simulator and the MAGNET with nitrogen gas, the simulator is isolated from the testbed using valving. Then a series of tests are performed to ensure the operation of the simulator. Chillers, compressors, and control valves will be tested to validate operation.

The test matrix for the shakedown tests are shown in Table 3.13. The matrix includes tests that operate one compressor followed by tests in which both compressors operate. For the single compressor tests, pressure ratios across the compressor will be varied from 2 to 3. The chiller's (HX-01) duty will be varied from 0 to the duties listed in the table to achieve temperatures measured at thermocouple T3 of 25°C and 50°C. The duties listed were estimated by using an Aspen HYSYS model of the PCU simulator. The temperatures given when the chiller's duty is set to zero were also estimated using the same model. With two compressors, the pressure ratio was set to be identical for both compressors. That is the pressure ratio listed in Table 3.13. The pressure at P2 is controlled by CV-01 and the temperature measured at T3 is controlled by chiller, HX-01.



CV-01		
Cg	1832	
Resistance (Cv or K)	54.73	USGPM(60F,1psi)
Actuator Current Position	50.00	%
Pressure Drop	877.3	kPa

Recup HX 1		
Duty	0.2660	MW
LMTD	72.21	C
UA	3684	W/C
Minimum Approach	70.89	C

Recup HX 2		
Duty	0.1127	MW
LMTD	7.446	C
UA	1.514e+004	W/C
Minimum Approach	7.177	C

Simulator Compressor 1		
Adiabatic Efficiency	75	
Duty	0.1321	MW
Pressure Ratio	2.868	

Simulator Compressor 2		
Adiabatic Efficiency	75	
Duty	0.1321	MW
Pressure Ratio	2.868	

HX Chiller 1		
Duty	6.533e-002	MW

Figure 3.28 PCU Simulator with Final Design Specifications

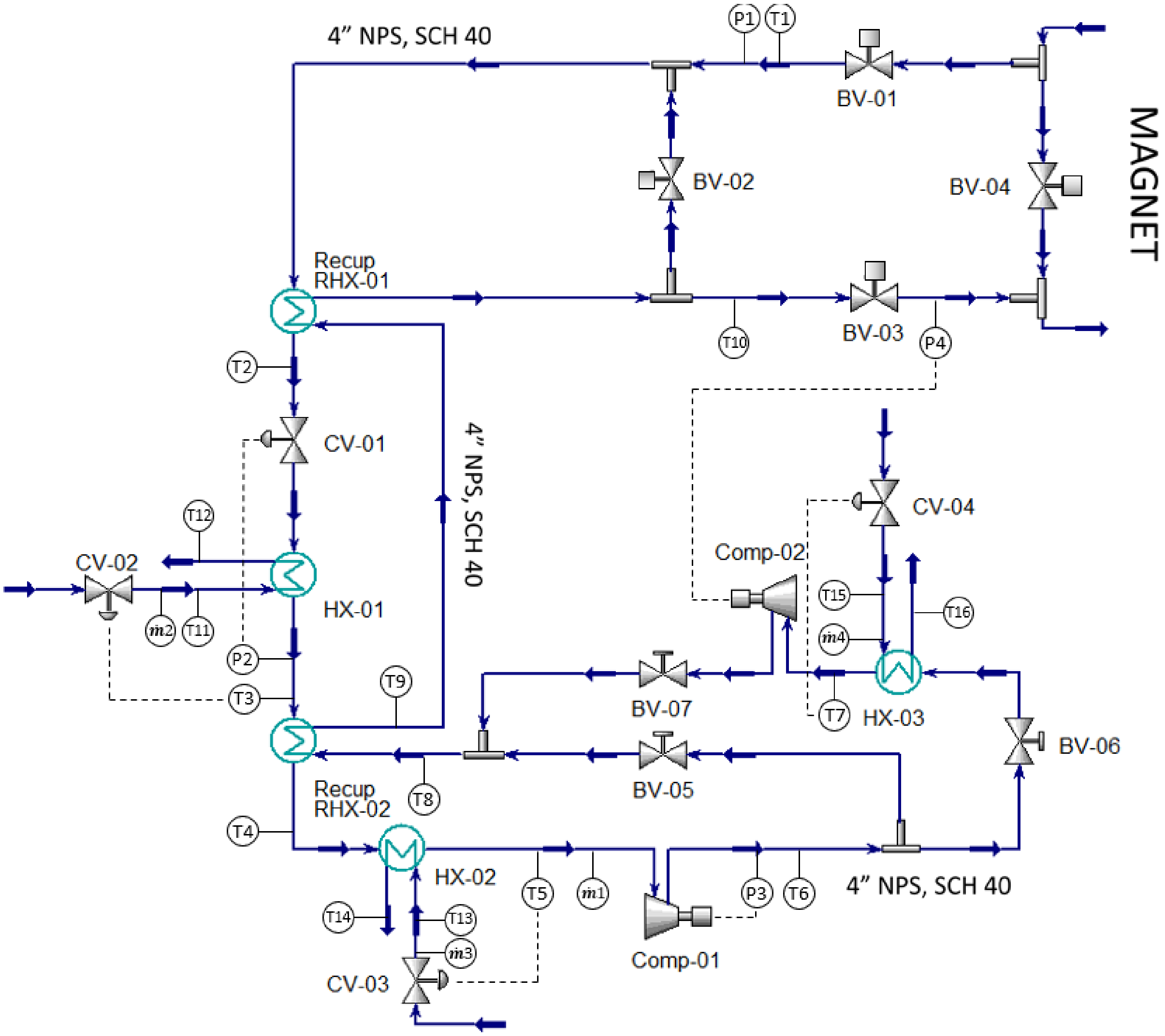


Figure 3.29 Pipe and Instrumentation Diagram for the PCU Simulator

3.3.5.1 Shakedown Test Procedure of Power Conversion Unit Simulator

1. Valves BV-01, BV-02, BV-03, BV-04, BV-05, BV-06, BV-07, and CV-01 are fully open.
2. Purge testbed and power conversion loop of oxygen.
3. Fill and pressurize from nitrogen storage tanks the testbed and the power conversion loop with nitrogen.
4. For one compressor power conversion simulation:
    a. Close BV-01, BV-03, BV-06, and BV-07.
    b. Begin operation of chiller HX-02, which coolant flow is controlled by temperature T5, into compressor Comp-01.

    c. Close CV-01 to 25% of full open.
    d. Start compressor Comp-01 to achieve desired pressure at P4.

5. For two compressor power conversion simulation:
    a. Close BV-01, BV-03, and BV-05.
    b. Begin operation of chiller HX-02, which coolant flow is controlled by temperature T5, into compressor Comp-01.
    c. Begin operation of chiller HX-03, which coolant flow is controlled by temperature T7, into compressor Comp-02.
    d. Close CV-01 to 25% of full open.
    e. Start compressor Comp-01 to achieve desired pressure at P3.
    f. Start compressor Comp-02 to achieve desired pressure at P4.
6. Adjust CV-01 to obtain desired pressure at P2.
7. Allow power conversion unit simulator to come to steady state.
8. Begin operation of chiller HX-01 which coolant flow is controlled by temperature T3.
9. Allow power conversion unit simulator to come to steady state.

Table 3.13 Shakedown Test Matrix for PCU Simulator

Single Compressor				
Test Name	Compressor Pressure Ratio	Chiller Duty (kW)	P2 (MPa)	T3 (°C)
Shk_1Cmp_PR2_0kW	2	0	0.570	94
Shk_1Cmp_PR2_50C	2	2.4	0.570	50
Shk_1Cmp_PR2_25C	2	3.6	0.570	25
Shk_1Cmp_PR2.5_0kW	2.5	0	0.456	125
Shk_1Cmp_PR2.5_50C	2.5	4.2	0.456	50
Shk_1Cmp_PR2.5_25C	2.5	5.6	0.456	25
Shk_1Cmp_PR3.0_0kW	3.0	0	0.380	150
Shk_1Cmp_PR3.0_50C	3.0	5.8	0.380	50
Shk_1Cmp_PR3.0_25C	3.0	7.2	0.380	25
Two Compressor				
Test Name	Compressor Pressure Ratio	Chiller Duty (kW)	P2 (MPa)	T3 (°C)
Shk_2Cmp_PR1.5_0kW	1.5	0	0.507	51
Shk_2Cmp_PR1.5_25C	1.5	1.4	0.507	25
Shk_2Cmp_PR2_0kW	2	0	0.285	88
Shk_2Cmp_PR2_50C	2	2.0	0.285	50
Shk_2Cmp_PR2_25C	2	3.4	0.285	25
Shk_2Cmp_PR2.5_0kW	2.5	0	0.182	121
Shk_2Cmp_PR2.5_50C	2.5	3.9	0.182	50
Shk_2Cmp_PR2.5_25C	2.5	5.2	0.182	25

A test procedure was developed to simulate the operation of the simple and the recuperated nitrogen Brayton cycles.

3.3.5.2 Power Conversion Unit Simulator Test Procedure

1. Open valves BV-02, BV-04, and CV-01.
2. For one compressor power conversion simulation:

   a. Close BV-01, BV-03, BV-06, and BV-07.
   b. Begin operation of chiller HX-02, which coolant flow is controlled by temperature T5, into compressor Comp-01.
   c. Close CV-01 to 25% of full open.
   d. Start compressor Comp-01 to achieve desired pressure at P4.

3. For two compressor power conversion simulation:
   a. Open BV-06 and BV-07.
   b. Close BV-05.
   c. Begin operation of chiller HX-02, which coolant flow is controlled by temperature T5, into compressor Comp-01.
   d. Begin operation of chiller HX-03, which coolant flow is controlled by temperature T7, into compressor Comp-02.
   e. Close CV-01 to 25% of full open.
   f. Start compressor, Comp-01, to achieve desired pressure at P3.
   g. Start compressor, Comp-02, to achieve desired pressure at P4.
4. Adjust CV-01 to obtain desired pressure at P2.
5. Allow power conversion unit simulator to come to steady state.
6. Begin operation of chiller, HX-01, which coolant flow is controlled by temperature T3.
7. Allow power conversion unit simulator to come to steady state.
8. Set pressure, P2 using CV-01, and temperature, T3 using chiller HX-01 to simulate power conversion unit start up before heat introduction.
9. Open BV-01 and BV-03
10. Close BV-02
11. Close BV-04
12. Allow power conversion unit simulator to come to steady state.
13. Set pressure P2 using CV-01 and set temperature T3 using chiller HX-01 to simulate power conversion unit start up at self-sustaining state.
14. Allow power conversion unit simulator to come to steady state.
15. Set pressure P2 using CV-01 and set temperature T3 using chiller HX-01 to simulate operating design state of power conversion unit.

A test matrix was developed to simulate the nitrogen Brayton cycles, see Table 3.14. For the simple Brayton cycle, two start up conditions will be simulated. These conditions are based on the model simulations of a full-scale Brayton cycle presented in Chapter 4. The first condition that will be simulated is at the point where the PCU is driven by a motor just before heat addition. The second condition simulated is the point when the turbine can sustain the compressor without the aid of the start up motor - see Chapter 4 for detailed information on the start up of a non-recuperated Brayton cycle. All other conditions are the operating design conditions presented earlier in the report.

Table 3.14 PCU Simulator Tests

Simple Nitrogen Brayton Cycle	P2 (MPa)	T3 (°C)	Compressor Adiabatic Efficiency	Turbine Adiabatic Efficiency
Start up Before Heat Addition	0.711	63.1	70%	80%
Self-Sustaining State	0.503	460	70%	80%
Design	0.359	430	70%	80%
Start up Before Heat Addition	0.480	91.0	85%	90%
Self-Sustaining State	0.229	287	85%	90%
Design	0.144	284	85%	90%
Recuperated Nitrogen Brayton Cycle	**P2 (MPa)**	**T3 (°C)**	**Compressor Adiabatic Efficiency**	**Turbine Adiabatic Efficiency**
Design	.601	505	70%	80%
Design	.527	470	85%	90%

The PCU simulator has 16 thermocouples, 4 pressure transducers, 4 flow meters, 6 PID controllers, and 2 compressor power measurements for a total of 32 transducers. It is expected that a data file for each test will be 500 kbytes assuming 40 pieces of instrumentation (pressure transducers, thermocouple, mass flow meters, PID controllers etc.) with a test lasting 4 hours with 15 second intervals for data acquisition.

3.3.6 Economic Analysis for Power Conversion Unit Simulator

An economic analysis has been performed for the PCU simulator. Several methods of analyses have been performed to determine the estimated total capital cost for the simulator loop. Aspen HYSYS's economic package was used as well as the "0.6 rule" alongside quotes and estimates from companies to create the total cost estimate. It has been determined that the total capital cost for the PCU simulator approaches 2.15 million dollars. An equipment cost breakdown is shown in Table 3.15.

Table 3.15 Estimated Capital Cost for PCU Simulator Breakdown

Equipment Cost [USD]		
Comp-01	$	799,900.00
Comp-02	$	799,900.00
Recup RHX-01	$	67,500.00
Recup RHX-02	$	153,000.00
Chiller HX-01	$	8,500.00
Chiller HX-02	$	10,900.00
Chiller HX-03	$	10,000.00
CV-01	$	66,000.00
BV-01	$	55,000.00
BV-02	$	55,000.00
BV-03	$	55,000.00
BV-04	$	55,000.00
BV-05	$	1,000.00
BV-06	$	1,000.00
BV-07	$	1,000.00
Piping	$	10,000.00
Equipment Cost [USD]	$	2,150,000.00

The compressors, the heat exchangers, and the piping costs were estimated using various methods which are discussed below. The cost of CV-01 was determined from a quote from Flowserve, which is shown in Appendix J. The actuated isolation ball valves, BV-01 to BV-04, costs are determined from a quote, shown in Appendix K, and estimate from Flowserve. BV-01 quote was for a hand operated ball valve and the cost was estimated to be three times larger to make it actuated by a controller due to the extreme temperatures the valves will be exposed to (Flowserve, 2020). BV-05 to BV-07 are standard 4-inch ball valves that are hand operated.

3.3.6.1 Aspen HYSYS Economic Analysis

Aspen HYSYS's economic package was used as a method to estimate the total capital cost for the PCU simulator. Several Aspen HYSYS models of the PCU simulator were used to generate the economic analysis. The compressor estimate came from the simulation test with the highest compression ratio and greatest power, which is the simple air Brayton cycle with the compressor and turbine efficiencies of 70% and 80%, respectively. It is assumed that the same compressor is purchased twice. The recuperating heat exchanger estimates came from the simulation of the recuperated air Brayton cycle with compressor and turbine efficiencies of 70% and 80%, respectively. The chiller units were comparable in prices between the different economic models created. Their prices were determined from the simple Brayton cycle simulation with compressor and turbine efficiencies of 85% and 90%, respectively. The piping cost was estimated by inputting values into Aspen HYSYS's economic package. The piping was described as 4-inch stainless steel 316 schedule 40 pipe with 0.5 inch of insulation. The fittings were described to be welded.

Aspen HYSYS economic package estimated the capital cost for the PCU simulator to be near 2.05 million dollars. The economic package also details an estimated install cost for each equipment. The estimated total install cost, which includes the capital cost of the equipment, is 2.91 million dollars. The Aspen HYSYS component breakdown is shown in Table 3.16**.**

Table 3.16 Aspen HYSYS Cost Estimate for the PCU Simulator Breakdown

	Equipment Cost [USD]	Installed Cost [USD]
Comp-01	$ 799,900.00	$ 940,000.00
Comp-02	$ 799,900.00	$ 940,000.00
Recup RHX-01	$ 72,200.00	$ 260,500.00
Recup RHX-02	$ 54,000.00	$ 241,300.00
Chiller HX-01	$ 8,500.00	$ 97,600.00
Chiller HX-02	$ 10,900.00	$ 70,900.00
Chiller HX-03	$ 10,000.00	$ 69,800.00
CV-01	$ 66,193.00	$ 66,200.00
BV-01	$ 55,350.00	$ 55,400.00
BV-02	$ 55,350.00	$ 55,400.00
BV-03	$ 55,350.00	$ 55,400.00
BV-04	$ 55,350.00	$ 55,400.00
BV-05	$ 1,000.00	$ 1,000.00
BV-06	$ 1,000.00	$ 1,000.00
BV-07	$ 1,000.00	$ 1,000.00
Piping	$ 9,300.00	$ -
Equipment Cost [USD]	$2,055,293.00	
Total Installed Cost [USD]		$2,910,900.00

3.5.6.2 "0.6 Rule" Economic Estimate

A common method used to estimate the cost of various equipment is to use the "0.6 rule" (Whitesides, 2012). This method takes an existing cost of equipment with a known size and estimates the cost of a different sized equipment. Equation 3.12 is shown below.

$$C_2 = C_1\left(\frac{S_2}{S_1}\right)^N$$

Equation 3.12

Where: C_1 → Cost of Equipment 1

C_2 → Cost of Equipment 2

S_1 → Size of Equipment 1

S_2 → Size of Equipment 2

$N \rightarrow$ Size Exponent

N, the size exponent, was assumed to be 0.6 for a generalized estimate but can change depending on various process equipment, such as compressors. An initial estimate was obtained by using quotes used for INL's MAGNET compressor, chiller, and recuperating heat exchanger. These prices were used to estimate the cost of the equipment for the PCU simulator. Through this estimate, the total capital cost for the PCU simulator is approximated at 1.39 million dollars. Table 3.17 shows the results from the analysis.

The results for the 0.6 rule give reasonable values for the recuperating heat exchangers as well as the chillers. The 0.6 rule showed that the prices for RHX-01 and RHX-02 are similar to INL's quoted recuperating heat exchanger. This is to be expected as the determined duty and conditions are very similar to the MAGNET recuperating conditions. The chiller values seem to produce a reasonable estimate from the similarly sized chiller heat exchanger in the MAGNET that was quoted to INL. Aspen HYSYS estimate was used over the 0.6 rule as some of the temperature differences could be large in Chiller HX-01 in the PCU simulator, though the estimates only vary by ~$6000 each.

Table 3.17 0.6 Rule Cost Estimate for the PCU Simulator Breakdown

	INL Equipment	INL Quoted Cost [USD]	INL Quoted [kW]	Needed kW	Adjusted Cost [USD]	QTY	Estimated Cost [USD]
Comp-01	25 hp Compressor	$ 92,225.00	18.64	145.2	$ 316,028.42	1	$ 316,028.42
Comp-02	25 hp Compressor	$ 92,225.00	18.64	145.2	$ 316,028.42	1	$ 316,028.42
Recup RHX-01	350 kW Recuperator	$ 145,000.00	350	97.9	$ 67,514.46	1	$ 67,514.46
Recup RHX-02	350 kW Recuperator	$ 145,000.00	350	384.7	$ 153,461.87	1	$ 153,461.87
HX-01	MAGNET Chiller HX-01	$ 5,550.00	274.5	68.62	$ 2,415.67	1	$ 2,415.67
HX-02	MAGNET Chiller HX-01	$ 5,550.00	274.5	167.4	$ 4,124.97	1	$ 4,124.97
HX-03	MAGNET Chiller HX-01	$ 5,550.00	274.5	132	$ 3,576.94	1	$ 3,576.94
CV-01					$ 66,193.00	1	$ 66,193.00
BV-01-04					$ 55,350.00	4	$ 221,400.00
BV-05-07					$ 1,000.00	3	$ 3,000.00
Piping					$ 9,300.00	1	$ 9,300.00
Total Capital Cost [USD]							$1,163,043.75

The compressor estimate was based off the Corken compressor that was quoted for the MAGNET. This compressor's estimate was determined to be low and was rejected. The compressors in the PCU simulator are expected to deliver much higher-pressure ratios. The size of the compressors are also nearly 8 times the size of the MAGNET compressor. The reason for rejecting this price is for three reasons:

1. During initial cost estimates to compressor companies, Kobelco was approached to size a single compressor that could handle all the test conditions of the PCU simulator. This compressor would need to handle compression ratios from 1.8 to 7.6. They determined that a screw compressor would work best and gave an estimated cost for the compressor of 1.5 million dollars. Aspen HYSYS showed that the estimated capital cost for two compressors was close to 1.6 million dollars.
2. Another estimate of the cost ratio shown in Equation 3.12 was used to compare the costs for the compressors. The new comparison used a sizing ratio for the CFM into the compressors with a size exponent, N, equal to 0.67 up from 0.6 for single stage compressors (Whitesides, 2012). Table 3.18 shows the results of using the CFM ratio instead of a power ratio as shown in Table 3.17. This resulted in a wide variety of costs ranging for a single compressor of 356 to 865 thousand dollars. The higher flow rate comes from the simulation of the simple air Brayton cycle with the compressor and turbine efficiencies of 85% and 90%, respectively. This is due to the high pressure drop. From this analysis, it showed that the compressor would have a cost nearing 865 thousand dollars, which surpasses Aspen HYSYS's approximation.
3. Roots Systems gave a rough estimate for the price of the compressor set-up. Their representative said for one compressor on a skid with the controller, piping, valves, and intercooler, would be approximately 1 to 2 million dollars. However, during a phone call with the representative, they recommended 2 million dollars plus or minus 20% as their reasonable estimate for the price of the compressor system. They specified that the compressor would be a 12-inch piping, 2 stage rotary lobe compressor with a nominal 350 HP motor.

Table 3.18 Adjusted Compressor Capital Cost using ACFM

	INL Equipment	INL Quoted Cost [USD]	INL Quoted [ACFM]	Needed [ACFM]	Adjusted Capital Cost [USD]	QTY	Estimated Capital Cost [USD]
Comp-01	25 hp Compressor	$ 92,225.00	45	337.5	$ 355,745.74	2	$ 711,491.48
Comp-01	25 hp Compressor	$ 92,225.00	45	478.9	$ 449,738.76	2	$ 899,477.52
Comp-01	25 hp Compressor	$ 92,225.00	45	295.9	$ 325,734.24	2	$ 651,468.47
Comp-01	25 hp Compressor	$ 92,225.00	45	1272	$ 865,371.61	2	$ 1,730,743.22

For these reasons, the total estimated cost for one compressor is 799 thousand dollars, which was Aspen HYSYS's estimate. This estimate was within the reasonable range that the vendors said the compressors would cost. However, the price may vary slightly as Roots System's estimate would include piping and an intercooler. This would remove chiller HX-03 from the breakdown. Their compressor set also used 12 inch piping, which would increase the estimated piping cost outside of what they would provide; however, the cost for increasing the pipe size would be minimal when compared to the other large components in the system. The pipe sizing would only need to be increased after the gas is expanded past CV-01. This would only marginally increase the piping cost. Therefore, the total estimated capital cost for the PCU simulator is 2.15 million dollars, see Table 3.15.

Chapter 4: Estimated Start Up Analysis for PCU using Aspen HYSYS

4.1 Introduction

A modular power conversion unit will be used to generate power from heat provided by microreactors. These PCUs are around 1-20 MW_e (Office of Nuclear Energy, 2018). The nuclear microreactor's PCU being investigated will be similar to an air breathing compressor-turbine unit. It is noted that there are many different potential PCU configurations that could be utilized with nuclear microreactors. A detailed search was performed on actual compressor-turbine units. These units could provide an accurate representation of the size and efficiencies that would be used for modular nuclear microreactors.

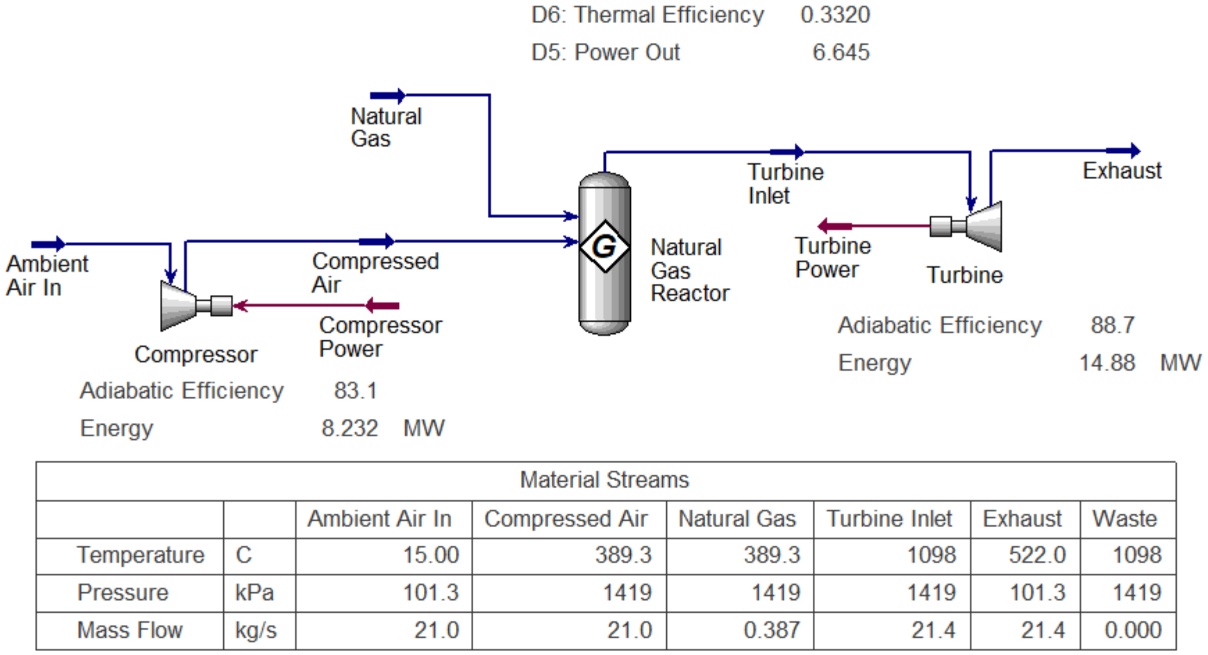
Knowing the sizing of a full scale modular PCU nuclear reactor will also aid in the development and versatility of the PCU simulator. A key factor for the PCU simulator is that it is capable of simulating state points in a power cycle. These state points do not have to come from steady-state operations of the power cycles. Understanding the start up procedure gives the three key data points discussed in the previous chapter. These three key points are the conditions of the working fluid entering and leaving the turbine and entering the reactor (vacuum chamber in the MAGNET). During the start up processes, these three key points for a non-recuperated Brayton cycle could be simulated. Similar steps described later in the chapter could be applied to a recuperated Brayton cycle.

4.2 Aspen HYSYS Analysis of Siemen's SGT-A05 KB7HE

Siemens Automation Company manufactures a small, portable, compressor-turbine unit, the SGT-A05 KB7HE, which produces around 5 MW_e. This power generation unit was selected to perform an analysis on, as it falls within the expected power range of the modular nuclear microreactors (1-20 MW). Analyzing the commercial unit provided representative efficiencies for the compressor and turbine. An Aspen HYSYS model was designed to replicate the Siemens' public data sheet for this unit. The unit's data sheet is shown in Table 4.1 and the Aspen HYSYS model is shown in Figure 4.1.

Table 4.1 Siemens’ SGT-A05 Public Data Sheet (Siemens, 2019)

	SGT-A05 KB5S	SGT-A05 KB7S	SGT-A05 KB7 HE
Power Output	4.0 MWe	5.4 MWe	5.8 MWe
Fuel	Natural gas, liquid fuel, duel fuel; other fuels on request; automatic changeover from primary to secondary fuel at any load		
Frequency	50/60 Hz	50/60 Hz	50/60 Hz
Gross Efficiency	29.70%	32.30%	33.20%
Heat Rate	12,137 kJ/kWh	11,152 kJ/kWh	10,848 kJ/kWh
Turbine Speed	14,200 rpm	14,600 rpm	14,600 rpm
Pressure Ratio	10.3 : 1	13.9 : 1	14.0 : 1
Exhaust mass flow	15.4 kg/s	21.3 kg/s	21.4 kg/s
Exhaust Temperature	560°C (1,404°F)	484°C (921°F)	522°C (972F)
NOx emissions	≤ 25 ppmvd at 15% O2 on fuel gas (with DLE)		



D6: Thermal Efficiency 0.3320

D5: Power Out 6.645

Compressor

Adiabatic Efficiency 83.1

Energy 8.232 MW

Turbine

Adiabatic Efficiency 88.7

Energy 14.88 MW

Material Streams							
		Ambient Air In	Compressed Air	Natural Gas	Turbine Inlet	Exhaust	Waste
Temperature	C	15.00	389.3	389.3	1098	522.0	1098
Pressure	kPa	101.3	1419	1419	1419	101.3	1419
Mass Flow	kg/s	21.0	21.0	0.387	21.4	21.4	0.000

Figure 4.1 SGT-A05 KB7HE Air Brayton Cycle Aspen HYSYS Model

The SGT-A05 KB7HE Aspen HYSYS model was created to determine the representative efficiencies for the compressor and turbine for a similarly sized PCU for nuclear microreactors. The compressor efficiencies are expected to be within the range of 70%-85% and turbine efficiencies are expected to be between 75%-90% (Wark, 1995). Through parametric studies using the Aspen HYSYS model, a compressor efficiency of 83.1% and a turbine efficiency of 88.7% was obtained. It is shown that some of the values in the Aspen HYSYS model do not match the Siemens' data sheet. This is likely due to Siemens' data sheet being collected from a physical unit which includes losses in the system and the generator. The efficiencies found in Aspen HYSYS are, however, reasonable according to the traditional ranges presented by Wark. This data provided useful information that these smaller PCUs can still obtain high adiabatic efficiencies for compressors and turbines. Therefore, two cases were analyzed to give a range of data: a scenario assuming compressor and turbine efficiencies at 85% and 90% and a scenario assuming a compressor and turbine efficiencies of 70% and 80%, respectively.

An analysis was performed to compare the performance between the Siemen's SGT-A05 KB7HE unit and an optimized 85% compressor and 90% turbine efficiency heat pipe nuclear reactor PCU using 600°C turbine inlet temperature. This temperature is the expected temperature found in the MAGNET leaving the heat pipe section as well as within the range of normal operations for a heat pipe cooled reactor (Westinghouse, 2019). Both units were assumed to use dry air as the working fluid and were both an open air Brayton cycle. This comparison is shown in Table 4.2. It is shown that the heat pipe powered PCU does not produce as much power or have a high thermal efficiency compared to Siemens combustion powered PCU. This is expected due to the turbine inlet temperature and pressure ratios of the SGT-A05 being much greater. However, the thermal efficiency for the heat pipe powered Brayton cycle is still reasonable.

Table 4.2 Comparison Between a Heat Pipe Powered PCU and a Natural Gas Power PCU

	Thermal Efficiency	Pressure Ratio	Power Out [MW]	Turb In Temp [ºC]	Exhaust Temp [ºC]	Mass Flow Rate [kg/s]	Comp Efficiency	Turb Efficiency	Carnot Efficiency	Second Law Efficiency
Heat Pipe Power Simple Air Brayton Cycle	23.4	7.38	2.34	600	280	28.7	85	90	66.3	35.3
Siemen's SGT-A05 KB7HE Natural Gas Combustion Brayton Cycle	33.2	14	6.65	1100	522	21.4	83.1	88.7	78.6	42.3

4.3 Estimated Start Up Analysis for Heat Pipe Nuclear Reactor Operating at 650°C

A simplified air Brayton cycle was constructed in Aspen HYSYS to simulate the performance of the PCU. Figure 4.2 shows the Aspen HYSYS model for the Brayton cycle using the higher compressor and turbine efficiencies, the process flow diagram for both efficiency model is in Appendix M. The heat source used in the model could be representative of a gas combustion unit or some other heat source such as nuclear power. The "Air Compressor" and "Air Turbine" are both functioning from design curves presented above. For the dynamic analysis, an approximation of a quasi-steady-state process is assumed. This assumption implies that the PCU responds instantaneously to small incremental steps. This approach is valid for dynamic analysis as these systems do respond quickly. According to J. Kim et al., many mathematical models simulate start up of gas turbine engines with a quasi-steady-state assumption (Kim, Song, Kim, & Ro, 2002). Therefore, the start up analysis was performed using a quasi-steady-state assumption.

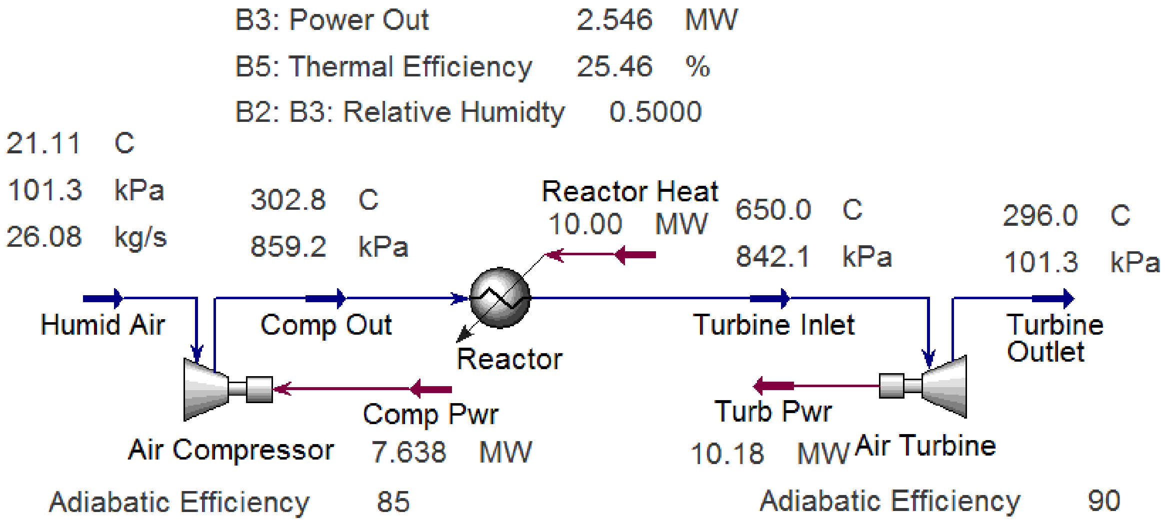


Figure 4.2 Air Brayton Cycle with 85% Compressor and 90% Turbine Adiabatic Efficiencies with a Turbine Inlet Temperature of 650ºC

To perform an analysis on the start up of the simple air Brayton cycle, the start up process needs to be understood. The process of starting up a simple air Brayton cycle power conversion unit was described by a representative from Siemens for one of their larger power production plants (Siemens, 2019).

Kim et al. also described that during start up, “Turbine efficiencies must be high enough, at a speed approximately 40% to 85% of its design speed, in order for the engine to sustain itself without starter power” (Kim, Song, Kim, & Ro, 2002)**.** They also describe that it is slightly different for each engine. Kim et al.’s data was comparable to Siemens’ report.

Using guidance from both sources, the start up process used for this analysis was as follows:

1. A motor begins to turn the compressor. The motor can be a 480 V motor, or the unit can be started by reversing the power into the generator to act as a motor.
2. The motor drives the compressor to the shaft rotational speed range of 61 – 63% of the operating speed at which time the fuel is injected into the combustion chamber. At this point, the combustion is considered unstable.
3. The generator continues to drive the compressor to about 83.33% of the operational speed when the combustion process is considered stable and the turbine can sustain the compression process.
4. The turbine drives the system at this point and the fuel rate is increased until the turbine speed reaches the system’s operational speed.

These start up steps are used for a conventional natural gas powered PCU. They outline when the fuel would be added during the start up of the PCU. However, there was discussion on how a nuclear powered heat pipe reactor could start up. Sodium cooled heat pipes, as the ones used for the MAGNET, could take a considerable amount of time to get to their operating point (Reid, Sena, & Martinez, 2001) and could use a loop for cooling separated from the PCU. Once the heat pipes are at their operating point, the PCU could start up and the PCU working fluid could be directed through the heat pipe heat exchanger through a series of valving which would add heat to the PCU as well as continued cooling to the heat pipes. Making sure that the heat pipes always had sufficient mass flow rate for cooling while switching from the heat pipe primary cooling loop and the PCU would need to be considered. However, for the remained of this chapter, the start up analysis used the conventional natural gas PCU start up detailed above.

Generic compressor and turbine curves were obtained to help simulate the performance of the PCU during off design conditions. The generic curves were scaled to the operating points expected from the optimized heat pipe PCUs, such as the one in Figure 4.2. The curves have been scaled to fit a higher efficiency compressor and turbine case as well as a lower efficiency compressor and turbine scenario. These curves were generated for two separate simple Brayton cycles with a turbine inlet temperature of 650ºC: one with an 85% compressor efficiency and 90% turbine efficiency and the other with a 70% compressor efficiency and 80% turbine efficiency. The curves also assume that 100% rotational speed is the same as Siemens' SGT-A05-KB7HE which is 14600 rpm. The curves are shown below in Figure 4.3 to Figure 4.6. The curves were entered into Aspen HYSYS to estimate the performance of the PCUs at different shaft rotation speeds and varying efficiencies.

An approximate mass flow rate equation was used during the quasi-steady-state analysis. Equation 4.1 relates the density of the inlet fluid, volume of the unit, and the rotational speed of the unit to the mass flow rate. The mass flow rate at a given speed is proportional to the compressor speed percentage multiplied by the design mass flow rate when the inlet density is considered constant, shown in Equation 4.2. This estimation was used to determine the mass flow rate at varying rotational speeds of the PCU.

$$\dot{m} = \frac{\rho V n}{60} \left(\frac{kg}{s}\right) \qquad \textbf{Equation 4.1}$$

$$\dot{m} = \frac{n}{n_{op}} \dot{m}_{op} \qquad \textbf{Equation 4.2}$$

Where:

$\dot{m} \rightarrow mass\ flow\ rate \left(\frac{kg}{s}\right)$

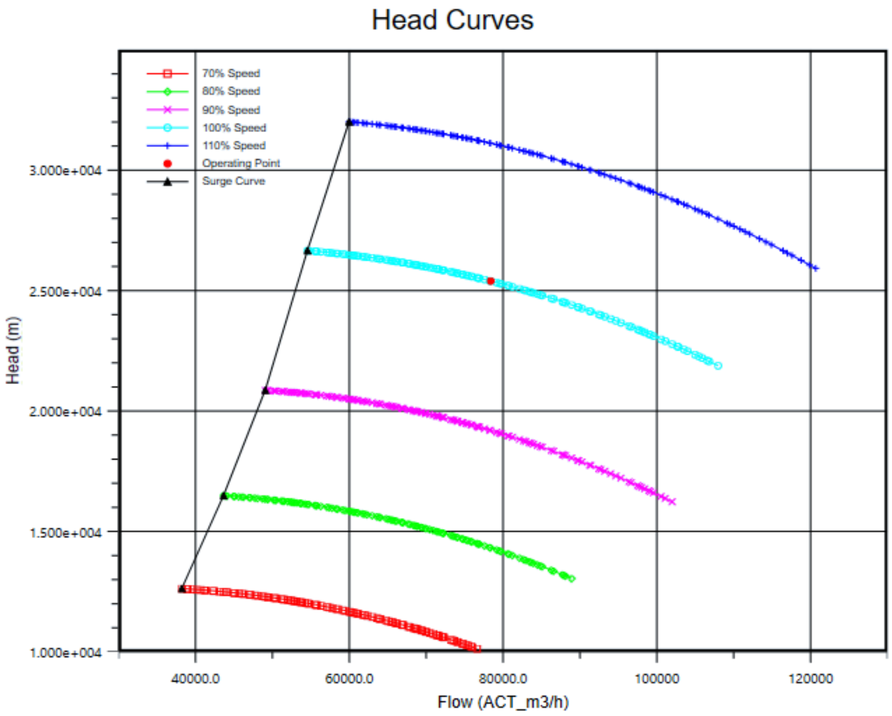
$\rho \rightarrow Inlet\ mass\ density \left(\frac{kg}{m^3}\right)$

$V \rightarrow Unit\ volume\ (m^3)$

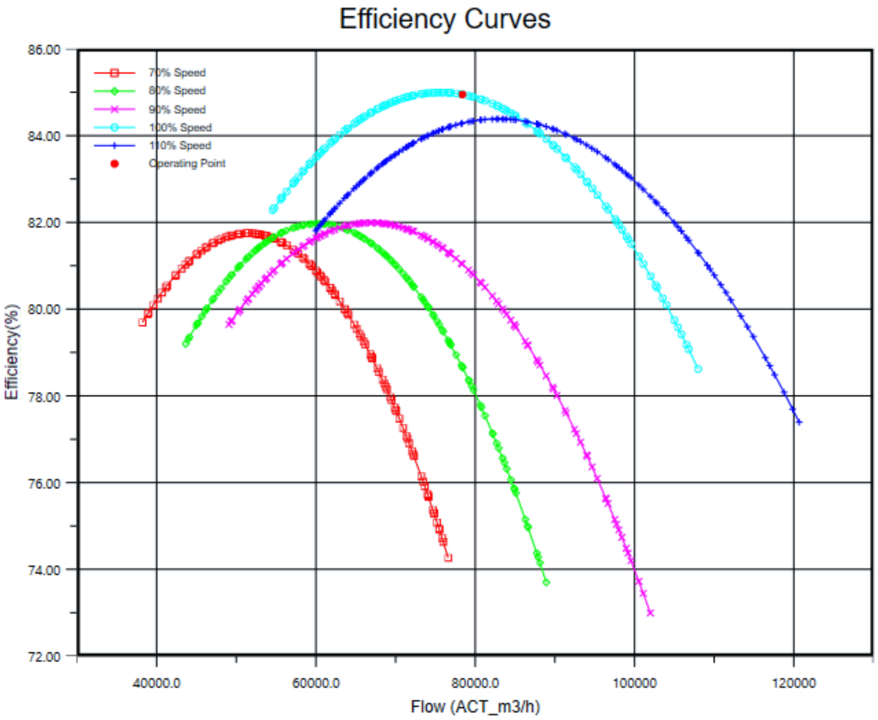
$n \rightarrow Unit's\ speed \left(\frac{rev}{min}\right)$

$\dot{m}_{op} \rightarrow Operational\ mass\ flow\ rate \left(\frac{kg}{s}\right)$

$n_{op} \rightarrow Unit's\ operational\ speed \left(\frac{rev}{min}\right)$

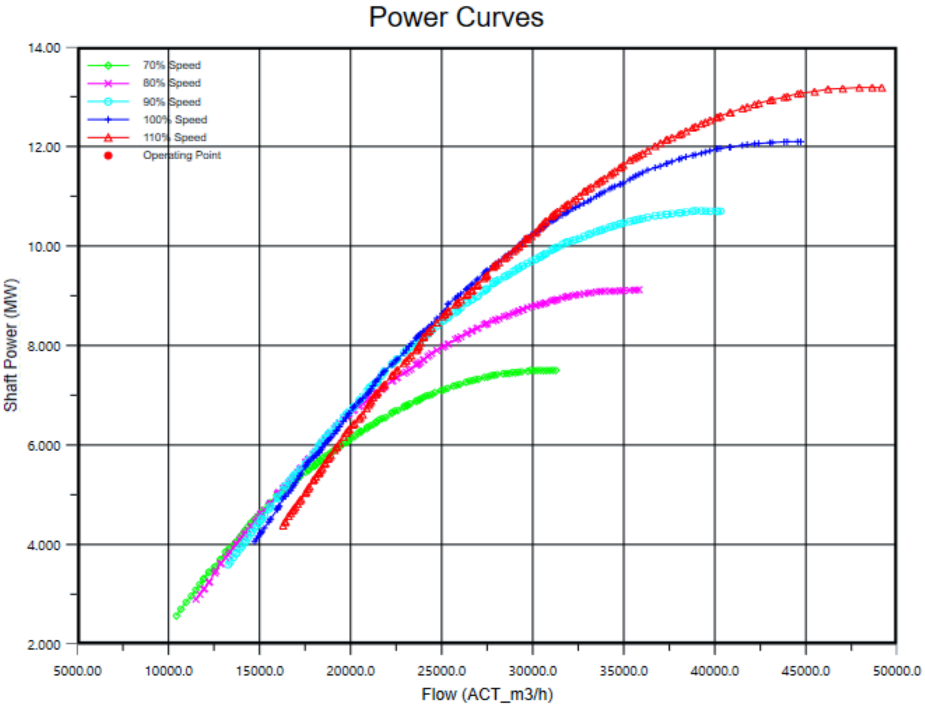


a. Head Curve

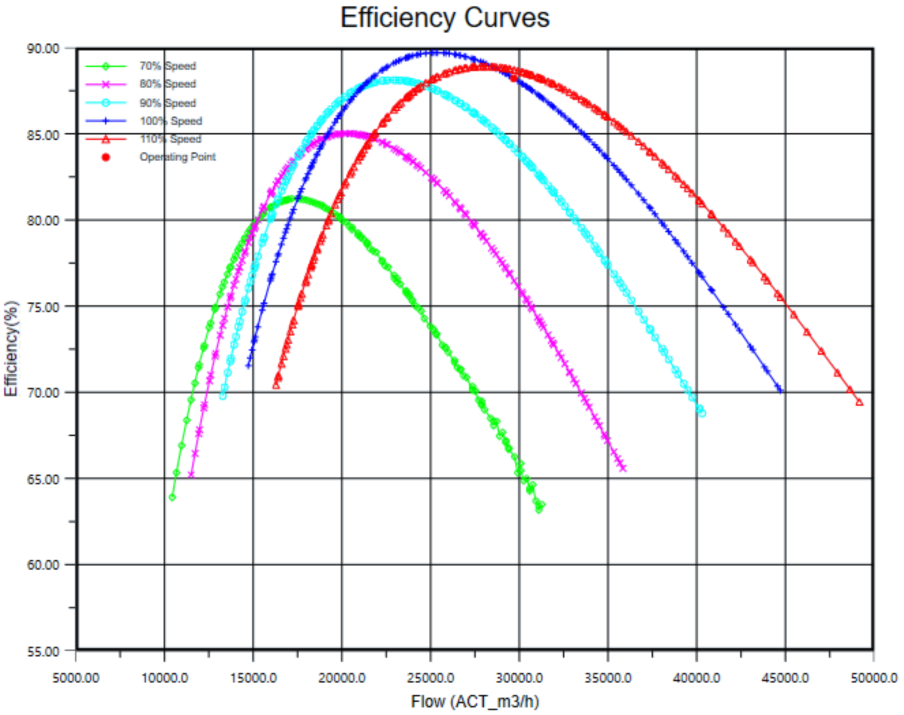


b. Efficiency Curve

Figure 4.3 Compressor Curves for the 85% Compressor and 90% Turbine Adiabatic Efficiencies Case with a Turbine Inlet Temperature of 650ºC

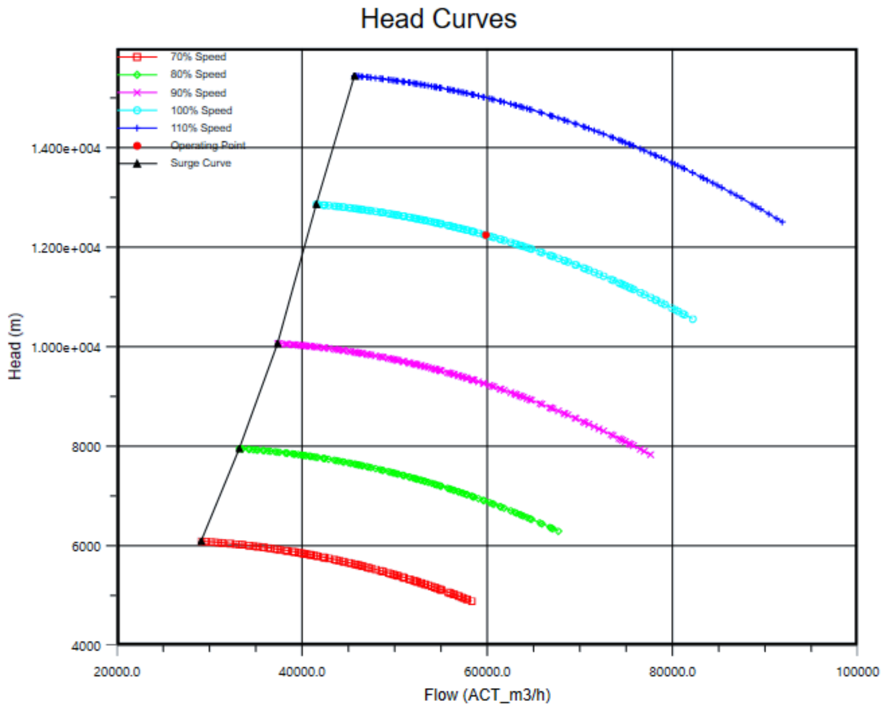


a. Head Curve

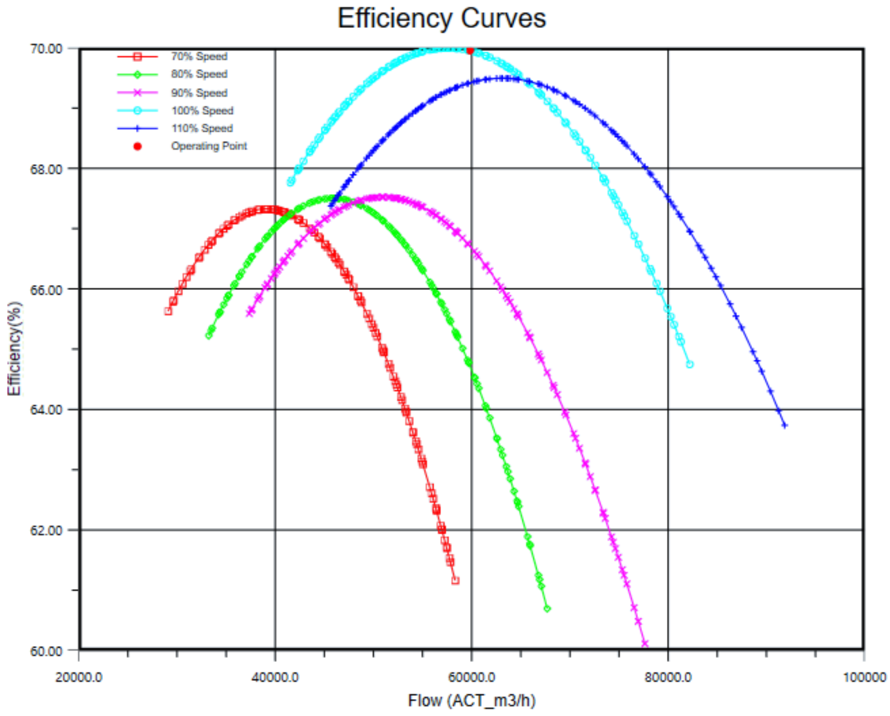


b. Efficiency Curve

Figure 4.4 Turbine Curves for the 85% Compressor and 90% Turbine Adiabatic Efficiencies Case with a Turbine Inlet Temperature of 650ºC

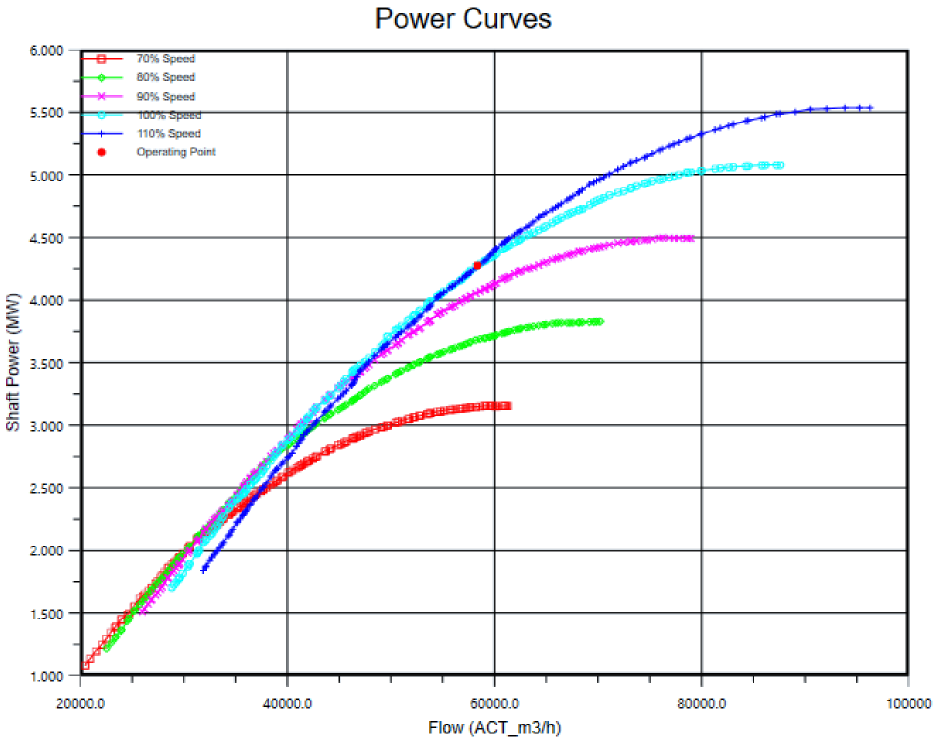


a. Head Curve

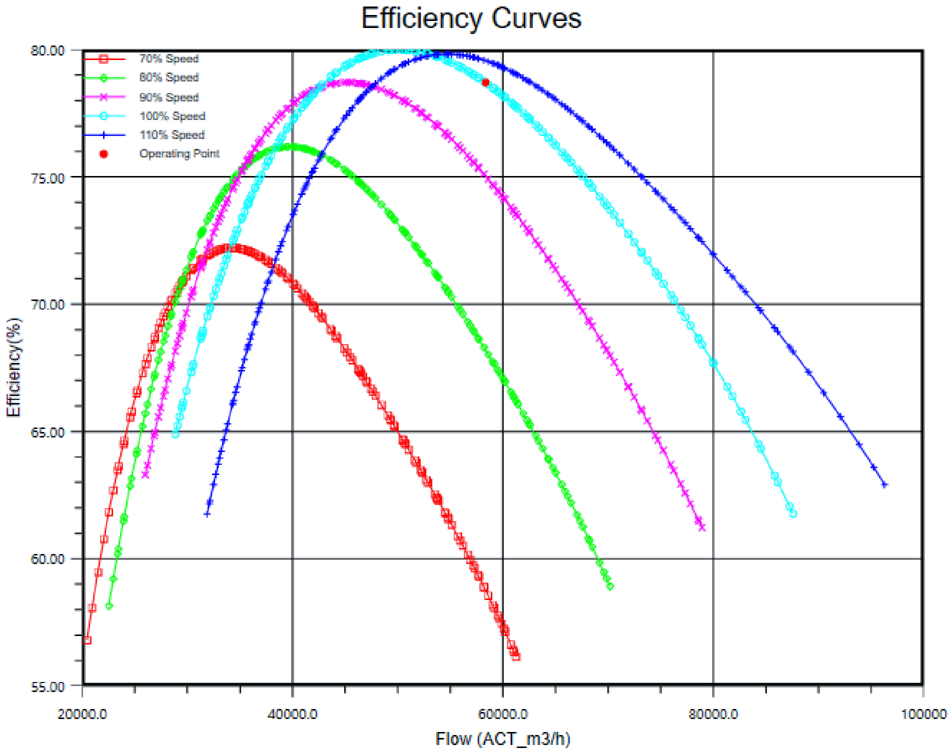


b. Efficiency Curve

Figure 4.5 Compressor Curves for 70% Compressor and 80% Turbine Adiabatic Efficiencies Case with a Turbine Inlet Temperature of 650ºC



a. Head Curve



b. Efficiency Curve

Figure 4.6 Turbine Curves for 70% Compressor and 80% Turbine Adiabatic Efficiencies Case with a Turbine Inlet Temperature of 650ºC

During start up, it was assumed that the compressor drives the system in terms of rotational speed and mass flow rate due to the start up motor turning the compressor which is shafted to the turbine. The turbine then controls the system once the temperature and pressure reach the point where the turbine generates sufficient power to overcome the work of the compressor. It was assumed that the operating rotational speed was 14600 rpm, which mimics the operating rotational speed of Siemens' SGT-A05 KB7HE PCU. The results for the start up analysis for both the highest and lowest efficiencies for the compressor and turbine case scenarios are shown below in Table 4.3 to Table 4.4 and Figure 4.7 to Figure 4.10. It is assumed that the power out is the compressor power subtracted from the turbine power and it does not include inefficiencies in the generator unit.

Table 4.3 Results of Start Up Analysis for 85% Compressor and 95% Turbine Adiabatic Efficiencies with a Turbine Inlet Temperature of 650°C

RPM	Power Out (MW)	Compressor Power (MW)	Turbine Power (MW)	Turbine Inlet Temp (°C)	Comp Outlet Pres (MPa)	Exhaust Temp (°C)	Mass Flow Rate (kg/s)
0	0	0	0	21.1	0.101	21.1	0
61.64%	-1.34	1.71	0.362	125	0.251	103	16
86%	0.00846	4.85	4.86	512	0.524	313	22.4
100%	2.35	7.63	9.97	651	0.86	304	26
110%	2.24	10.1	12.4	674	1.17	283	28.6

Table 4.4 Results of Start Up Analysis for 70% Compressor and 80% Turbine Adiabatic Efficiencies with a Turbine Inlet Temperature of 650°C

RPM	Power Out (MW)	Comp Power (MW)	Turbine Power (MW)	Turbine Inlet Temp (°C)	Comp Outlet Pres (MPa)	Exhaust Temp (°C)	Mass Flow Rate (kg/s)
0	0	0	0	21.1	0.101	21.1	0
61.64%	-0.629	0.761	0.131	79.7	0.162	69.2	12.2
83%	0.00657	1.95	1.95	552	0.233	445	16.5
100%	0.791	3.4	4.2	649	0.333	460	19.8
110%	0.75	4.53	5.28	640	0.406	423	21.8

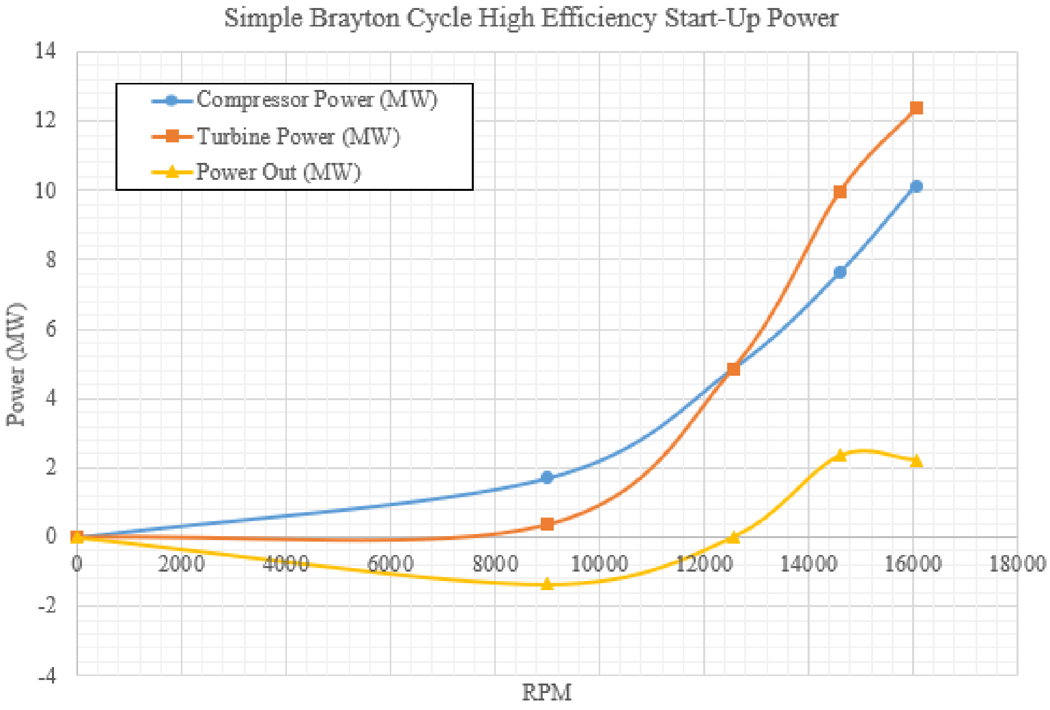


Figure 4.7 Power Profiles for Start Up Analysis of Air Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 85% and 90% with a Turbine Inlet Temperature of 650ºC

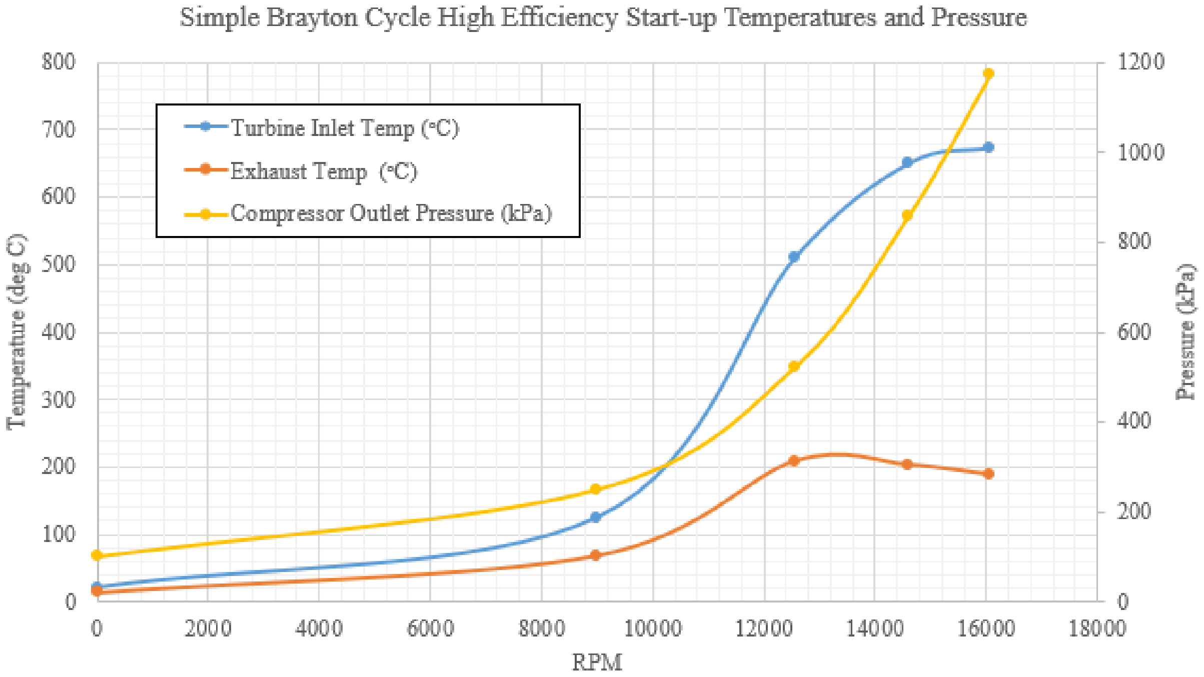


Figure 4.8 Temperature and Pressure Profiles for Start Up Analysis of Air Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 85% and 90% with a Turbine Inlet Temperature of 650ºC

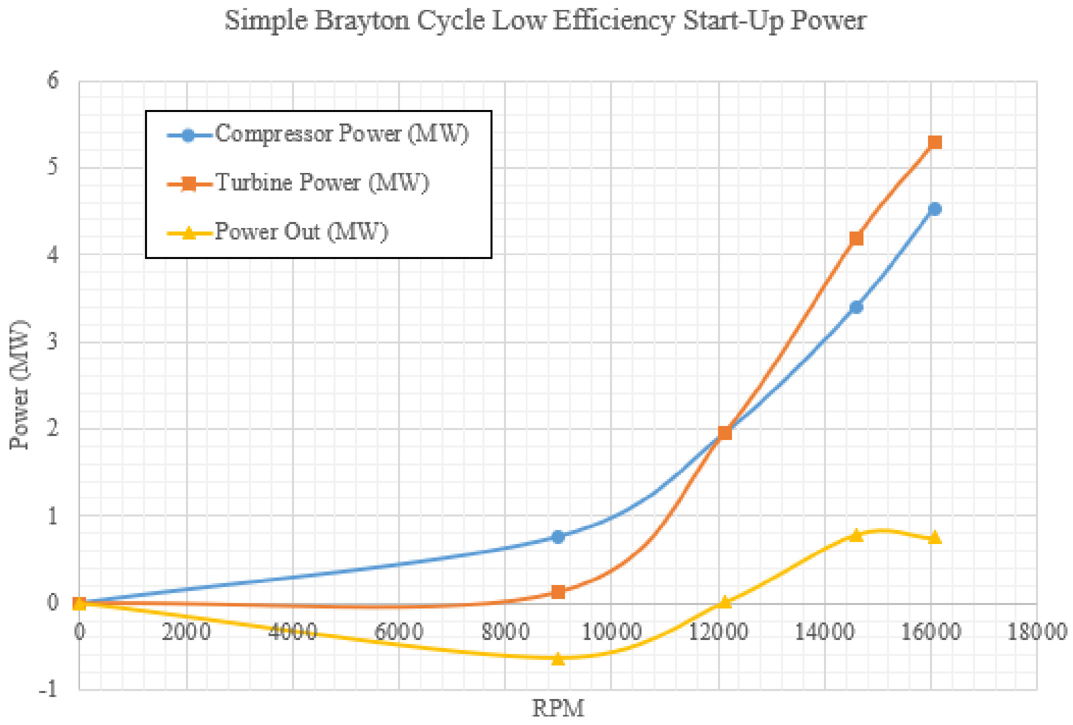


Figure 4.9 Power Profiles for Start Up Analysis of Air Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 70% and 80% with a Turbine Inlet Temperature of 650ºC

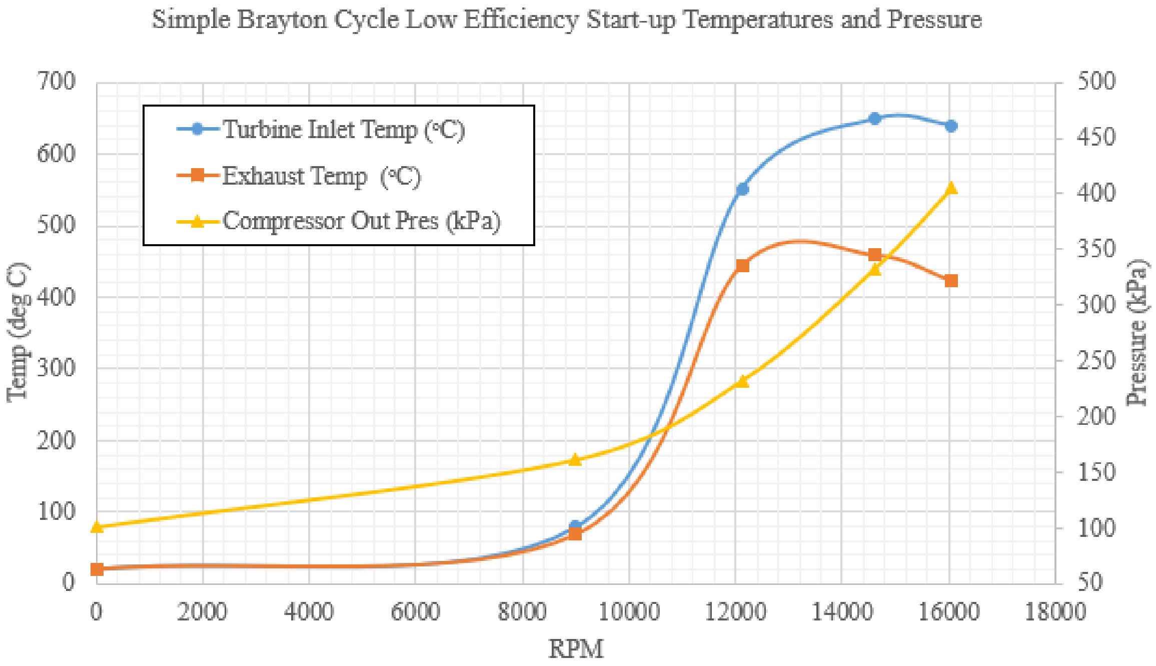


Figure 4.10 Temperature and Pressure Profiles for Start Up Analysis of Air Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 70% and 80% with a Turbine Inlet Temperature of 650ºC

The analysis shows that the higher efficiency case scenario has enough turbine power to self-sustain the system when the rotational speed is close to 86% of the operating speed. The lower efficiency case scenario showed the turbine generated enough power to self-sustain near 83% of the operating rotational speed. Both these values are within the range that Kim et al and Siemens described for start up. However, their data was based off natural gas combustion and required the combustion to be stable. The microreactor heat pipes could possibly start heating the air sooner, requiring less power input into the power conversion unit.

4.4 Estimated Start Up Analysis for Heat Pipe Nuclear Reactor Operating at 600°C

A similar analysis was performed on a heat pipe PCU assuming the working fluid was pure nitrogen, and the turbine inlet temperature was 600ºC instead of 650ºC. The other assumptions remained the same. This analysis is analogous to the fluid and turbine inlet temperature of the MAGNET. To be simulated in the PCU simulator, the pressures would only need to be adjusted to acquire the correct pressure ratio at each start up state point. This analysis required a new set of curves to be generated for the compressor and turbine at their different paired efficiencies: 70% and 80% compressor and turbine efficiencies respectively, and 85% and 90% compressor and turbine efficiencies, respectively. This was done because the operating temperature was adjusted. These models were optimized to obtain the highest possible thermal efficiency. The higher efficiency model is shown in Figure 4.11, the process flow diagram for both efficiency model is in Appendix M. The compressor and turbine curves are shown in Figure 4.12 to Figure 4.15 for the high and low efficiency cases. The results of the analyses are shown in Table 4.5 to Table 4.6 and Figure 4.16 to Figure 4.19.

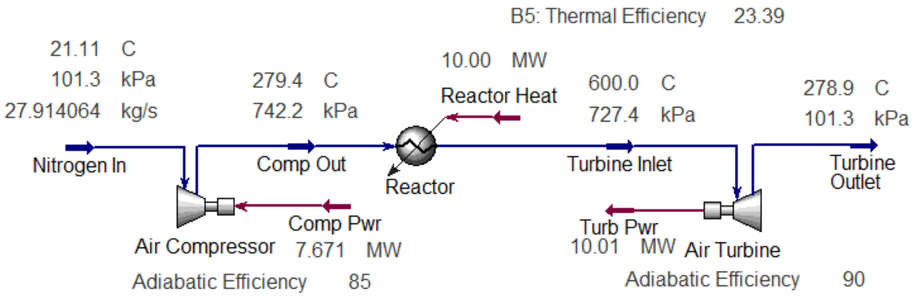
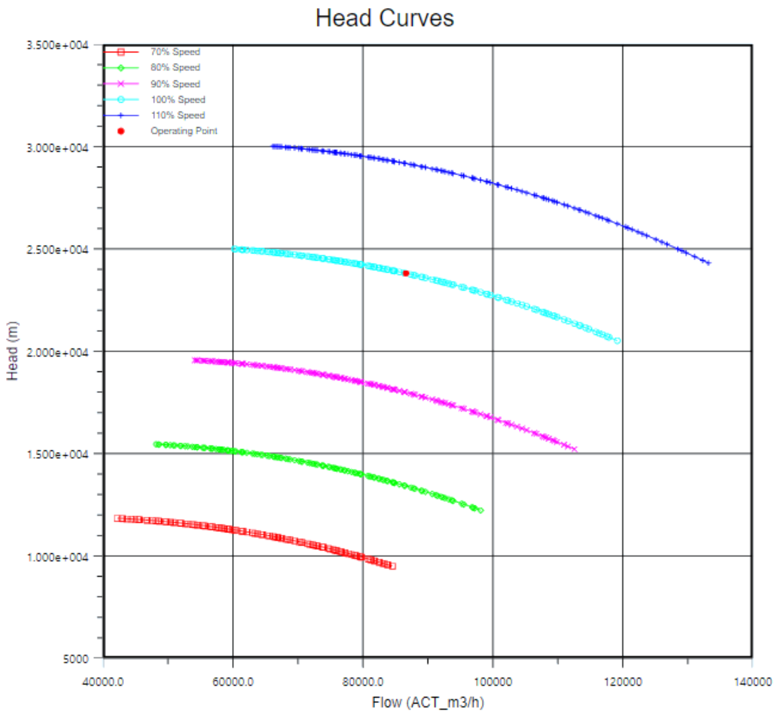
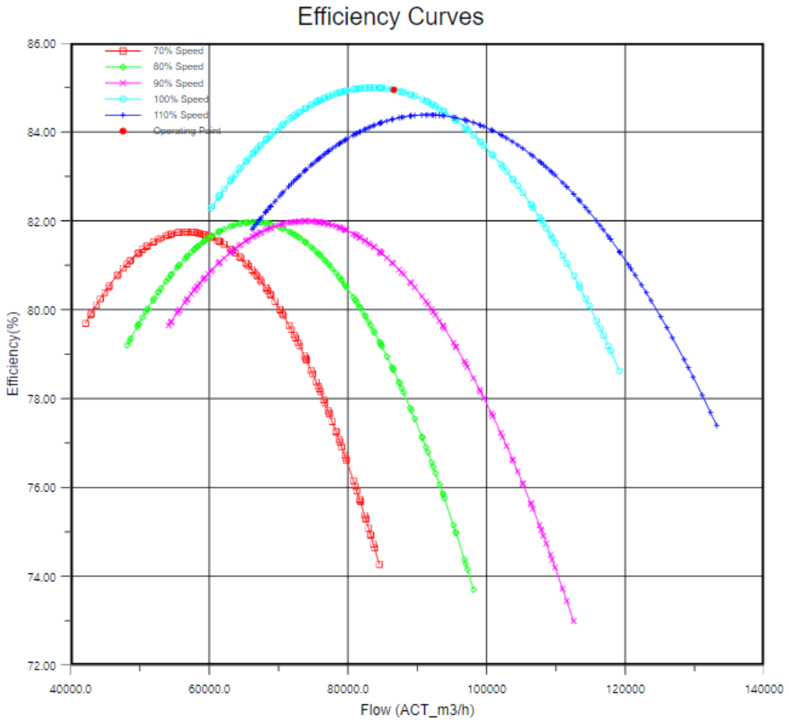


Figure 4.11 Simple Nitrogen Brayton Cycle with 85% Compressor and 90% Turbine Adiabatic Efficiencies with a Turbine Inlet Temperature of 600ºC

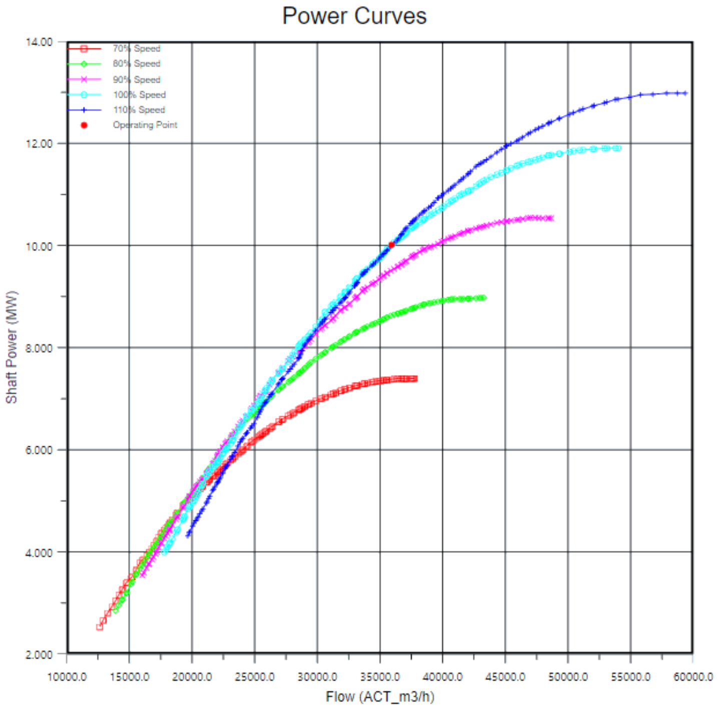


a. Head Curve

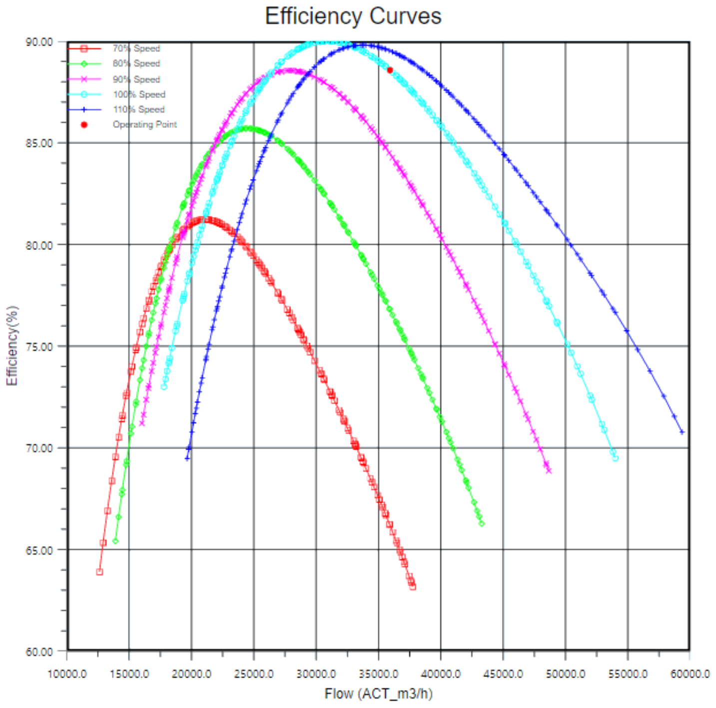


b. Efficiency Curve

Figure 4.12 Compressor Curves for the 85% Compressor and 90% Turbine Adiabatic Efficiencies Case with a Turbine Inlet Temperature of 600ºC

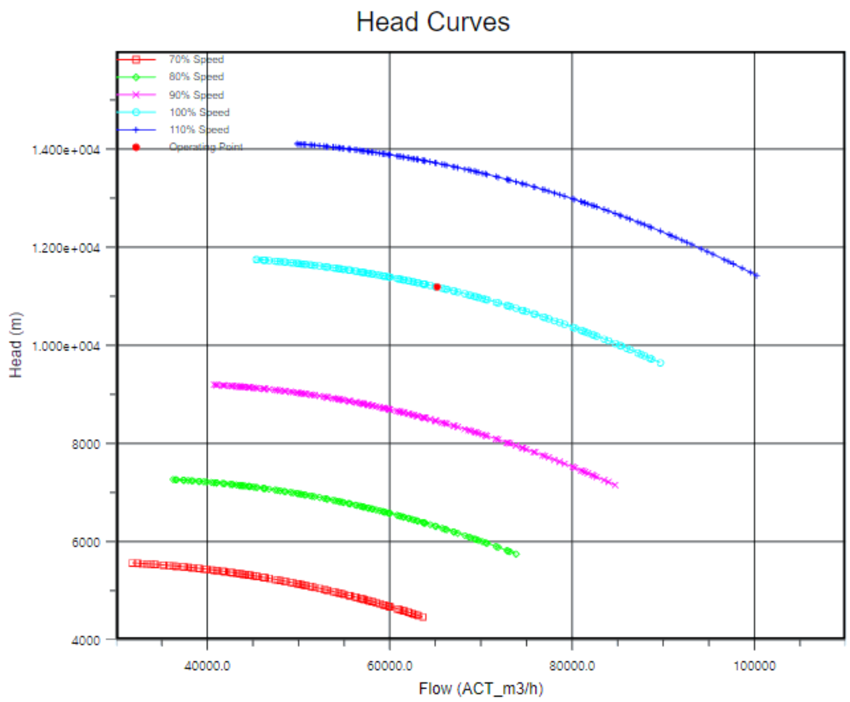


a. Head Curve

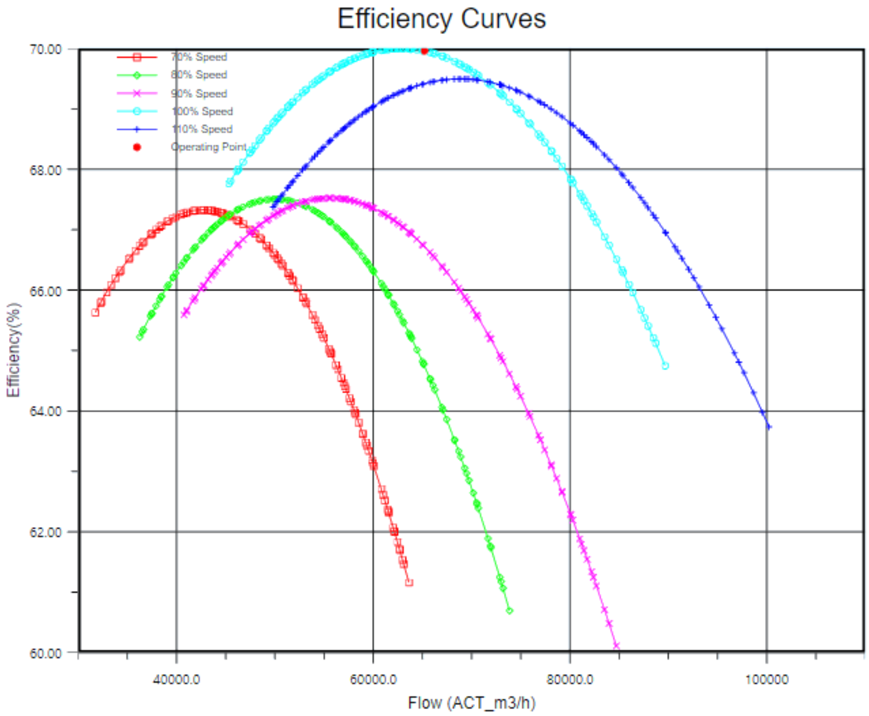


b. Efficiency Curve

Figure 4.13 Turbine Curves for the 85% Compressor and 90% Turbine Adiabatic Efficiencies Case with a Turbine Inlet Temperature of 600ºC



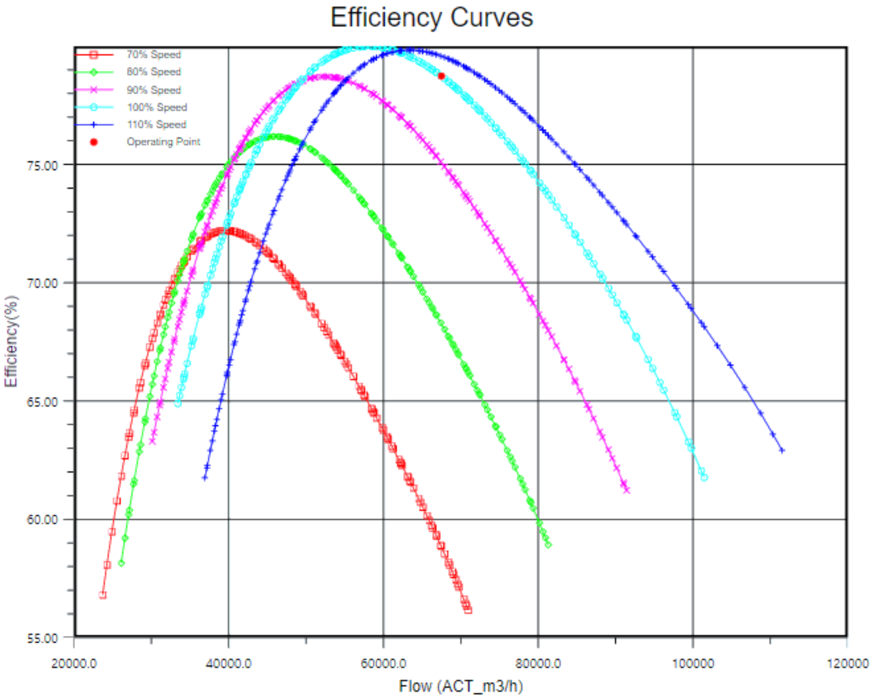
a. Head Curve



b. Efficiency Curve

Figure 4.14 Compressor Curves for 70% Compressor and 80% Turbine Adiabatic Efficiencies Case with a Turbine Inlet Temperature of 600ºC

a. Head Curve



b. Efficiency Curve

Figure 4.15 Turbine Curves for 70% Compressor and 80% Turbine Adiabatic Efficiencies Case with a Turbine Inlet Temperature of 600ºC

Table 4.5 Results of Start Up Analysis for 85% Compressor and 95% Turbine Adiabatic Efficiencies Case with a Turbine Inlet Temperature of 600°C

RPM (%)	Pressure Ratio	Turbine Inlet Temp (°C)	Exhaust Temp (°C)	Comp Outlet Temp (°C)	Comp Outlet Pres (MPa)	Turbine Adiabatic Efficiency	Compressor Adiabatic Efficiency	Reactor Heat (MW)	Compressor Power (MW)	Turbine Power (MW)	Power Out (MW)	Mass Flow Rate (kg/s)
0	0	21.1	21.1	21.1	0.101	0	0	0	0	0	0	0
60	2.19	110	91	110	0.222	25	82.8	0	1.55	0.327	-1.23	16.7
86	4.58	471	287	213	0.464	74.5	81.8	6.8	4.88	4.89	0.00431	24
100	7.32	600	284	279	0.742	88.6	85	10	7.67	9.85	2.18	27.9

Table 4.6 Results of Start Up Analysis for 70% Compressor and 80% Turbine Adiabatic Efficiencies Case with a Turbine Inlet Temperature of 600°C

RPM (%)	Pressure Ratio	Turbine Inlet Temp (°C)	Exhaust Temp (°C)	Comp Outlet Temp (°C)	Comp Outlet Pres (MPa)	Turbine Adiabatic Efficiency	Compressor Adiabatic Efficiency	Reactor Heat (MW)	Compressor Power (MW)	Turbine Power (MW)	Power Out (MW)	Mass Flow Rate (kg/s)
0	0	21.1	21.1	21.1	0.101	0	0	0	0	0	0	0
60	1.48	71.8	63.1	71.8	0.15	25	68.2	0	0.667	0.113	-0.554	12.6
82.30	2.09	554	460	122	0.212	66.3	67.4	8.2	1.84	1.84	0.00334	17.3
100	2.93	600	434	170	0.297	78.7	70	10	3.3	3.95	0.655	21

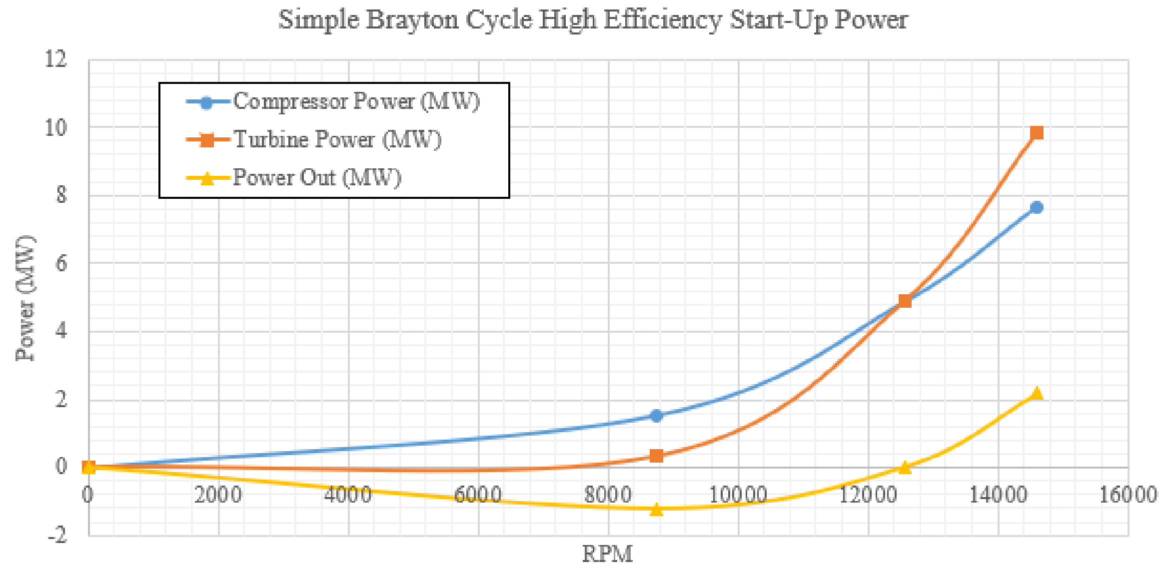


Figure 4.16 Power Profiles for Start Up Analysis of Air Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 85% and 90% with a Turbine Inlet Temperature of 650ºC

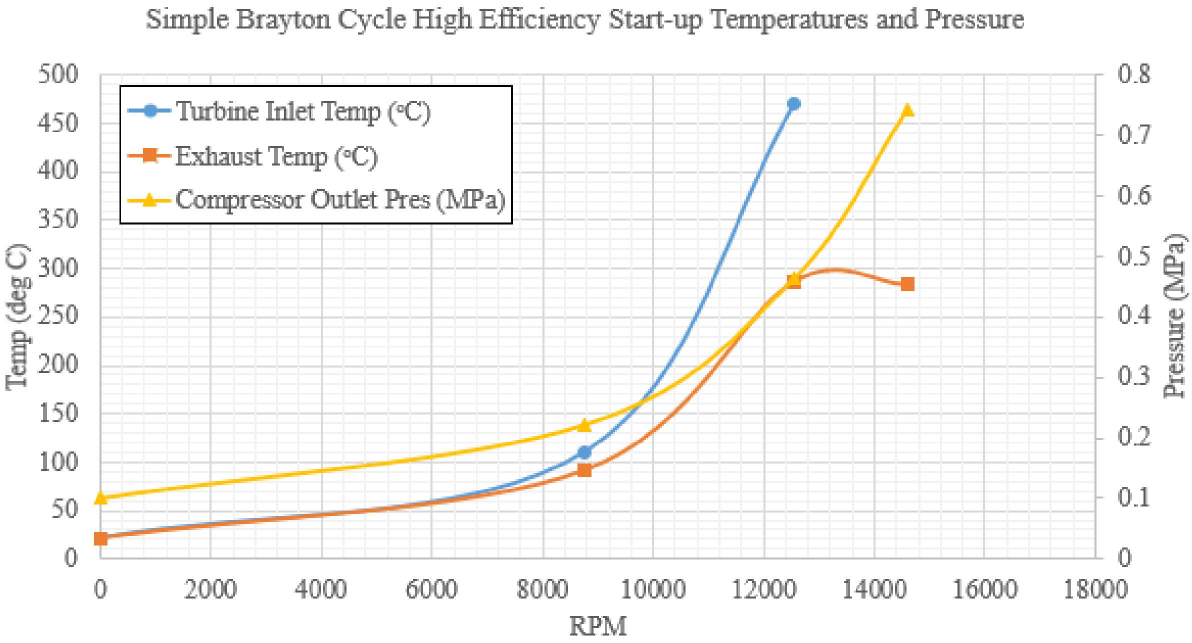


Figure 4.17 Temperature and Pressure Profiles for Start Up Analysis of Air Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 85% and 90% with a Turbine Inlet Temperature of 600ºC

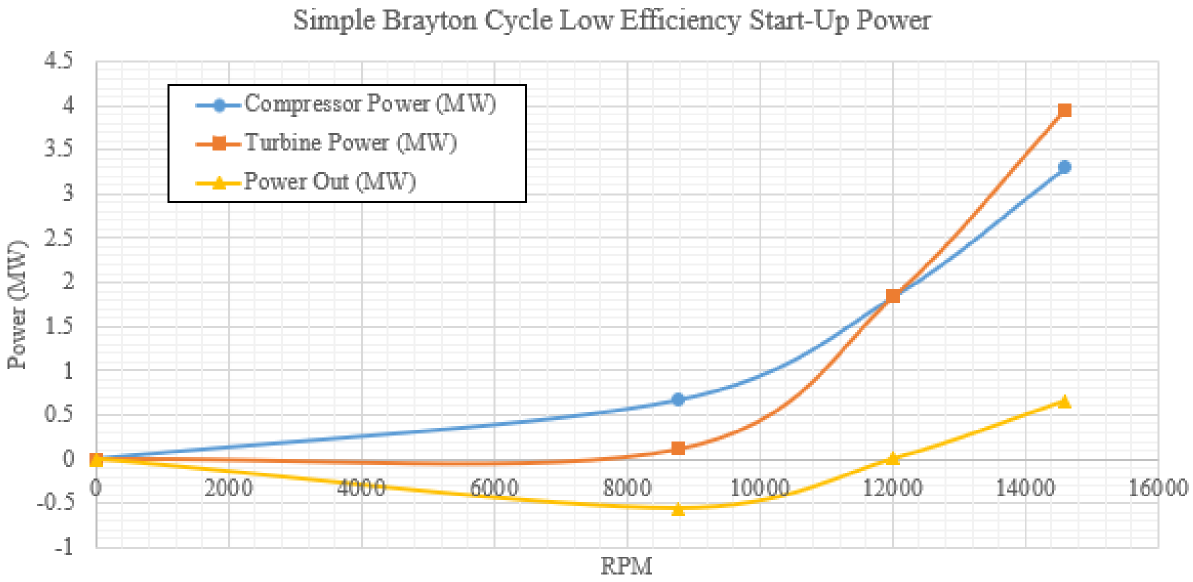


Figure 4.18 Power Profiles for Start Up Analysis of Air Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 70% and 80% with a Turbine Inlet Temperature of 600ºC.

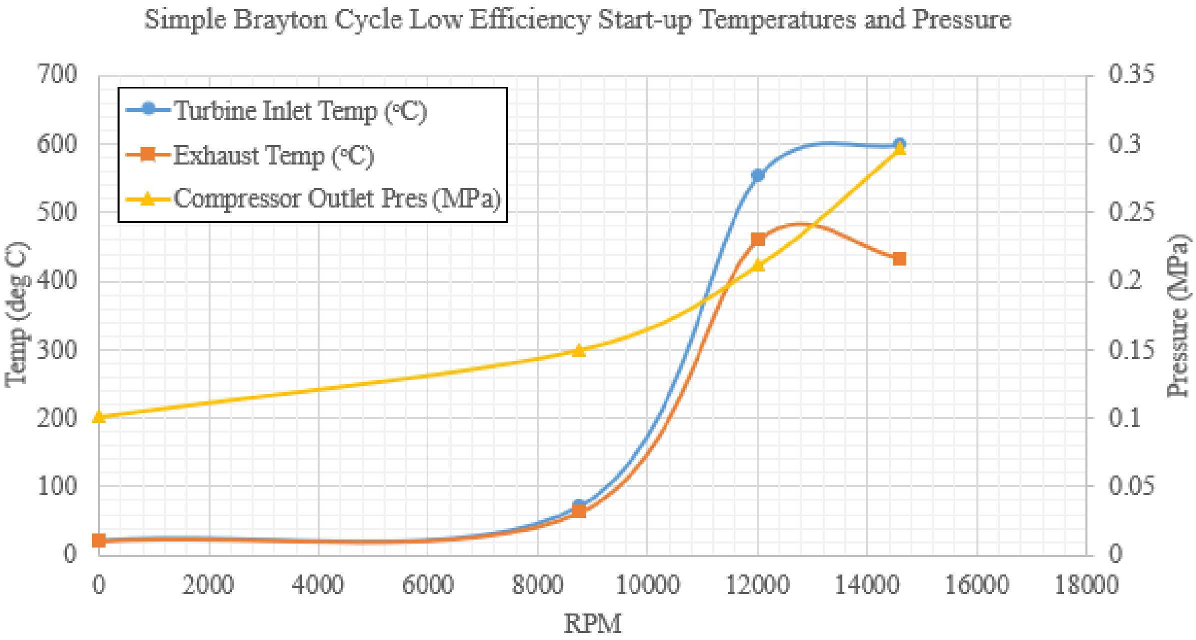


Figure 4.19 Temperature and Pressure Profiles for Start Up Analysis of Air Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 70% and 80% with a Turbine Inlet Temperature of 600ºC

The start up points between the two cycles are similar in terms of percent RPM when the unit is self-sustaining. The curves have a similar shape between the high and low efficiencies.

The power out is lower than the 650°C cases analyzed earlier, which is expected since the mass flow rate and the turbine inlet temperature is lower. However, the results follow a similar pattern.

A start up process could be simulated within the power conversion unit simulator by simulating the temperatures and pressure ratios found at the inlet and outlet of the turbine and the temperature entering the MAGNET vacuum chamber. As shown in the above tables and figures, four key rotation speeds simulate the start up process with the needed key points. Using similar analysis, the PCU simulator would be able to simulate different start up process of various power cycles as well as their shut down process.

Chapter 5: Conclusion and Recommendations

5.1 Conclusion

5.1.1 MAGNET Conclusions

The INL is developing the MAGNET to help test and prove various types of modular nuclear microreactors. Many Aspen HYSYS models were created to aid in this development. These models were designed after the equipment being placed within the MAGNET, including heat exchangers, piping, insulation, valving, pumps, and compressors. These models provide detailed process conditions at many state points within the MAGNET and several conclusions are drawn from the models.

- The MAGNET Aspen HYSYS models are rigorous models estimating many aspects throughout the loop. This makes them a great starting point for the expected process conditions until the equipment and heat exchanger models can be validated.
- Models for conditions that could be potentially dangerous if we pushed the system. Ensure safety while operations.
- The MAGNET models could be used to simulate potential experiments for the MAGNET. Running experiments can be costly due to labor and energy requirements. The HYSYS models could aid in the development of experiments to provide the most relevant information with the least amount of time and cost by eliminating experiments that provide little value.
- The MAGNET HYSYS models could be used to simulate off design conditions to determine safety parameters. The models could provide when the pressure or temperatures reach an extreme that could be potentially dangerous.
- The MAGNET was designed with the intent for using nitrogen as the main working fluid, but it was also considered to use helium. The MAGNET model estimated the performance of the heat exchangers and showed that helium will reach a higher temperature than nitrogen by approximately 34°C at similar heat pipe power. This puts the highest temperature in the system close to 634°C. The piping was designed for an operating temperature of 650°C which makes helium push near the design limit of the piping.

- The heat pipe heat exchanger designed showed that the desired temperature increase is possible.
- The models are a more rigorous analysis of the pressure drops throughout the MAGNET, estimating the pressure drop across the heat exchangers, piping, and valves. Using the designed 250 kW of heat pipe power with nitrogen, the total pressure drop through the MAGNET was approximately 146 kPa or a pressure ratio of 1.12. Approximately half of the pressure loss in the system was from the heat exchangers estimating close to 66 kPa. Similar cases using helium showed a pressure ratio across the MAGNET similar to nitrogen nearing 1.10.
- From the pressure ratio data, the MAGNET compressor being purchased should be able to handle the expected pressure ratios. However, there is some concern if the compressor can handle the higher flow rates required in the MAGNET. The required volumetric flow rate for nitrogen operating at 250 kW of heat pipe power is near 143 ACFM where the compressor is rated at 48 ACFM.
- The MAGNET models estimated the temperature drop and heat loss from the piping. Using the assumptions for the piping and insulation, the heat loss from the piping is minimal and could be neglected in the larger heat pipe power loads. The heat loss was less than 5% in the system with a heat pipe power load of at least 75 kW.

5.1.2 MAGNET with Different PCU Configurations Conclusions

A major feature of modular nuclear microreactors is the ability to generate power and as such, the MAGNET has been designed with a feature to connect a PCU or PCU simulator to it. A PCU attached to the MAGNET consists of a compressor and turbine set. The PCU simulator consists of a series of valves and heat exchangers to perform the simulation.

- The MAGNET Aspen HYSYS models were equipped with a compressor and a turbine for power generation. The configuration added was a closed-loop recuperated Brayton cycle. The pressure ratio was optimized across the turbine to achieve the highest thermal efficiency which was 8.57% for nitrogen as the working fluid and 15.5% for helium as the working fluid. The MAGNET could generate 21 kW of power with nitrogen and 39 kW of power with helium.

- Simple Brayton cycles and recuperated Brayton cycles can be uniquely identified by three state points if the pressure ratio is the same across the compressor and through the exhaust of the system. The three state points are the compressor exhaust, the turbine inlet, and the turbine exhaust.
- Power cycles are largely pressure ratio driven. Maintaining the optimized pressure ratio for the maximum thermal efficiency preserves the thermal efficiency with different working fluids, even at varying compressor inlet pressures. The analysis showed that maintaining the pressure ratio and the turbine inlet temperature, the Brayton cycles maintained the optimized thermal efficiencies using air or nitrogen at varying compressor inlet pressures.
- A physical PCU connected to the MAGNET has the advantage that it would be a physical PCU being tested. This would provide dynamic data for operating the unit while generating power at design conditions. It would also provide data for off design conditions, the start up process, and shutting down the unit. These tests would provide data that is not estimated. However, the tests would be limited to a single type of power cycle.
- The PCU simulator is advantageous as it allows for testing of many simple Brayton cycles and recuperated Brayton cycles of varying thermal efficiencies and compressor and turbine adiabatic efficiencies. This could all be done with a single unit. However, the simulation of the start up and shutdown for a PCU would be estimated from other analyses.
- The PCU simulator's major disadvantage is that it is expensive. It has been estimated to have a total capital cost nearing 2.15 million dollars. The estimate was performed by three different methods.

5.1.3 PCU Start Up Analysis Conclusions

An analysis was performed on the start up of a simple Brayton cycle. The start up provides information of how an actual system could start, as well as how the system could be simulated during start up.

- A Siemens' SGT-A05 was modeled in Aspen HYSYS based on their data sheet. This unit is a natural gas unit and was used to provide a baseline for information regarding the adiabatic efficiencies of the compressor and turbine. From these models, it was determined that a high-end adiabatic efficiency for the compressor and turbine could be upwards of 85% and 90%, respectively.

- During the start up of a natural gas PCU, a motor turns the compressor turbine shaft until approximately 63% of the maximum speed at which point the fuel is added. The motor continues to turn the shaft until the combustion process is considered stable. Then the turbine would generate enough energy to offset the energy of compression. However, when nuclear power is used there is no issue of an unstable combustion. The full heat load of the reactor could be added at the beginning of the start up process instead of at 63% of maximum speed. Thus, the PCU could generate power sooner.
- Assuming that a nuclear powered PCU would start similar to a natural gas PCU, the three unique state points were collected. These three state points are the compressor exhaust, the turbine inlet, and the turbine exhaust. These points throughout the start up process could be simulated in the PCU simulator which would simulate the start up of the PCU.

5.2 Recommendations

The MAGNET Aspen HYSYS and the PCU simulator models provided a starting point for further analysis and process condition predictions. However, there is more work that needs to be performed for further validation of the models.

5.2.1 MAGNET Recommendations

- The MAGNET Aspen HYSYS models have not been validated by the physical MAGNET.
- Though the heat exchangers have been compared to other solvers, the heat exchangers models need to be validated by comparing their performance to the physical heat exchangers.
- The main chiller heat exchanger in the main MAGNET loop was not modeled. There were many unknowns about the heat transfer correlations to properly solve the heat exchanger models. The physical heat exchanger would need to be tested to create an accurate computer model of the heat exchanger for the Aspen HYSYS model.

- The MAGNET has a large chiller unit attached to it for cooling. This unit could be modeled to provide an accurate total energy consumption through the entire MAGNET system.
- The MAGNET compressor unit should be checked to ensure it can handle helium and the required flow rates for the system.
- If helium were to be used, the piping in the system may need to be redesigned to handle working temperatures around 650°C.
- The mass flow rate of helium throughout the system is a lot lower compared to nitrogen which produces lower velocities throughout the piping. The mass flow rate could be increased to use more capacity of the system. If this were to be done, larger heaters could be added for the heat pipes to still reach the desired outlet temperatures.
- Currently, the Aspen HYSYS models of the MAGNET are solved in a steady-state environment. The process of making the models work dynamically would provide useful information in the loop.

5.2.2 MAGNET PCU Simulator Recommendations

- The PCU simulator is at a point of building and constructing.
- The PCU simulator could benefit from being modeled dynamically, as well as being modeled dynamically while being attached to the MAGNET model.

5.2.3 PCU Start Up Recommendations

- Start up analyses of recuperated Brayton cycles were not performed. This would be valuable data for understanding how modular nuclear microreactors would operate under these PCU configurations. The point where the turbine provides enough energy to sustain the compression process could be found and these data points could be used in the PCU simulator.
- Shutdown analyses on both the simple and recuperated Brayton cycles were not performed. This data could be used for shutdown of the MAGNET attached to the PCU simulator.
- Development is needed on how a nuclear powered PCU would undergo the start up process. There would be a possibility of having two separate loops, one loop would be for the PCU and the second would be for the primary cooling system of the heat pipe

nuclear reactor. Once the heat pipes are at full operations, the PCU could start up and route the air through valving to cool the heat pipe heat exchanger. This would add the needed heat to the PCU for operations.

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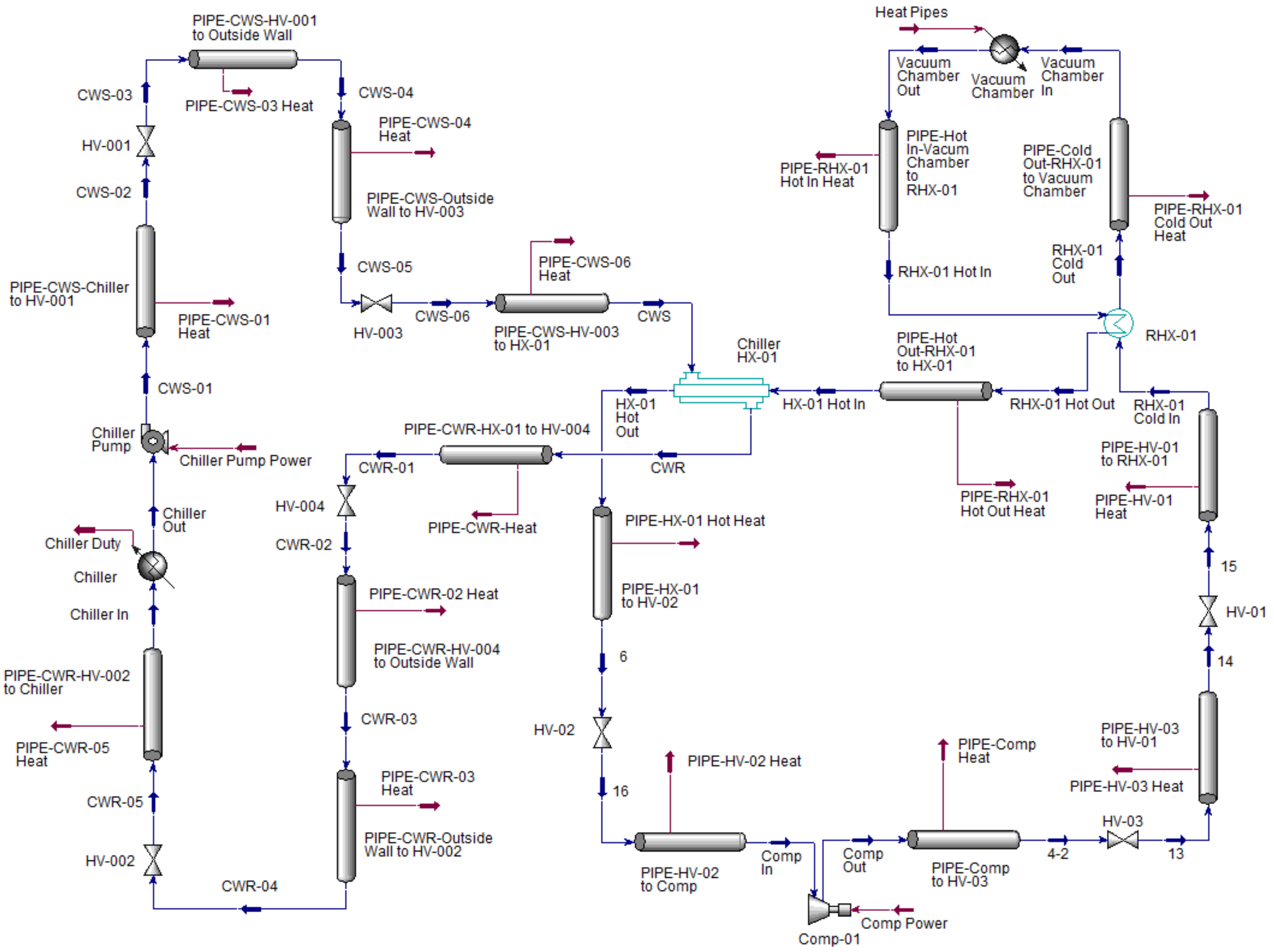
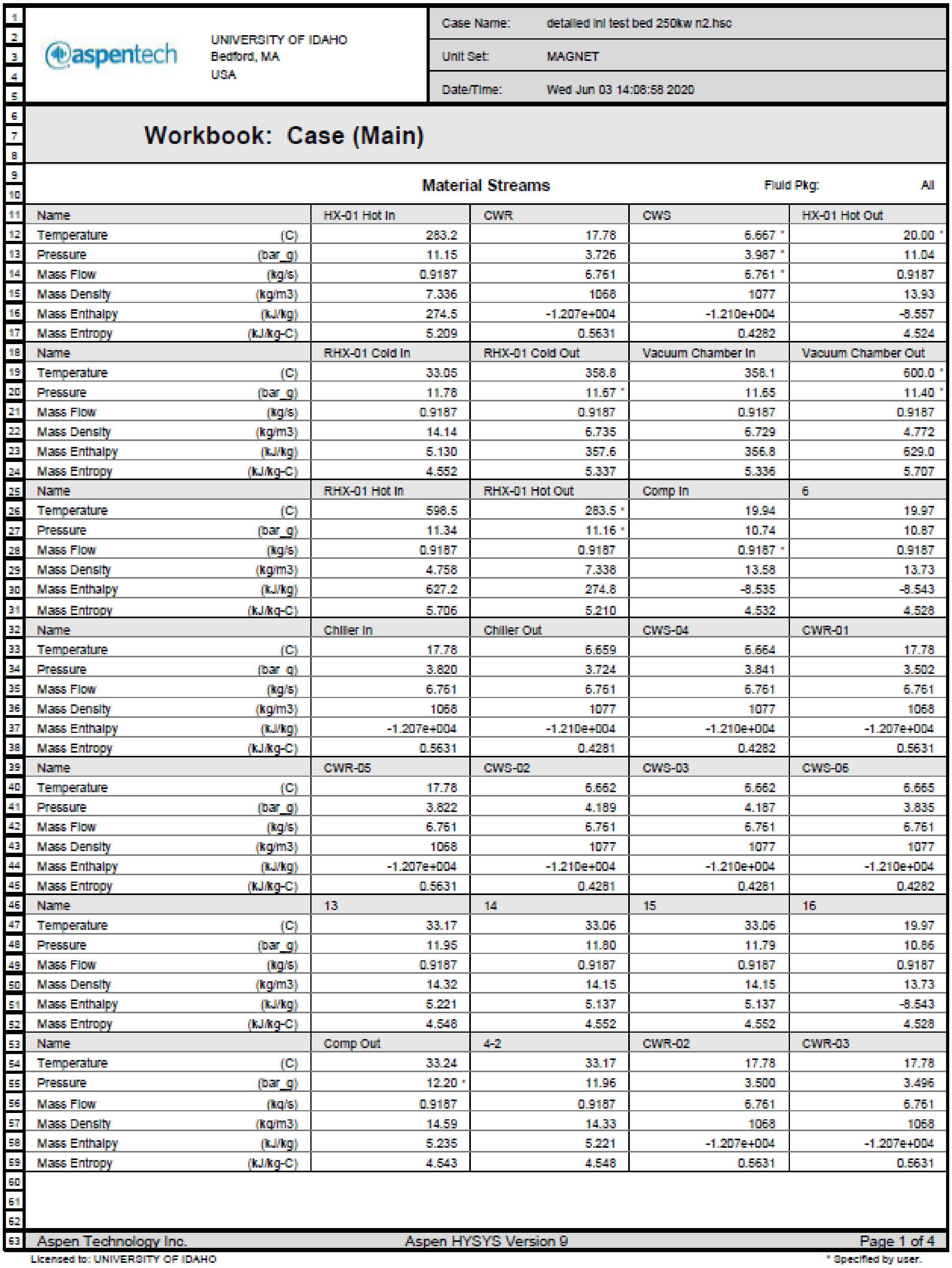
Appendix A: Aspen HYSYS Models for the Microreactor AGile Non-nuclear Experimental Testbed

Aspen HYSYS Process Model of Microreactor AGile Non-nuclear Experimental Testbed with Nitrogen Operating at 600ºC and 250 kW of Heat Pipe Power





UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	detailed inl test bed 250kw n2.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:08:58 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Temperature	(C)	283.2	17.78	6.667 *	20.00 *
Pressure	(bar_g)	11.15	3.726	3.987 *	11.04
Mass Flow	(kg/s)	0.9187	6.761	6.761 *	0.9187
Mass Density	(kg/m3)	7.336	1068	1077	13.93
Mass Enthalpy	(kJ/kg)	274.5	-1.207e+004	-1.210e+004	-8.557
Mass Entropy	(kJ/kg-C)	5.209	0.5631	0.4282	4.524

Name		RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Temperature	(C)	33.05	358.8	358.1	600.0 *
Pressure	(bar_g)	11.78	11.67 *	11.65	11.40 *
Mass Flow	(kg/s)	0.9187	0.9187	0.9187	0.9187
Mass Density	(kg/m3)	14.14	6.735	6.729	4.772
Mass Enthalpy	(kJ/kg)	5.130	357.6	356.8	629.0
Mass Entropy	(kJ/kg-C)	4.552	5.337	5.336	5.707

Name		RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Temperature	(C)	598.5	283.5 *	19.94	19.97
Pressure	(bar_g)	11.34	11.16 *	10.74	10.87
Mass Flow	(kg/s)	0.9187	0.9187	0.9187 *	0.9187
Mass Density	(kg/m3)	4.758	7.338	13.58	13.73
Mass Enthalpy	(kJ/kg)	627.2	274.8	-8.535	-8.543
Mass Entropy	(kJ/kg-C)	5.706	5.210	4.532	4.528

Name		Chiller In	Chiller Out	CWS-04	CWR-01
Temperature	(C)	17.78	6.659	6.664	17.78
Pressure	(bar_g)	3.820	3.724	3.841	3.502
Mass Flow	(kg/s)	6.761	6.761	6.761	6.761
Mass Density	(kg/m3)	1068	1077	1077	1068
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.210e+004	-1.210e+004	-1.207e+004
Mass Entropy	(kJ/kg-C)	0.5631	0.4281	0.4282	0.5631

Name		CWR-05	CWS-02	CWS-03	CWS-06
Temperature	(C)	17.78	6.662	6.662	6.665
Pressure	(bar_g)	3.822	4.189	4.187	3.835
Mass Flow	(kg/s)	6.761	6.761	6.761	6.761
Mass Density	(kg/m3)	1068	1077	1077	1077
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.210e+004	-1.210e+004	-1.210e+004
Mass Entropy	(kJ/kg-C)	0.5631	0.4281	0.4281	0.4282

Name		13	14	15	16
Temperature	(C)	33.17	33.06	33.06	19.97
Pressure	(bar_g)	11.95	11.80	11.79	10.86
Mass Flow	(kg/s)	0.9187	0.9187	0.9187	0.9187
Mass Density	(kg/m3)	14.32	14.15	14.15	13.73
Mass Enthalpy	(kJ/kg)	5.221	5.137	5.137	-8.543
Mass Entropy	(kJ/kg-C)	4.548	4.552	4.552	4.528

Name		Comp Out	4-2	CWR-02	CWR-03
Temperature	(C)	33.24	33.17	17.78	17.78
Pressure	(bar_g)	12.20 *	11.96	3.500	3.496
Mass Flow	(kg/s)	0.9187	0.9187	6.761	6.761
Mass Density	(kg/m3)	14.59	14.33	1068	1068
Mass Enthalpy	(kJ/kg)	5.235	5.221	-1.207e+004	-1.207e+004
Mass Entropy	(kJ/kg-C)	4.543	4.548	0.5631	0.5631

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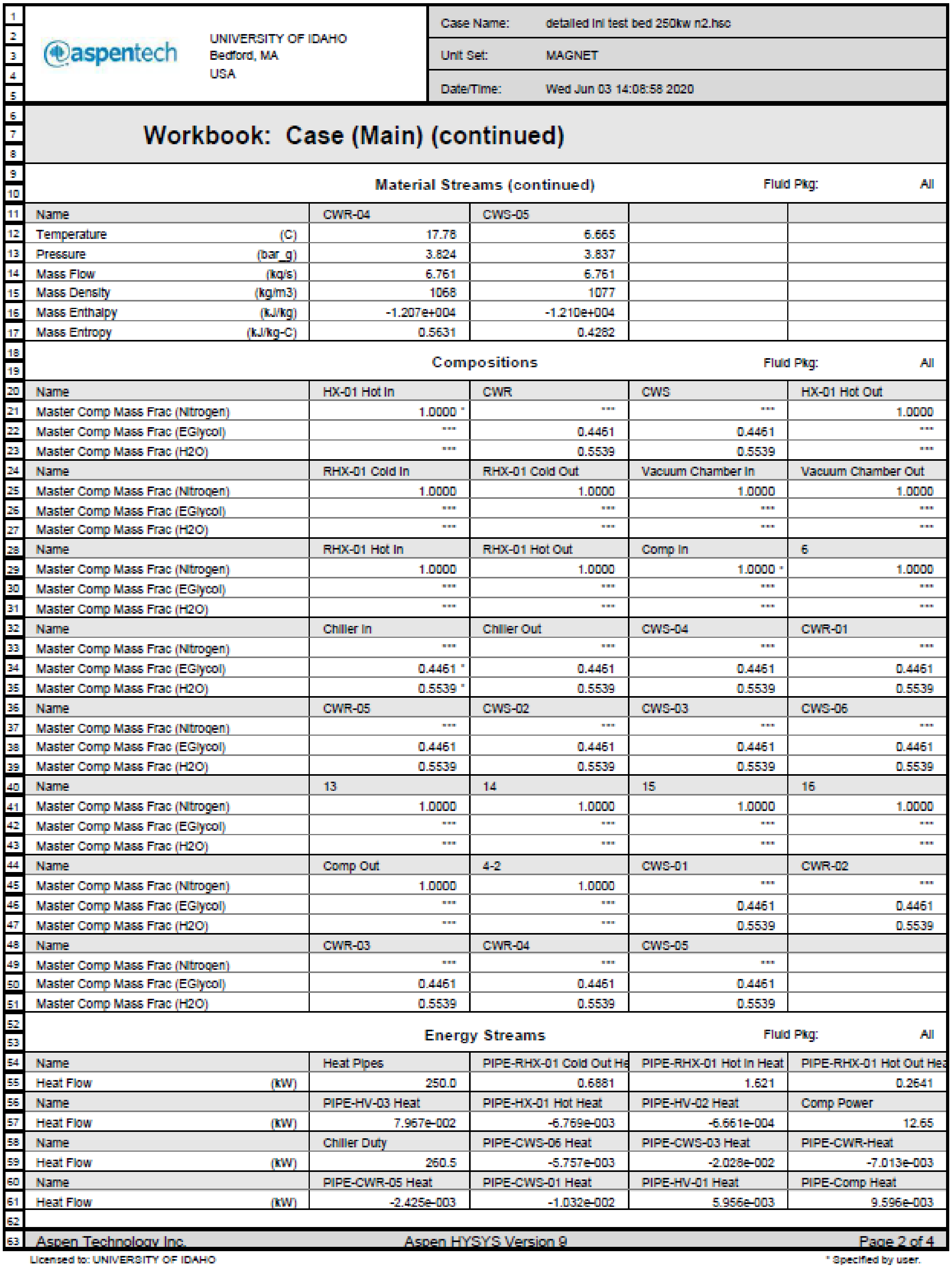

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed inl test bed 250kw n2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:08:58 2020

Workbook: Case (Main) (continued)

Material Streams (continued)

Fluid Pkg: All

Name		CWR-04	CWS-05		
Temperature	(C)	17.78	6.665		
Pressure	(bar_g)	3.824	3.837		
Mass Flow	(kg/s)	6.761	6.761		
Mass Density	(kg/m3)	1068	1077		
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.210e+004		
Mass Entropy	(kJ/kg-C)	0.5631	0.4282		

Compositions

Fluid Pkg: All

Name	HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Master Comp Mass Frac (Nitrogen)	1.0000 *	***	***	1.0000
Master Comp Mass Frac (EGlycol)	***	0.4461	0.4461	***
Master Comp Mass Frac (H2O)	***	0.5539	0.5539	***
Name	RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Name	RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000 *	1.0000
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Name	Chiller In	Chiller Out	CWS-04	CWR-01
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (EGlycol)	0.4461 *	0.4461	0.4461	0.4461
Master Comp Mass Frac (H2O)	0.5539 *	0.5539	0.5539	0.5539
Name	CWR-05	CWS-02	CWS-03	CWS-06
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	0.4461	0.4461
Master Comp Mass Frac (H2O)	0.5539	0.5539	0.5539	0.5539
Name	13	14	15	16
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Name	Comp Out	4-2	CWS-01	CWR-02
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	***	***
Master Comp Mass Frac (EGlycol)	***	***	0.4461	0.4461
Master Comp Mass Frac (H2O)	***	***	0.5539	0.5539
Name	CWR-03	CWR-04	CWS-05	
Master Comp Mass Frac (Nitrogen)	***	***	***	
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	0.4461	
Master Comp Mass Frac (H2O)	0.5539	0.5539	0.5539	

Energy Streams

Fluid Pkg: All

Name		Heat Pipes	PIPE-RHX-01 Cold Out He	PIPE-RHX-01 Hot In Heat	PIPE-RHX-01 Hot Out Hea
Heat Flow	(kW)	250.0	0.6881	1.621	0.2641
Name		PIPE-HV-03 Heat	PIPE-HX-01 Hot Heat	PIPE-HV-02 Heat	Comp Power
Heat Flow	(kW)	7.967e-002	-6.769e-003	-6.661e-004	12.65
Name		Chiller Duty	PIPE-CWS-06 Heat	PIPE-CWS-03 Heat	PIPE-CWR-Heat
Heat Flow	(kW)	260.5	-5.757e-003	-2.028e-002	-7.013e-003
Name		PIPE-CWR-05 Heat	PIPE-CWS-01 Heat	PIPE-HV-01 Heat	PIPE-Comp Heat
Heat Flow	(kW)	-2.425e-003	-1.032e-002	5.956e-003	9.596e-003

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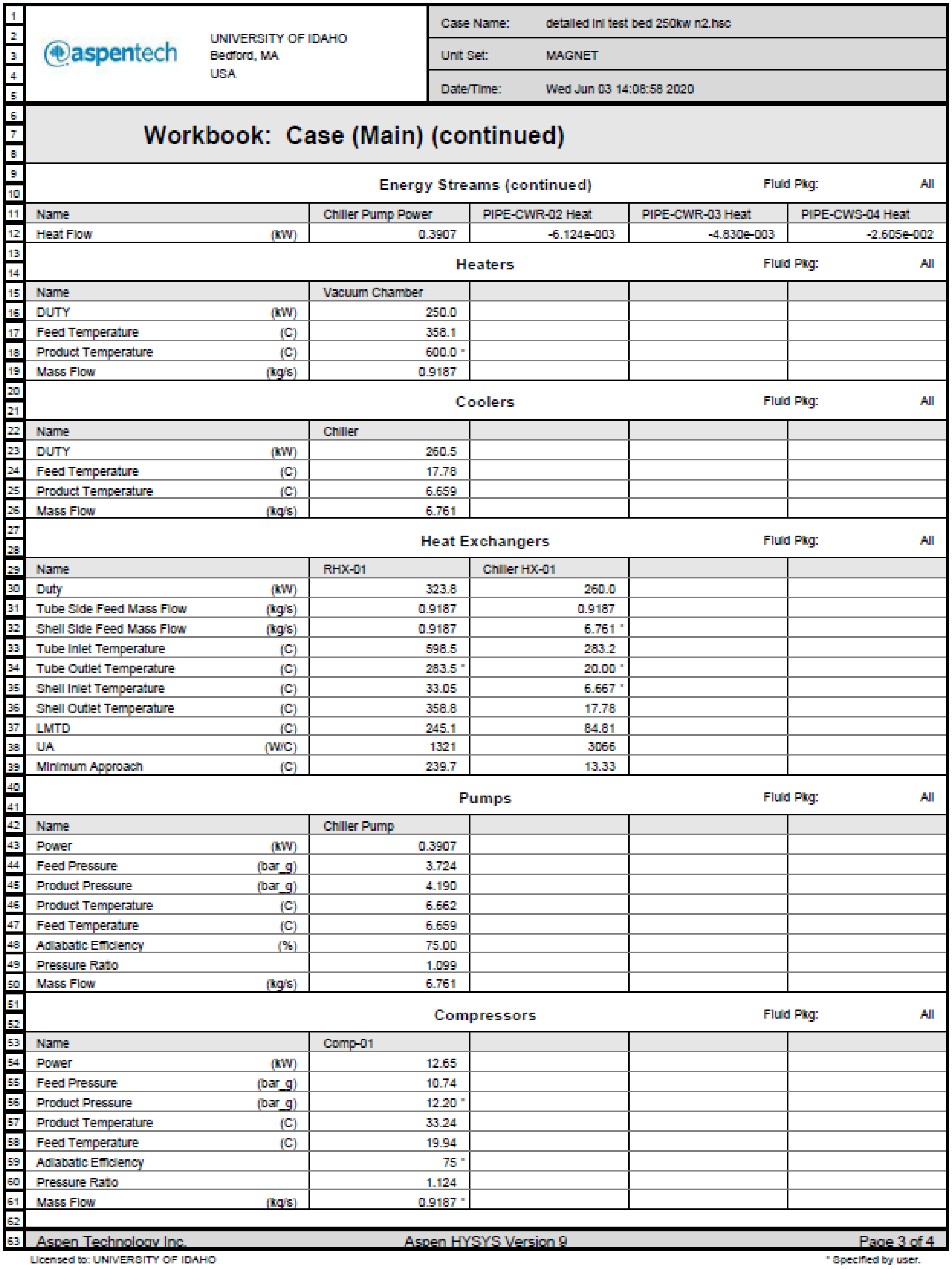

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Case Name: detailed inl test bed 250kw n2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:08:58 2020

Workbook: Case (Main) (continued)

Energy Streams (continued)

Fluid Pkg: All

Name		Chiller Pump Power	PIPE-CWR-02 Heat	PIPE-CWR-03 Heat	PIPE-CWS-04 Heat
Heat Flow	(kW)	0.3907	-6.124e-003	-4.830e-003	-2.605e-002

Heaters

Fluid Pkg: All

Name		Vacuum Chamber			
DUTY	(kW)	250.0			
Feed Temperature	(C)	358.1			
Product Temperature	(C)	600.0 *			
Mass Flow	(kg/s)	0.9187			

Coolers

Fluid Pkg: All

Name		Chiller			
DUTY	(kW)	260.5			
Feed Temperature	(C)	17.78			
Product Temperature	(C)	6.659			
Mass Flow	(kg/s)	6.761			

Heat Exchangers

Fluid Pkg: All

Name		RHX-01	Chiller HX-01		
Duty	(kW)	323.8	260.0		
Tube Side Feed Mass Flow	(kg/s)	0.9187	0.9187		
Shell Side Feed Mass Flow	(kg/s)	0.9187	6.761 *		
Tube Inlet Temperature	(C)	598.5	283.2		
Tube Outlet Temperature	(C)	283.5 *	20.00 *		
Shell Inlet Temperature	(C)	33.05	6.667 *		
Shell Outlet Temperature	(C)	358.8	17.78		
LMTD	(C)	245.1	84.81		
UA	(W/C)	1321	3066		
Minimum Approach	(C)	239.7	13.33		

Pumps

Fluid Pkg: All

Name		Chiller Pump			
Power	(kW)	0.3907			
Feed Pressure	(bar_g)	3.724			
Product Pressure	(bar_g)	4.190			
Product Temperature	(C)	6.662			
Feed Temperature	(C)	6.659			
Adiabatic Efficiency	(%)	75.00			
Pressure Ratio		1.099			
Mass Flow	(kg/s)	6.761			

Compressors

Fluid Pkg: All

Name		Comp-01			
Power	(kW)	12.65			
Feed Pressure	(bar_g)	10.74			
Product Pressure	(bar_g)	12.20 *			
Product Temperature	(C)	33.24			
Feed Temperature	(C)	19.94			
Adiabatic Efficiency		75 *			
Pressure Ratio		1.124			
Mass Flow	(kg/s)	0.9187 *			

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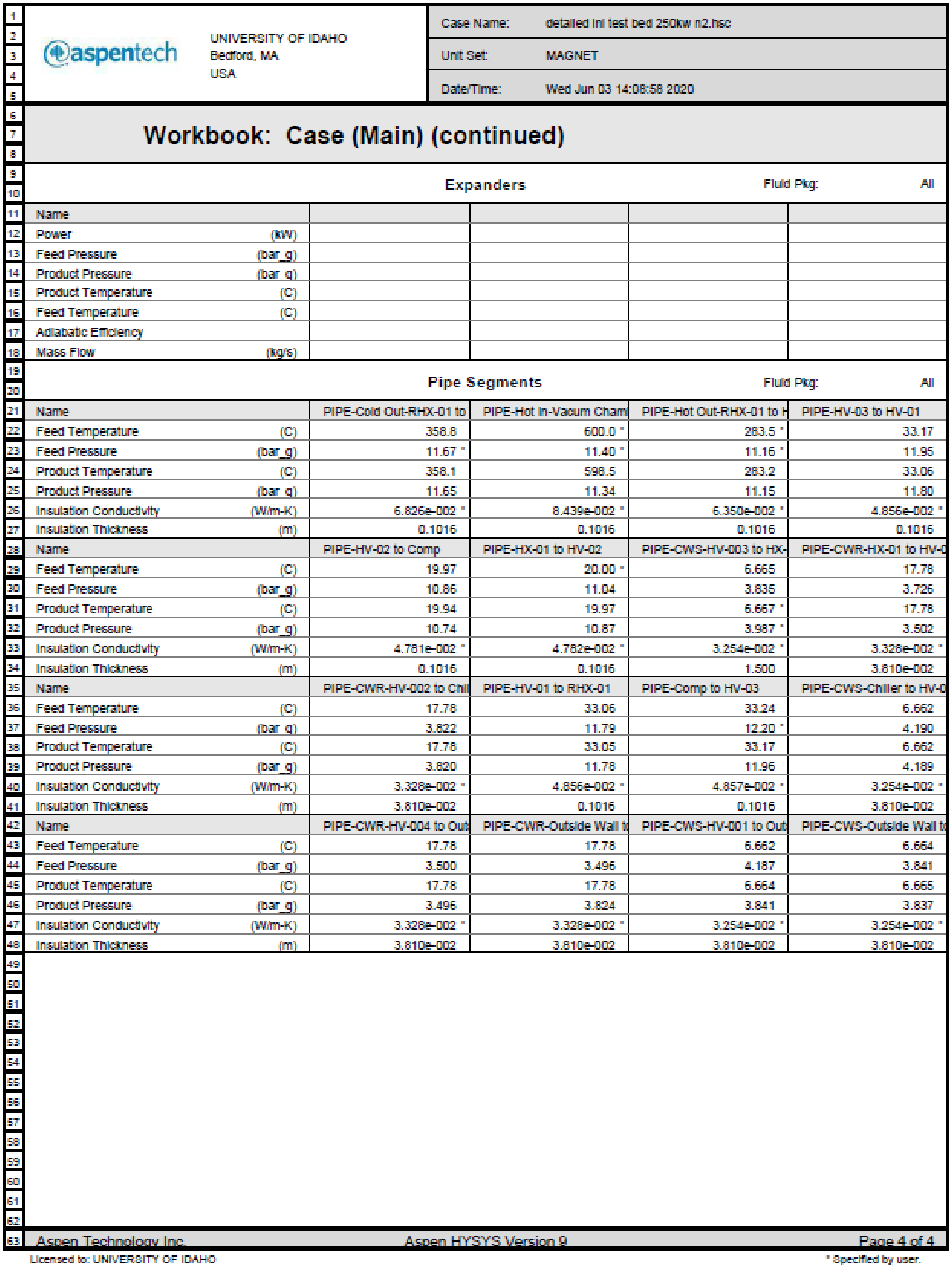

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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed inl test bed 250kw n2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:08:58 2020

Workbook: Case (Main) (continued)

Expanders Fluid Pkg: All

Name				
Power (kW)				
Feed Pressure (bar_g)				
Product Pressure (bar_g)				
Product Temperature (C)				
Feed Temperature (C)				
Adiabatic Efficiency				
Mass Flow (kg/s)				

Pipe Segments Fluid Pkg: All

Name	PIPE-Cold Out-RHX-01 to	PIPE-Hot In-Vacum Cham	PIPE-Hot Out-RHX-01 to H	PIPE-HV-03 to HV-01
Feed Temperature (C)	358.8	600.0 *	283.5 *	33.17
Feed Pressure (bar_g)	11.67 *	11.40 *	11.16 *	11.95
Product Temperature (C)	358.1	598.5	283.2	33.06
Product Pressure (bar_g)	11.65	11.34	11.15	11.80
Insulation Conductivity (W/m-K)	6.826e-002 *	8.439e-002 *	6.350e-002 *	4.856e-002 *
Insulation Thickness (m)	0.1016	0.1016	0.1016	0.1016
Name	PIPE-HV-02 to Comp	PIPE-HX-01 to HV-02	PIPE-CWS-HV-003 to HX-	PIPE-CWR-HX-01 to HV-0
Feed Temperature (C)	19.97	20.00 *	6.665	17.78
Feed Pressure (bar_g)	10.86	11.04	3.835	3.726
Product Temperature (C)	19.94	19.97	6.667 *	17.78
Product Pressure (bar_g)	10.74	10.87	3.987 *	3.502
Insulation Conductivity (W/m-K)	4.781e-002 *	4.782e-002 *	3.254e-002 *	3.328e-002 *
Insulation Thickness (m)	0.1016	0.1016	1.500	3.810e-002
Name	PIPE-CWR-HV-002 to Chil	PIPE-HV-01 to RHX-01	PIPE-Comp to HV-03	PIPE-CWS-Chiller to HV-0
Feed Temperature (C)	17.78	33.06	33.24	6.662
Feed Pressure (bar_g)	3.822	11.79	12.20 *	4.190
Product Temperature (C)	17.78	33.05	33.17	6.662
Product Pressure (bar_g)	3.820	11.78	11.96	4.189
Insulation Conductivity (W/m-K)	3.328e-002 *	4.856e-002 *	4.857e-002 *	3.254e-002 *
Insulation Thickness (m)	3.810e-002	0.1016	0.1016	3.810e-002
Name	PIPE-CWR-HV-004 to Out	PIPE-CWR-Outside Wall t	PIPE-CWS-HV-001 to Out	PIPE-CWS-Outside Wall t
Feed Temperature (C)	17.78	17.78	6.662	6.664
Feed Pressure (bar_g)	3.500	3.496	4.187	3.841
Product Temperature (C)	17.78	17.78	6.664	6.665
Product Pressure (bar_g)	3.496	3.824	3.841	3.837
Insulation Conductivity (W/m-K)	3.328e-002 *	3.328e-002 *	3.254e-002 *	3.254e-002 *
Insulation Thickness (m)	3.810e-002	3.810e-002	3.810e-002	3.810e-002

Aspen Technology Inc. Aspen HYSYS Version 9 Page 4 of 4

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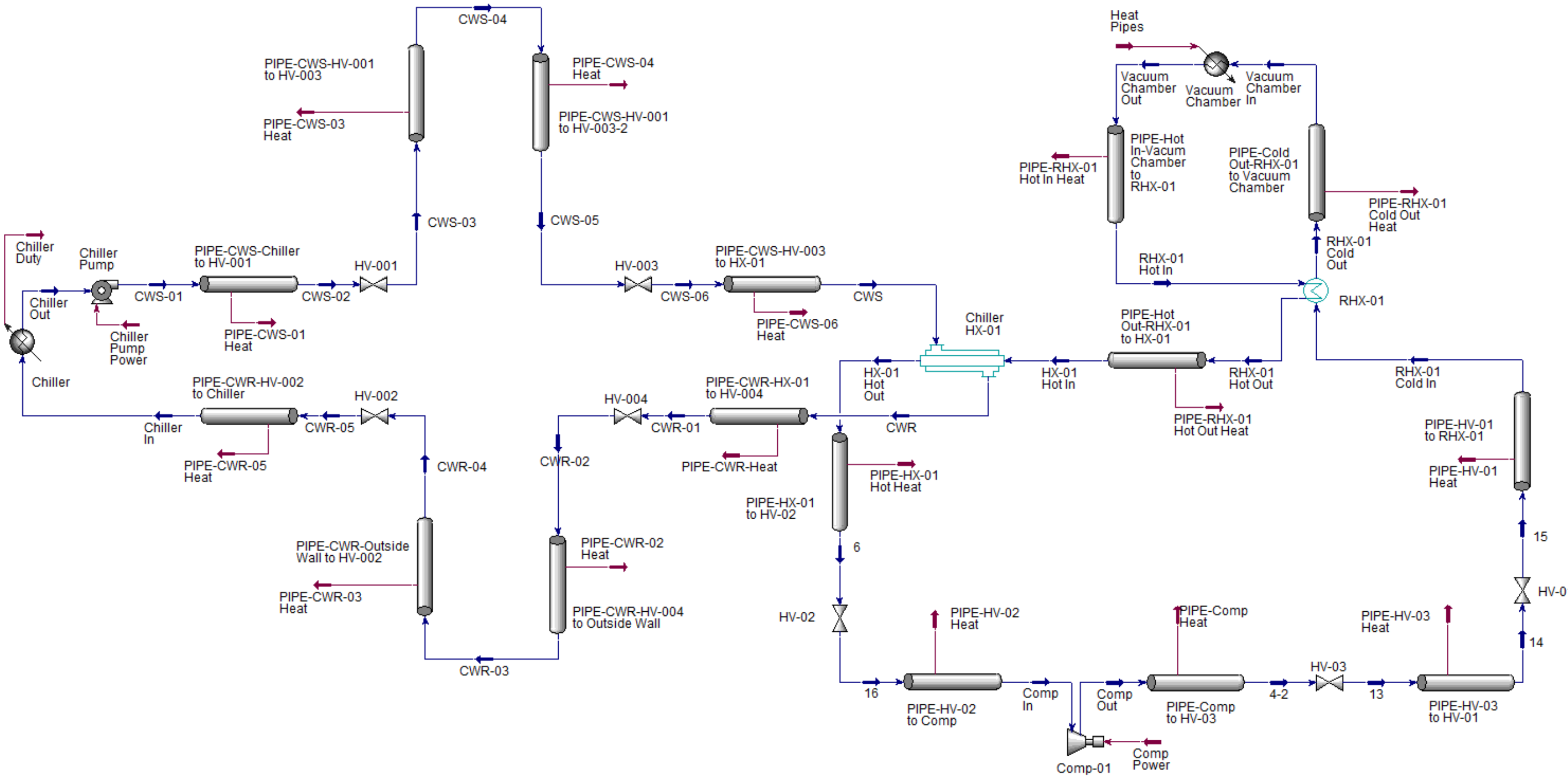
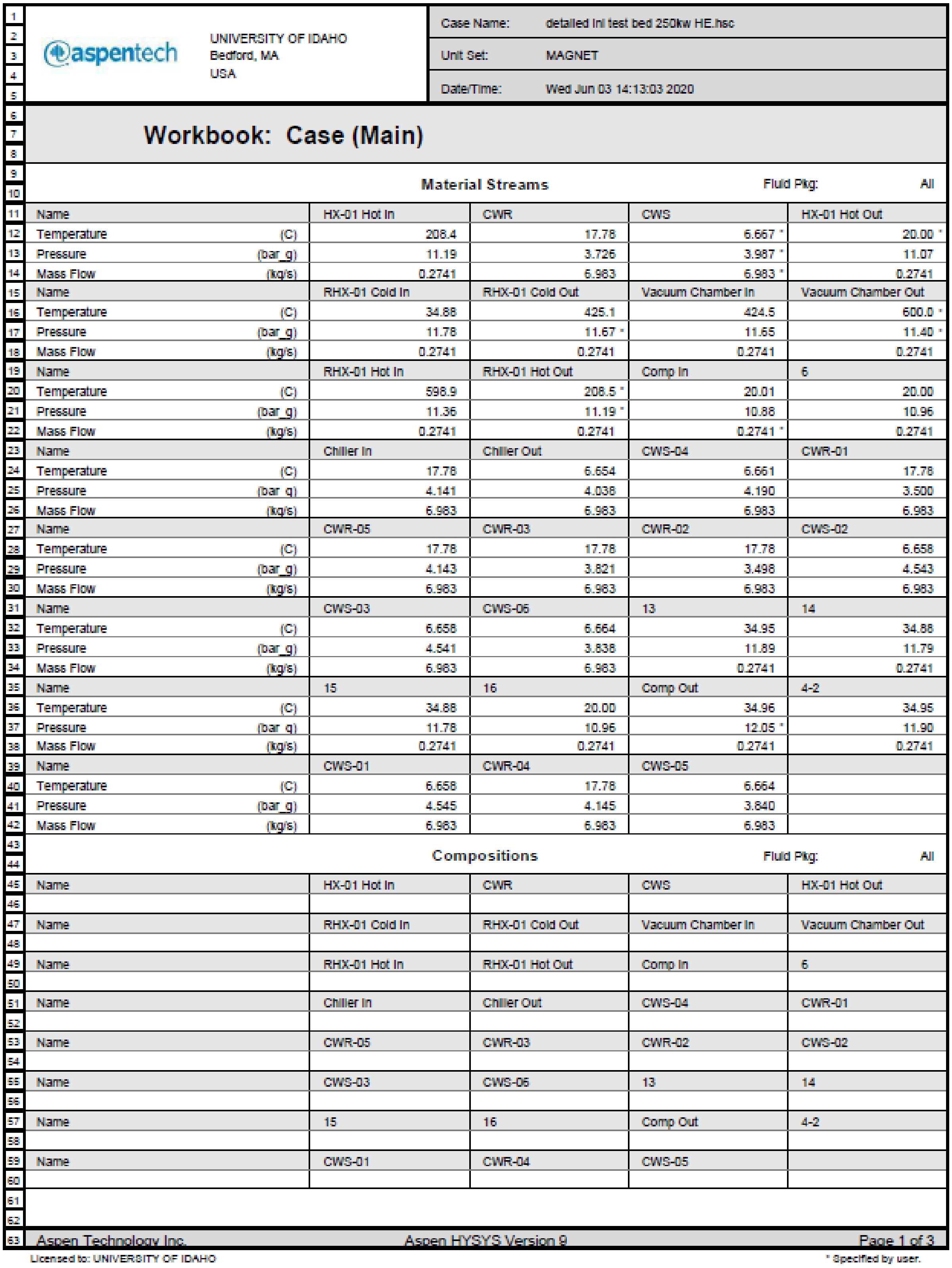
Aspen HYSYS Process Model of Microreactor AGile Non-nuclear Experimental Testbed with Helium Operating at 600ºC and 250 kW of Heat Pipe Power





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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	detailed inl test bed 250kw HE.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:13:03 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name	HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Temperature (C)	208.4	17.78	6.667 *	20.00 *
Pressure (bar_g)	11.19	3.726	3.987 *	11.07
Mass Flow (kg/s)	0.2741	6.983	6.983 *	0.2741
Name	RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Temperature (C)	34.88	425.1	424.5	600.0 *
Pressure (bar_g)	11.78	11.67 *	11.65	11.40 *
Mass Flow (kg/s)	0.2741	0.2741	0.2741	0.2741
Name	RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Temperature (C)	598.9	208.5 *	20.01	20.00
Pressure (bar_g)	11.36	11.19 *	10.88	10.96
Mass Flow (kg/s)	0.2741	0.2741	0.2741 *	0.2741
Name	Chiller In	Chiller Out	CWS-04	CWR-01
Temperature (C)	17.78	6.654	6.661	17.78
Pressure (bar_g)	4.141	4.038	4.190	3.500
Mass Flow (kg/s)	6.983	6.983	6.983	6.983
Name	CWR-05	CWR-03	CWR-02	CWS-02
Temperature (C)	17.78	17.78	17.78	6.658
Pressure (bar_g)	4.143	3.821	3.498	4.543
Mass Flow (kg/s)	6.983	6.983	6.983	6.983
Name	CWS-03	CWS-06	13	14
Temperature (C)	6.658	6.664	34.95	34.88
Pressure (bar_g)	4.541	3.838	11.89	11.79
Mass Flow (kg/s)	6.983	6.983	0.2741	0.2741
Name	15	16	Comp Out	4-2
Temperature (C)	34.88	20.00	34.96	34.95
Pressure (bar_g)	11.78	10.96	12.05 *	11.90
Mass Flow (kg/s)	0.2741	0.2741	0.2741	0.2741
Name	CWS-01	CWR-04	CWS-05	
Temperature (C)	6.658	17.78	6.664	
Pressure (bar_g)	4.545	4.145	3.840	
Mass Flow (kg/s)	6.983	6.983	6.983	

Compositions

Fluid Pkg: All

Name	HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Name	RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Name	RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Name	Chiller In	Chiller Out	CWS-04	CWR-01
Name	CWR-05	CWR-03	CWR-02	CWS-02
Name	CWS-03	CWS-06	13	14
Name	15	16	Comp Out	4-2
Name	CWS-01	CWR-04	CWS-05	

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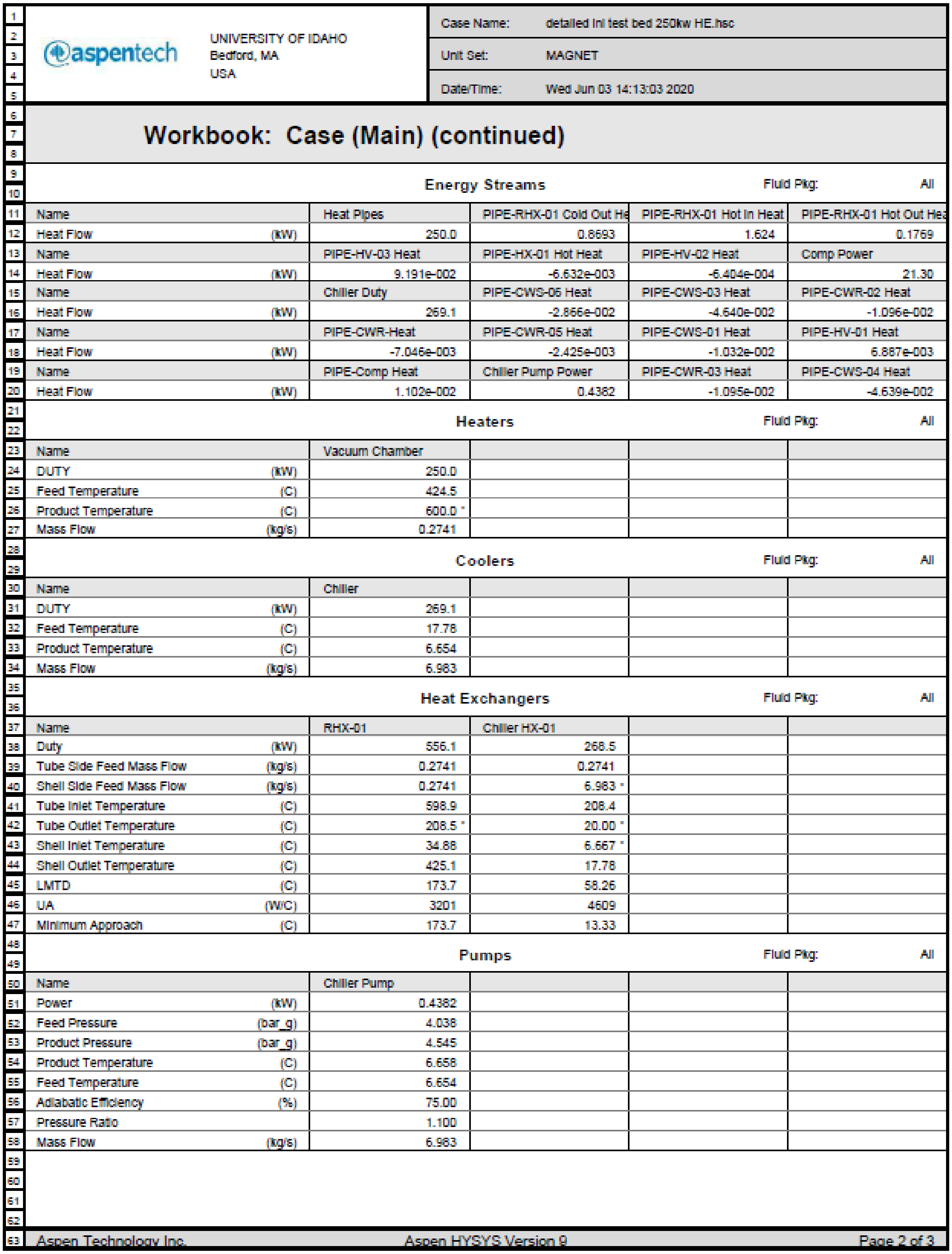

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Bedford, MA
USA

Case Name:	detailed inl test bed 250kw HE.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:13:03 2020

Workbook: Case (Main) (continued)

Energy Streams

Fluid Pkg: All

Name		Heat Pipes	PIPE-RHX-01 Cold Out He	PIPE-RHX-01 Hot In Heat	PIPE-RHX-01 Hot Out Hea
Heat Flow	(kW)	250.0	0.8693	1.624	0.1769
Name		PIPE-HV-03 Heat	PIPE-HX-01 Hot Heat	PIPE-HV-02 Heat	Comp Power
Heat Flow	(kW)	9.191e-002	-6.632e-003	-6.404e-004	21.30
Name		Chiller Duty	PIPE-CWS-06 Heat	PIPE-CWS-03 Heat	PIPE-CWR-02 Heat
Heat Flow	(kW)	269.1	-2.866e-002	-4.640e-002	-1.096e-002
Name		PIPE-CWR-Heat	PIPE-CWR-05 Heat	PIPE-CWS-01 Heat	PIPE-HV-01 Heat
Heat Flow	(kW)	-7.046e-003	-2.425e-003	-1.032e-002	6.887e-003
Name		PIPE-Comp Heat	Chiller Pump Power	PIPE-CWR-03 Heat	PIPE-CWS-04 Heat
Heat Flow	(kW)	1.102e-002	0.4382	-1.095e-002	-4.639e-002

Heaters

Fluid Pkg: All

Name		Vacuum Chamber			
DUTY	(kW)	250.0			
Feed Temperature	(C)	424.5			
Product Temperature	(C)	600.0 *			
Mass Flow	(kg/s)	0.2741			

Coolers

Fluid Pkg: All

Name		Chiller			
DUTY	(kW)	269.1			
Feed Temperature	(C)	17.78			
Product Temperature	(C)	6.654			
Mass Flow	(kg/s)	6.983			

Heat Exchangers

Fluid Pkg: All

Name		RHX-01	Chiller HX-01		
Duty	(kW)	556.1	268.5		
Tube Side Feed Mass Flow	(kg/s)	0.2741	0.2741		
Shell Side Feed Mass Flow	(kg/s)	0.2741	6.983 *		
Tube Inlet Temperature	(C)	598.9	208.4		
Tube Outlet Temperature	(C)	208.5 *	20.00 *		
Shell Inlet Temperature	(C)	34.88	6.667 *		
Shell Outlet Temperature	(C)	425.1	17.78		
LMTD	(C)	173.7	58.26		
UA	(W/C)	3201	4609		
Minimum Approach	(C)	173.7	13.33		

Pumps

Fluid Pkg: All

Name		Chiller Pump			
Power	(kW)	0.4382			
Feed Pressure	(bar_g)	4.038			
Product Pressure	(bar_g)	4.545			
Product Temperature	(C)	6.658			
Feed Temperature	(C)	6.654			
Adiabatic Efficiency	(%)	75.00			
Pressure Ratio		1.100			
Mass Flow	(kg/s)	6.983			

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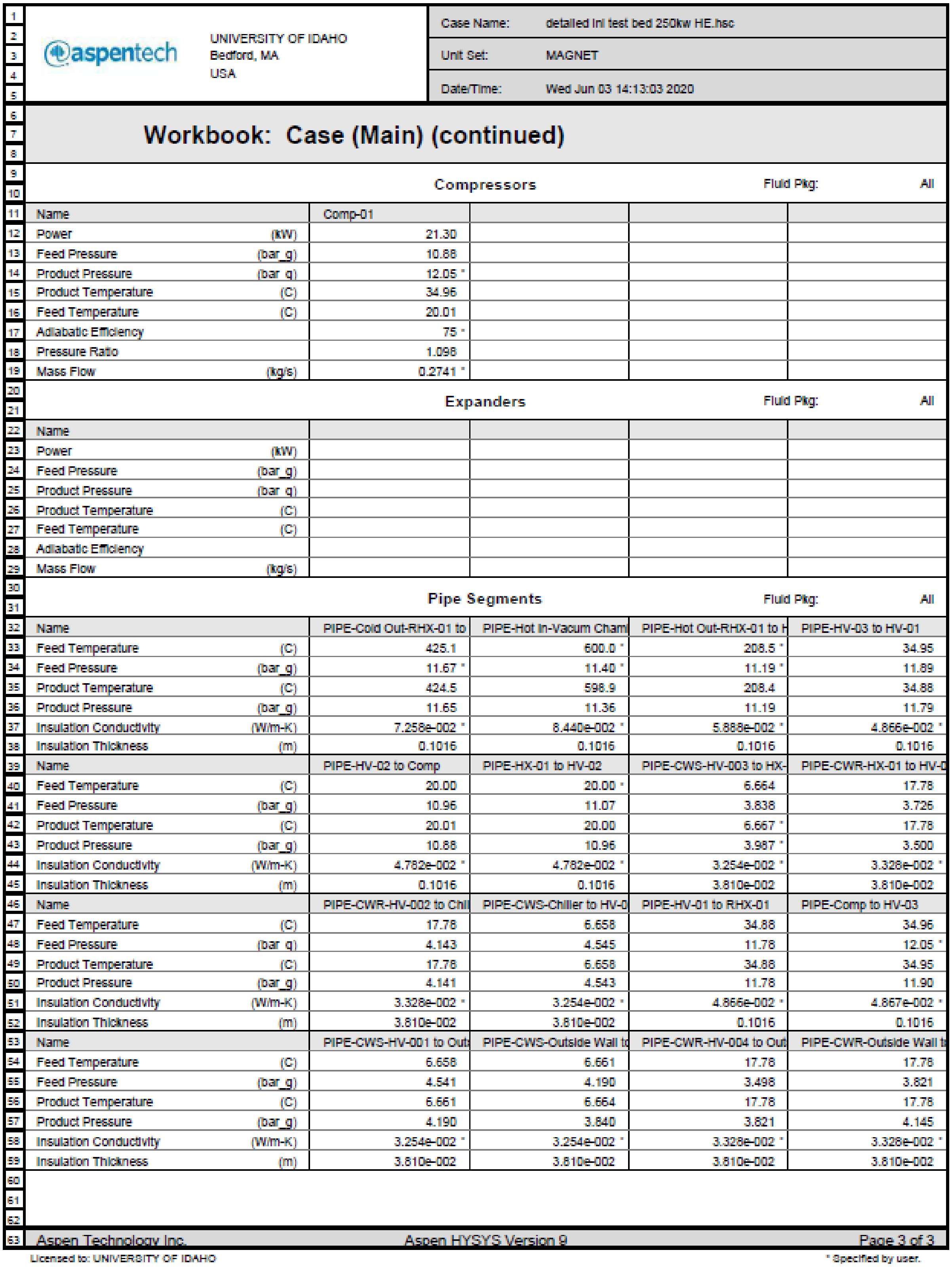

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USA

Case Name:	detailed inl test bed 250kw HE.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:13:03 2020

Workbook: Case (Main) (continued)

Compressors

Fluid Pkg: All

Name	Comp-01			
Power (kW)	21.30			
Feed Pressure (bar_g)	10.88			
Product Pressure (bar_g)	12.05 *			
Product Temperature (C)	34.96			
Feed Temperature (C)	20.01			
Adiabatic Efficiency	75 *			
Pressure Ratio	1.098			
Mass Flow (kg/s)	0.2741 *			

Expanders

Fluid Pkg: All

Name				
Power (kW)				
Feed Pressure (bar_g)				
Product Pressure (bar_g)				
Product Temperature (C)				
Feed Temperature (C)				
Adiabatic Efficiency				
Mass Flow (kg/s)				

Pipe Segments

Fluid Pkg: All

Name	PIPE-Cold Out-RHX-01 to	PIPE-Hot In-Vacum Cham	PIPE-Hot Out-RHX-01 to	PIPE-HV-03 to HV-01
Feed Temperature (C)	425.1	600.0 *	208.5 *	34.95
Feed Pressure (bar_g)	11.67 *	11.40 *	11.19 *	11.89
Product Temperature (C)	424.5	598.9	208.4	34.88
Product Pressure (bar_g)	11.65	11.36	11.19	11.79
Insulation Conductivity (W/m-K)	7.258e-002 *	8.440e-002 *	5.888e-002 *	4.866e-002 *
Insulation Thickness (m)	0.1016	0.1016	0.1016	0.1016
Name	PIPE-HV-02 to Comp	PIPE-HX-01 to HV-02	PIPE-CWS-HV-003 to HX-	PIPE-CWR-HX-01 to HV-
Feed Temperature (C)	20.00	20.00 *	6.664	17.78
Feed Pressure (bar_g)	10.96	11.07	3.838	3.726
Product Temperature (C)	20.01	20.00	6.667 *	17.78
Product Pressure (bar_g)	10.88	10.96	3.987 *	3.500
Insulation Conductivity (W/m-K)	4.782e-002 *	4.782e-002 *	3.254e-002 *	3.328e-002 *
Insulation Thickness (m)	0.1016	0.1016	3.810e-002	3.810e-002
Name	PIPE-CWR-HV-002 to Chil	PIPE-CWS-Chiller to HV-	PIPE-HV-01 to RHX-01	PIPE-Comp to HV-03
Feed Temperature (C)	17.78	6.658	34.88	34.96
Feed Pressure (bar_g)	4.143	4.545	11.78	12.05 *
Product Temperature (C)	17.78	6.658	34.88	34.95
Product Pressure (bar_g)	4.141	4.543	11.78	11.90
Insulation Conductivity (W/m-K)	3.328e-002 *	3.254e-002 *	4.866e-002 *	4.867e-002 *
Insulation Thickness (m)	3.810e-002	3.810e-002	0.1016	0.1016
Name	PIPE-CWS-HV-001 to Out	PIPE-CWS-Outside Wall t	PIPE-CWR-HV-004 to Out	PIPE-CWR-Outside Wall
Feed Temperature (C)	6.658	6.661	17.78	17.78
Feed Pressure (bar_g)	4.541	4.190	3.498	3.821
Product Temperature (C)	6.661	6.664	17.78	17.78
Product Pressure (bar_g)	4.190	3.840	3.821	4.145
Insulation Conductivity (W/m-K)	3.254e-002 *	3.254e-002 *	3.328e-002 *	3.328e-002 *
Insulation Thickness (m)	3.810e-002	3.810e-002	3.810e-002	3.810e-002

Aspen Technology Inc. Aspen HYSYS Version 9 Page 3 of 3

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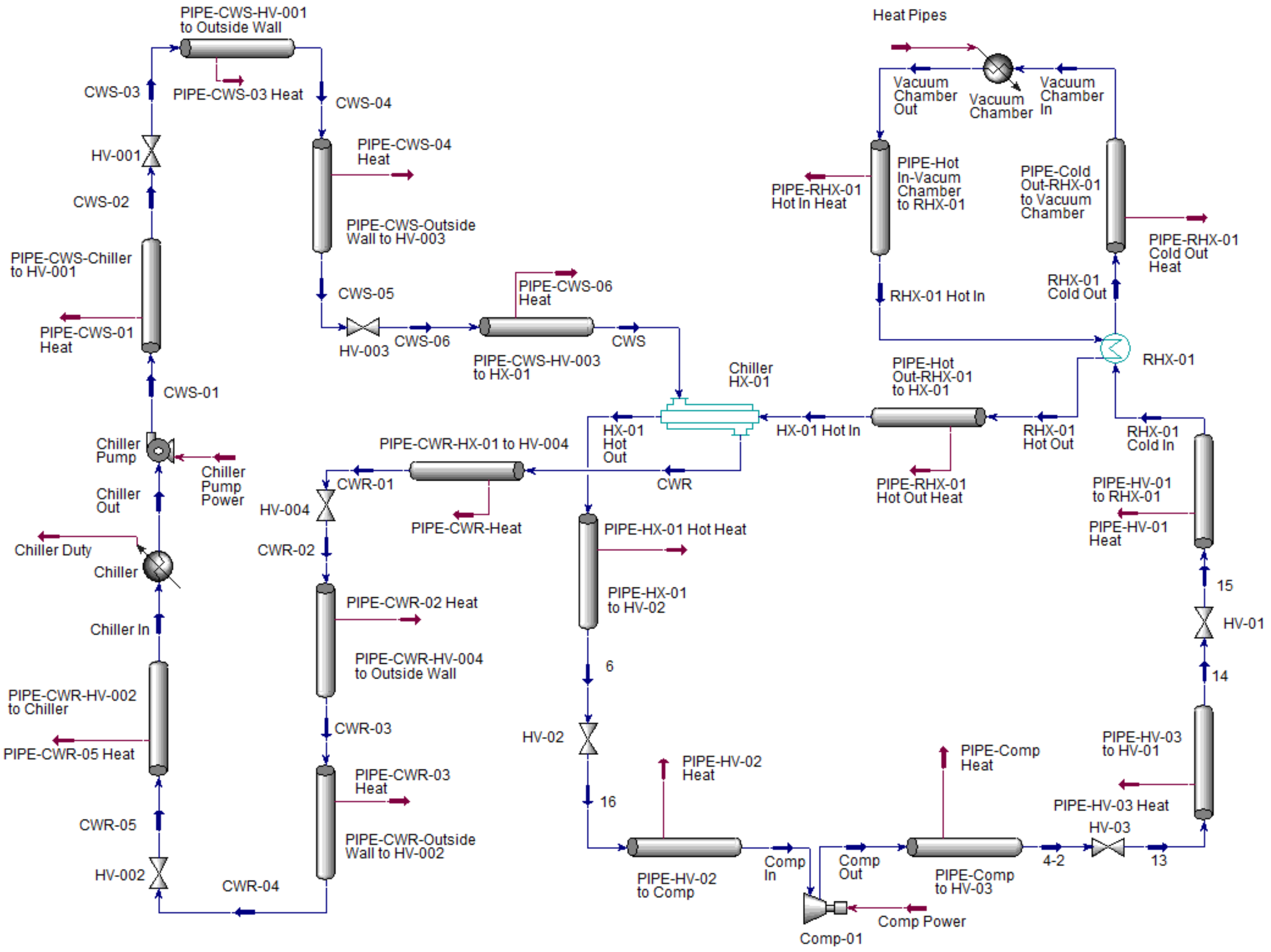
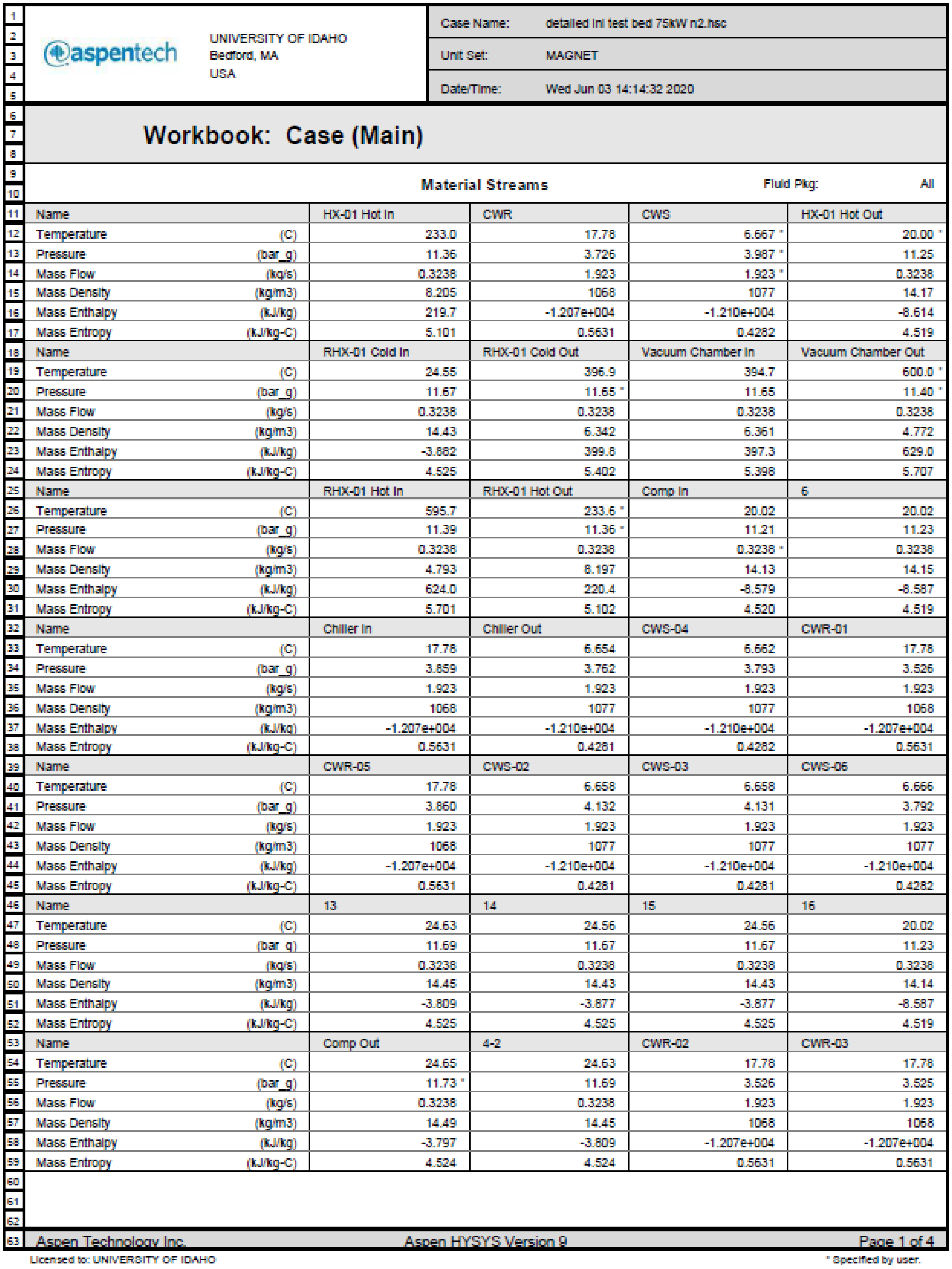
Aspen HYSYS Process Model of Microreactor AGile Non-nuclear Experimental Testbed with Nitrogen Operating at 600ºC and 75 kW of Heat Pipe Power





UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed inl test bed 75kW n2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:14:32 2020

Workbook: Case (Main)

Material Streams Fluid Pkg: All

Name		HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Temperature	(C)	233.0	17.78	6.667 *	20.00 *
Pressure	(bar_g)	11.36	3.726	3.987 *	11.25
Mass Flow	(kg/s)	0.3238	1.923	1.923 *	0.3238
Mass Density	(kg/m3)	8.205	1068	1077	14.17
Mass Enthalpy	(kJ/kg)	219.7	-1.207e+004	-1.210e+004	-8.614
Mass Entropy	(kJ/kg-C)	5.101	0.5631	0.4282	4.519
Name		RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Temperature	(C)	24.55	396.9	394.7	600.0 *
Pressure	(bar_g)	11.67	11.65 *	11.65	11.40 *
Mass Flow	(kg/s)	0.3238	0.3238	0.3238	0.3238
Mass Density	(kg/m3)	14.43	6.342	6.361	4.772
Mass Enthalpy	(kJ/kg)	-3.882	399.8	397.3	629.0
Mass Entropy	(kJ/kg-C)	4.525	5.402	5.398	5.707
Name		RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Temperature	(C)	595.7	233.6 *	20.02	20.02
Pressure	(bar_g)	11.39	11.36 *	11.21	11.23
Mass Flow	(kg/s)	0.3238	0.3238	0.3238 *	0.3238
Mass Density	(kg/m3)	4.793	8.197	14.13	14.15
Mass Enthalpy	(kJ/kg)	624.0	220.4	-8.579	-8.587
Mass Entropy	(kJ/kg-C)	5.701	5.102	4.520	4.519
Name		Chiller In	Chiller Out	CWS-04	CWR-01
Temperature	(C)	17.78	6.654	6.662	17.78
Pressure	(bar_g)	3.859	3.762	3.793	3.526
Mass Flow	(kg/s)	1.923	1.923	1.923	1.923
Mass Density	(kg/m3)	1068	1077	1077	1068
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.210e+004	-1.210e+004	-1.207e+004
Mass Entropy	(kJ/kg-C)	0.5631	0.4281	0.4282	0.5631
Name		CWR-05	CWS-02	CWS-03	CWS-06
Temperature	(C)	17.78	6.658	6.658	6.666
Pressure	(bar_g)	3.860	4.132	4.131	3.792
Mass Flow	(kg/s)	1.923	1.923	1.923	1.923
Mass Density	(kg/m3)	1068	1077	1077	1077
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.210e+004	-1.210e+004	-1.210e+004
Mass Entropy	(kJ/kg-C)	0.5631	0.4281	0.4281	0.4282
Name		13	14	15	16
Temperature	(C)	24.63	24.56	24.56	20.02
Pressure	(bar_g)	11.69	11.67	11.67	11.23
Mass Flow	(kg/s)	0.3238	0.3238	0.3238	0.3238
Mass Density	(kg/m3)	14.45	14.43	14.43	14.14
Mass Enthalpy	(kJ/kg)	-3.809	-3.877	-3.877	-8.587
Mass Entropy	(kJ/kg-C)	4.525	4.525	4.525	4.519
Name		Comp Out	4-2	CWR-02	CWR-03
Temperature	(C)	24.65	24.63	17.78	17.78
Pressure	(bar_g)	11.73 *	11.69	3.526	3.525
Mass Flow	(kg/s)	0.3238	0.3238	1.923	1.923
Mass Density	(kg/m3)	14.49	14.45	1068	1068
Mass Enthalpy	(kJ/kg)	-3.797	-3.809	-1.207e+004	-1.207e+004
Mass Entropy	(kJ/kg-C)	4.524	4.524	0.5631	0.5631

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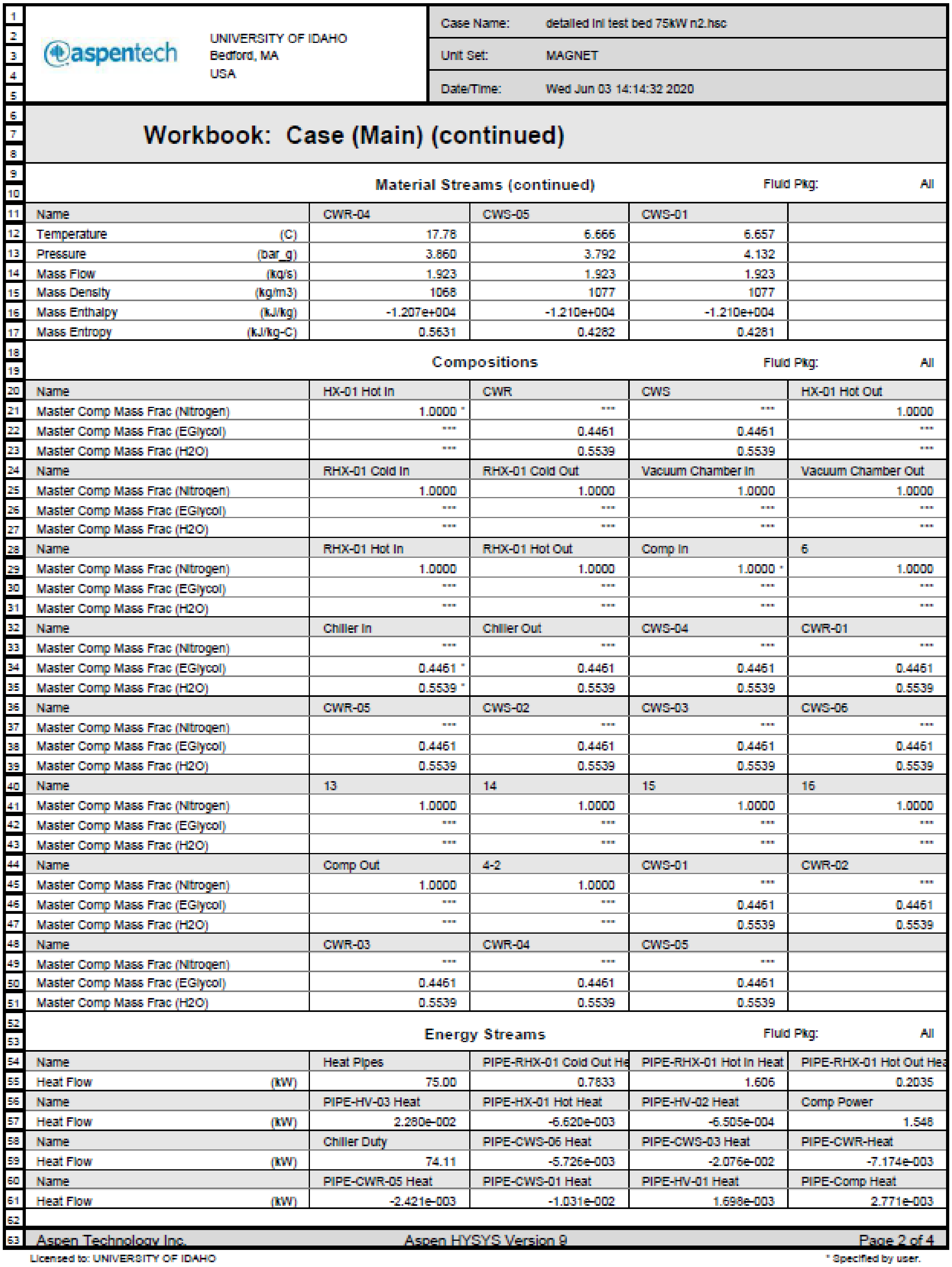

aspentech	UNIVERSITY OF IDAHO Bedford, MA USA	Case Name: detailed inl test bed 75kW n2.hsc Unit Set: MAGNET Date/Time: Wed Jun 03 14:14:32 2020

Workbook: Case (Main) (continued)

Material Streams (continued)

Fluid Pkg: All

Name		CWR-04	CWS-05	CWS-01	
Temperature	(C)	17.78	6.666	6.657	
Pressure	(bar_g)	3.860	3.792	4.132	
Mass Flow	(kg/s)	1.923	1.923	1.923	
Mass Density	(kg/m3)	1068	1077	1077	
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.210e+004	-1.210e+004	
Mass Entropy	(kJ/kg-C)	0.5631	0.4282	0.4281	

Compositions

Fluid Pkg: All

Name	HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Master Comp Mass Frac (Nitrogen)	1.0000 *	***	***	1.0000
Master Comp Mass Frac (EGlycol)	***	0.4461	0.4461	***
Master Comp Mass Frac (H2O)	***	0.5539	0.5539	***
Name	RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Name	RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000 *	1.0000
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Name	Chiller In	Chiller Out	CWS-04	CWR-01
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (EGlycol)	0.4461 *	0.4461	0.4461	0.4461
Master Comp Mass Frac (H2O)	0.5539 *	0.5539	0.5539	0.5539
Name	CWR-05	CWS-02	CWS-03	CWS-06
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	0.4461	0.4461
Master Comp Mass Frac (H2O)	0.5539	0.5539	0.5539	0.5539
Name	13	14	15	16
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Name	Comp Out	4-2	CWS-01	CWR-02
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	***	***
Master Comp Mass Frac (EGlycol)	***	***	0.4461	0.4461
Master Comp Mass Frac (H2O)	***	***	0.5539	0.5539
Name	CWR-03	CWR-04	CWS-05	
Master Comp Mass Frac (Nitrogen)	***	***	***	
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	0.4461	
Master Comp Mass Frac (H2O)	0.5539	0.5539	0.5539	

Energy Streams

Fluid Pkg: All

Name		Heat Pipes	PIPE-RHX-01 Cold Out He	PIPE-RHX-01 Hot In Heat	PIPE-RHX-01 Hot Out Hea
Heat Flow	(kW)	75.00	0.7833	1.606	0.2035
Name		PIPE-HV-03 Heat	PIPE-HX-01 Hot Heat	PIPE-HV-02 Heat	Comp Power
Heat Flow	(kW)	2.280e-002	-6.620e-003	-6.505e-004	1.548
Name		Chiller Duty	PIPE-CWS-06 Heat	PIPE-CWS-03 Heat	PIPE-CWR-Heat
Heat Flow	(kW)	74.11	-5.726e-003	-2.076e-002	-7.174e-003
Name		PIPE-CWR-05 Heat	PIPE-CWS-01 Heat	PIPE-HV-01 Heat	PIPE-Comp Heat
Heat Flow	(kW)	-2.421e-003	-1.031e-002	1.698e-003	2.771e-003

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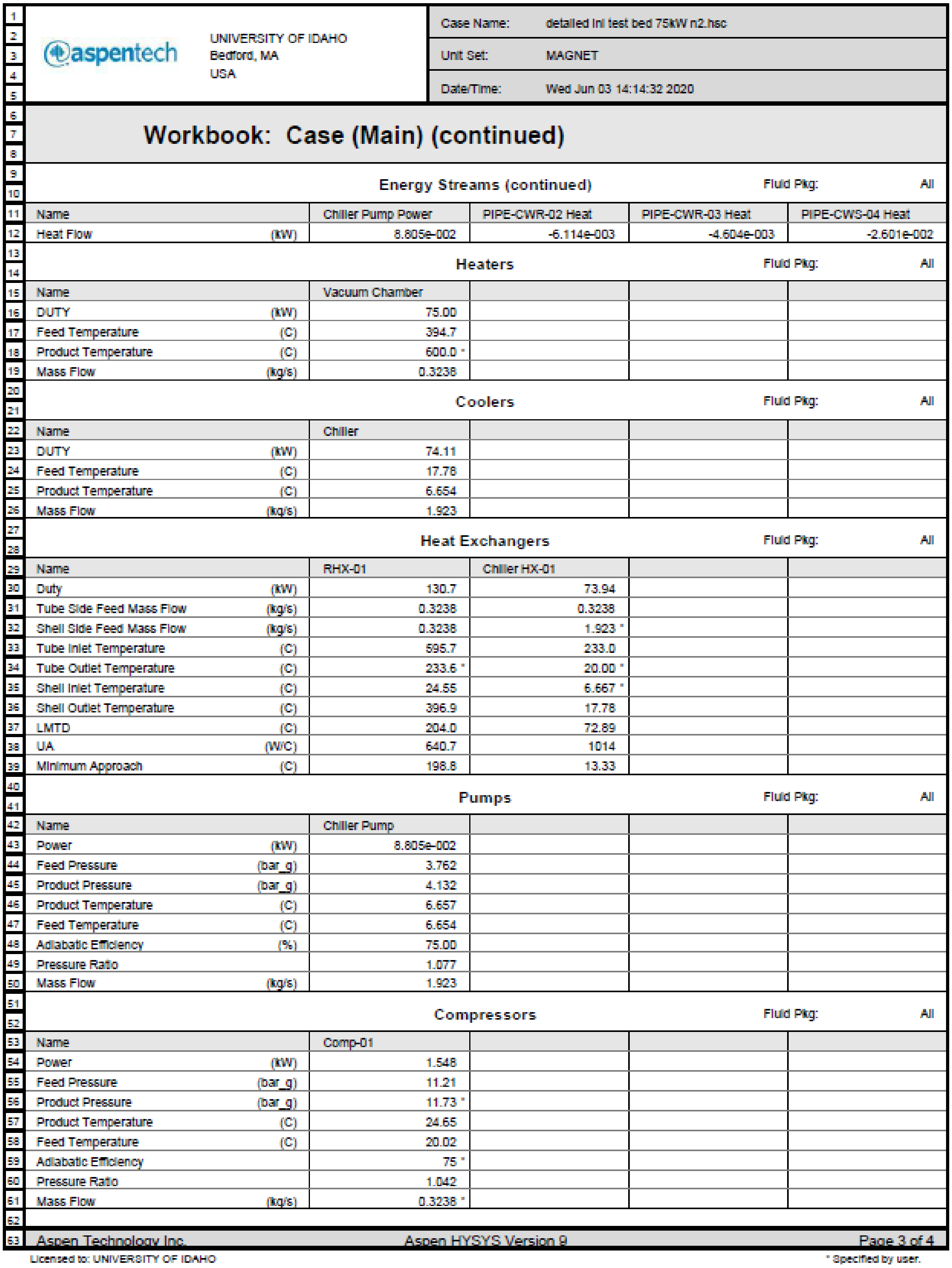

aspentech

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	detailed ini test bed 75kW n2.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:14:32 2020

Workbook: Case (Main) (continued)

Energy Streams (continued)

Fluid Pkg: All

Name		Chiller Pump Power	PIPE-CWR-02 Heat	PIPE-CWR-03 Heat	PIPE-CWS-04 Heat
Heat Flow	(kW)	8.805e-002	-6.114e-003	-4.604e-003	-2.601e-002

Heaters

Fluid Pkg: All

Name		Vacuum Chamber			
DUTY	(kW)	75.00			
Feed Temperature	(C)	394.7			
Product Temperature	(C)	600.0 *			
Mass Flow	(kg/s)	0.3238			

Coolers

Fluid Pkg: All

Name		Chiller			
DUTY	(kW)	74.11			
Feed Temperature	(C)	17.78			
Product Temperature	(C)	6.654			
Mass Flow	(kg/s)	1.923			

Heat Exchangers

Fluid Pkg: All

Name		RHX-01	Chiller HX-01		
Duty	(kW)	130.7	73.94		
Tube Side Feed Mass Flow	(kg/s)	0.3238	0.3238		
Shell Side Feed Mass Flow	(kg/s)	0.3238	1.923 *		
Tube Inlet Temperature	(C)	595.7	233.0		
Tube Outlet Temperature	(C)	233.6 *	20.00 *		
Shell Inlet Temperature	(C)	24.55	6.667 *		
Shell Outlet Temperature	(C)	396.9	17.78		
LMTD	(C)	204.0	72.89		
UA	(W/C)	640.7	1014		
Minimum Approach	(C)	198.8	13.33		

Pumps

Fluid Pkg: All

Name		Chiller Pump			
Power	(kW)	8.805e-002			
Feed Pressure	(bar_g)	3.762			
Product Pressure	(bar_g)	4.132			
Product Temperature	(C)	6.657			
Feed Temperature	(C)	6.654			
Adiabatic Efficiency	(%)	75.00			
Pressure Ratio		1.077			
Mass Flow	(kg/s)	1.923			

Compressors

Fluid Pkg: All

Name		Comp-01			
Power	(kW)	1.548			
Feed Pressure	(bar_g)	11.21			
Product Pressure	(bar_g)	11.73 *			
Product Temperature	(C)	24.65			
Feed Temperature	(C)	20.02			
Adiabatic Efficiency		75 *			
Pressure Ratio		1.042			
Mass Flow	(kg/s)	0.3238 *			

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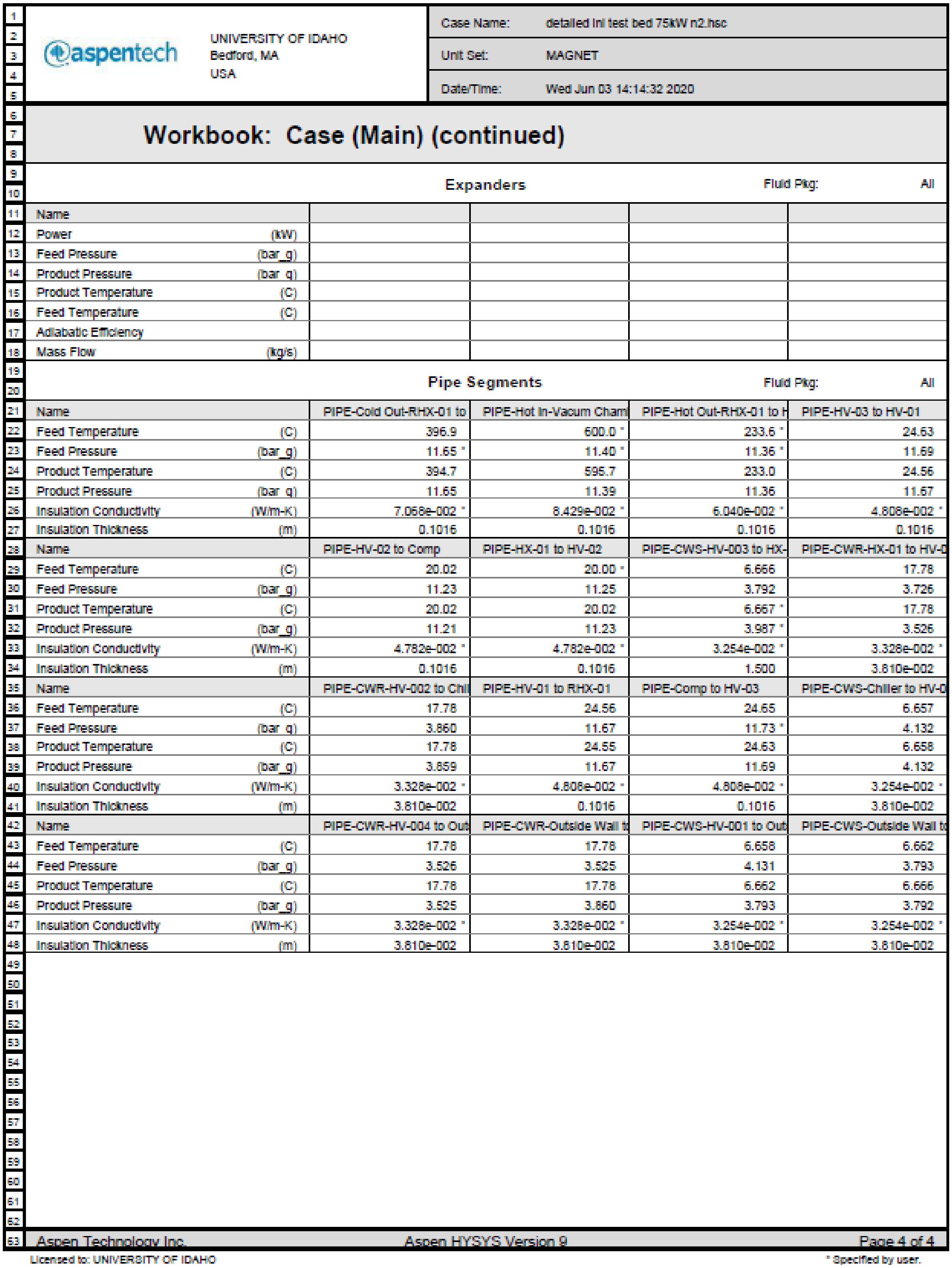

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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed lnl test bed 75kW n2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:14:32 2020

Workbook: Case (Main) (continued)

Expanders Fluid Pkg: All

Name				
Power (kW)				
Feed Pressure (bar_g)				
Product Pressure (bar_g)				
Product Temperature (C)				
Feed Temperature (C)				
Adiabatic Efficiency				
Mass Flow (kg/s)				

Pipe Segments Fluid Pkg: All

Name	PIPE-Cold Out-RHX-01 to	PIPE-Hot In-Vacum Cham	PIPE-Hot Out-RHX-01 to H	PIPE-HV-03 to HV-01
Feed Temperature (C)	396.9	600.0 *	233.6 *	24.63
Feed Pressure (bar_g)	11.65 *	11.40 *	11.36 *	11.69
Product Temperature (C)	394.7	595.7	233.0	24.56
Product Pressure (bar_g)	11.65	11.39	11.36	11.67
Insulation Conductivity (W/m-K)	7.068e-002 *	8.429e-002 *	6.040e-002 *	4.808e-002 *
Insulation Thickness (m)	0.1016	0.1016	0.1016	0.1016
Name	**PIPE-HV-02 to Comp**	**PIPE-HX-01 to HV-02**	**PIPE-CWS-HV-003 to HX-**	**PIPE-CWR-HX-01 to HV-0**
Feed Temperature (C)	20.02	20.00 *	6.666	17.78
Feed Pressure (bar_g)	11.23	11.25	3.792	3.726
Product Temperature (C)	20.02	20.02	6.667 *	17.78
Product Pressure (bar_g)	11.21	11.23	3.987 *	3.526
Insulation Conductivity (W/m-K)	4.782e-002 *	4.782e-002 *	3.254e-002 *	3.328e-002 *
Insulation Thickness (m)	0.1016	0.1016	1.500	3.810e-002
Name	**PIPE-CWR-HV-002 to Chil**	**PIPE-HV-01 to RHX-01**	**PIPE-Comp to HV-03**	**PIPE-CWS-Chiller to HV-0**
Feed Temperature (C)	17.78	24.56	24.65	6.657
Feed Pressure (bar_g)	3.860	11.67	11.73 *	4.132
Product Temperature (C)	17.78	24.55	24.63	6.658
Product Pressure (bar_g)	3.859	11.67	11.69	4.132
Insulation Conductivity (W/m-K)	3.328e-002 *	4.808e-002 *	4.808e-002 *	3.254e-002 *
Insulation Thickness (m)	3.810e-002	0.1016	0.1016	3.810e-002
Name	**PIPE-CWR-HV-004 to Out**	**PIPE-CWR-Outside Wall t**	**PIPE-CWS-HV-001 to Out**	**PIPE-CWS-Outside Wall t**
Feed Temperature (C)	17.78	17.78	6.658	6.662
Feed Pressure (bar_g)	3.526	3.525	4.131	3.793
Product Temperature (C)	17.78	17.78	6.662	6.666
Product Pressure (bar_g)	3.525	3.860	3.793	3.792
Insulation Conductivity (W/m-K)	3.328e-002 *	3.328e-002 *	3.254e-002 *	3.254e-002 *
Insulation Thickness (m)	3.810e-002	3.810e-002	3.810e-002	3.810e-002

Aspen Technology Inc. Aspen HYSYS Version 9 Page 4 of 4

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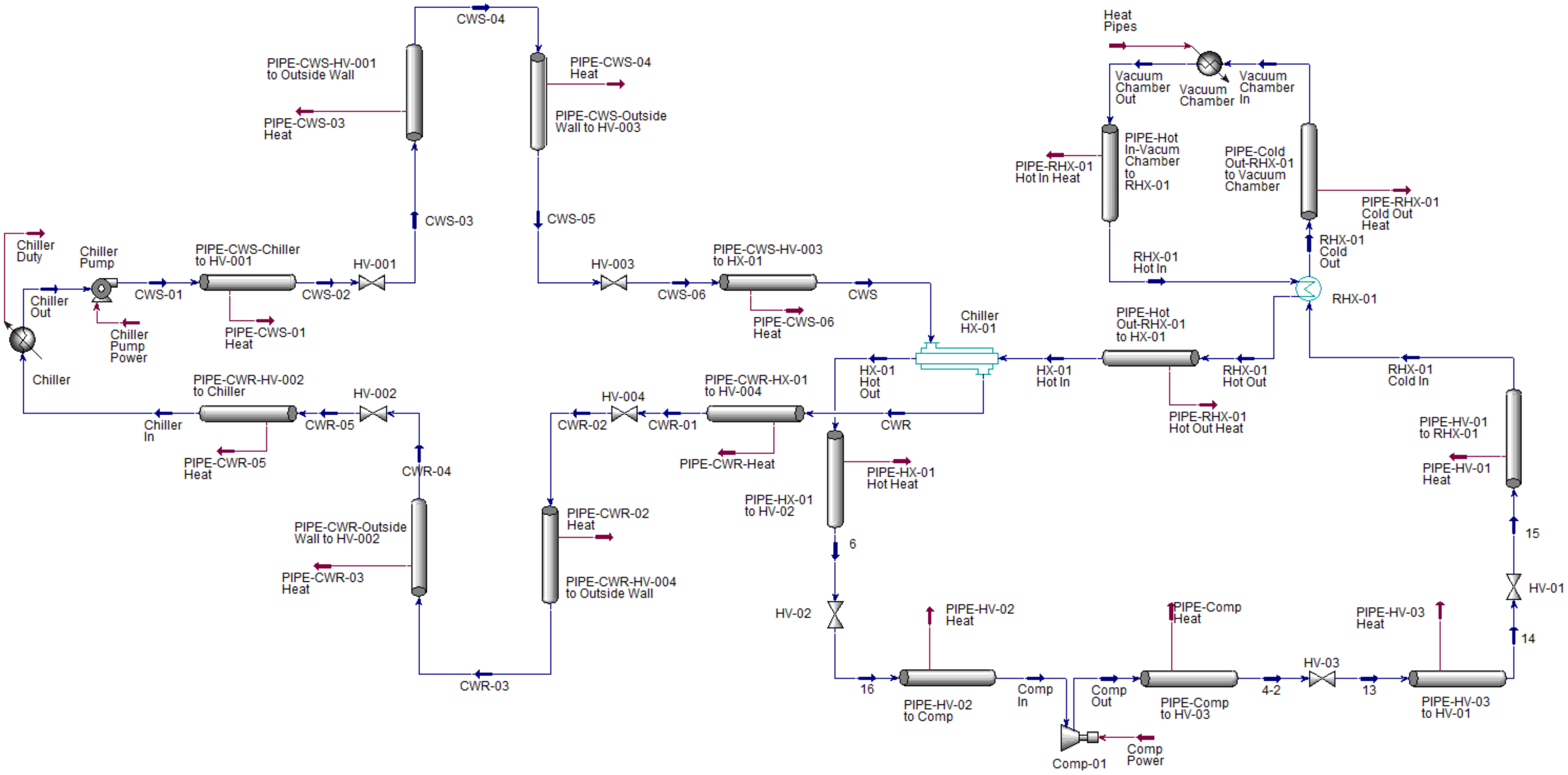
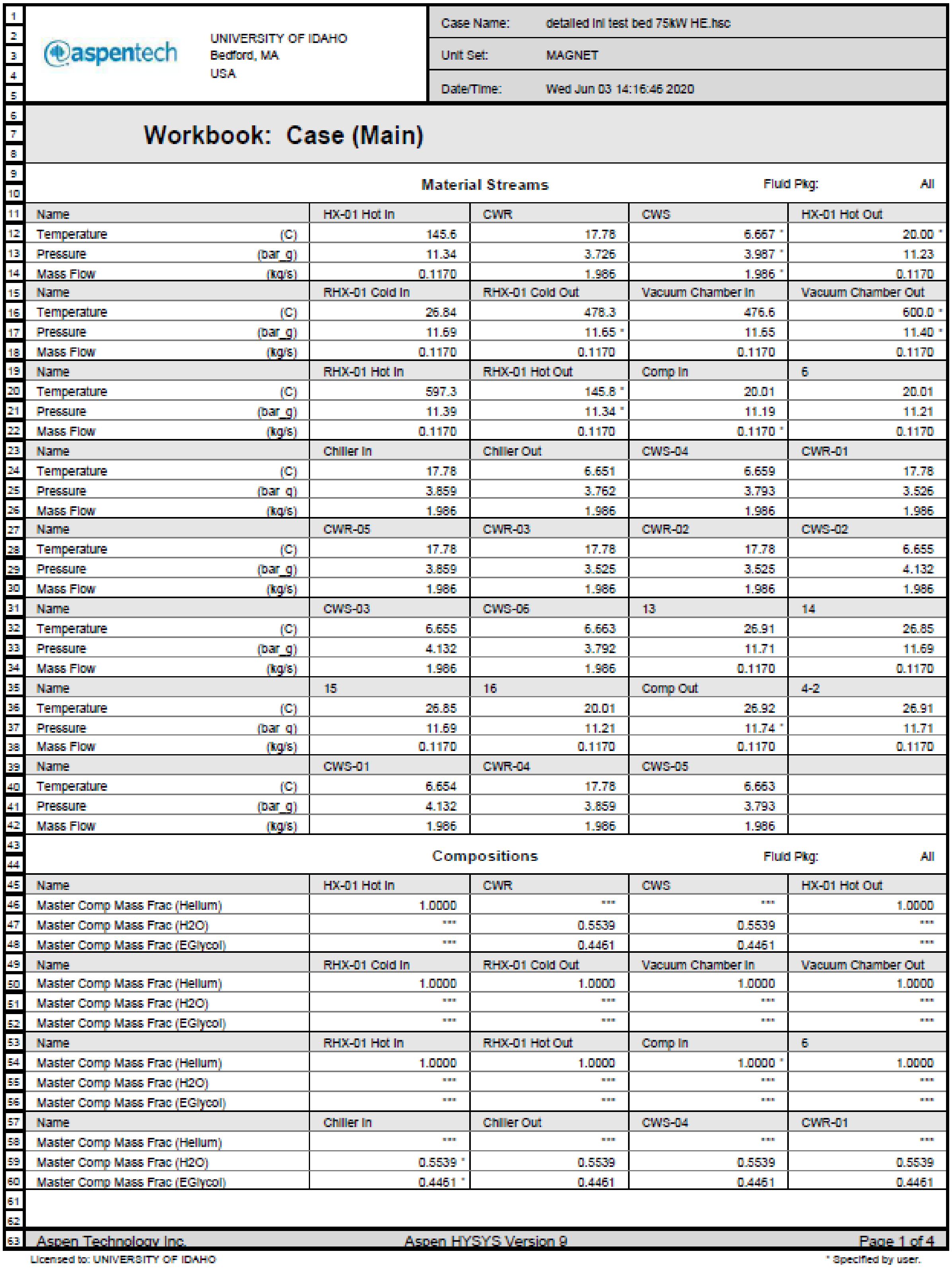
Aspen HYSYS Process Model of Microreactor AGile Non-nuclear Experimental Testbed with Helium Operating at 600°C and 75 kW of Heat Pipe Power





aspentech

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed Inl test bed 75kW HE.hsc

Unit Set: MAGNET

Date/Time: Wed Jun 03 14:16:46 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Temperature	(C)	145.6	17.78	6.667 *	20.00 *
Pressure	(bar_g)	11.34	3.726	3.987 *	11.23
Mass Flow	(kg/s)	0.1170	1.986	1.986 *	0.1170
Name		RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Temperature	(C)	26.84	478.3	476.6	600.0 *
Pressure	(bar_g)	11.69	11.65 *	11.65	11.40 *
Mass Flow	(kg/s)	0.1170	0.1170	0.1170	0.1170
Name		RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Temperature	(C)	597.3	145.8 *	20.01	20.01
Pressure	(bar_g)	11.39	11.34 *	11.19	11.21
Mass Flow	(kg/s)	0.1170	0.1170	0.1170 *	0.1170
Name		Chiller In	Chiller Out	CWS-04	CWR-01
Temperature	(C)	17.78	6.651	6.659	17.78
Pressure	(bar_g)	3.859	3.762	3.793	3.526
Mass Flow	(kg/s)	1.986	1.986	1.986	1.986
Name		CWR-05	CWR-03	CWR-02	CWS-02
Temperature	(C)	17.78	17.78	17.78	6.655
Pressure	(bar_g)	3.859	3.525	3.525	4.132
Mass Flow	(kg/s)	1.986	1.986	1.986	1.986
Name		CWS-03	CWS-06	13	14
Temperature	(C)	6.655	6.663	26.91	26.85
Pressure	(bar_g)	4.132	3.792	11.71	11.69
Mass Flow	(kg/s)	1.986	1.986	0.1170	0.1170
Name		15	16	Comp Out	4-2
Temperature	(C)	26.85	20.01	26.92	26.91
Pressure	(bar_g)	11.69	11.21	11.74 *	11.71
Mass Flow	(kg/s)	0.1170	0.1170	0.1170	0.1170
Name		CWS-01	CWR-04	CWS-05	
Temperature	(C)	6.654	17.78	6.663	
Pressure	(bar_g)	4.132	3.859	3.793	
Mass Flow	(kg/s)	1.986	1.986	1.986	

Compositions

Fluid Pkg: All

Name	HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Master Comp Mass Frac (Helium)	1.0000	***	***	1.0000
Master Comp Mass Frac (H2O)	***	0.5539	0.5539	***
Master Comp Mass Frac (EGlycol)	***	0.4461	0.4461	***
Name	RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Master Comp Mass Frac (Helium)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Name	RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Master Comp Mass Frac (Helium)	1.0000	1.0000	1.0000 *	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Name	Chiller In	Chiller Out	CWS-04	CWR-01
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539 *	0.5539	0.5539	0.5539
Master Comp Mass Frac (EGlycol)	0.4461 *	0.4461	0.4461	0.4461

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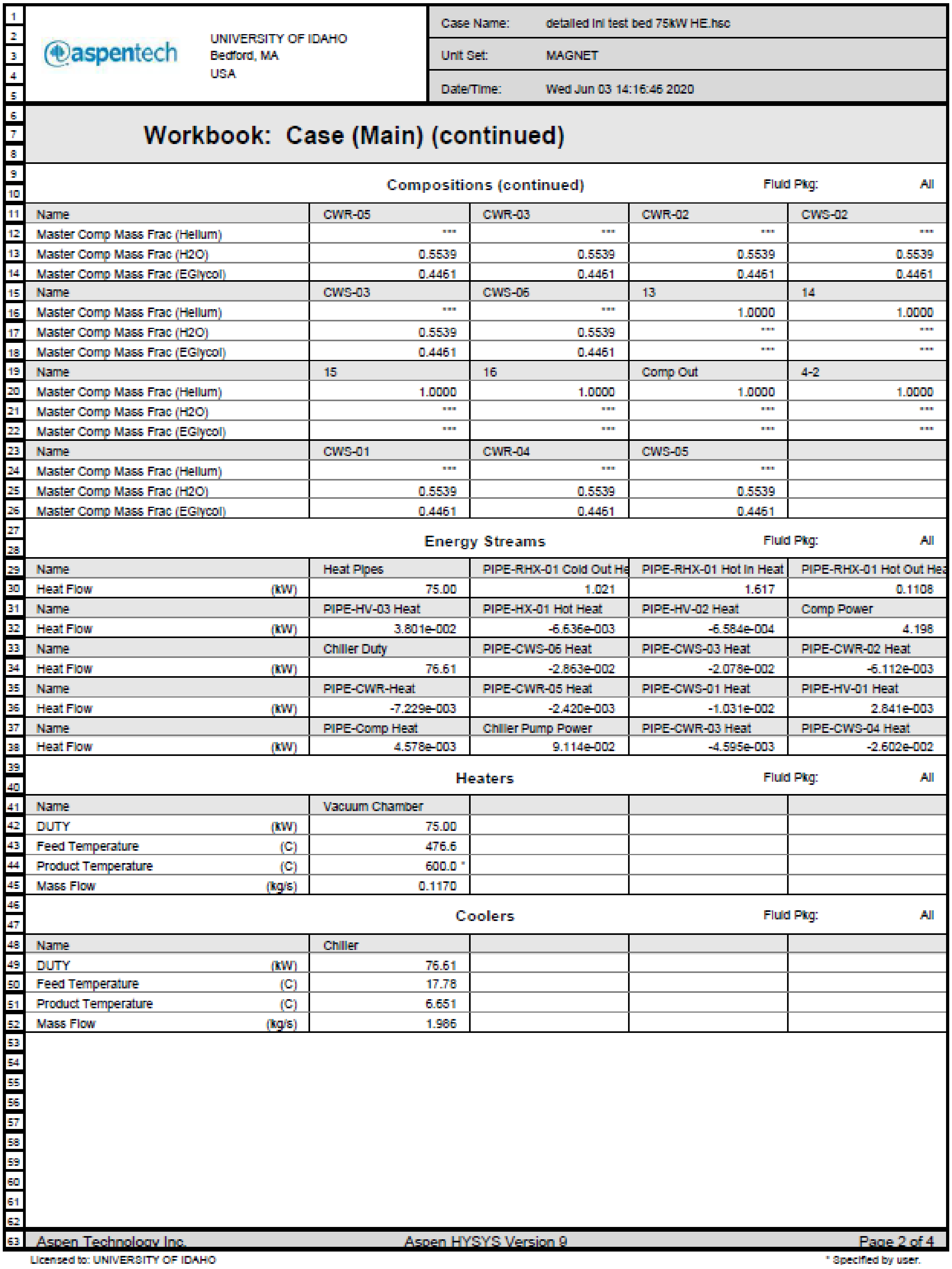

UNIVERSITY OF IDAHO Bedford, MA USA	Case Name: detailed inl test bed 75kW HE.hsc Unit Set: MAGNET Date/Time: Wed Jun 03 14:16:46 2020

Workbook: Case (Main) (continued)

Compositions (continued)

Fluid Pkg: All

Name	CWR-05	CWR-03	CWR-02	CWS-02
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539	0.5539	0.5539	0.5539
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	0.4461	0.4461
Name	CWS-03	CWS-06	13	14
Master Comp Mass Frac (Helium)	***	***	1.0000	1.0000
Master Comp Mass Frac (H2O)	0.5539	0.5539	***	***
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	***	***
Name	15	16	Comp Out	4-2
Master Comp Mass Frac (Helium)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Name	CWS-01	CWR-04	CWS-05	
Master Comp Mass Frac (Helium)	***	***	***	
Master Comp Mass Frac (H2O)	0.5539	0.5539	0.5539	
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	0.4461	

Energy Streams

Fluid Pkg: All

Name	Heat Pipes	PIPE-RHX-01 Cold Out He	PIPE-RHX-01 Hot In Heat	PIPE-RHX-01 Hot Out Hea
Heat Flow (kW)	75.00	1.021	1.617	0.1108
Name	PIPE-HV-03 Heat	PIPE-HX-01 Hot Heat	PIPE-HV-02 Heat	Comp Power
Heat Flow (kW)	3.801e-002	-6.636e-003	-6.584e-004	4.198
Name	Chiller Duty	PIPE-CWS-06 Heat	PIPE-CWS-03 Heat	PIPE-CWR-02 Heat
Heat Flow (kW)	76.61	-2.863e-002	-2.078e-002	-6.112e-003
Name	PIPE-CWR-Heat	PIPE-CWR-05 Heat	PIPE-CWS-01 Heat	PIPE-HV-01 Heat
Heat Flow (kW)	-7.229e-003	-2.420e-003	-1.031e-002	2.841e-003
Name	PIPE-Comp Heat	Chiller Pump Power	PIPE-CWR-03 Heat	PIPE-CWS-04 Heat
Heat Flow (kW)	4.578e-003	9.114e-002	-4.595e-003	-2.602e-002

Heaters

Fluid Pkg: All

Name	Vacuum Chamber			
DUTY (kW)	75.00			
Feed Temperature (C)	476.6			
Product Temperature (C)	600.0 *			
Mass Flow (kg/s)	0.1170			

Coolers

Fluid Pkg: All

Name	Chiller			
DUTY (kW)	76.61			
Feed Temperature (C)	17.78			
Product Temperature (C)	6.651			
Mass Flow (kg/s)	1.966			

Aspen Technology Inc. Aspen HYSYS Version 9 Page 2 of 4

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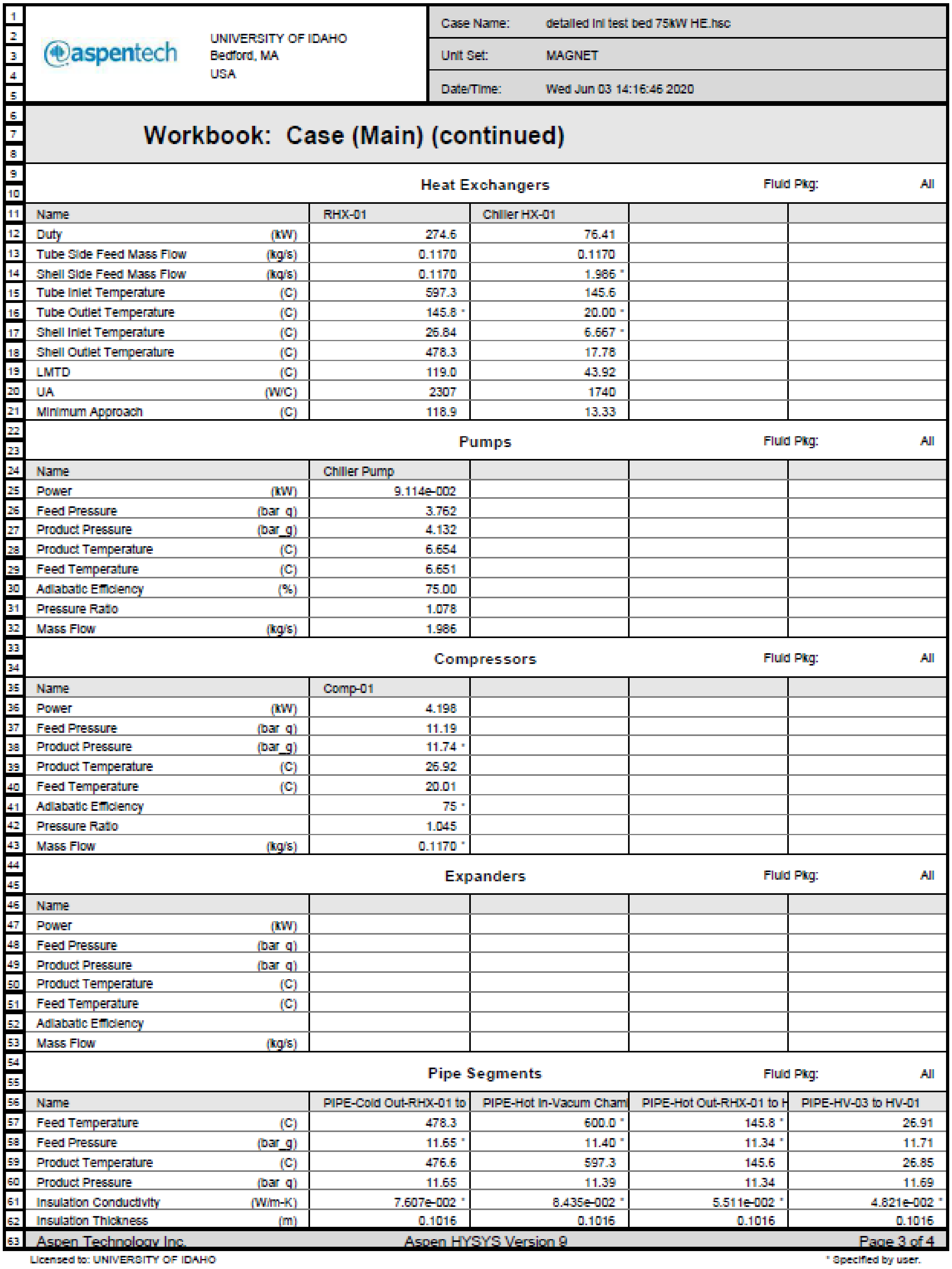

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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed Inl test bed 75kW HE.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:16:46 2020

Workbook: Case (Main) (continued)

Heat Exchangers

Fluid Pkg: All

Name		RHX-01	Chiller HX-01		
Duty	(kW)	274.6	76.41		
Tube Side Feed Mass Flow	(kg/s)	0.1170	0.1170		
Shell Side Feed Mass Flow	(kg/s)	0.1170	1.986 *		
Tube Inlet Temperature	(C)	597.3	145.6		
Tube Outlet Temperature	(C)	145.8 *	20.00 *		
Shell Inlet Temperature	(C)	26.84	6.667 *		
Shell Outlet Temperature	(C)	478.3	17.78		
LMTD	(C)	119.0	43.92		
UA	(W/C)	2307	1740		
Minimum Approach	(C)	118.9	13.33		

Pumps

Fluid Pkg: All

Name		Chiller Pump			
Power	(kW)	9.114e-002			
Feed Pressure	(bar_g)	3.762			
Product Pressure	(bar_g)	4.132			
Product Temperature	(C)	6.654			
Feed Temperature	(C)	6.651			
Adiabatic Efficiency	(%)	75.00			
Pressure Ratio		1.078			
Mass Flow	(kg/s)	1.986			

Compressors

Fluid Pkg: All

Name		Comp-01			
Power	(kW)	4.198			
Feed Pressure	(bar_g)	11.19			
Product Pressure	(bar_g)	11.74 *			
Product Temperature	(C)	26.92			
Feed Temperature	(C)	20.01			
Adiabatic Efficiency		75 *			
Pressure Ratio		1.045			
Mass Flow	(kg/s)	0.1170 *			

Expanders

Fluid Pkg: All

Name					
Power	(kW)				
Feed Pressure	(bar_g)				
Product Pressure	(bar_g)				
Product Temperature	(C)				
Feed Temperature	(C)				
Adiabatic Efficiency					
Mass Flow	(kg/s)				

Pipe Segments

Fluid Pkg: All

Name		PIPE-Cold Out-RHX-01 to	PIPE-Hot In-Vacum Cham	PIPE-Hot Out-RHX-01 to H	PIPE-HV-03 to HV-01
Feed Temperature	(C)	478.3	600.0 *	145.8 *	26.91
Feed Pressure	(bar_g)	11.65 *	11.40 *	11.34 *	11.71
Product Temperature	(C)	476.6	597.3	145.6	26.85
Product Pressure	(bar_g)	11.65	11.39	11.34	11.69
Insulation Conductivity	(W/m-K)	7.607e-002 *	8.435e-002 *	5.511e-002 *	4.821e-002 *
Insulation Thickness	(m)	0.1016	0.1016	0.1016	0.1016

Aspen Technology Inc. Aspen HYSYS Version 9 Page 3 of 4

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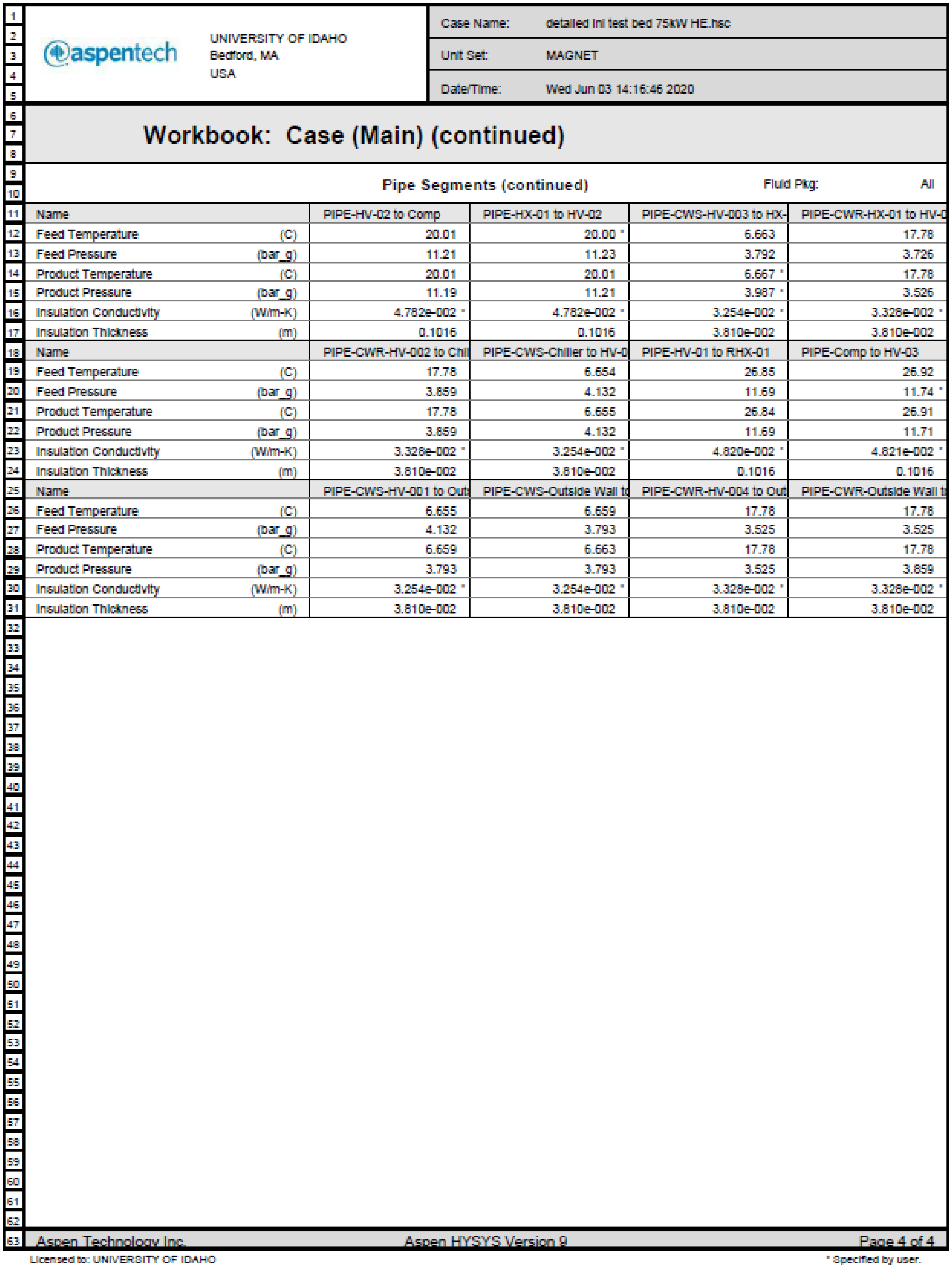

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Bedford, MA
USA

Case Name: detailed lnl test bed 75kW HE.hsc

Unit Set: MAGNET

Date/Time: Wed Jun 03 14:16:46 2020

Workbook: Case (Main) (continued)

Pipe Segments (continued)

Fluid Pkg: All

Name		PIPE-HV-02 to Comp	PIPE-HX-01 to HV-02	PIPE-CWS-HV-003 to HX-	PIPE-CWR-HX-01 to HV-
Feed Temperature	(C)	20.01	20.00 *	6.663	17.78
Feed Pressure	(bar_g)	11.21	11.23	3.792	3.726
Product Temperature	(C)	20.01	20.01	6.667 *	17.78
Product Pressure	(bar_g)	11.19	11.21	3.987 *	3.526
Insulation Conductivity	(W/m-K)	4.782e-002 *	4.782e-002 *	3.254e-002 *	3.328e-002 *
Insulation Thickness	(m)	0.1016	0.1016	3.810e-002	3.810e-002

Name		PIPE-CWR-HV-002 to Chil	PIPE-CWS-Chiller to HV-	PIPE-HV-01 to RHX-01	PIPE-Comp to HV-03
Feed Temperature	(C)	17.78	6.654	26.85	26.92
Feed Pressure	(bar_g)	3.859	4.132	11.69	11.74 *
Product Temperature	(C)	17.78	6.655	26.84	26.91
Product Pressure	(bar_g)	3.859	4.132	11.69	11.71
Insulation Conductivity	(W/m-K)	3.328e-002 *	3.254e-002 *	4.820e-002 *	4.821e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	0.1016	0.1016

Name		PIPE-CWS-HV-001 to Out	PIPE-CWS-Outside Wall t	PIPE-CWR-HV-004 to Out	PIPE-CWR-Outside Wall t
Feed Temperature	(C)	6.655	6.659	17.78	17.78
Feed Pressure	(bar_g)	4.132	3.793	3.525	3.525
Product Temperature	(C)	6.659	6.663	17.78	17.78
Product Pressure	(bar_g)	3.793	3.793	3.525	3.859
Insulation Conductivity	(W/m-K)	3.254e-002 *	3.254e-002 *	3.328e-002 *	3.328e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	3.810e-002	3.810e-002

Aspen Technology Inc. Aspen HYSYS Version 9 Page 4 of 4

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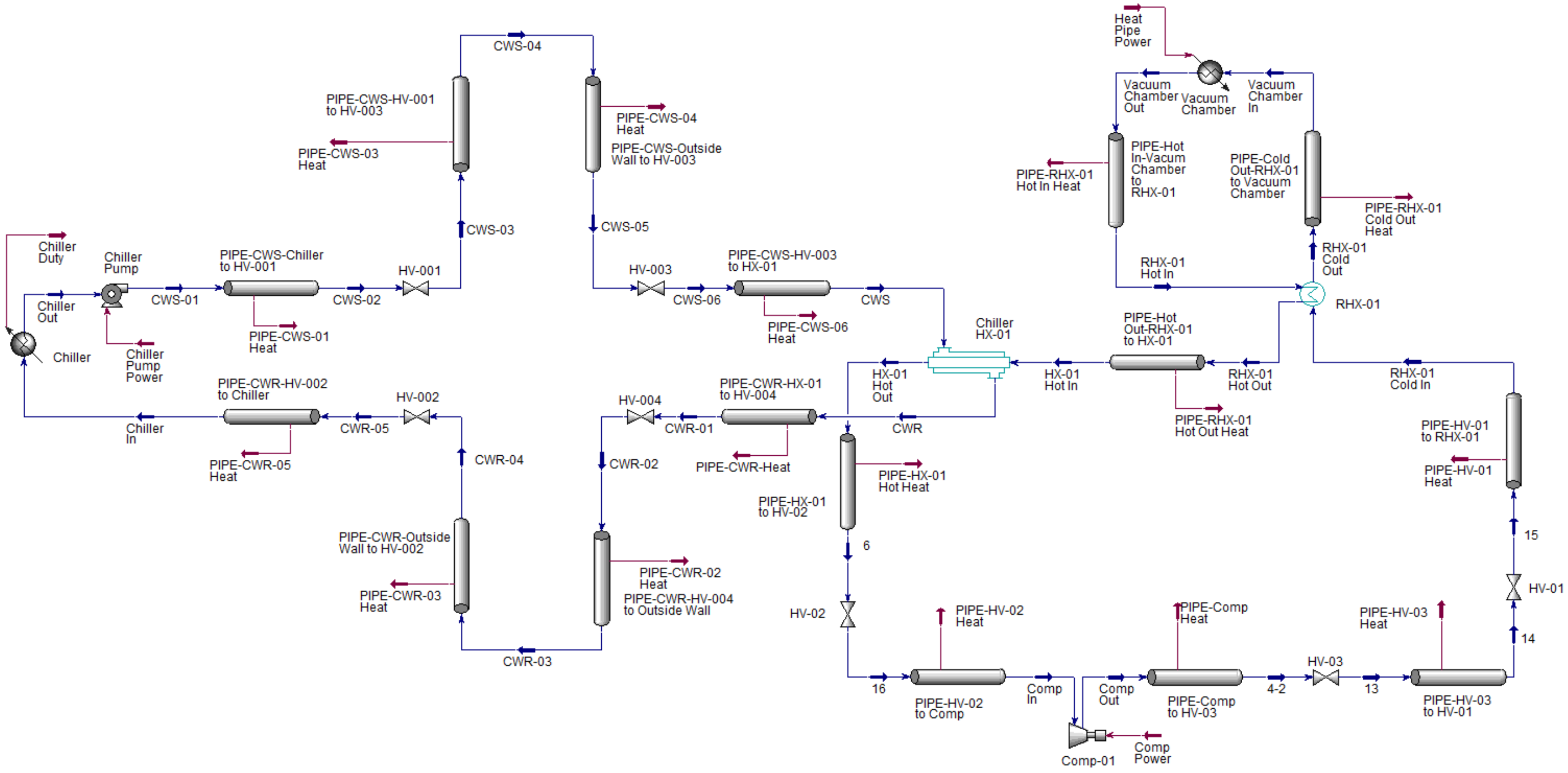
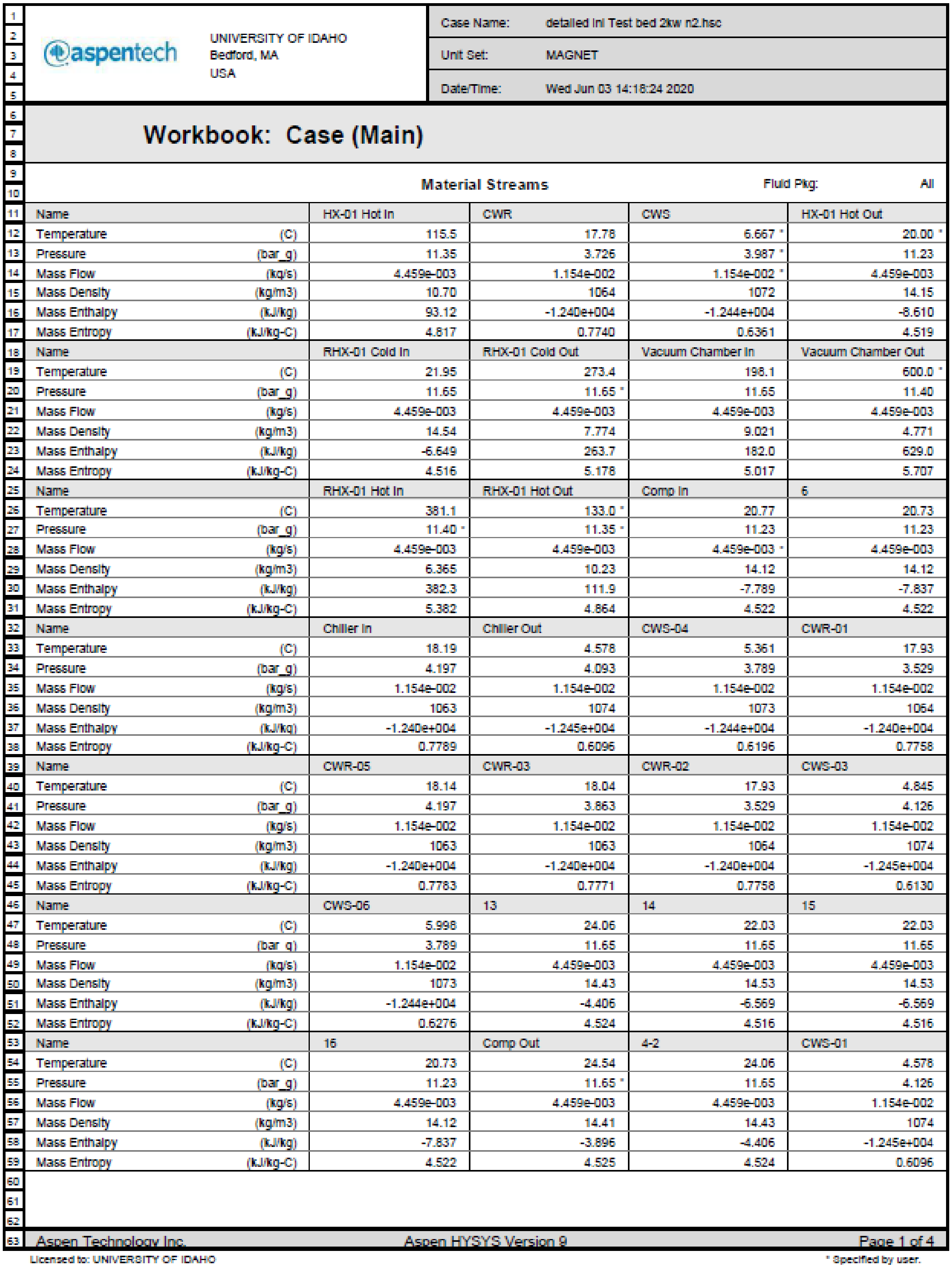
Aspen HYSYS Process Model of Microreactor AGile Non-nuclear Experimental Testbed with Nitrogen Operating at 600°C and 2 kW of Heat Pipe Power





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Bedford, MA
USA

Case Name: detailed lnl Test bed 2kw n2.hsc

Unit Set: MAGNET

Date/Time: Wed Jun 03 14:18:24 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Temperature	(C)	115.5	17.78	6.667 *	20.00 *
Pressure	(bar_g)	11.35	3.726	3.987 *	11.23
Mass Flow	(kg/s)	4.459e-003	1.154e-002	1.154e-002 *	4.459e-003
Mass Density	(kg/m3)	10.70	1064	1072	14.15
Mass Enthalpy	(kJ/kg)	93.12	-1.240e+004	-1.244e+004	-8.610
Mass Entropy	(kJ/kg-C)	4.817	0.7740	0.6361	4.519
Name		RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Temperature	(C)	21.95	273.4	198.1	600.0 *
Pressure	(bar_g)	11.65	11.65 *	11.65	11.40
Mass Flow	(kg/s)	4.459e-003	4.459e-003	4.459e-003	4.459e-003
Mass Density	(kg/m3)	14.54	7.774	9.021	4.771
Mass Enthalpy	(kJ/kg)	-6.649	263.7	182.0	629.0
Mass Entropy	(kJ/kg-C)	4.516	5.178	5.017	5.707
Name		RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Temperature	(C)	381.1	133.0 *	20.77	20.73
Pressure	(bar_g)	11.40 *	11.35 *	11.23	11.23
Mass Flow	(kg/s)	4.459e-003	4.459e-003	4.459e-003 *	4.459e-003
Mass Density	(kg/m3)	6.365	10.23	14.12	14.12
Mass Enthalpy	(kJ/kg)	382.3	111.9	-7.789	-7.837
Mass Entropy	(kJ/kg-C)	5.382	4.864	4.522	4.522
Name		Chiller In	Chiller Out	CWS-04	CWR-01
Temperature	(C)	18.19	4.578	5.361	17.93
Pressure	(bar_g)	4.197	4.093	3.789	3.529
Mass Flow	(kg/s)	1.154e-002	1.154e-002	1.154e-002	1.154e-002
Mass Density	(kg/m3)	1063	1074	1073	1064
Mass Enthalpy	(kJ/kg)	-1.240e+004	-1.245e+004	-1.244e+004	-1.240e+004
Mass Entropy	(kJ/kg-C)	0.7789	0.6096	0.6196	0.7758
Name		CWR-05	CWR-03	CWR-02	CWS-03
Temperature	(C)	18.14	18.04	17.93	4.845
Pressure	(bar_g)	4.197	3.863	3.529	4.126
Mass Flow	(kg/s)	1.154e-002	1.154e-002	1.154e-002	1.154e-002
Mass Density	(kg/m3)	1063	1063	1064	1074
Mass Enthalpy	(kJ/kg)	-1.240e+004	-1.240e+004	-1.240e+004	-1.245e+004
Mass Entropy	(kJ/kg-C)	0.7783	0.7771	0.7758	0.6130
Name		CWS-06	13	14	15
Temperature	(C)	5.998	24.06	22.03	22.03
Pressure	(bar_g)	3.789	11.65	11.65	11.65
Mass Flow	(kg/s)	1.154e-002	4.459e-003	4.459e-003	4.459e-003
Mass Density	(kg/m3)	1073	14.43	14.53	14.53
Mass Enthalpy	(kJ/kg)	-1.244e+004	-4.406	-6.569	-6.569
Mass Entropy	(kJ/kg-C)	0.6276	4.524	4.516	4.516
Name		16	Comp Out	4-2	CWS-01
Temperature	(C)	20.73	24.54	24.06	4.578
Pressure	(bar_g)	11.23	11.65 *	11.65	4.126
Mass Flow	(kg/s)	4.459e-003	4.459e-003	4.459e-003	1.154e-002
Mass Density	(kg/m3)	14.12	14.41	14.43	1074
Mass Enthalpy	(kJ/kg)	-7.837	-3.896	-4.406	-1.245e+004
Mass Entropy	(kJ/kg-C)	4.522	4.525	4.524	0.6096

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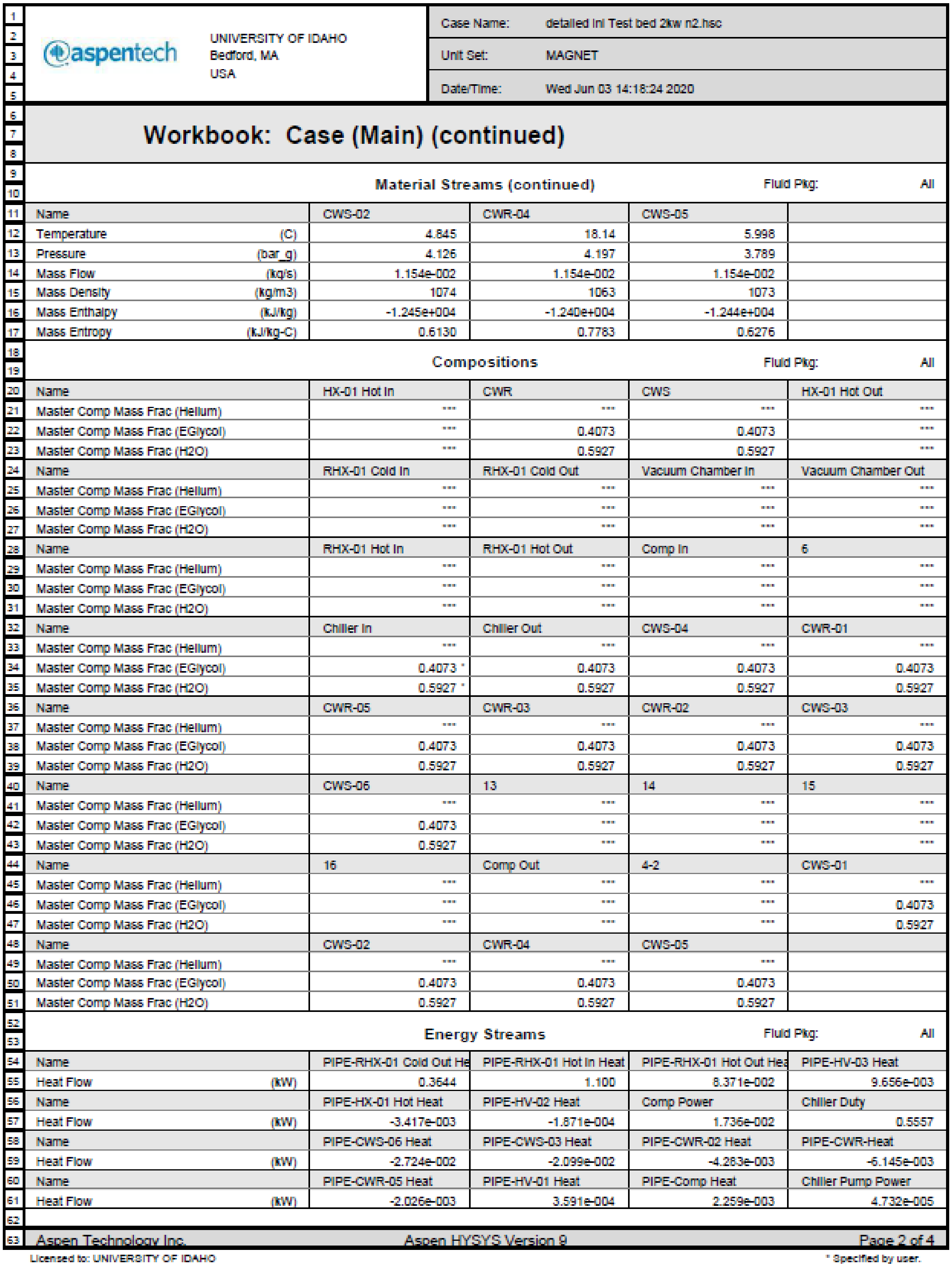

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USA

Case Name: detailed lnl Test bed 2kw n2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:18:24 2020

Workbook: Case (Main) (continued)

Material Streams (continued)

Fluid Pkg: All

Name		CWS-02	CWR-04	CWS-05	
Temperature	(C)	4.845	18.14	5.998	
Pressure	(bar_g)	4.126	4.197	3.789	
Mass Flow	(kg/s)	1.154e-002	1.154e-002	1.154e-002	
Mass Density	(kg/m3)	1074	1063	1073	
Mass Enthalpy	(kJ/kg)	-1.245e+004	-1.240e+004	-1.244e+004	
Mass Entropy	(kJ/kg-C)	0.6130	0.7783	0.6276	

Compositions

Fluid Pkg: All

Name	HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	0.4073	0.4073	***
Master Comp Mass Frac (H2O)	***	0.5927	0.5927	***
Name	RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Name	RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Name	Chiller In	Chiller Out	CWS-04	CWR-01
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (EGlycol)	0.4073 *	0.4073	0.4073	0.4073
Master Comp Mass Frac (H2O)	0.5927 *	0.5927	0.5927	0.5927
Name	CWR-05	CWR-03	CWR-02	CWS-03
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (EGlycol)	0.4073	0.4073	0.4073	0.4073
Master Comp Mass Frac (H2O)	0.5927	0.5927	0.5927	0.5927
Name	CWS-06	13	14	15
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (EGlycol)	0.4073	***	***	***
Master Comp Mass Frac (H2O)	0.5927	***	***	***
Name	16	Comp Out	4-2	CWS-01
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	0.4073
Master Comp Mass Frac (H2O)	***	***	***	0.5927
Name	CWS-02	CWR-04	CWS-05	
Master Comp Mass Frac (Helium)	***	***	***	
Master Comp Mass Frac (EGlycol)	0.4073	0.4073	0.4073	
Master Comp Mass Frac (H2O)	0.5927	0.5927	0.5927	

Energy Streams

Fluid Pkg: All

Name		PIPE-RHX-01 Cold Out He	PIPE-RHX-01 Hot In Heat	PIPE-RHX-01 Hot Out Hea	PIPE-HV-03 Heat
Heat Flow	(kW)	0.3644	1.100	8.371e-002	9.656e-003
Name		PIPE-HX-01 Hot Heat	PIPE-HV-02 Heat	Comp Power	Chiller Duty
Heat Flow	(kW)	-3.417e-003	-1.871e-004	1.736e-002	0.5557
Name		PIPE-CWS-06 Heat	PIPE-CWS-03 Heat	PIPE-CWR-02 Heat	PIPE-CWR-Heat
Heat Flow	(kW)	-2.724e-002	-2.099e-002	-4.283e-003	-6.145e-003
Name		PIPE-CWR-05 Heat	PIPE-HV-01 Heat	PIPE-Comp Heat	Chiller Pump Power
Heat Flow	(kW)	-2.026e-003	3.591e-004	2.259e-003	4.732e-005

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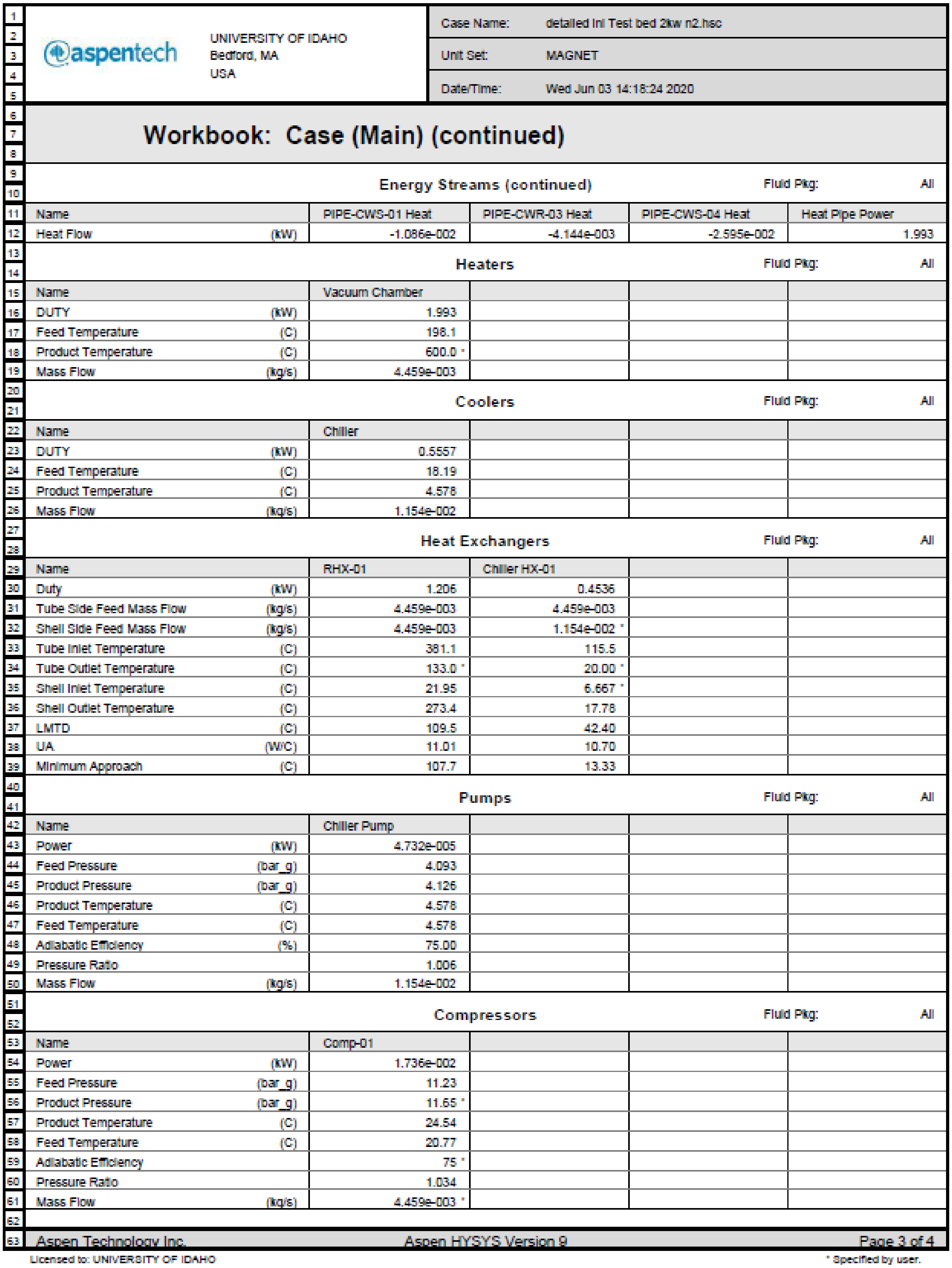

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Case Name:	detailed inl Test bed 2kw n2.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:18:24 2020

Workbook: Case (Main) (continued)

Energy Streams (continued)

Fluid Pkg: All

Name		PIPE-CWS-01 Heat	PIPE-CWR-03 Heat	PIPE-CWS-04 Heat	Heat Pipe Power
Heat Flow	(kW)	-1.086e-002	-4.144e-003	-2.595e-002	1.993

Heaters

Fluid Pkg: All

Name		Vacuum Chamber			
DUTY	(kW)	1.993			
Feed Temperature	(C)	198.1			
Product Temperature	(C)	600.0 *			
Mass Flow	(kg/s)	4.459e-003			

Coolers

Fluid Pkg: All

Name		Chiller			
DUTY	(kW)	0.5557			
Feed Temperature	(C)	18.19			
Product Temperature	(C)	4.578			
Mass Flow	(kg/s)	1.154e-002			

Heat Exchangers

Fluid Pkg: All

Name		RHX-01	Chiller HX-01		
Duty	(kW)	1.206	0.4536		
Tube Side Feed Mass Flow	(kg/s)	4.459e-003	4.459e-003		
Shell Side Feed Mass Flow	(kg/s)	4.459e-003	1.154e-002 *		
Tube Inlet Temperature	(C)	381.1	115.5		
Tube Outlet Temperature	(C)	133.0 *	20.00 *		
Shell Inlet Temperature	(C)	21.95	6.667 *		
Shell Outlet Temperature	(C)	273.4	17.78		
LMTD	(C)	109.5	42.40		
UA	(W/C)	11.01	10.70		
Minimum Approach	(C)	107.7	13.33		

Pumps

Fluid Pkg: All

Name		Chiller Pump			
Power	(kW)	4.732e-005			
Feed Pressure	(bar_g)	4.093			
Product Pressure	(bar_g)	4.126			
Product Temperature	(C)	4.578			
Feed Temperature	(C)	4.578			
Adiabatic Efficiency	(%)	75.00			
Pressure Ratio		1.006			
Mass Flow	(kg/s)	1.154e-002			

Compressors

Fluid Pkg: All

Name		Comp-01			
Power	(kW)	1.736e-002			
Feed Pressure	(bar_g)	11.23			
Product Pressure	(bar_g)	11.65 *			
Product Temperature	(C)	24.54			
Feed Temperature	(C)	20.77			
Adiabatic Efficiency		75 *			
Pressure Ratio		1.034			
Mass Flow	(kg/s)	4.459e-003 *			

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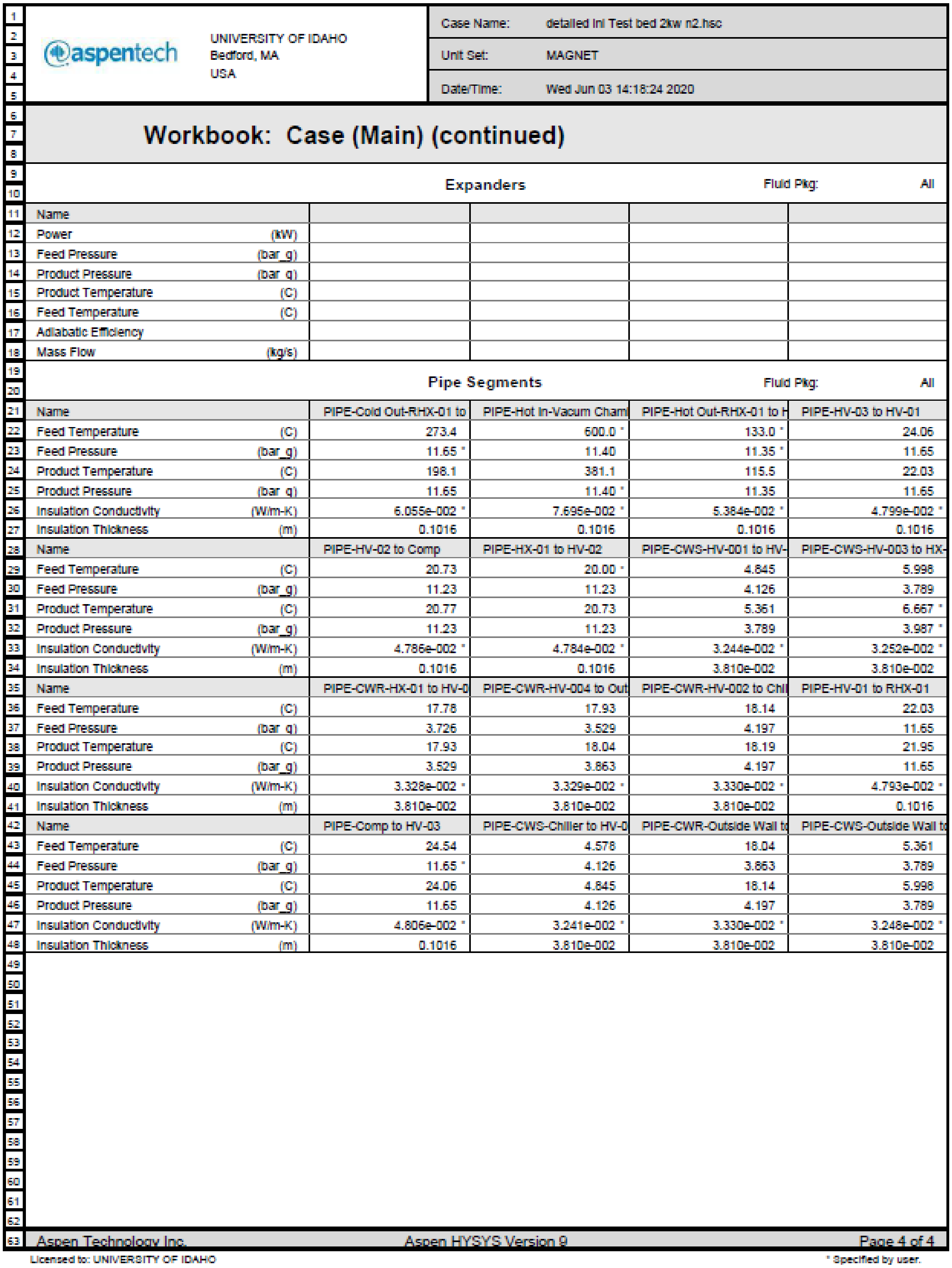

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Bedford, MA
USA

Case Name:	detailed Inl Test bed 2kw n2.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:18:24 2020

Workbook: Case (Main) (continued)

Expanders Fluid Pkg: All

Name					
Power	(kW)				
Feed Pressure	(bar_g)				
Product Pressure	(bar_g)				
Product Temperature	(C)				
Feed Temperature	(C)				
Adiabatic Efficiency					
Mass Flow	(kg/s)				

Pipe Segments Fluid Pkg: All

Name		PIPE-Cold Out-RHX-01 to	PIPE-Hot In-Vacum Cham	PIPE-Hot Out-RHX-01 to H	PIPE-HV-03 to HV-01
Feed Temperature	(C)	273.4	600.0 *	133.0 *	24.06
Feed Pressure	(bar_g)	11.65 *	11.40	11.35 *	11.65
Product Temperature	(C)	198.1	381.1	115.5	22.03
Product Pressure	(bar_g)	11.65	11.40 *	11.35	11.65
Insulation Conductivity	(W/m-K)	6.055e-002 *	7.695e-002 *	5.384e-002 *	4.799e-002 *
Insulation Thickness	(m)	0.1016	0.1016	0.1016	0.1016
Name		**PIPE-HV-02 to Comp**	**PIPE-HX-01 to HV-02**	**PIPE-CWS-HV-001 to HV-**	**PIPE-CWS-HV-003 to HX-**
Feed Temperature	(C)	20.73	20.00 *	4.845	5.998
Feed Pressure	(bar_g)	11.23	11.23	4.126	3.789
Product Temperature	(C)	20.77	20.73	5.361	6.667 *
Product Pressure	(bar_g)	11.23	11.23	3.789	3.987 *
Insulation Conductivity	(W/m-K)	4.786e-002 *	4.784e-002 *	3.244e-002 *	3.252e-002 *
Insulation Thickness	(m)	0.1016	0.1016	3.810e-002	3.810e-002
Name		**PIPE-CWR-HX-01 to HV-0**	**PIPE-CWR-HV-004 to Out**	**PIPE-CWR-HV-002 to Chil**	**PIPE-HV-01 to RHX-01**
Feed Temperature	(C)	17.78	17.93	18.14	22.03
Feed Pressure	(bar_g)	3.726	3.529	4.197	11.65
Product Temperature	(C)	17.93	18.04	18.19	21.95
Product Pressure	(bar_g)	3.529	3.863	4.197	11.65
Insulation Conductivity	(W/m-K)	3.328e-002 *	3.329e-002 *	3.330e-002 *	4.793e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	3.810e-002	0.1016
Name		**PIPE-Comp to HV-03**	**PIPE-CWS-Chiller to HV-0**	**PIPE-CWR-Outside Wall t**	**PIPE-CWS-Outside Wall t**
Feed Temperature	(C)	24.54	4.578	18.04	5.361
Feed Pressure	(bar_g)	11.65 *	4.126	3.863	3.789
Product Temperature	(C)	24.06	4.845	18.14	5.998
Product Pressure	(bar_g)	11.65	4.126	4.197	3.789
Insulation Conductivity	(W/m-K)	4.806e-002 *	3.241e-002 *	3.330e-002 *	3.248e-002 *
Insulation Thickness	(m)	0.1016	3.810e-002	3.810e-002	3.810e-002

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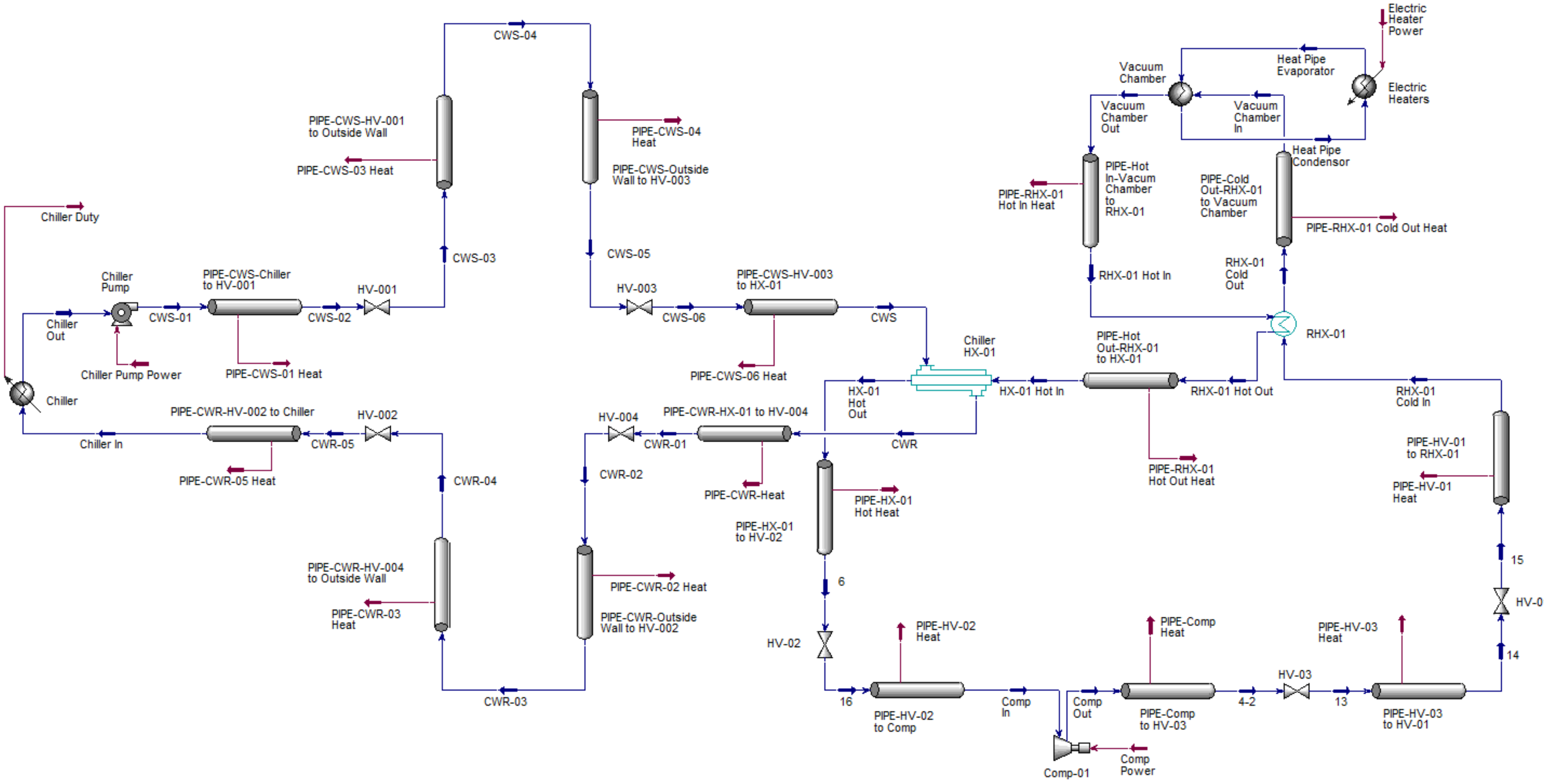
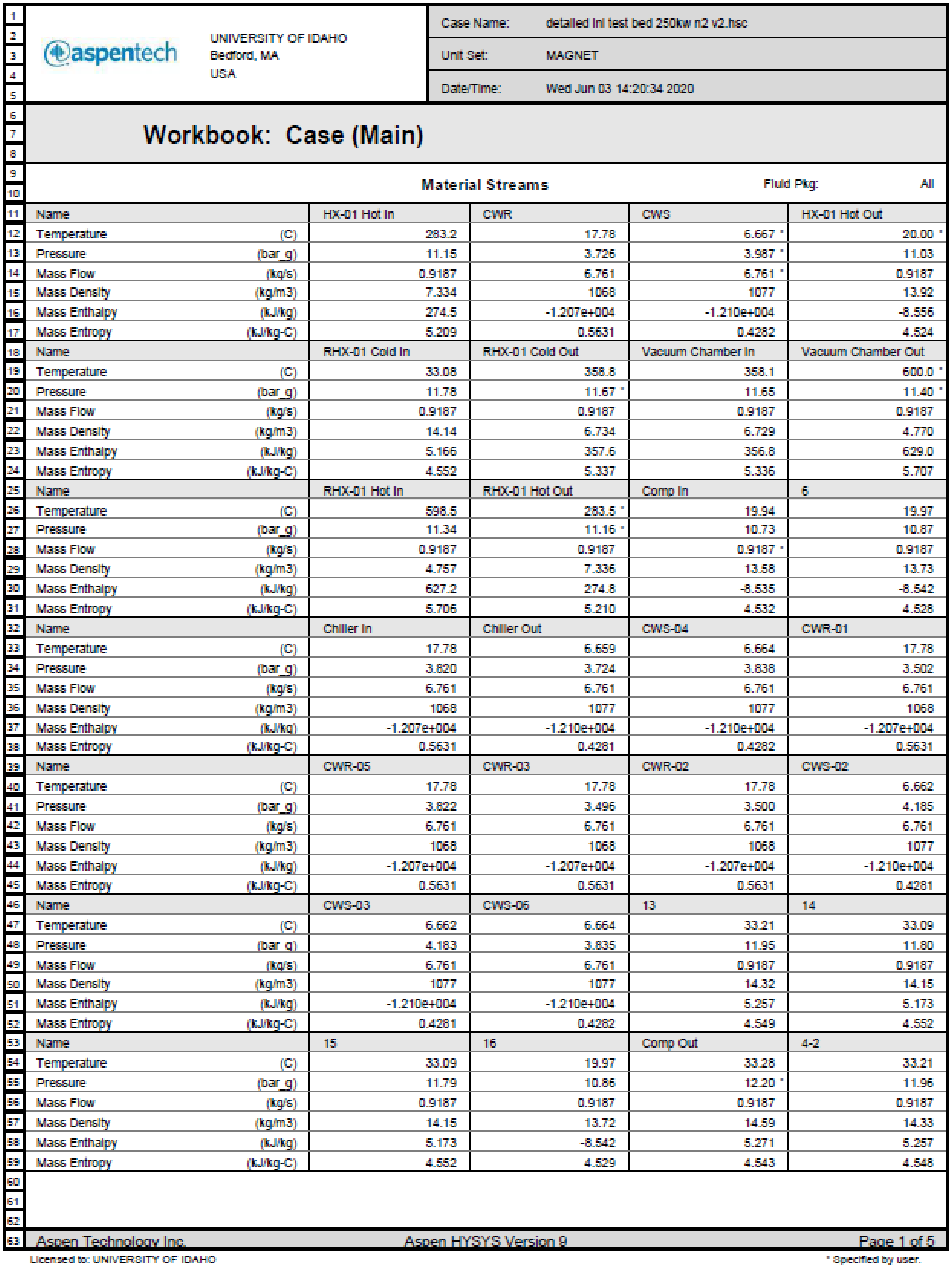
Appendix B: Aspen HYSYS Models for the Microreactor AGile Non-nuclear Experimental Testbed with Heat Pipe Heat Exchanger

Aspen HYSYS process model of Microreactor AGile Non-nuclear Experimental Testbed with Heat Pipe Heat Exchanger using Nitrogen Operating at 600°C and 250 kW of Heat Pipe Power





UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed inl test bed 250kw n2 v2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:20:34 2020

Workbook: Case (Main)

Material Streams Fluid Pkg: All

Name		HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Temperature	(C)	283.2	17.78	6.667 *	20.00 *
Pressure	(bar_g)	11.15	3.726	3.987 *	11.03
Mass Flow	(kg/s)	0.9187	6.761	6.761 *	0.9187
Mass Density	(kg/m3)	7.334	1068	1077	13.92
Mass Enthalpy	(kJ/kg)	274.5	-1.207e+004	-1.210e+004	-8.556
Mass Entropy	(kJ/kg-C)	5.209	0.5631	0.4282	4.524
Name		RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Temperature	(C)	33.08	358.8	358.1	600.0 *
Pressure	(bar_g)	11.78	11.67 *	11.65	11.40 *
Mass Flow	(kg/s)	0.9187	0.9187	0.9187	0.9187
Mass Density	(kg/m3)	14.14	6.734	6.729	4.770
Mass Enthalpy	(kJ/kg)	5.166	357.6	356.8	629.0
Mass Entropy	(kJ/kg-C)	4.552	5.337	5.336	5.707
Name		RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Temperature	(C)	598.5	283.5 *	19.94	19.97
Pressure	(bar_g)	11.34	11.16 *	10.73	10.87
Mass Flow	(kg/s)	0.9187	0.9187	0.9187 *	0.9187
Mass Density	(kg/m3)	4.757	7.336	13.58	13.73
Mass Enthalpy	(kJ/kg)	627.2	274.8	-8.535	-8.542
Mass Entropy	(kJ/kg-C)	5.706	5.210	4.532	4.528
Name		Chiller In	Chiller Out	CWS-04	CWR-01
Temperature	(C)	17.78	6.659	6.664	17.78
Pressure	(bar_g)	3.820	3.724	3.838	3.502
Mass Flow	(kg/s)	6.761	6.761	6.761	6.761
Mass Density	(kg/m3)	1068	1077	1077	1068
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.210e+004	-1.210e+004	-1.207e+004
Mass Entropy	(kJ/kg-C)	0.5631	0.4281	0.4282	0.5631
Name		CWR-05	CWR-03	CWR-02	CWS-02
Temperature	(C)	17.78	17.78	17.78	6.662
Pressure	(bar_g)	3.822	3.496	3.500	4.185
Mass Flow	(kg/s)	6.761	6.761	6.761	6.761
Mass Density	(kg/m3)	1068	1068	1068	1077
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.207e+004	-1.207e+004	-1.210e+004
Mass Entropy	(kJ/kg-C)	0.5631	0.5631	0.5631	0.4281
Name		CWS-03	CWS-06	13	14
Temperature	(C)	6.662	6.664	33.21	33.09
Pressure	(bar_g)	4.183	3.835	11.95	11.80
Mass Flow	(kg/s)	6.761	6.761	0.9187	0.9187
Mass Density	(kg/m3)	1077	1077	14.32	14.15
Mass Enthalpy	(kJ/kg)	-1.210e+004	-1.210e+004	5.257	5.173
Mass Entropy	(kJ/kg-C)	0.4281	0.4282	4.549	4.552
Name		15	16	Comp Out	4-2
Temperature	(C)	33.09	19.97	33.28	33.21
Pressure	(bar_g)	11.79	10.86	12.20 *	11.96
Mass Flow	(kg/s)	0.9187	0.9187	0.9187	0.9187
Mass Density	(kg/m3)	14.15	13.72	14.59	14.33
Mass Enthalpy	(kJ/kg)	5.173	-8.542	5.271	5.257
Mass Entropy	(kJ/kg-C)	4.552	4.529	4.543	4.548

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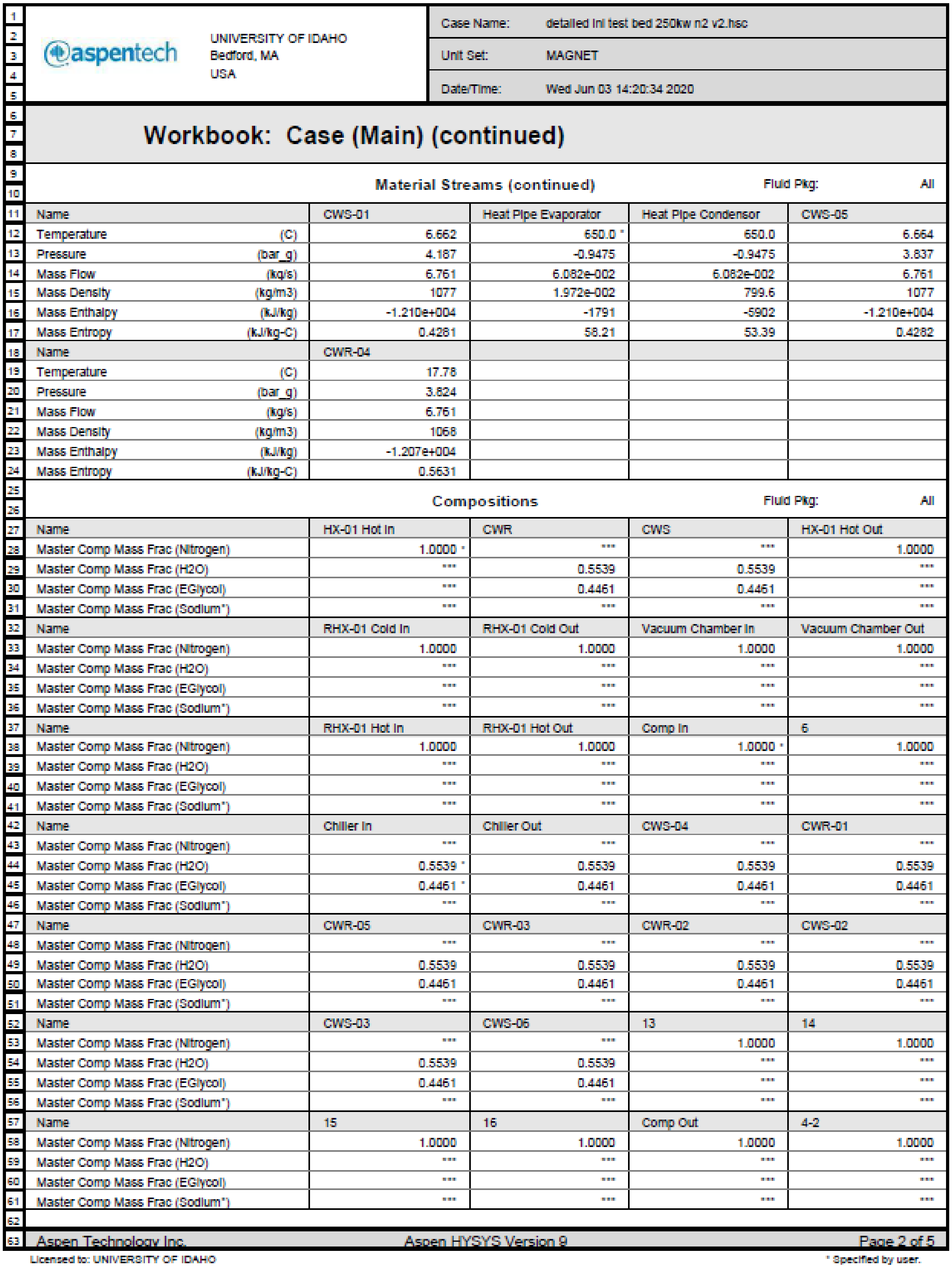

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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed inl test bed 250kw n2 v2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:20:34 2020

Workbook: Case (Main) (continued)

Material Streams (continued)

Fluid Pkg: All

Name	CWS-01	Heat Pipe Evaporator	Heat Pipe Condensor	CWS-05
Temperature (C)	6.662	650.0 *	650.0	6.664
Pressure (bar_g)	4.187	-0.9475	-0.9475	3.837
Mass Flow (kg/s)	6.761	6.082e-002	6.082e-002	6.761
Mass Density (kg/m3)	1077	1.972e-002	799.6	1077
Mass Enthalpy (kJ/kg)	-1.210e+004	-1791	-5902	-1.210e+004
Mass Entropy (kJ/kg-C)	0.4281	58.21	53.39	0.4282
Name	CWR-04			
Temperature (C)	17.78			
Pressure (bar_g)	3.824			
Mass Flow (kg/s)	6.761			
Mass Density (kg/m3)	1068			
Mass Enthalpy (kJ/kg)	-1.207e+004			
Mass Entropy (kJ/kg-C)	0.5631			

Compositions

Fluid Pkg: All

Name	HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Master Comp Mass Frac (Nitrogen)	1.0000 *	***	***	1.0000
Master Comp Mass Frac (H2O)	***	0.5539	0.5539	***
Master Comp Mass Frac (EGlycol)	***	0.4461	0.4461	***
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000 *	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	Chiller In	Chiller Out	CWS-04	CWR-01
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539 *	0.5539	0.5539	0.5539
Master Comp Mass Frac (EGlycol)	0.4461 *	0.4461	0.4461	0.4461
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	CWR-05	CWR-03	CWR-02	CWS-02
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539	0.5539	0.5539	0.5539
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	0.4461	0.4461
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	CWS-03	CWS-06	13	14
Master Comp Mass Frac (Nitrogen)	***	***	1.0000	1.0000
Master Comp Mass Frac (H2O)	0.5539	0.5539	***	***
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	15	16	Comp Out	4-2
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***

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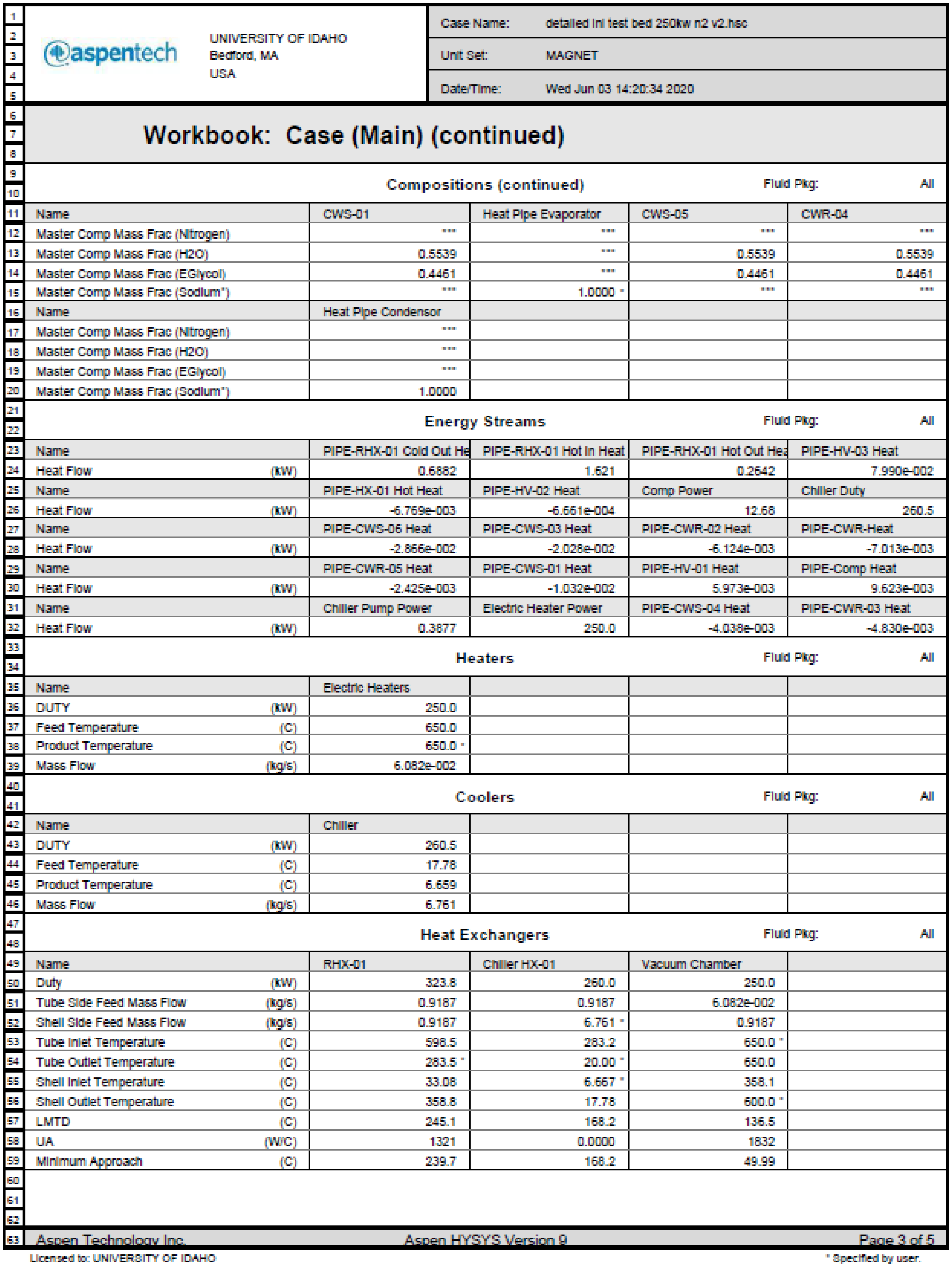

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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed inl test bed 250kw n2 v2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:20:34 2020

Workbook: Case (Main) (continued)

Compositions (continued)

Fluid Pkg: All

Name	CWS-01	Heat Pipe Evaporator	CWS-05	CWR-04
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539	***	0.5539	0.5539
Master Comp Mass Frac (EGlycol)	0.4461	***	0.4461	0.4461
Master Comp Mass Frac (Sodium*)	***	1.0000 *	***	***
Name	Heat Pipe Condensor			
Master Comp Mass Frac (Nitrogen)	***			
Master Comp Mass Frac (H2O)	***			
Master Comp Mass Frac (EGlycol)	***			
Master Comp Mass Frac (Sodium*)	1.0000			

Energy Streams

Fluid Pkg: All

Name	PIPE-RHX-01 Cold Out He	PIPE-RHX-01 Hot In Heat	PIPE-RHX-01 Hot Out Hea	PIPE-HV-03 Heat
Heat Flow (kW)	0.6882	1.621	0.2642	7.990e-002
Name	PIPE-HX-01 Hot Heat	PIPE-HV-02 Heat	Comp Power	Chiller Duty
Heat Flow (kW)	-6.769e-003	-6.661e-004	12.68	260.5
Name	PIPE-CWS-06 Heat	PIPE-CWS-03 Heat	PIPE-CWR-02 Heat	PIPE-CWR-Heat
Heat Flow (kW)	-2.866e-002	-2.028e-002	-6.124e-003	-7.013e-003
Name	PIPE-CWR-05 Heat	PIPE-CWS-01 Heat	PIPE-HV-01 Heat	PIPE-Comp Heat
Heat Flow (kW)	-2.425e-003	-1.032e-002	5.973e-003	9.623e-003
Name	Chiller Pump Power	Electric Heater Power	PIPE-CWS-04 Heat	PIPE-CWR-03 Heat
Heat Flow (kW)	0.3677	250.0	-4.038e-003	-4.830e-003

Heaters

Fluid Pkg: All

Name	Electric Heaters			
DUTY (kW)	250.0			
Feed Temperature (C)	650.0			
Product Temperature (C)	650.0 *			
Mass Flow (kg/s)	6.082e-002			

Coolers

Fluid Pkg: All

Name	Chiller			
DUTY (kW)	260.5			
Feed Temperature (C)	17.78			
Product Temperature (C)	6.659			
Mass Flow (kg/s)	6.761			

Heat Exchangers

Fluid Pkg: All

Name	RHX-01	Chiller HX-01	Vacuum Chamber	
Duty (kW)	323.8	260.0	250.0	
Tube Side Feed Mass Flow (kg/s)	0.9187	0.9187	6.082e-002	
Shell Side Feed Mass Flow (kg/s)	0.9187	6.761 *	0.9187	
Tube Inlet Temperature (C)	598.5	283.2	650.0 *	
Tube Outlet Temperature (C)	283.5 *	20.00 *	650.0	
Shell Inlet Temperature (C)	33.08	6.667 *	358.1	
Shell Outlet Temperature (C)	358.8	17.78	600.0 *	
LMTD (C)	245.1	168.2	136.5	
UA (W/C)	1321	0.0000	1832	
Minimum Approach (C)	239.7	168.2	49.99	

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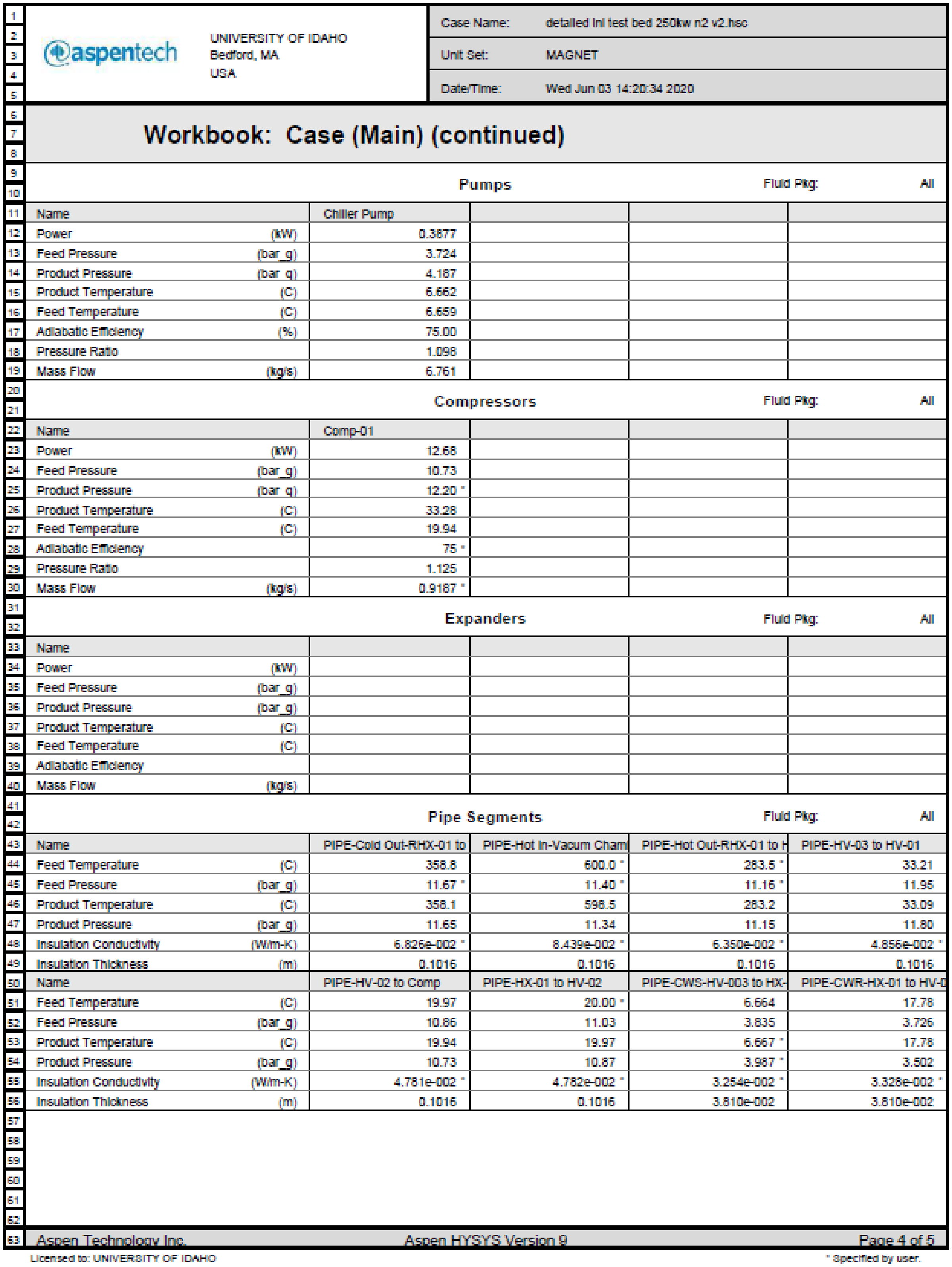

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Bedford, MA
USA

Case Name:	detailed inl test bed 250kw n2 v2.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:20:34 2020

Workbook: Case (Main) (continued)

Pumps

Fluid Pkg: All

Name		Chiller Pump			
Power	(kW)	0.3677			
Feed Pressure	(bar_g)	3.724			
Product Pressure	(bar_g)	4.187			
Product Temperature	(C)	6.662			
Feed Temperature	(C)	6.659			
Adiabatic Efficiency	(%)	75.00			
Pressure Ratio		1.098			
Mass Flow	(kg/s)	6.761			

Compressors

Fluid Pkg: All

Name		Comp-01			
Power	(kW)	12.68			
Feed Pressure	(bar_g)	10.73			
Product Pressure	(bar_g)	12.20 *			
Product Temperature	(C)	33.28			
Feed Temperature	(C)	19.94			
Adiabatic Efficiency		75 *			
Pressure Ratio		1.125			
Mass Flow	(kg/s)	0.9187 *			

Expanders

Fluid Pkg: All

Name					
Power	(kW)				
Feed Pressure	(bar_g)				
Product Pressure	(bar_g)				
Product Temperature	(C)				
Feed Temperature	(C)				
Adiabatic Efficiency					
Mass Flow	(kg/s)				

Pipe Segments

Fluid Pkg: All

Name		PIPE-Cold Out-RHX-01 to	PIPE-Hot In-Vacum Cham	PIPE-Hot Out-RHX-01 to H	PIPE-HV-03 to HV-01
Feed Temperature	(C)	358.8	600.0 *	283.5 *	33.21
Feed Pressure	(bar_g)	11.67 *	11.40 *	11.16 *	11.95
Product Temperature	(C)	358.1	598.5	283.2	33.09
Product Pressure	(bar_g)	11.65	11.34	11.15	11.80
Insulation Conductivity	(W/m-K)	6.826e-002 *	8.439e-002 *	6.350e-002 *	4.856e-002 *
Insulation Thickness	(m)	0.1016	0.1016	0.1016	0.1016
Name		PIPE-HV-02 to Comp	PIPE-HX-01 to HV-02	PIPE-CWS-HV-003 to HX-	PIPE-CWR-HX-01 to HV-0
Feed Temperature	(C)	19.97	20.00 *	6.664	17.78
Feed Pressure	(bar_g)	10.86	11.03	3.835	3.726
Product Temperature	(C)	19.94	19.97	6.667 *	17.78
Product Pressure	(bar_g)	10.73	10.87	3.987 *	3.502
Insulation Conductivity	(W/m-K)	4.781e-002 *	4.782e-002 *	3.254e-002 *	3.328e-002 *
Insulation Thickness	(m)	0.1016	0.1016	3.810e-002	3.810e-002

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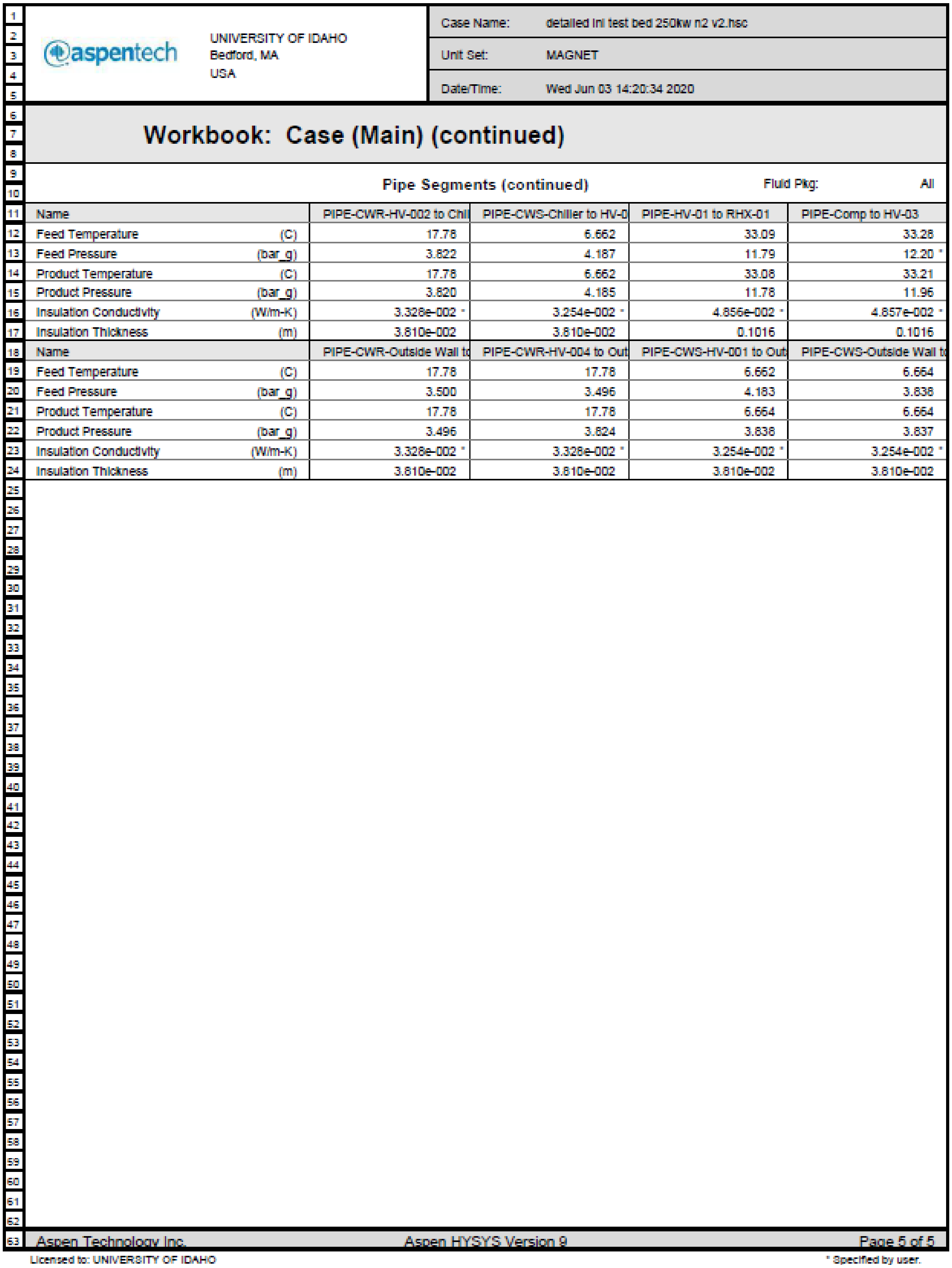

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed inl test bed 250kw n2 v2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:20:34 2020

Workbook: Case (Main) (continued)

Pipe Segments (continued)

Fluid Pkg: All

Name		PIPE-CWR-HV-002 to Chil	PIPE-CWS-Chiller to HV-0	PIPE-HV-01 to RHX-01	PIPE-Comp to HV-03
Feed Temperature	(C)	17.78	6.662	33.09	33.28
Feed Pressure	(bar_g)	3.822	4.187	11.79	12.20 *
Product Temperature	(C)	17.78	6.662	33.08	33.21
Product Pressure	(bar_g)	3.820	4.185	11.78	11.96
Insulation Conductivity	(W/m-K)	3.328e-002 *	3.254e-002 *	4.856e-002 *	4.857e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	0.1016	0.1016
Name		PIPE-CWR-Outside Wall to	PIPE-CWR-HV-004 to Out	PIPE-CWS-HV-001 to Out	PIPE-CWS-Outside Wall to
Feed Temperature	(C)	17.78	17.78	6.662	6.664
Feed Pressure	(bar_g)	3.500	3.496	4.183	3.838
Product Temperature	(C)	17.78	17.78	6.664	6.664
Product Pressure	(bar_g)	3.496	3.824	3.838	3.837
Insulation Conductivity	(W/m-K)	3.328e-002 *	3.328e-002 *	3.254e-002 *	3.254e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	3.810e-002	3.810e-002

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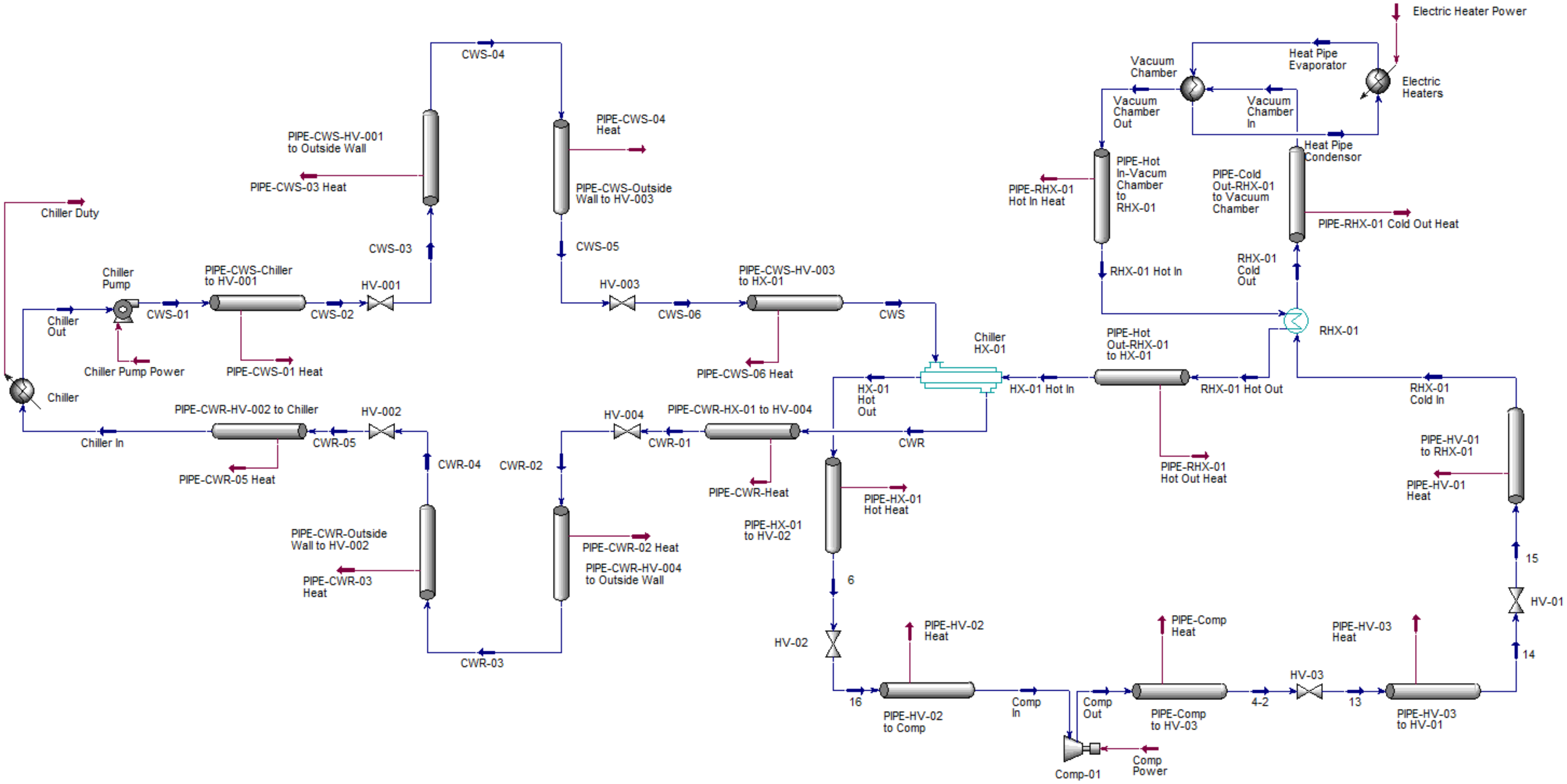
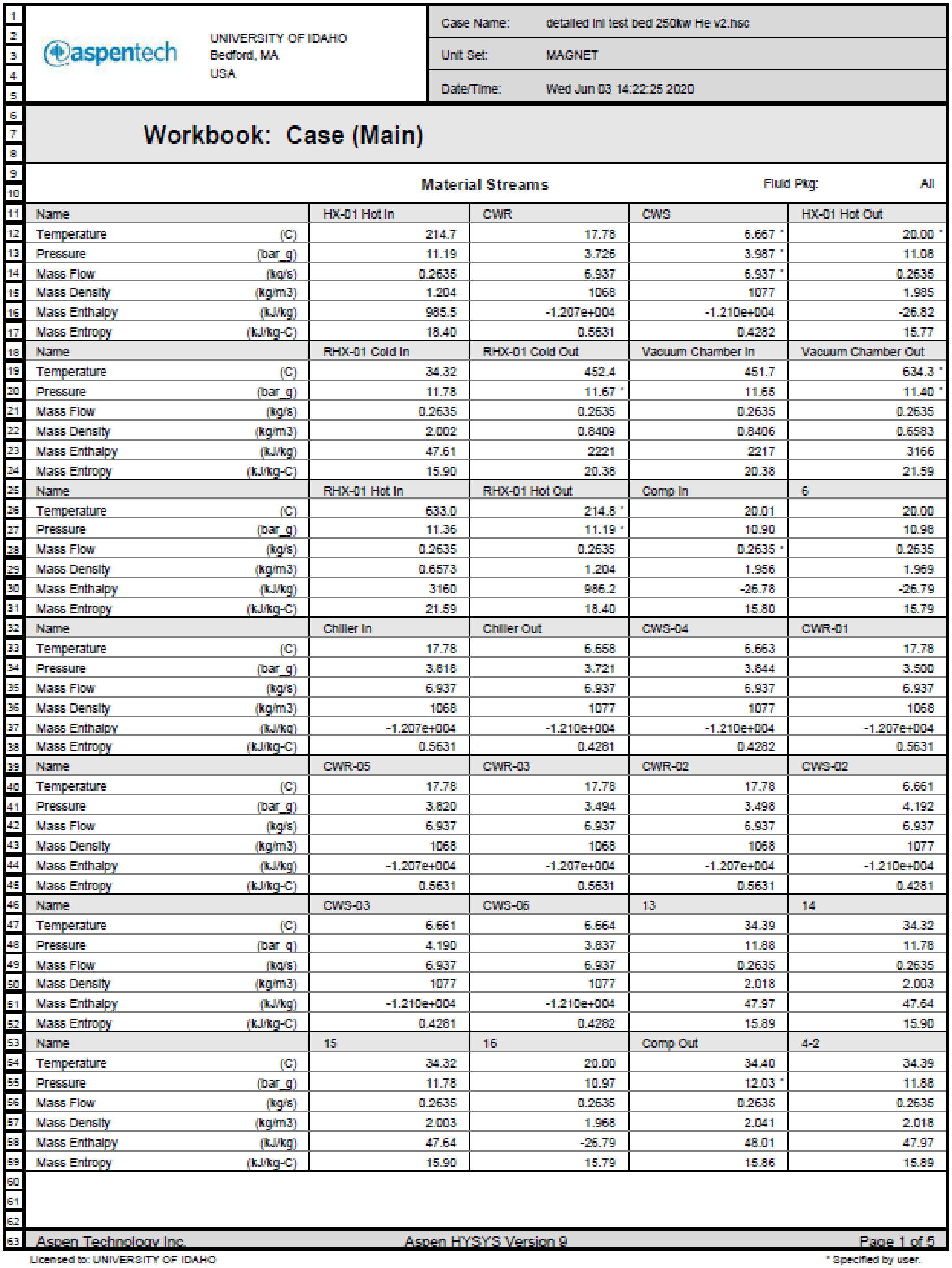
Aspen HYSYS Process Model of Microreactor AGile Non-nuclear Experimental Testbed with Heat Pipe Heat Exchanger using Helium Operating at 600°C and 250 kW of Heat Pipe Power





UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed inl test bed 250kw He v2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:22:25 2020

Workbook: Case (Main)

Material Streams Fluid Pkg: All

Name		HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Temperature	(C)	214.7	17.78	6.667 *	20.00 *
Pressure	(bar_g)	11.19	3.726	3.987 *	11.08
Mass Flow	(kg/s)	0.2635	6.937	6.937 *	0.2635
Mass Density	(kg/m3)	1.204	1068	1077	1.985
Mass Enthalpy	(kJ/kg)	985.5	-1.207e+004	-1.210e+004	-26.82
Mass Entropy	(kJ/kg-C)	18.40	0.5631	0.4282	15.77

Name		RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Temperature	(C)	34.32	452.4	451.7	634.3 *
Pressure	(bar_g)	11.78	11.67 *	11.65	11.40 *
Mass Flow	(kg/s)	0.2635	0.2635	0.2635	0.2635
Mass Density	(kg/m3)	2.002	0.8409	0.8406	0.6583
Mass Enthalpy	(kJ/kg)	47.61	2221	2217	3166
Mass Entropy	(kJ/kg-C)	15.90	20.38	20.38	21.59

Name		RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Temperature	(C)	633.0	214.8 *	20.01	20.00
Pressure	(bar_g)	11.36	11.19 *	10.90	10.98
Mass Flow	(kg/s)	0.2635	0.2635	0.2635 *	0.2635
Mass Density	(kg/m3)	0.6573	1.204	1.956	1.969
Mass Enthalpy	(kJ/kg)	3160	986.2	-26.78	-26.79
Mass Entropy	(kJ/kg-C)	21.59	18.40	15.80	15.79

Name		Chiller In	Chiller Out	CWS-04	CWR-01
Temperature	(C)	17.78	6.658	6.663	17.78
Pressure	(bar_g)	3.818	3.721	3.844	3.500
Mass Flow	(kg/s)	6.937	6.937	6.937	6.937
Mass Density	(kg/m3)	1068	1077	1077	1068
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.210e+004	-1.210e+004	-1.207e+004
Mass Entropy	(kJ/kg-C)	0.5631	0.4281	0.4282	0.5631

Name		CWR-05	CWR-03	CWR-02	CWS-02
Temperature	(C)	17.78	17.78	17.78	6.661
Pressure	(bar_g)	3.820	3.494	3.498	4.192
Mass Flow	(kg/s)	6.937	6.937	6.937	6.937
Mass Density	(kg/m3)	1068	1068	1068	1077
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.207e+004	-1.207e+004	-1.210e+004
Mass Entropy	(kJ/kg-C)	0.5631	0.5631	0.5631	0.4281

Name		CWS-03	CWS-06	13	14
Temperature	(C)	6.661	6.664	34.39	34.32
Pressure	(bar_g)	4.190	3.837	11.88	11.78
Mass Flow	(kg/s)	6.937	6.937	0.2635	0.2635
Mass Density	(kg/m3)	1077	1077	2.018	2.003
Mass Enthalpy	(kJ/kg)	-1.210e+004	-1.210e+004	47.97	47.64
Mass Entropy	(kJ/kg-C)	0.4281	0.4282	15.89	15.90

Name		15	16	Comp Out	4-2
Temperature	(C)	34.32	20.00	34.40	34.39
Pressure	(bar_g)	11.78	10.97	12.03 *	11.88
Mass Flow	(kg/s)	0.2635	0.2635	0.2635	0.2635
Mass Density	(kg/m3)	2.003	1.968	2.041	2.018
Mass Enthalpy	(kJ/kg)	47.64	-26.79	48.01	47.97
Mass Entropy	(kJ/kg-C)	15.90	15.79	15.86	15.89

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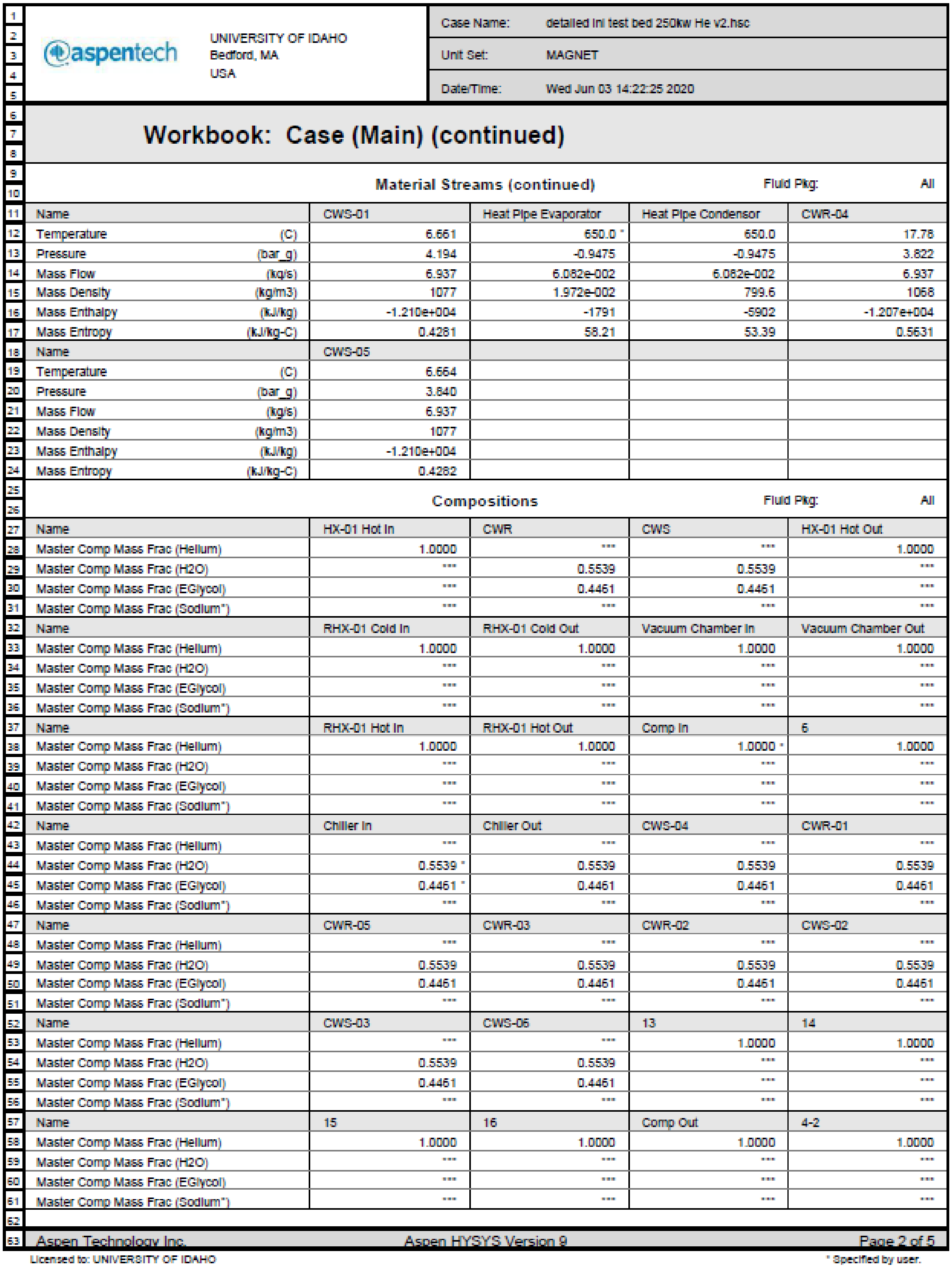

aspentech

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed ini test bed 250kw He v2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:22:25 2020

Workbook: Case (Main) (continued)

Material Streams (continued)

Fluid Pkg: All

Name	CWS-01	Heat Pipe Evaporator	Heat Pipe Condensor	CWR-04
Temperature (C)	6.661	650.0 *	650.0	17.78
Pressure (bar_g)	4.194	-0.9475	-0.9475	3.822
Mass Flow (kg/s)	6.937	6.082e-002	6.082e-002	6.937
Mass Density (kg/m3)	1077	1.972e-002	799.6	1068
Mass Enthalpy (kJ/kg)	-1.210e+004	-1791	-5902	-1.207e+004
Mass Entropy (kJ/kg-C)	0.4281	58.21	53.39	0.5631
Name	CWS-05			
Temperature (C)	6.664			
Pressure (bar_g)	3.840			
Mass Flow (kg/s)	6.937			
Mass Density (kg/m3)	1077			
Mass Enthalpy (kJ/kg)	-1.210e+004			
Mass Entropy (kJ/kg-C)	0.4282			

Compositions

Fluid Pkg: All

Name	HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Master Comp Mass Frac (Helium)	1.0000	***	***	1.0000
Master Comp Mass Frac (H2O)	***	0.5539	0.5539	***
Master Comp Mass Frac (EGlycol)	***	0.4461	0.4461	***
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Master Comp Mass Frac (Helium)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Master Comp Mass Frac (Helium)	1.0000	1.0000	1.0000 *	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	Chiller In	Chiller Out	CWS-04	CWR-01
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539 *	0.5539	0.5539	0.5539
Master Comp Mass Frac (EGlycol)	0.4461 *	0.4461	0.4461	0.4461
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	CWR-05	CWR-03	CWR-02	CWS-02
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539	0.5539	0.5539	0.5539
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	0.4461	0.4461
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	CWS-03	CWS-06	13	14
Master Comp Mass Frac (Helium)	***	***	1.0000	1.0000
Master Comp Mass Frac (H2O)	0.5539	0.5539	***	***
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	15	16	Comp Out	4-2
Master Comp Mass Frac (Helium)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***

Aspen Technology Inc. Aspen HYSYS Version 9 Page 2 of 5

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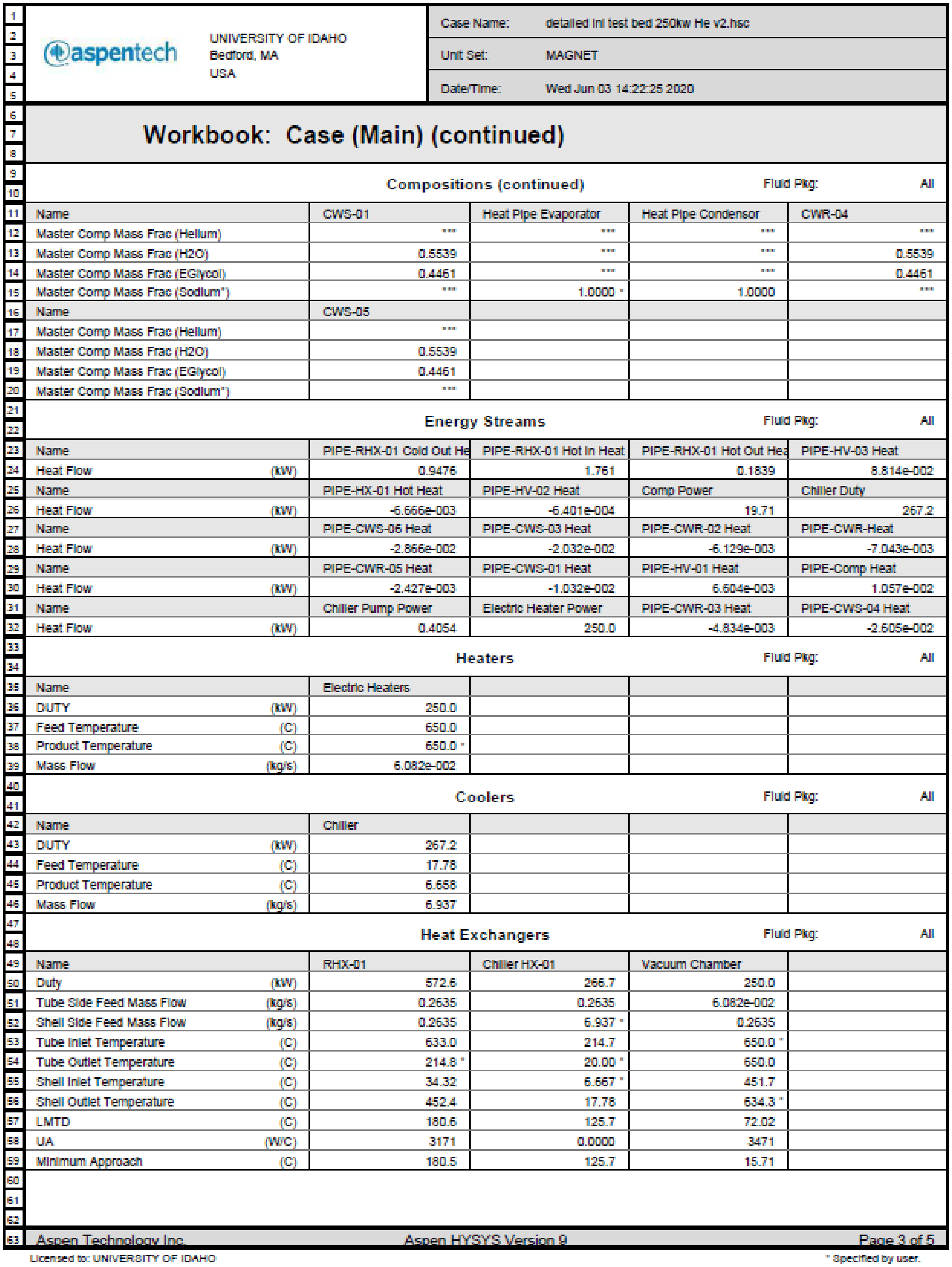

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Bedford, MA
USA

Case Name: detailed inl test bed 250kw He v2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:22:25 2020

Workbook: Case (Main) (continued)

Compositions (continued)

Fluid Pkg: All

Name	CWS-01	Heat Pipe Evaporator	Heat Pipe Condensor	CWR-04
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539	***	***	0.5539
Master Comp Mass Frac (EGlycol)	0.4461	***	***	0.4461
Master Comp Mass Frac (Sodium*)	***	1.0000 *	1.0000	***
Name	CWS-05			
Master Comp Mass Frac (Helium)	***			
Master Comp Mass Frac (H2O)	0.5539			
Master Comp Mass Frac (EGlycol)	0.4461			
Master Comp Mass Frac (Sodium*)	***			

Energy Streams

Fluid Pkg: All

Name		PIPE-RHX-01 Cold Out He	PIPE-RHX-01 Hot In Heat	PIPE-RHX-01 Hot Out Hea	PIPE-HV-03 Heat
Heat Flow	(kW)	0.9476	1.761	0.1839	8.814e-002
Name		PIPE-HX-01 Hot Heat	PIPE-HV-02 Heat	Comp Power	Chiller Duty
Heat Flow	(kW)	-6.666e-003	-6.401e-004	19.71	267.2
Name		PIPE-CWS-06 Heat	PIPE-CWS-03 Heat	PIPE-CWR-02 Heat	PIPE-CWR-Heat
Heat Flow	(kW)	-2.866e-002	-2.032e-002	-6.129e-003	-7.043e-003
Name		PIPE-CWR-05 Heat	PIPE-CWS-01 Heat	PIPE-HV-01 Heat	PIPE-Comp Heat
Heat Flow	(kW)	-2.427e-003	-1.032e-002	6.604e-003	1.057e-002
Name		Chiller Pump Power	Electric Heater Power	PIPE-CWR-03 Heat	PIPE-CWS-04 Heat
Heat Flow	(kW)	0.4054	250.0	-4.834e-003	-2.605e-002

Heaters

Fluid Pkg: All

Name		Electric Heaters			
DUTY	(kW)	250.0			
Feed Temperature	(C)	650.0			
Product Temperature	(C)	650.0 *			
Mass Flow	(kg/s)	6.082e-002			

Coolers

Fluid Pkg: All

Name		Chiller			
DUTY	(kW)	267.2			
Feed Temperature	(C)	17.78			
Product Temperature	(C)	6.658			
Mass Flow	(kg/s)	6.937			

Heat Exchangers

Fluid Pkg: All

Name		RHX-01	Chiller HX-01	Vacuum Chamber	
Duty	(kW)	572.6	266.7	250.0	
Tube Side Feed Mass Flow	(kg/s)	0.2635	0.2635	6.082e-002	
Shell Side Feed Mass Flow	(kg/s)	0.2635	6.937 *	0.2635	
Tube Inlet Temperature	(C)	633.0	214.7	650.0 *	
Tube Outlet Temperature	(C)	214.8 *	20.00 *	650.0	
Shell Inlet Temperature	(C)	34.32	6.667 *	451.7	
Shell Outlet Temperature	(C)	452.4	17.78	634.3 *	
LMTD	(C)	180.6	125.7	72.02	
UA	(W/C)	3171	0.0000	3471	
Minimum Approach	(C)	180.5	125.7	15.71	

Aspen Technology Inc. Aspen HYSYS Version 9 Page 3 of 5

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Workbook: Case (Main) (continued)

Pumps

Fluid Pkg: All

Name		Chiller Pump			
Power	(kW)	0.4054			
Feed Pressure	(bar_g)	3.721			
Product Pressure	(bar_g)	4.194			
Product Temperature	(C)	6.661			
Feed Temperature	(C)	6.658			
Adiabatic Efficiency	(%)	75.00			
Pressure Ratio		1.100			
Mass Flow	(kg/s)	6.937			

Compressors

Fluid Pkg: All

Name		Comp-01			
Power	(kW)	19.71			
Feed Pressure	(bar_g)	10.90			
Product Pressure	(bar_g)	12.03 *			
Product Temperature	(C)	34.40			
Feed Temperature	(C)	20.01			
Adiabatic Efficiency		75 *			
Pressure Ratio		1.095			
Mass Flow	(kg/s)	0.2635 *			

Expanders

Fluid Pkg: All

Name					
Power	(kW)				
Feed Pressure	(bar_g)				
Product Pressure	(bar_g)				
Product Temperature	(C)				
Feed Temperature	(C)				
Adiabatic Efficiency					
Mass Flow	(kg/s)				

Pipe Segments

Fluid Pkg: All

Name		PIPE-Cold Out-RHX-01 to	PIPE-Hot In-Vacum Cham	PIPE-Hot Out-RHX-01 to H	PIPE-HV-03 to HV-01
Feed Temperature	(C)	452.4	634.3 *	214.8 *	34.39
Feed Pressure	(bar_g)	11.67 *	11.40 *	11.19 *	11.88
Product Temperature	(C)	451.7	633.0	214.7	34.32
Product Pressure	(bar_g)	11.65	11.36	11.19	11.78
Insulation Conductivity	(W/m-K)	7.438e-002 *	8.680e-002 *	5.927e-002 *	4.863e-002 *
Insulation Thickness	(m)	0.1016	0.1016	0.1016	0.1016
Name		PIPE-HV-02 to Comp	PIPE-HX-01 to HV-02	PIPE-CWS-HV-003 to HX-	PIPE-CWR-HX-01 to HV-0
Feed Temperature	(C)	20.00	20.00 *	6.664	17.78
Feed Pressure	(bar_g)	10.97	11.08	3.837	3.726
Product Temperature	(C)	20.01	20.00	6.667 *	17.78
Product Pressure	(bar_g)	10.90	10.98	3.987 *	3.500
Insulation Conductivity	(W/m-K)	4.782e-002 *	4.782e-002 *	3.254e-002 *	3.328e-002 *
Insulation Thickness	(m)	0.1016	0.1016	3.810e-002	3.810e-002

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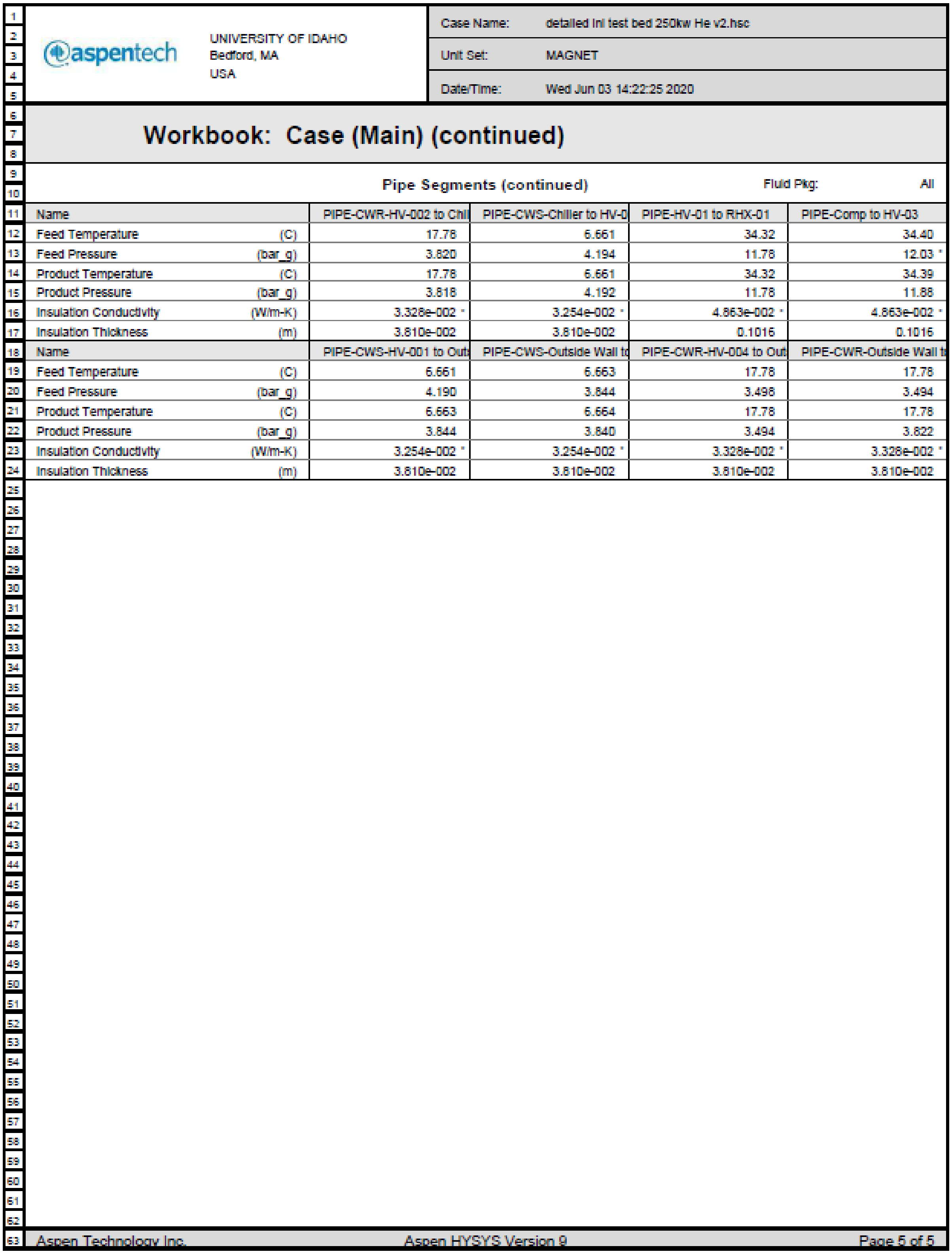

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Bedford, MA
USA

Case Name:	detailed inl test bed 250kw He v2.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:22:25 2020

Workbook: Case (Main) (continued)

Pipe Segments (continued)

Fluid Pkg: All

Name		PIPE-CWR-HV-002 to Chil	PIPE-CWS-Chiller to HV-0	PIPE-HV-01 to RHX-01	PIPE-Comp to HV-03
Feed Temperature	(C)	17.78	6.661	34.32	34.40
Feed Pressure	(bar_g)	3.820	4.194	11.78	12.03 *
Product Temperature	(C)	17.78	6.661	34.32	34.39
Product Pressure	(bar_g)	3.818	4.192	11.78	11.88
Insulation Conductivity	(W/m-K)	3.328e-002 *	3.254e-002 *	4.863e-002 *	4.863e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	0.1016	0.1016
Name		PIPE-CWS-HV-001 to Out	PIPE-CWS-Outside Wall to	PIPE-CWR-HV-004 to Out	PIPE-CWR-Outside Wall t
Feed Temperature	(C)	6.661	6.663	17.78	17.78
Feed Pressure	(bar_g)	4.190	3.844	3.498	3.494
Product Temperature	(C)	6.663	6.664	17.78	17.78
Product Pressure	(bar_g)	3.844	3.840	3.494	3.822
Insulation Conductivity	(W/m-K)	3.254e-002 *	3.254e-002 *	3.328e-002 *	3.328e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	3.810e-002	3.810e-002

Aspen Technology Inc. Aspen HYSYS Version 9 Page 5 of 5

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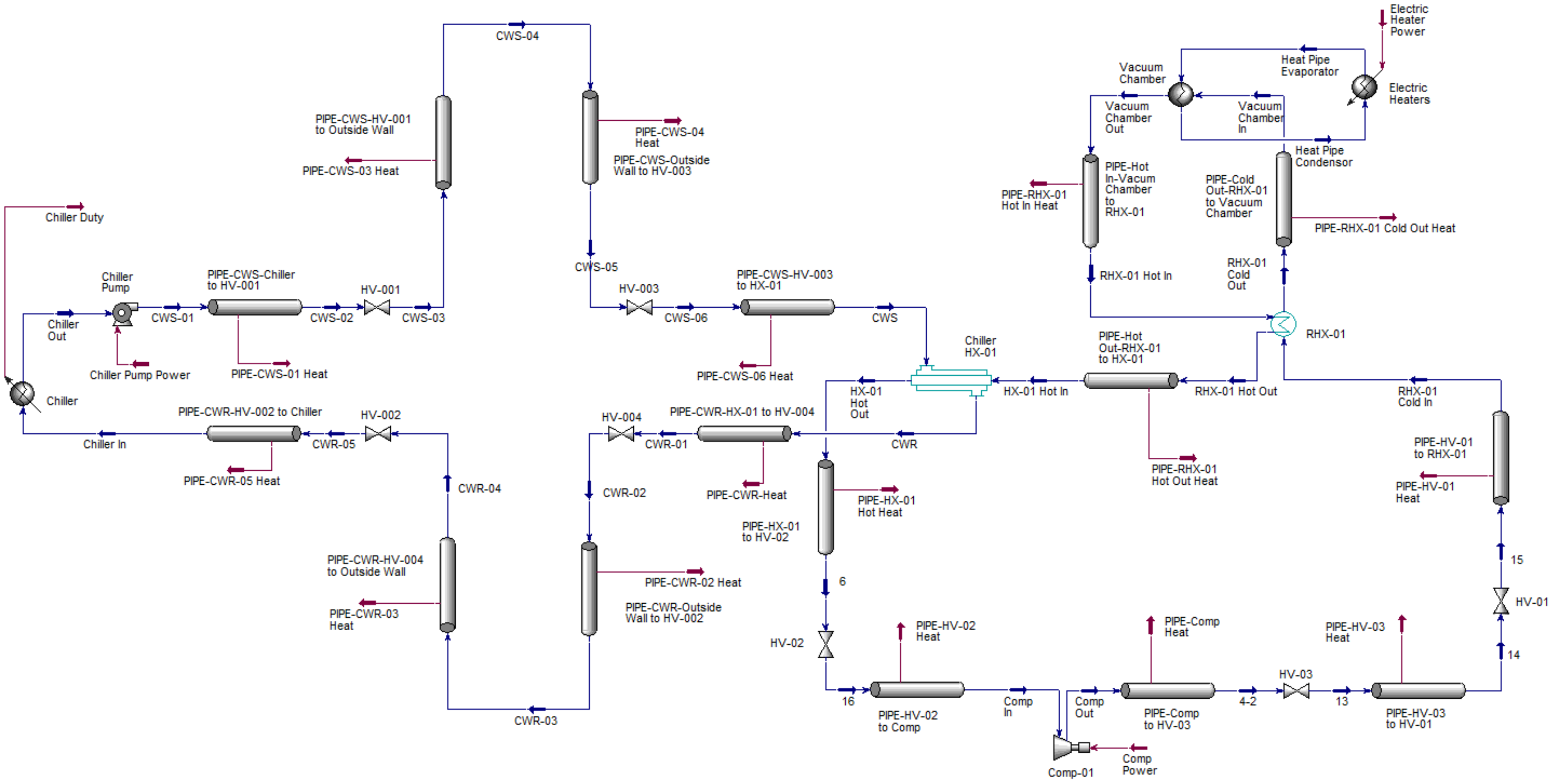
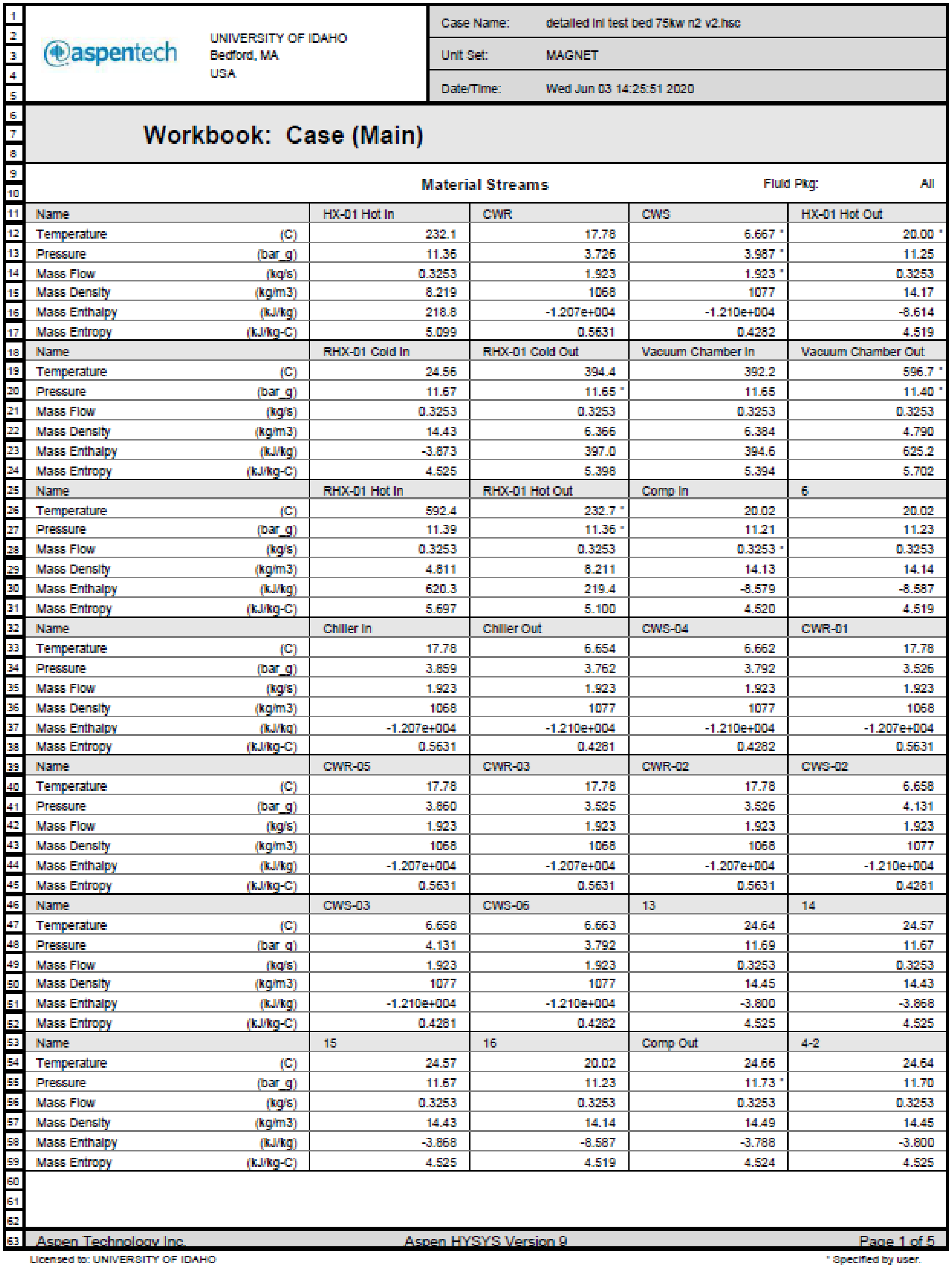
Aspen HYSYS Process Model of Microreactor AGile Non-nuclear Experimental Testbed with Heat Pipe Heat Exchanger using Nitrogen Operating at 600°C and 75 kW of Heat Pipe Power





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Bedford, MA
USA

Case Name: detailed inl test bed 75kw n2 v2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:25:51 2020

Workbook: Case (Main)

Material Streams Fluid Pkg: All

Name		HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Temperature	(C)	232.1	17.78	6.667 *	20.00 *
Pressure	(bar_g)	11.36	3.726	3.987 *	11.25
Mass Flow	(kg/s)	0.3253	1.923	1.923 *	0.3253
Mass Density	(kg/m3)	8.219	1068	1077	14.17
Mass Enthalpy	(kJ/kg)	218.8	-1.207e+004	-1.210e+004	-8.614
Mass Entropy	(kJ/kg-C)	5.099	0.5631	0.4282	4.519
Name		RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Temperature	(C)	24.56	394.4	392.2	596.7 *
Pressure	(bar_g)	11.67	11.65 *	11.65	11.40 *
Mass Flow	(kg/s)	0.3253	0.3253	0.3253	0.3253
Mass Density	(kg/m3)	14.43	6.366	6.384	4.790
Mass Enthalpy	(kJ/kg)	-3.873	397.0	394.6	625.2
Mass Entropy	(kJ/kg-C)	4.525	5.398	5.394	5.702
Name		RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Temperature	(C)	592.4	232.7 *	20.02	20.02
Pressure	(bar_g)	11.39	11.36 *	11.21	11.23
Mass Flow	(kg/s)	0.3253	0.3253	0.3253 *	0.3253
Mass Density	(kg/m3)	4.811	8.211	14.13	14.14
Mass Enthalpy	(kJ/kg)	620.3	219.4	-8.579	-8.587
Mass Entropy	(kJ/kg-C)	5.697	5.100	4.520	4.519
Name		Chiller In	Chiller Out	CWS-04	CWR-01
Temperature	(C)	17.78	6.654	6.662	17.78
Pressure	(bar_g)	3.859	3.762	3.792	3.526
Mass Flow	(kg/s)	1.923	1.923	1.923	1.923
Mass Density	(kg/m3)	1068	1077	1077	1068
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.210e+004	-1.210e+004	-1.207e+004
Mass Entropy	(kJ/kg-C)	0.5631	0.4281	0.4282	0.5631
Name		CWR-05	CWR-03	CWR-02	CWS-02
Temperature	(C)	17.78	17.78	17.78	6.658
Pressure	(bar_g)	3.860	3.525	3.526	4.131
Mass Flow	(kg/s)	1.923	1.923	1.923	1.923
Mass Density	(kg/m3)	1068	1068	1068	1077
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.207e+004	-1.207e+004	-1.210e+004
Mass Entropy	(kJ/kg-C)	0.5631	0.5631	0.5631	0.4281
Name		CWS-03	CWS-06	13	14
Temperature	(C)	6.658	6.663	24.64	24.57
Pressure	(bar_g)	4.131	3.792	11.69	11.67
Mass Flow	(kg/s)	1.923	1.923	0.3253	0.3253
Mass Density	(kg/m3)	1077	1077	14.45	14.43
Mass Enthalpy	(kJ/kg)	-1.210e+004	-1.210e+004	-3.800	-3.868
Mass Entropy	(kJ/kg-C)	0.4281	0.4282	4.525	4.525
Name		15	16	Comp Out	4-2
Temperature	(C)	24.57	20.02	24.66	24.64
Pressure	(bar_g)	11.67	11.23	11.73 *	11.70
Mass Flow	(kg/s)	0.3253	0.3253	0.3253	0.3253
Mass Density	(kg/m3)	14.43	14.14	14.49	14.45
Mass Enthalpy	(kJ/kg)	-3.868	-8.587	-3.788	-3.800
Mass Entropy	(kJ/kg-C)	4.525	4.519	4.524	4.525

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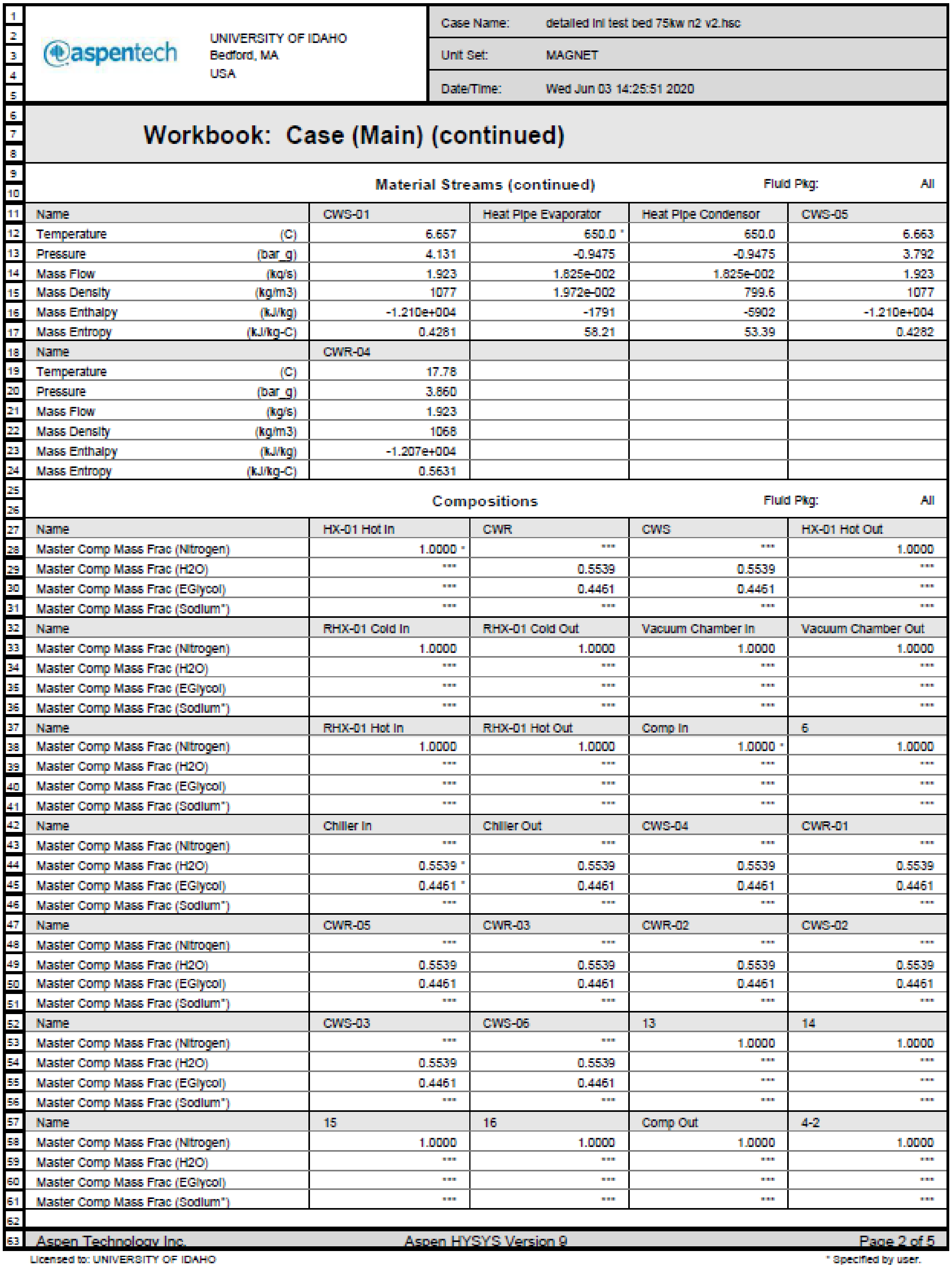

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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed inl test bed 75kw n2 v2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:25:51 2020

Workbook: Case (Main) (continued)

Material Streams (continued)

Fluid Pkg: All

Name		CWS-01	Heat Pipe Evaporator	Heat Pipe Condensor	CWS-05
Temperature	(C)	6.657	650.0 *	650.0	6.663
Pressure	(bar_g)	4.131	-0.9475	-0.9475	3.792
Mass Flow	(kg/s)	1.923	1.825e-002	1.825e-002	1.923
Mass Density	(kg/m3)	1077	1.972e-002	799.6	1077
Mass Enthalpy	(kJ/kg)	-1.210e+004	-1791	-5902	-1.210e+004
Mass Entropy	(kJ/kg-C)	0.4281	58.21	53.39	0.4282
Name		**CWR-04**			
Temperature	(C)	17.78			
Pressure	(bar_g)	3.860			
Mass Flow	(kg/s)	1.923			
Mass Density	(kg/m3)	1068			
Mass Enthalpy	(kJ/kg)	-1.207e+004			
Mass Entropy	(kJ/kg-C)	0.5631			

Compositions

Fluid Pkg: All

Name	HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Master Comp Mass Frac (Nitrogen)	1.0000 *	***	***	1.0000
Master Comp Mass Frac (H2O)	***	0.5539	0.5539	***
Master Comp Mass Frac (EGlycol)	***	0.4461	0.4461	***
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	**RHX-01 Cold In**	**RHX-01 Cold Out**	**Vacuum Chamber In**	**Vacuum Chamber Out**
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	**RHX-01 Hot In**	**RHX-01 Hot Out**	**Comp In**	**6**
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000 *	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	**Chiller In**	**Chiller Out**	**CWS-04**	**CWR-01**
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539 *	0.5539	0.5539	0.5539
Master Comp Mass Frac (EGlycol)	0.4461 *	0.4461	0.4461	0.4461
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	**CWR-05**	**CWR-03**	**CWR-02**	**CWS-02**
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539	0.5539	0.5539	0.5539
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	0.4461	0.4461
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	**CWS-03**	**CWS-06**	**13**	**14**
Master Comp Mass Frac (Nitrogen)	***	***	1.0000	1.0000
Master Comp Mass Frac (H2O)	0.5539	0.5539	***	***
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	**15**	**16**	**Comp Out**	**4-2**
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***

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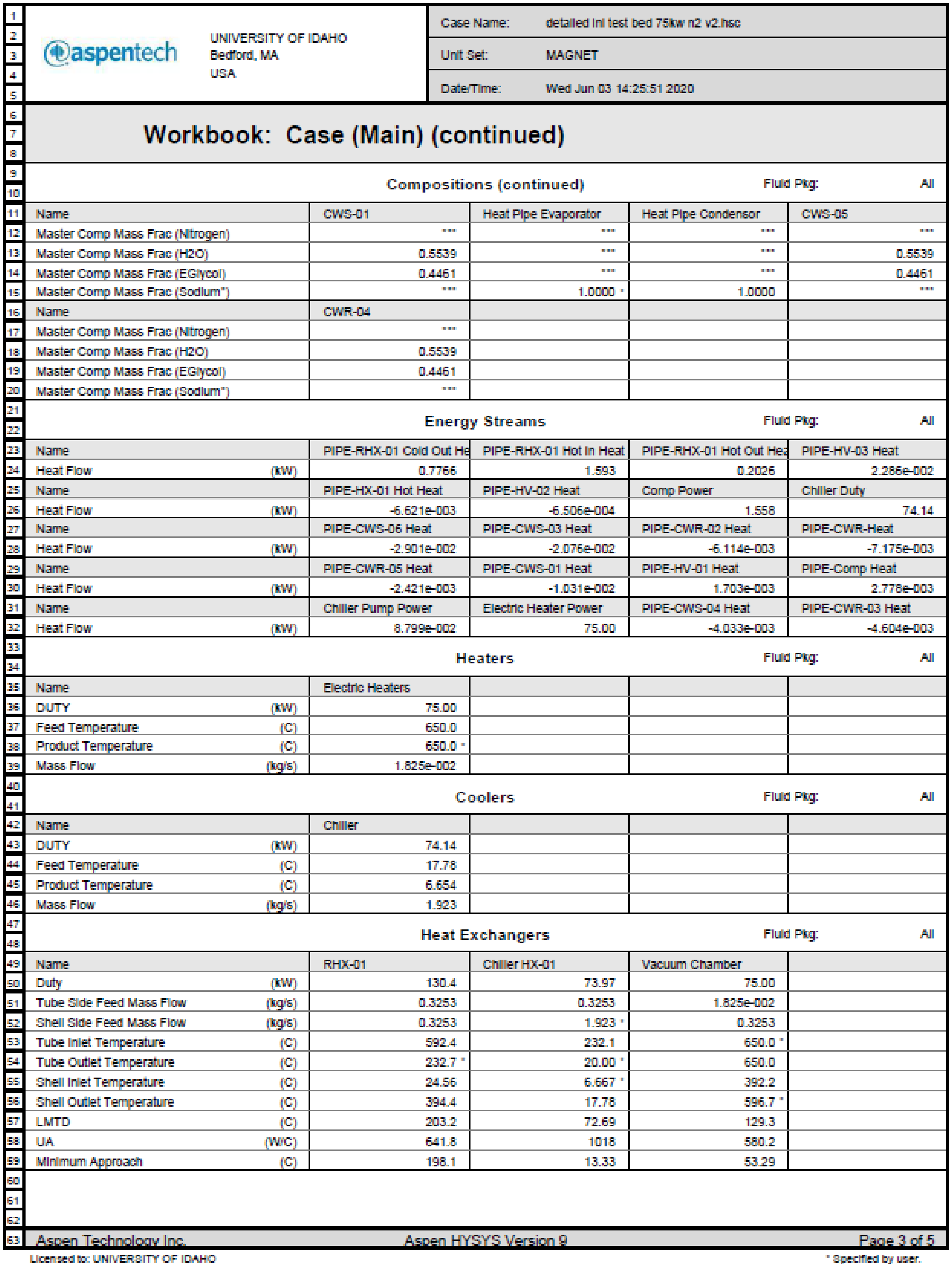

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Bedford, MA
USA

Case Name:	detailed inl test bed 75kw n2 v2.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:25:51 2020

Workbook: Case (Main) (continued)

Compositions (continued)

Fluid Pkg: All

Name	CWS-01	Heat Pipe Evaporator	Heat Pipe Condensor	CWS-05
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539	***	***	0.5539
Master Comp Mass Frac (EGlycol)	0.4461	***	***	0.4461
Master Comp Mass Frac (Sodium*)	***	1.0000 *	1.0000	***
Name	**CWR-04**			
Master Comp Mass Frac (Nitrogen)	***			
Master Comp Mass Frac (H2O)	0.5539			
Master Comp Mass Frac (EGlycol)	0.4461			
Master Comp Mass Frac (Sodium*)	***			

Energy Streams

Fluid Pkg: All

Name		PIPE-RHX-01 Cold Out He	PIPE-RHX-01 Hot In Heat	PIPE-RHX-01 Hot Out Hea	PIPE-HV-03 Heat
Heat Flow	(kW)	0.7766	1.593	0.2026	2.286e-002
Name		**PIPE-HX-01 Hot Heat**	**PIPE-HV-02 Heat**	**Comp Power**	**Chiller Duty**
Heat Flow	(kW)	-6.621e-003	-6.506e-004	1.558	74.14
Name		**PIPE-CWS-06 Heat**	**PIPE-CWS-03 Heat**	**PIPE-CWR-02 Heat**	**PIPE-CWR-Heat**
Heat Flow	(kW)	-2.901e-002	-2.076e-002	-6.114e-003	-7.175e-003
Name		**PIPE-CWR-05 Heat**	**PIPE-CWS-01 Heat**	**PIPE-HV-01 Heat**	**PIPE-Comp Heat**
Heat Flow	(kW)	-2.421e-003	-1.031e-002	1.703e-003	2.778e-003
Name		**Chiller Pump Power**	**Electric Heater Power**	**PIPE-CWS-04 Heat**	**PIPE-CWR-03 Heat**
Heat Flow	(kW)	8.799e-002	75.00	-4.033e-003	-4.604e-003

Heaters

Fluid Pkg: All

Name		Electric Heaters			
DUTY	(kW)	75.00			
Feed Temperature	(C)	650.0			
Product Temperature	(C)	650.0 *			
Mass Flow	(kg/s)	1.825e-002			

Coolers

Fluid Pkg: All

Name		Chiller			
DUTY	(kW)	74.14			
Feed Temperature	(C)	17.78			
Product Temperature	(C)	6.654			
Mass Flow	(kg/s)	1.923			

Heat Exchangers

Fluid Pkg: All

Name		RHX-01	Chiller HX-01	Vacuum Chamber	
Duty	(kW)	130.4	73.97	75.00	
Tube Side Feed Mass Flow	(kg/s)	0.3253	0.3253	1.825e-002	
Shell Side Feed Mass Flow	(kg/s)	0.3253	1.923 *	0.3253	
Tube Inlet Temperature	(C)	592.4	232.1	650.0 *	
Tube Outlet Temperature	(C)	232.7 *	20.00 *	650.0	
Shell Inlet Temperature	(C)	24.56	6.667 *	392.2	
Shell Outlet Temperature	(C)	394.4	17.78	596.7 *	
LMTD	(C)	203.2	72.69	129.3	
UA	(W/C)	641.8	1018	580.2	
Minimum Approach	(C)	198.1	13.33	53.29	

Aspen Technology Inc. Aspen HYSYS Version 9 Page 3 of 5

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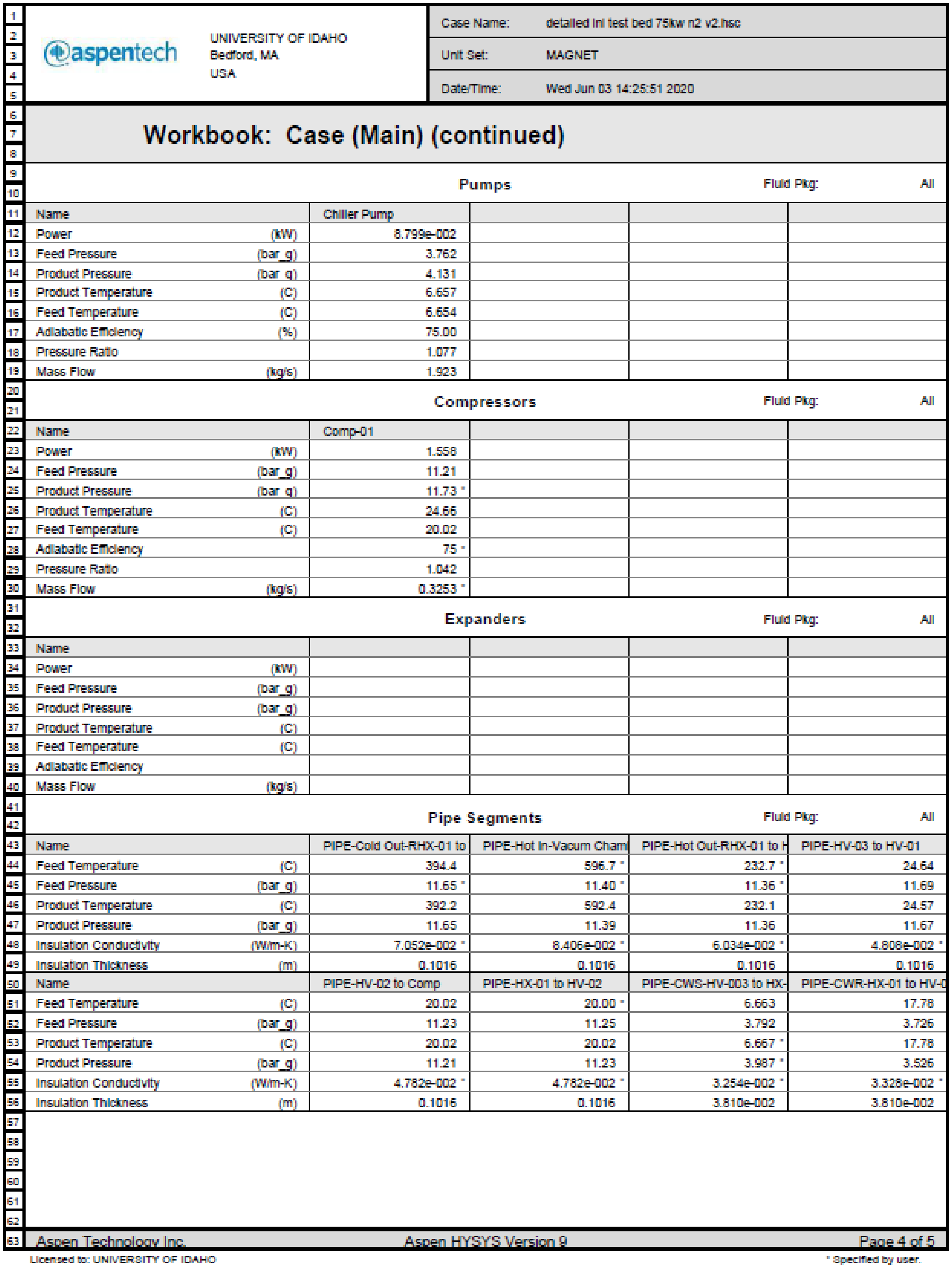

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed lnl test bed 75kw n2 v2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:25:51 2020

Workbook: Case (Main) (continued)

Pumps

Fluid Pkg: All

Name	Chiller Pump			
Power (kW)	8.799e-002			
Feed Pressure (bar_g)	3.762			
Product Pressure (bar_g)	4.131			
Product Temperature (C)	6.657			
Feed Temperature (C)	6.654			
Adiabatic Efficiency (%)	75.00			
Pressure Ratio	1.077			
Mass Flow (kg/s)	1.923			

Compressors

Fluid Pkg: All

Name	Comp-01			
Power (kW)	1.558			
Feed Pressure (bar_g)	11.21			
Product Pressure (bar_g)	11.73 *			
Product Temperature (C)	24.66			
Feed Temperature (C)	20.02			
Adiabatic Efficiency	75 *			
Pressure Ratio	1.042			
Mass Flow (kg/s)	0.3253 *			

Expanders

Fluid Pkg: All

Name				
Power (kW)				
Feed Pressure (bar_g)				
Product Pressure (bar_g)				
Product Temperature (C)				
Feed Temperature (C)				
Adiabatic Efficiency				
Mass Flow (kg/s)				

Pipe Segments

Fluid Pkg: All

Name	PIPE-Cold Out-RHX-01 to	PIPE-Hot In-Vacum Cham	PIPE-Hot Out-RHX-01 to H	PIPE-HV-03 to HV-01
Feed Temperature (C)	394.4	596.7 *	232.7 *	24.64
Feed Pressure (bar_g)	11.65 *	11.40 *	11.36 *	11.69
Product Temperature (C)	392.2	592.4	232.1	24.57
Product Pressure (bar_g)	11.65	11.39	11.36	11.67
Insulation Conductivity (W/m-K)	7.052e-002 *	8.406e-002 *	6.034e-002 *	4.808e-002 *
Insulation Thickness (m)	0.1016	0.1016	0.1016	0.1016
Name	**PIPE-HV-02 to Comp**	**PIPE-HX-01 to HV-02**	**PIPE-CWS-HV-003 to HX-**	**PIPE-CWR-HX-01 to HV-0**
Feed Temperature (C)	20.02	20.00 *	6.663	17.78
Feed Pressure (bar_g)	11.23	11.25	3.792	3.726
Product Temperature (C)	20.02	20.02	6.667 *	17.78
Product Pressure (bar_g)	11.21	11.23	3.987 *	3.526
Insulation Conductivity (W/m-K)	4.782e-002 *	4.782e-002 *	3.254e-002 *	3.328e-002 *
Insulation Thickness (m)	0.1016	0.1016	3.810e-002	3.810e-002

Aspen Technology Inc. Aspen HYSYS Version 9 Page 4 of 5

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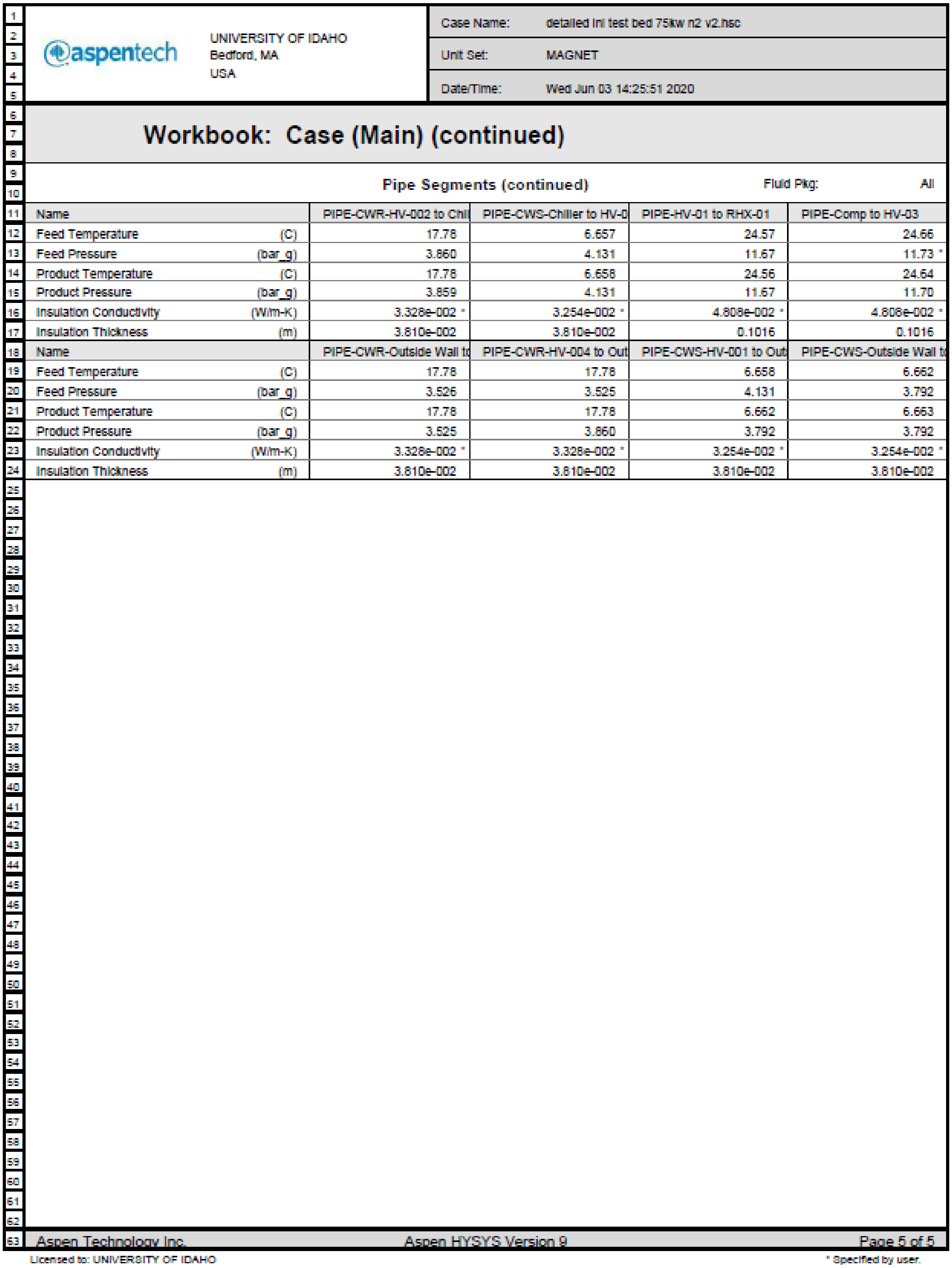

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Case Name:	detailed inl test bed 75kw n2 v2.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:25:51 2020

Workbook: Case (Main) (continued)

Pipe Segments (continued)

Fluid Pkg: All

Name		PIPE-CWR-HV-002 to Chil	PIPE-CWS-Chiller to HV-0	PIPE-HV-01 to RHX-01	PIPE-Comp to HV-03
Feed Temperature	(C)	17.78	6.657	24.57	24.66
Feed Pressure	(bar_g)	3.860	4.131	11.67	11.73 *
Product Temperature	(C)	17.78	6.658	24.56	24.64
Product Pressure	(bar_g)	3.859	4.131	11.67	11.70
Insulation Conductivity	(W/m-K)	3.328e-002 *	3.254e-002 *	4.808e-002 *	4.808e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	0.1016	0.1016
Name		PIPE-CWR-Outside Wall t	PIPE-CWR-HV-004 to Out	PIPE-CWS-HV-001 to Out	PIPE-CWS-Outside Wall t
Feed Temperature	(C)	17.78	17.78	6.658	6.662
Feed Pressure	(bar_g)	3.526	3.525	4.131	3.792
Product Temperature	(C)	17.78	17.78	6.662	6.663
Product Pressure	(bar_g)	3.525	3.860	3.792	3.792
Insulation Conductivity	(W/m-K)	3.328e-002 *	3.328e-002 *	3.254e-002 *	3.254e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	3.810e-002	3.810e-002

Aspen Technology Inc. Aspen HYSYS Version 9 Page 5 of 5

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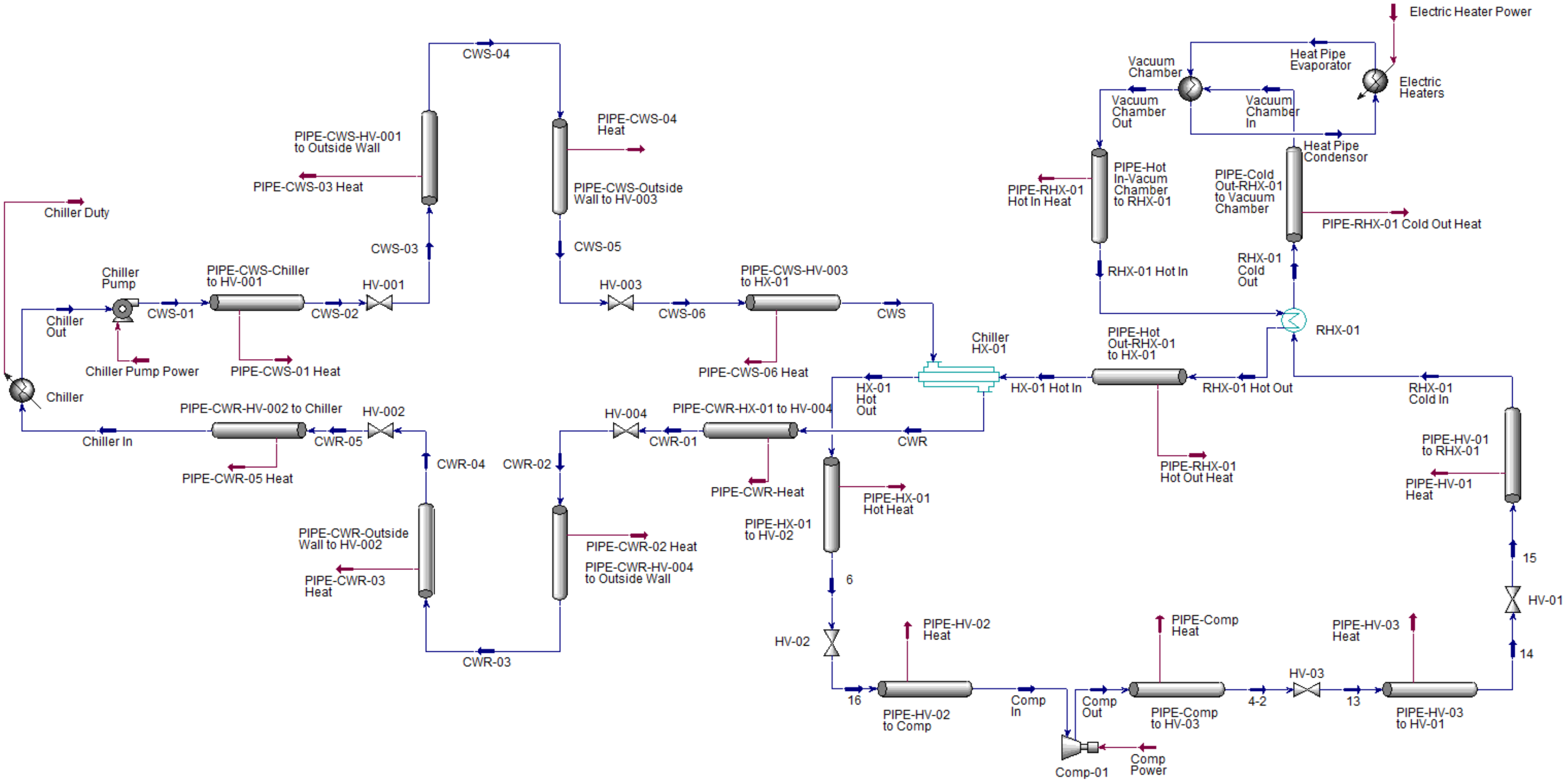
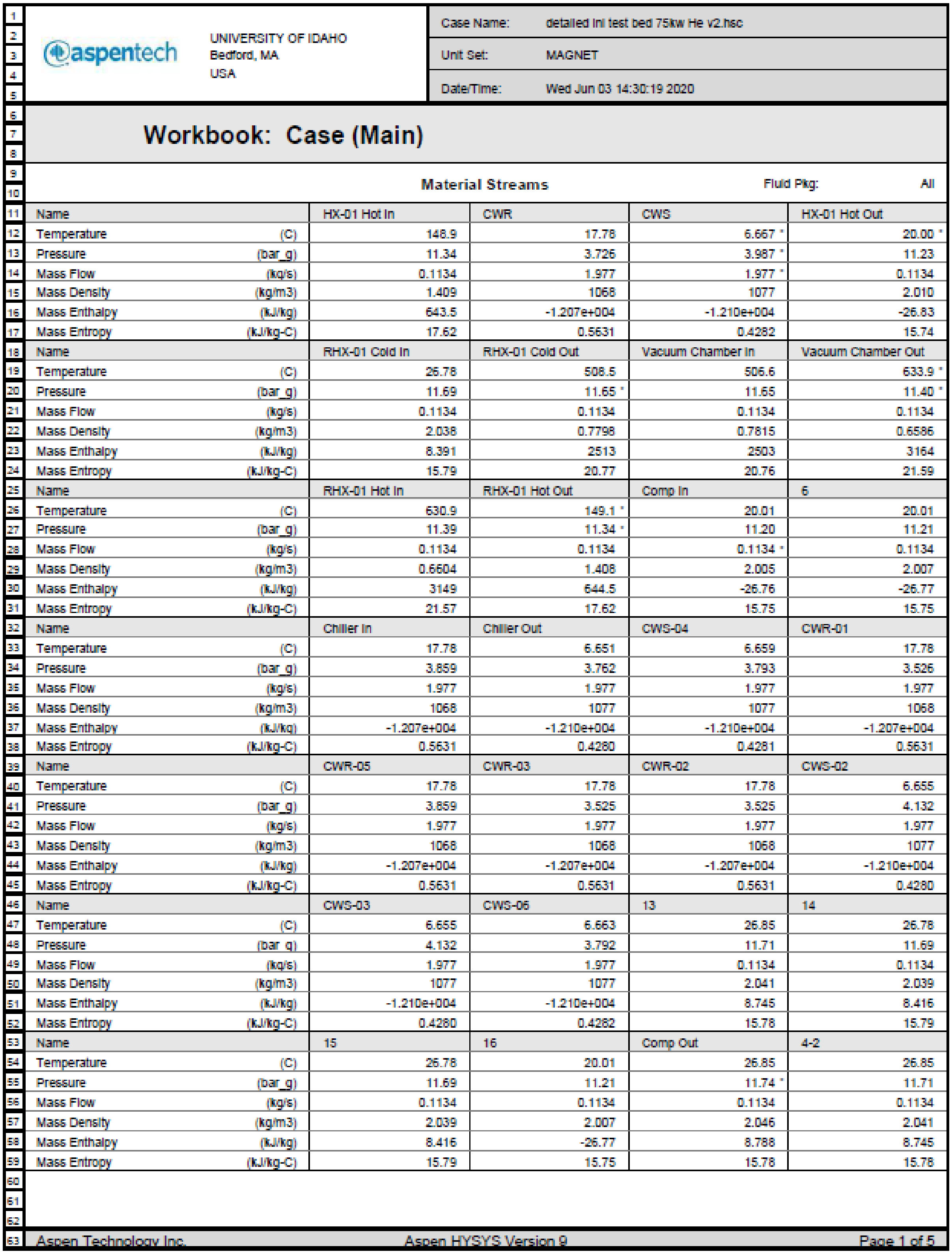
Aspen HYSYS Process Model of Microreactor AGile Non-nuclear Experimental Testbed with Heat Pipe Heat Exchanger using Helium Operating at 600°C and 75 kW of Heat Pipe Power





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Case Name: detailed inl test bed 75kw He v2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:30:19 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Temperature	(C)	148.9	17.78	6.667 *	20.00 *
Pressure	(bar_g)	11.34	3.726	3.987 *	11.23
Mass Flow	(kg/s)	0.1134	1.977	1.977 *	0.1134
Mass Density	(kg/m3)	1.409	1068	1077	2.010
Mass Enthalpy	(kJ/kg)	643.5	-1.207e+004	-1.210e+004	-26.83
Mass Entropy	(kJ/kg-C)	17.62	0.5631	0.4282	15.74

Name		RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Temperature	(C)	26.78	508.5	506.6	633.9 *
Pressure	(bar_g)	11.69	11.65 *	11.65	11.40 *
Mass Flow	(kg/s)	0.1134	0.1134	0.1134	0.1134
Mass Density	(kg/m3)	2.038	0.7798	0.7815	0.6586
Mass Enthalpy	(kJ/kg)	8.391	2513	2503	3164
Mass Entropy	(kJ/kg-C)	15.79	20.77	20.76	21.59

Name		RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Temperature	(C)	630.9	149.1 *	20.01	20.01
Pressure	(bar_g)	11.39	11.34 *	11.20	11.21
Mass Flow	(kg/s)	0.1134	0.1134	0.1134 *	0.1134
Mass Density	(kg/m3)	0.6604	1.408	2.005	2.007
Mass Enthalpy	(kJ/kg)	3149	644.5	-26.76	-26.77
Mass Entropy	(kJ/kg-C)	21.57	17.62	15.75	15.75

Name		Chiller In	Chiller Out	CWS-04	CWR-01
Temperature	(C)	17.78	6.651	6.659	17.78
Pressure	(bar_g)	3.859	3.762	3.793	3.526
Mass Flow	(kg/s)	1.977	1.977	1.977	1.977
Mass Density	(kg/m3)	1068	1077	1077	1068
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.210e+004	-1.210e+004	-1.207e+004
Mass Entropy	(kJ/kg-C)	0.5631	0.4280	0.4281	0.5631

Name		CWR-05	CWR-03	CWR-02	CWS-02
Temperature	(C)	17.78	17.78	17.78	6.655
Pressure	(bar_g)	3.859	3.525	3.525	4.132
Mass Flow	(kg/s)	1.977	1.977	1.977	1.977
Mass Density	(kg/m3)	1068	1068	1068	1077
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.207e+004	-1.207e+004	-1.210e+004
Mass Entropy	(kJ/kg-C)	0.5631	0.5631	0.5631	0.4280

Name		CWS-03	CWS-06	13	14
Temperature	(C)	6.655	6.663	26.85	26.78
Pressure	(bar_g)	4.132	3.792	11.71	11.69
Mass Flow	(kg/s)	1.977	1.977	0.1134	0.1134
Mass Density	(kg/m3)	1077	1077	2.041	2.039
Mass Enthalpy	(kJ/kg)	-1.210e+004	-1.210e+004	8.745	8.416
Mass Entropy	(kJ/kg-C)	0.4280	0.4282	15.78	15.79

Name		15	16	Comp Out	4-2
Temperature	(C)	26.78	20.01	26.85	26.85
Pressure	(bar_g)	11.69	11.21	11.74 *	11.71
Mass Flow	(kg/s)	0.1134	0.1134	0.1134	0.1134
Mass Density	(kg/m3)	2.039	2.007	2.046	2.041
Mass Enthalpy	(kJ/kg)	8.416	-26.77	8.788	8.745
Mass Entropy	(kJ/kg-C)	15.79	15.75	15.78	15.78

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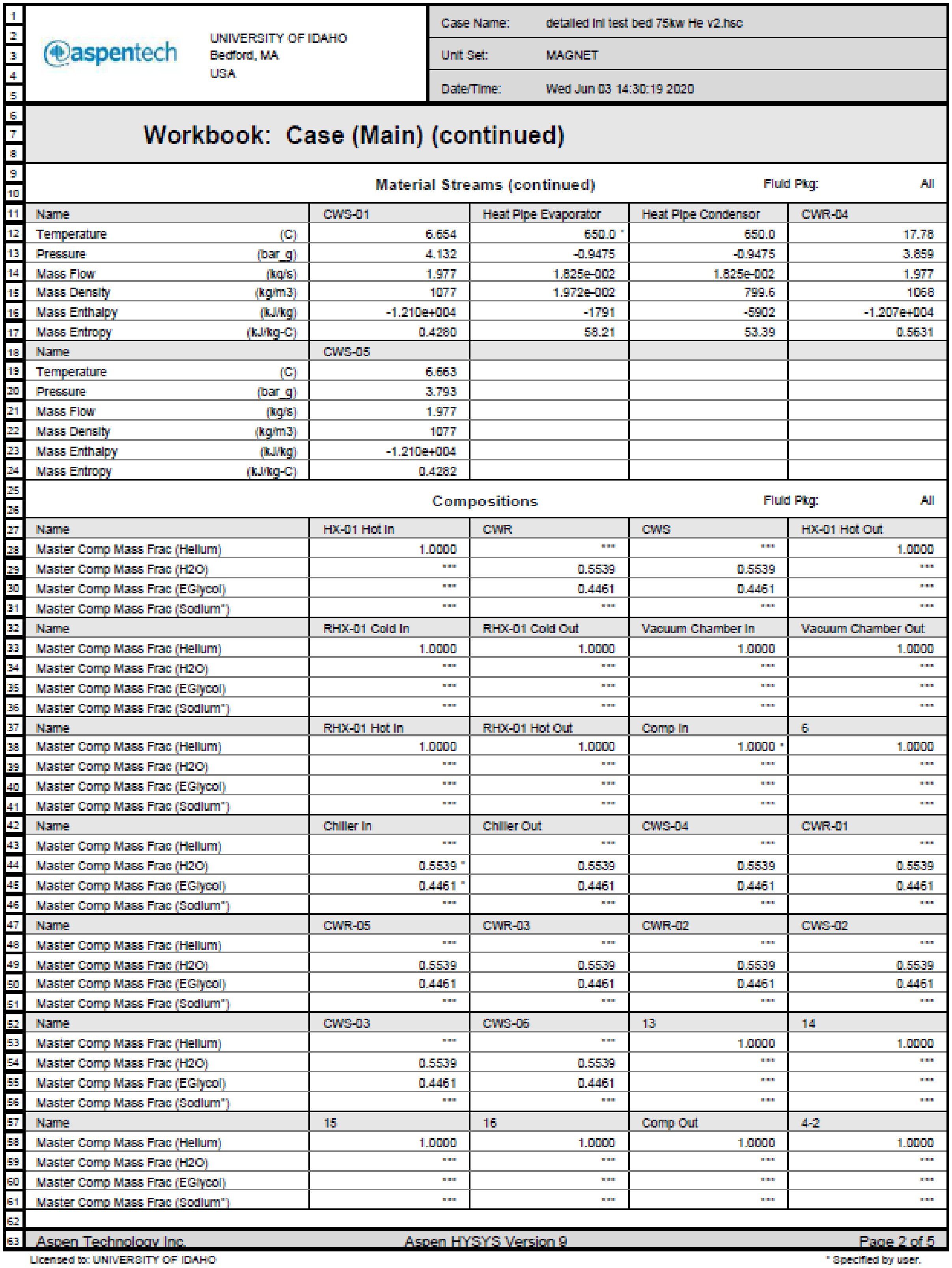

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Case Name: detailed lnl test bed 75kw He v2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:30:19 2020

Workbook: Case (Main) (continued)

Material Streams (continued)

Fluid Pkg: All

Name	CWS-01	Heat Pipe Evaporator	Heat Pipe Condensor	CWR-04
Temperature (C)	6.654	650.0 *	650.0	17.78
Pressure (bar_g)	4.132	-0.9475	-0.9475	3.859
Mass Flow (kg/s)	1.977	1.825e-002	1.825e-002	1.977
Mass Density (kg/m3)	1077	1.972e-002	799.6	1068
Mass Enthalpy (kJ/kg)	-1.210e+004	-1791	-5902	-1.207e+004
Mass Entropy (kJ/kg-C)	0.4280	58.21	53.39	0.5631

Name	CWS-05			
Temperature (C)	6.663			
Pressure (bar_g)	3.793			
Mass Flow (kg/s)	1.977			
Mass Density (kg/m3)	1077			
Mass Enthalpy (kJ/kg)	-1.210e+004			
Mass Entropy (kJ/kg-C)	0.4282			

Compositions

Fluid Pkg: All

Name	HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Master Comp Mass Frac (Helium)	1.0000	***	***	1.0000
Master Comp Mass Frac (H2O)	***	0.5539	0.5539	***
Master Comp Mass Frac (EGlycol)	***	0.4461	0.4461	***
Master Comp Mass Frac (Sodium*)	***	***	***	***

Name	RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Master Comp Mass Frac (Helium)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***

Name	RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Master Comp Mass Frac (Helium)	1.0000	1.0000	1.0000 *	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***

Name	Chiller In	Chiller Out	CWS-04	CWR-01
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539 *	0.5539	0.5539	0.5539
Master Comp Mass Frac (EGlycol)	0.4461 *	0.4461	0.4461	0.4461
Master Comp Mass Frac (Sodium*)	***	***	***	***

Name	CWR-05	CWR-03	CWR-02	CWS-02
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539	0.5539	0.5539	0.5539
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	0.4461	0.4461
Master Comp Mass Frac (Sodium*)	***	***	***	***

Name	CWS-03	CWS-06	13	14
Master Comp Mass Frac (Helium)	***	***	1.0000	1.0000
Master Comp Mass Frac (H2O)	0.5539	0.5539	***	***
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***

Name	15	16	Comp Out	4-2
Master Comp Mass Frac (Helium)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***

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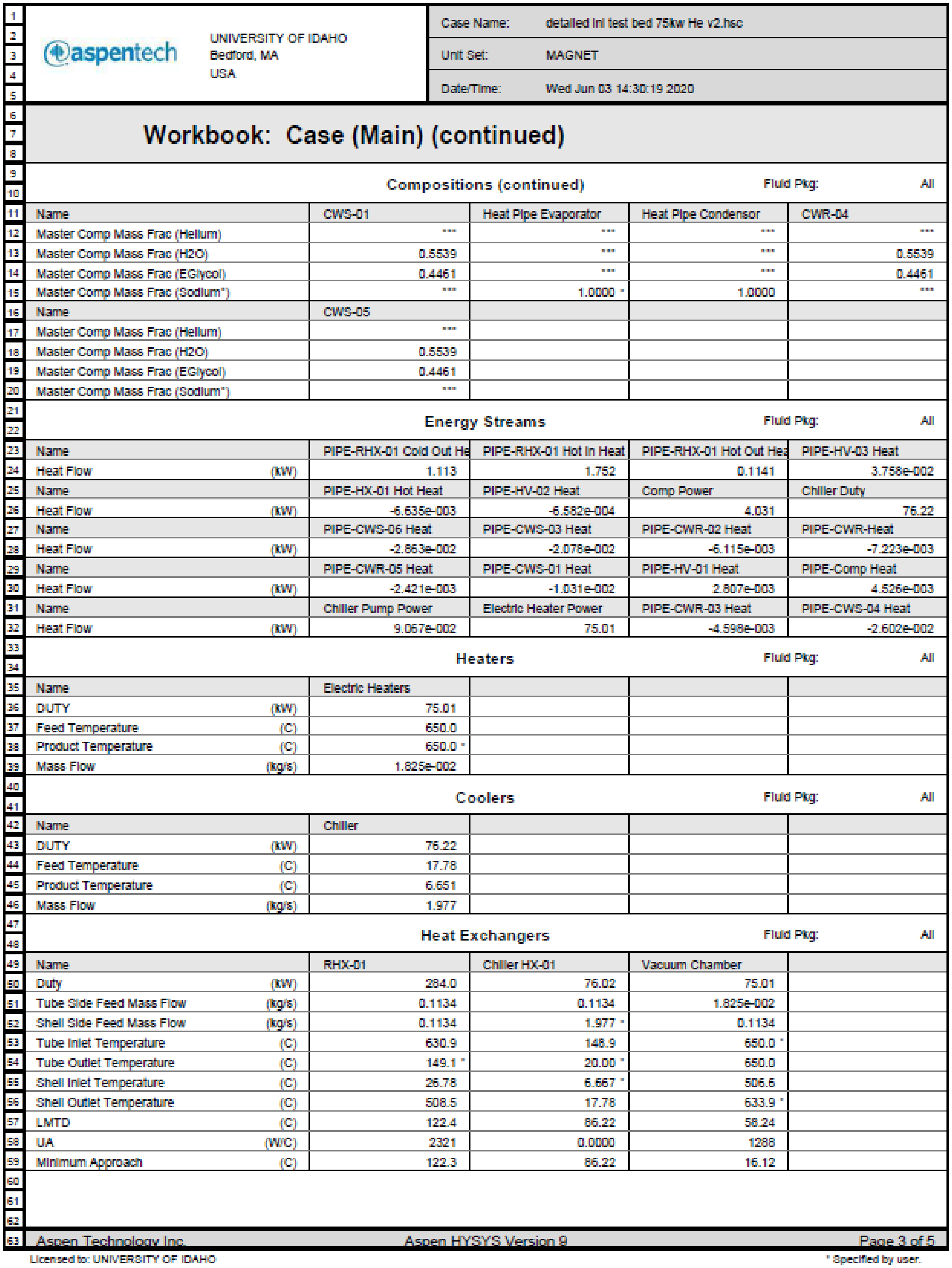

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Case Name:	detailed inl test bed 75kw He v2.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:30:19 2020

Workbook: Case (Main) (continued)

Compositions (continued)

Fluid Pkg: All

Name	CWS-01	Heat Pipe Evaporator	Heat Pipe Condensor	CWR-04
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539	***	***	0.5539
Master Comp Mass Frac (EGlycol)	0.4461	***	***	0.4461
Master Comp Mass Frac (Sodium*)	***	1.0000 *	1.0000	***
Name	CWS-05			
Master Comp Mass Frac (Helium)	***			
Master Comp Mass Frac (H2O)	0.5539			
Master Comp Mass Frac (EGlycol)	0.4461			
Master Comp Mass Frac (Sodium*)	***			

Energy Streams

Fluid Pkg: All

Name	PIPE-RHX-01 Cold Out He	PIPE-RHX-01 Hot In Heat	PIPE-RHX-01 Hot Out Hea	PIPE-HV-03 Heat
Heat Flow (kW)	1.113	1.752	0.1141	3.758e-002
Name	PIPE-HX-01 Hot Heat	PIPE-HV-02 Heat	Comp Power	Chiller Duty
Heat Flow (kW)	-6.635e-003	-6.582e-004	4.031	76.22
Name	PIPE-CWS-06 Heat	PIPE-CWS-03 Heat	PIPE-CWR-02 Heat	PIPE-CWR-Heat
Heat Flow (kW)	-2.863e-002	-2.078e-002	-6.115e-003	-7.223e-003
Name	PIPE-CWR-05 Heat	PIPE-CWS-01 Heat	PIPE-HV-01 Heat	PIPE-Comp Heat
Heat Flow (kW)	-2.421e-003	-1.031e-002	2.807e-003	4.526e-003
Name	Chiller Pump Power	Electric Heater Power	PIPE-CWR-03 Heat	PIPE-CWS-04 Heat
Heat Flow (kW)	9.067e-002	75.01	-4.598e-003	-2.602e-002

Heaters

Fluid Pkg: All

Name	Electric Heaters			
DUTY (kW)	75.01			
Feed Temperature (C)	650.0			
Product Temperature (C)	650.0 *			
Mass Flow (kg/s)	1.825e-002			

Coolers

Fluid Pkg: All

Name	Chiller			
DUTY (kW)	76.22			
Feed Temperature (C)	17.78			
Product Temperature (C)	6.651			
Mass Flow (kg/s)	1.977			

Heat Exchangers

Fluid Pkg: All

Name	RHX-01	Chiller HX-01	Vacuum Chamber	
Duty (kW)	284.0	76.02	75.01	
Tube Side Feed Mass Flow (kg/s)	0.1134	0.1134	1.825e-002	
Shell Side Feed Mass Flow (kg/s)	0.1134	1.977 *	0.1134	
Tube Inlet Temperature (C)	630.9	148.9	650.0 *	
Tube Outlet Temperature (C)	149.1 *	20.00 *	650.0	
Shell Inlet Temperature (C)	26.78	6.667 *	506.6	
Shell Outlet Temperature (C)	508.5	17.78	633.9 *	
LMTD (C)	122.4	86.22	58.24	
UA (W/C)	2321	0.0000	1288	
Minimum Approach (C)	122.3	86.22	16.12	

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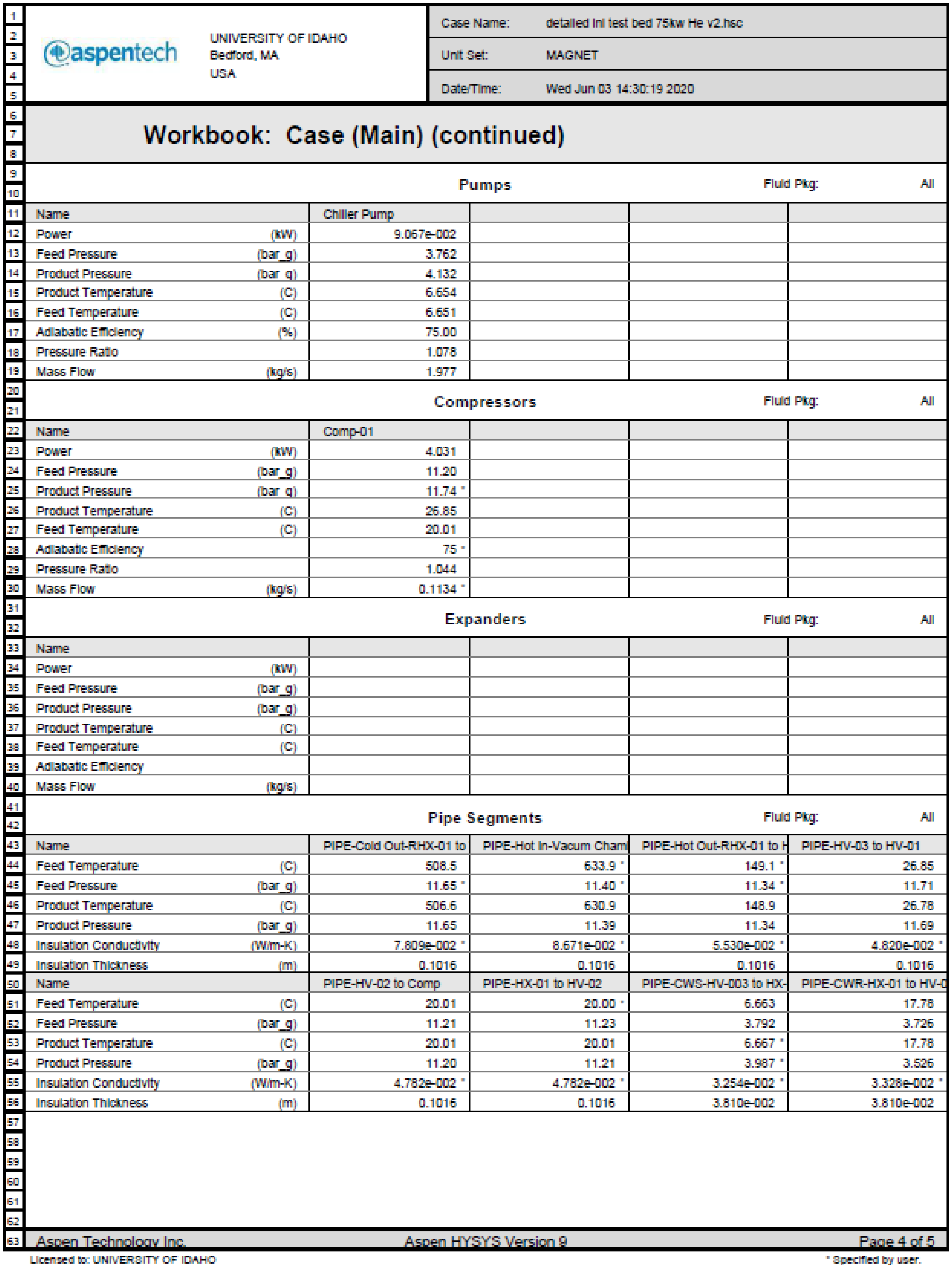

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Case Name: detailed inl test bed 75kw He v2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:30:19 2020

Workbook: Case (Main) (continued)

Pumps

Fluid Pkg: All

Name		Chiller Pump			
Power	(kW)	9.067e-002			
Feed Pressure	(bar_g)	3.762			
Product Pressure	(bar_g)	4.132			
Product Temperature	(C)	6.654			
Feed Temperature	(C)	6.651			
Adiabatic Efficiency	(%)	75.00			
Pressure Ratio		1.078			
Mass Flow	(kg/s)	1.977			

Compressors

Fluid Pkg: All

Name		Comp-01			
Power	(kW)	4.031			
Feed Pressure	(bar_g)	11.20			
Product Pressure	(bar_g)	11.74 *			
Product Temperature	(C)	26.85			
Feed Temperature	(C)	20.01			
Adiabatic Efficiency		75 *			
Pressure Ratio		1.044			
Mass Flow	(kg/s)	0.1134 *			

Expanders

Fluid Pkg: All

Name					
Power	(kW)				
Feed Pressure	(bar_g)				
Product Pressure	(bar_g)				
Product Temperature	(C)				
Feed Temperature	(C)				
Adiabatic Efficiency					
Mass Flow	(kg/s)				

Pipe Segments

Fluid Pkg: All

Name		PIPE-Cold Out-RHX-01 to	PIPE-Hot In-Vacum Cham	PIPE-Hot Out-RHX-01 to H	PIPE-HV-03 to HV-01
Feed Temperature	(C)	508.5	633.9 *	149.1 *	26.85
Feed Pressure	(bar_g)	11.65 *	11.40 *	11.34 *	11.71
Product Temperature	(C)	506.6	630.9	148.9	26.78
Product Pressure	(bar_g)	11.65	11.39	11.34	11.69
Insulation Conductivity	(W/m-K)	7.809e-002 *	8.671e-002 *	5.530e-002 *	4.820e-002 *
Insulation Thickness	(m)	0.1016	0.1016	0.1016	0.1016
Name		PIPE-HV-02 to Comp	PIPE-HX-01 to HV-02	PIPE-CWS-HV-003 to HX-	PIPE-CWR-HX-01 to HV-0
Feed Temperature	(C)	20.01	20.00 *	6.663	17.78
Feed Pressure	(bar_g)	11.21	11.23	3.792	3.726
Product Temperature	(C)	20.01	20.01	6.667 *	17.78
Product Pressure	(bar_g)	11.20	11.21	3.987 *	3.526
Insulation Conductivity	(W/m-K)	4.782e-002 *	4.782e-002 *	3.254e-002 *	3.328e-002 *
Insulation Thickness	(m)	0.1016	0.1016	3.810e-002	3.810e-002

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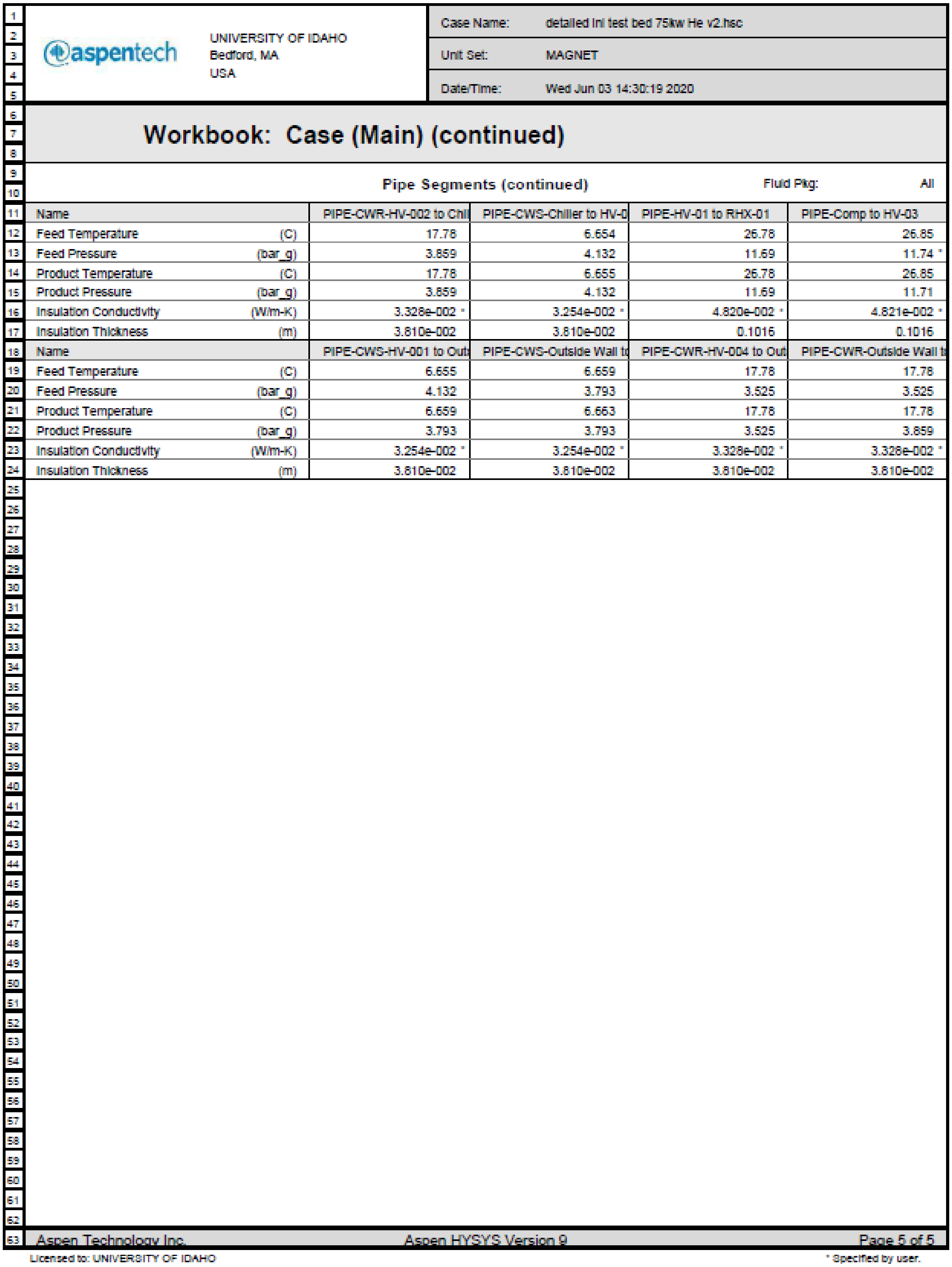

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Bedford, MA
USA

Case Name:	detailed inl test bed 75kw He v2.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:30:19 2020

Workbook: Case (Main) (continued)

Pipe Segments (continued)

Fluid Pkg: All

Name		PIPE-CWR-HV-002 to Chil	PIPE-CWS-Chiller to HV-0	PIPE-HV-01 to RHX-01	PIPE-Comp to HV-03
Feed Temperature	(C)	17.78	6.654	26.78	26.85
Feed Pressure	(bar_g)	3.859	4.132	11.69	11.74 *
Product Temperature	(C)	17.78	6.655	26.78	26.85
Product Pressure	(bar_g)	3.859	4.132	11.69	11.71
Insulation Conductivity	(W/m-K)	3.328e-002 *	3.254e-002 *	4.820e-002 *	4.821e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	0.1016	0.1016
Name		PIPE-CWS-HV-001 to Out	PIPE-CWS-Outside Wall t	PIPE-CWR-HV-004 to Out	PIPE-CWR-Outside Wall t
Feed Temperature	(C)	6.655	6.659	17.78	17.78
Feed Pressure	(bar_g)	4.132	3.793	3.525	3.525
Product Temperature	(C)	6.659	6.663	17.78	17.78
Product Pressure	(bar_g)	3.793	3.793	3.525	3.859
Insulation Conductivity	(W/m-K)	3.254e-002 *	3.254e-002 *	3.328e-002 *	3.328e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	3.810e-002	3.810e-002

Aspen Technology Inc. Aspen HYSYS Version 9 Page 5 of 5

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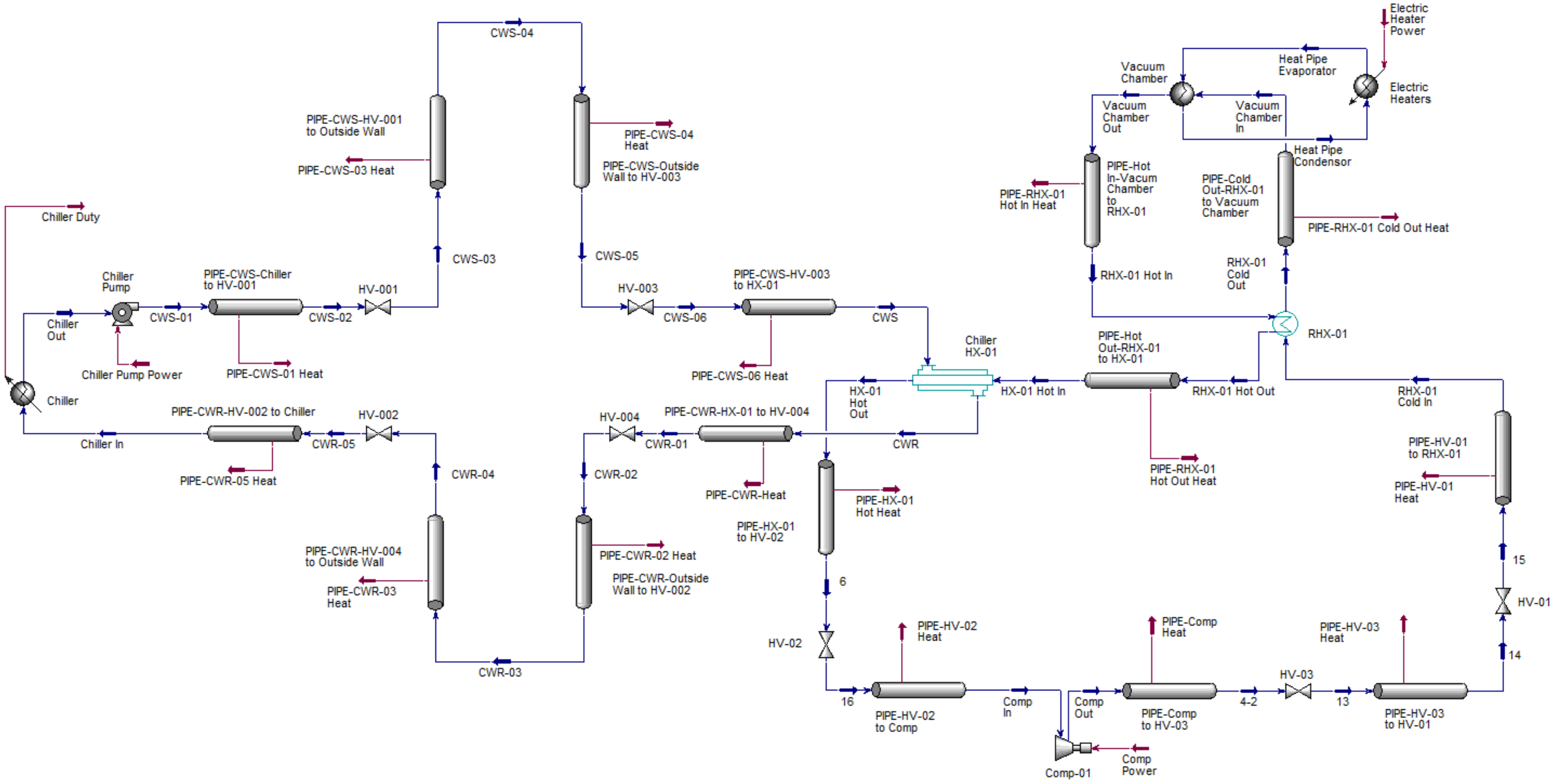
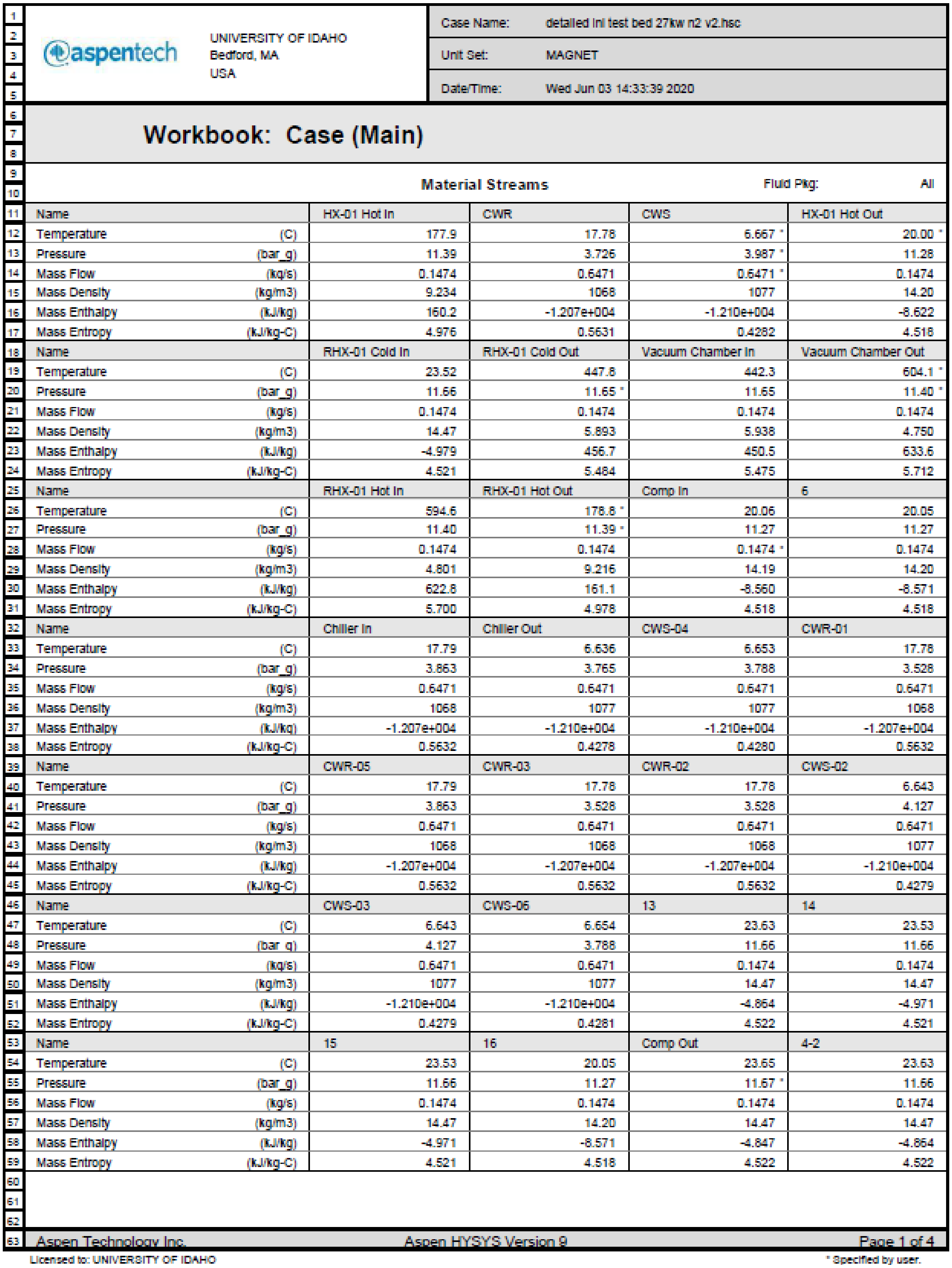
Aspen HYSYS Process Model of Microreactor AGile Non-nuclear Experimental Testbed with Heat Pipe Heat Exchanger using Nitrogen Operating at 600°C and 27 kW of Heat Pipe Power





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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed inl test bed 27kw n2 v2.hsc

Unit Set: MAGNET

Date/Time: Wed Jun 03 14:33:39 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Temperature	(C)	177.9	17.78	6.667 *	20.00 *
Pressure	(bar_g)	11.39	3.726	3.987 *	11.28
Mass Flow	(kg/s)	0.1474	0.6471	0.6471 *	0.1474
Mass Density	(kg/m3)	9.234	1068	1077	14.20
Mass Enthalpy	(kJ/kg)	160.2	-1.207e+004	-1.210e+004	-8.622
Mass Entropy	(kJ/kg-C)	4.976	0.5631	0.4282	4.518
Name		RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Temperature	(C)	23.52	447.8	442.3	604.1 *
Pressure	(bar_g)	11.66	11.65 *	11.65	11.40 *
Mass Flow	(kg/s)	0.1474	0.1474	0.1474	0.1474
Mass Density	(kg/m3)	14.47	5.893	5.938	4.750
Mass Enthalpy	(kJ/kg)	-4.979	456.7	450.5	633.6
Mass Entropy	(kJ/kg-C)	4.521	5.484	5.475	5.712
Name		RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Temperature	(C)	594.6	178.8 *	20.06	20.05
Pressure	(bar_g)	11.40	11.39 *	11.27	11.27
Mass Flow	(kg/s)	0.1474	0.1474	0.1474 *	0.1474
Mass Density	(kg/m3)	4.801	9.216	14.19	14.20
Mass Enthalpy	(kJ/kg)	622.8	161.1	-8.560	-8.571
Mass Entropy	(kJ/kg-C)	5.700	4.978	4.518	4.518
Name		Chiller In	Chiller Out	CWS-04	CWR-01
Temperature	(C)	17.79	6.636	6.653	17.78
Pressure	(bar_g)	3.863	3.765	3.788	3.528
Mass Flow	(kg/s)	0.6471	0.6471	0.6471	0.6471
Mass Density	(kg/m3)	1068	1077	1077	1068
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.210e+004	-1.210e+004	-1.207e+004
Mass Entropy	(kJ/kg-C)	0.5632	0.4278	0.4280	0.5632
Name		CWR-05	CWR-03	CWR-02	CWS-02
Temperature	(C)	17.79	17.78	17.78	6.643
Pressure	(bar_g)	3.863	3.528	3.528	4.127
Mass Flow	(kg/s)	0.6471	0.6471	0.6471	0.6471
Mass Density	(kg/m3)	1068	1068	1068	1077
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.207e+004	-1.207e+004	-1.210e+004
Mass Entropy	(kJ/kg-C)	0.5632	0.5632	0.5632	0.4279
Name		CWS-03	CWS-06	13	14
Temperature	(C)	6.643	6.654	23.63	23.53
Pressure	(bar_g)	4.127	3.788	11.66	11.66
Mass Flow	(kg/s)	0.6471	0.6471	0.1474	0.1474
Mass Density	(kg/m3)	1077	1077	14.47	14.47
Mass Enthalpy	(kJ/kg)	-1.210e+004	-1.210e+004	-4.864	-4.971
Mass Entropy	(kJ/kg-C)	0.4279	0.4281	4.522	4.521
Name		15	16	Comp Out	4-2
Temperature	(C)	23.53	20.05	23.65	23.63
Pressure	(bar_g)	11.66	11.27	11.67 *	11.66
Mass Flow	(kg/s)	0.1474	0.1474	0.1474	0.1474
Mass Density	(kg/m3)	14.47	14.20	14.47	14.47
Mass Enthalpy	(kJ/kg)	-4.971	-8.571	-4.847	-4.864
Mass Entropy	(kJ/kg-C)	4.521	4.518	4.522	4.522

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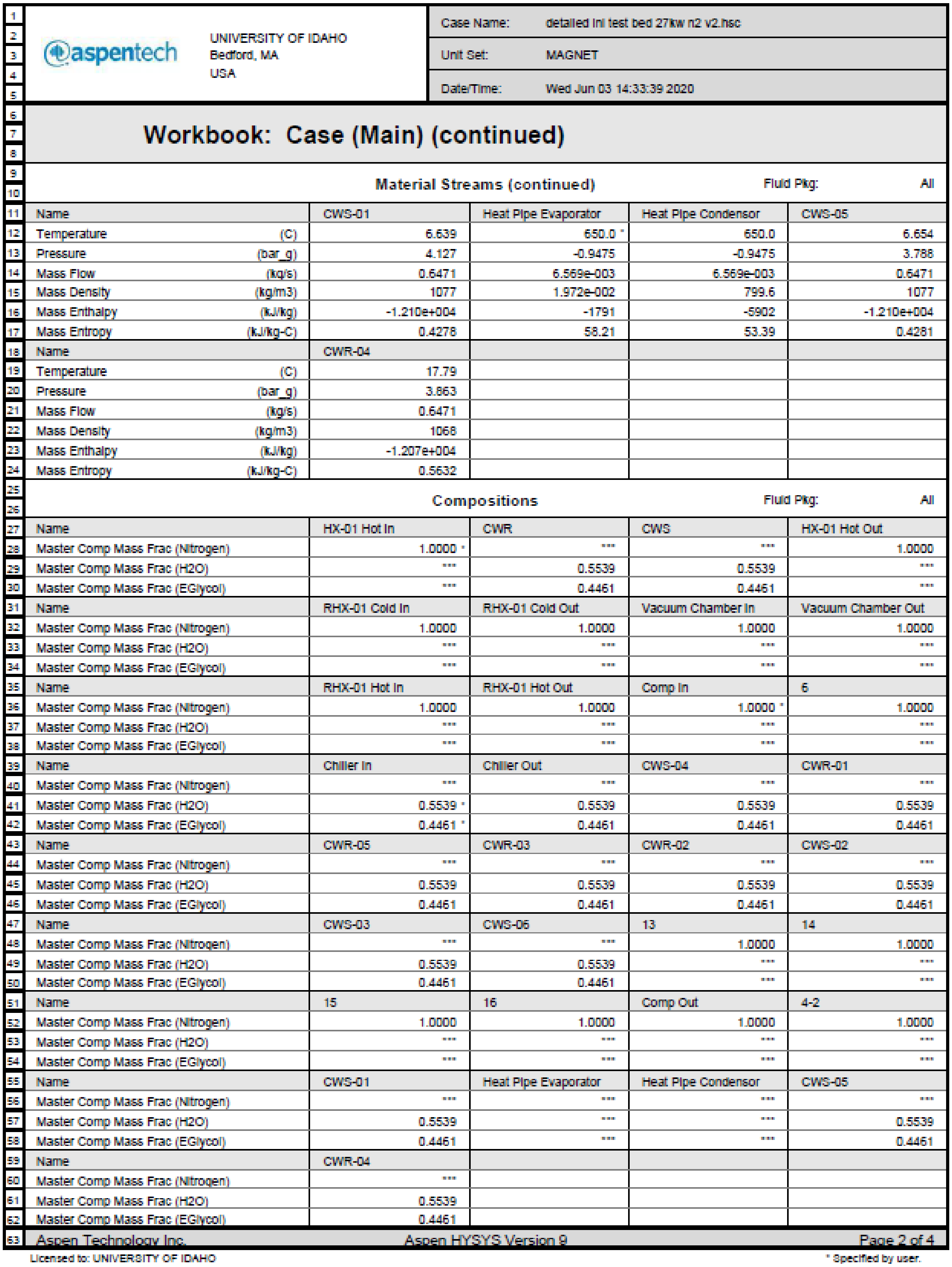

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Bedford, MA
USA

Case Name:	detailed inl test bed 27kw n2 v2.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:33:39 2020

Workbook: Case (Main) (continued)

Material Streams (continued)

Fluid Pkg: All

Name	CWS-01	Heat Pipe Evaporator	Heat Pipe Condensor	CWS-05
Temperature (C)	6.639	650.0 *	650.0	6.654
Pressure (bar_g)	4.127	-0.9475	-0.9475	3.788
Mass Flow (kg/s)	0.6471	6.569e-003	6.569e-003	0.6471
Mass Density (kg/m3)	1077	1.972e-002	799.6	1077
Mass Enthalpy (kJ/kg)	-1.210e+004	-1791	-5902	-1.210e+004
Mass Entropy (kJ/kg-C)	0.4278	58.21	53.39	0.4281
Name	CWR-04			
Temperature (C)	17.79			
Pressure (bar_g)	3.863			
Mass Flow (kg/s)	0.6471			
Mass Density (kg/m3)	1068			
Mass Enthalpy (kJ/kg)	-1.207e+004			
Mass Entropy (kJ/kg-C)	0.5632			

Compositions

Fluid Pkg: All

Name	HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Master Comp Mass Frac (Nitrogen)	1.0000 *	***	***	1.0000
Master Comp Mass Frac (H2O)	***	0.5539	0.5539	***
Master Comp Mass Frac (EGlycol)	***	0.4461	0.4461	***
Name	RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Name	RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000 *	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Name	Chiller In	Chiller Out	CWS-04	CWR-01
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539 *	0.5539	0.5539	0.5539
Master Comp Mass Frac (EGlycol)	0.4461 *	0.4461	0.4461	0.4461
Name	CWR-05	CWR-03	CWR-02	CWS-02
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539	0.5539	0.5539	0.5539
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	0.4461	0.4461
Name	CWS-03	CWS-06	13	14
Master Comp Mass Frac (Nitrogen)	***	***	1.0000	1.0000
Master Comp Mass Frac (H2O)	0.5539	0.5539	***	***
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	***	***
Name	15	16	Comp Out	4-2
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Name	CWS-01	Heat Pipe Evaporator	Heat Pipe Condensor	CWS-05
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (H2O)	0.5539	***	***	0.5539
Master Comp Mass Frac (EGlycol)	0.4461	***	***	0.4461
Name	CWR-04			
Master Comp Mass Frac (Nitrogen)	***			
Master Comp Mass Frac (H2O)	0.5539			
Master Comp Mass Frac (EGlycol)	0.4461			

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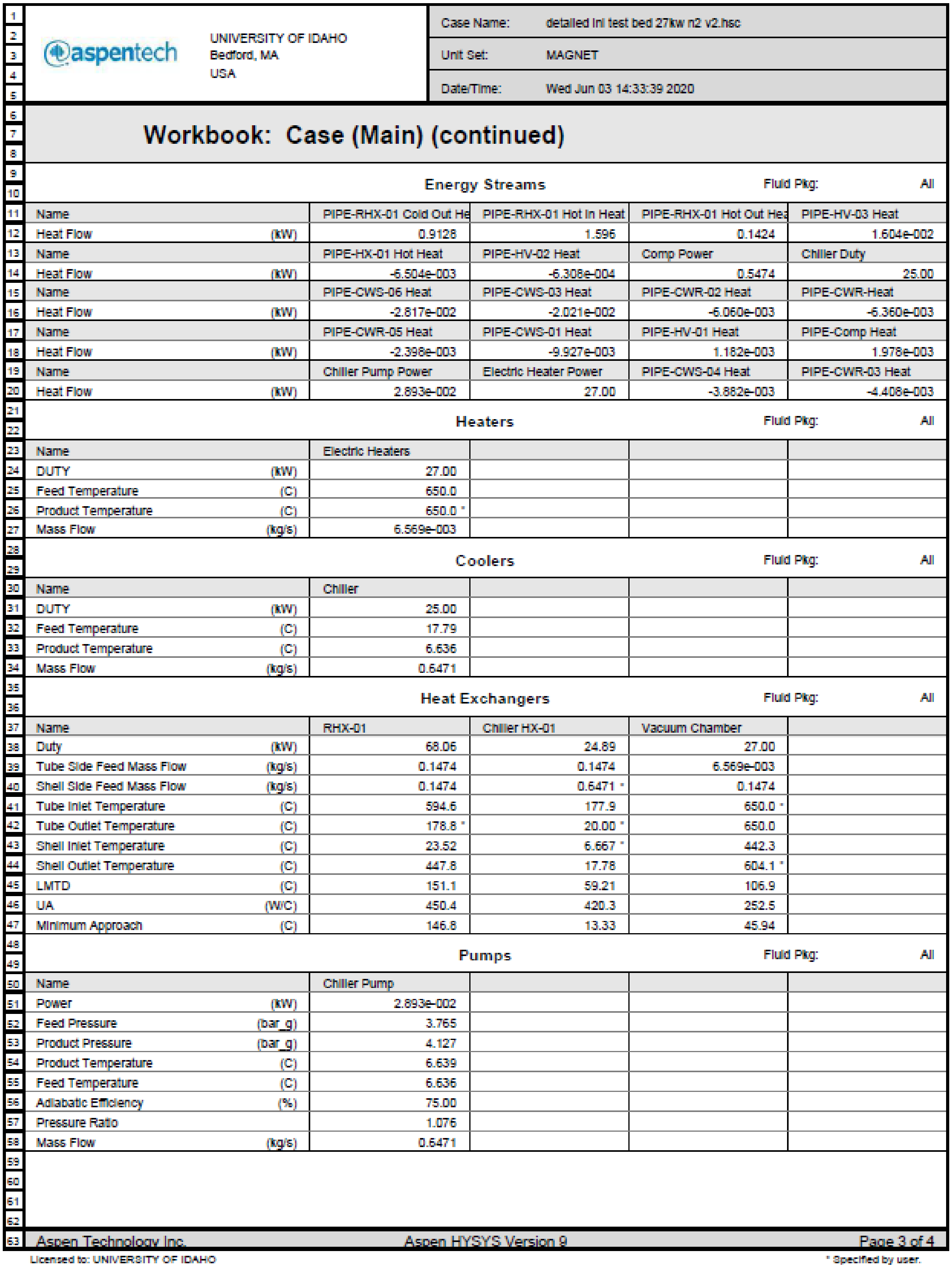

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USA

Case Name: detailed inl test bed 27kw n2 v2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:33:39 2020

Workbook: Case (Main) (continued)

Energy Streams

Fluid Pkg: All

Name		PIPE-RHX-01 Cold Out He	PIPE-RHX-01 Hot In Heat	PIPE-RHX-01 Hot Out Hea	PIPE-HV-03 Heat
Heat Flow	(kW)	0.9128	1.596	0.1424	1.604e-002
Name		PIPE-HX-01 Hot Heat	PIPE-HV-02 Heat	Comp Power	Chiller Duty
Heat Flow	(kW)	-6.504e-003	-6.308e-004	0.5474	25.00
Name		PIPE-CWS-06 Heat	PIPE-CWS-03 Heat	PIPE-CWR-02 Heat	PIPE-CWR-Heat
Heat Flow	(kW)	-2.817e-002	-2.021e-002	-6.060e-003	-6.360e-003
Name		PIPE-CWR-05 Heat	PIPE-CWS-01 Heat	PIPE-HV-01 Heat	PIPE-Comp Heat
Heat Flow	(kW)	-2.398e-003	-9.927e-003	1.182e-003	1.978e-003
Name		Chiller Pump Power	Electric Heater Power	PIPE-CWS-04 Heat	PIPE-CWR-03 Heat
Heat Flow	(kW)	2.893e-002	27.00	-3.882e-003	-4.408e-003

Heaters

Fluid Pkg: All

Name		Electric Heaters			
DUTY	(kW)	27.00			
Feed Temperature	(C)	650.0			
Product Temperature	(C)	650.0 *			
Mass Flow	(kg/s)	6.569e-003			

Coolers

Fluid Pkg: All

Name		Chiller			
DUTY	(kW)	25.00			
Feed Temperature	(C)	17.79			
Product Temperature	(C)	6.636			
Mass Flow	(kg/s)	0.6471			

Heat Exchangers

Fluid Pkg: All

Name		RHX-01	Chiller HX-01	Vacuum Chamber	
Duty	(kW)	68.06	24.89	27.00	
Tube Side Feed Mass Flow	(kg/s)	0.1474	0.1474	6.569e-003	
Shell Side Feed Mass Flow	(kg/s)	0.1474	0.6471 *	0.1474	
Tube Inlet Temperature	(C)	594.6	177.9	650.0 *	
Tube Outlet Temperature	(C)	178.8 *	20.00 *	650.0	
Shell Inlet Temperature	(C)	23.52	6.667 *	442.3	
Shell Outlet Temperature	(C)	447.8	17.78	604.1 *	
LMTD	(C)	151.1	59.21	106.9	
UA	(W/C)	450.4	420.3	252.5	
Minimum Approach	(C)	146.8	13.33	45.94	

Pumps

Fluid Pkg: All

Name		Chiller Pump			
Power	(kW)	2.893e-002			
Feed Pressure	(bar_g)	3.765			
Product Pressure	(bar_g)	4.127			
Product Temperature	(C)	6.639			
Feed Temperature	(C)	6.636			
Adiabatic Efficiency	(%)	75.00			
Pressure Ratio		1.076			
Mass Flow	(kg/s)	0.6471			

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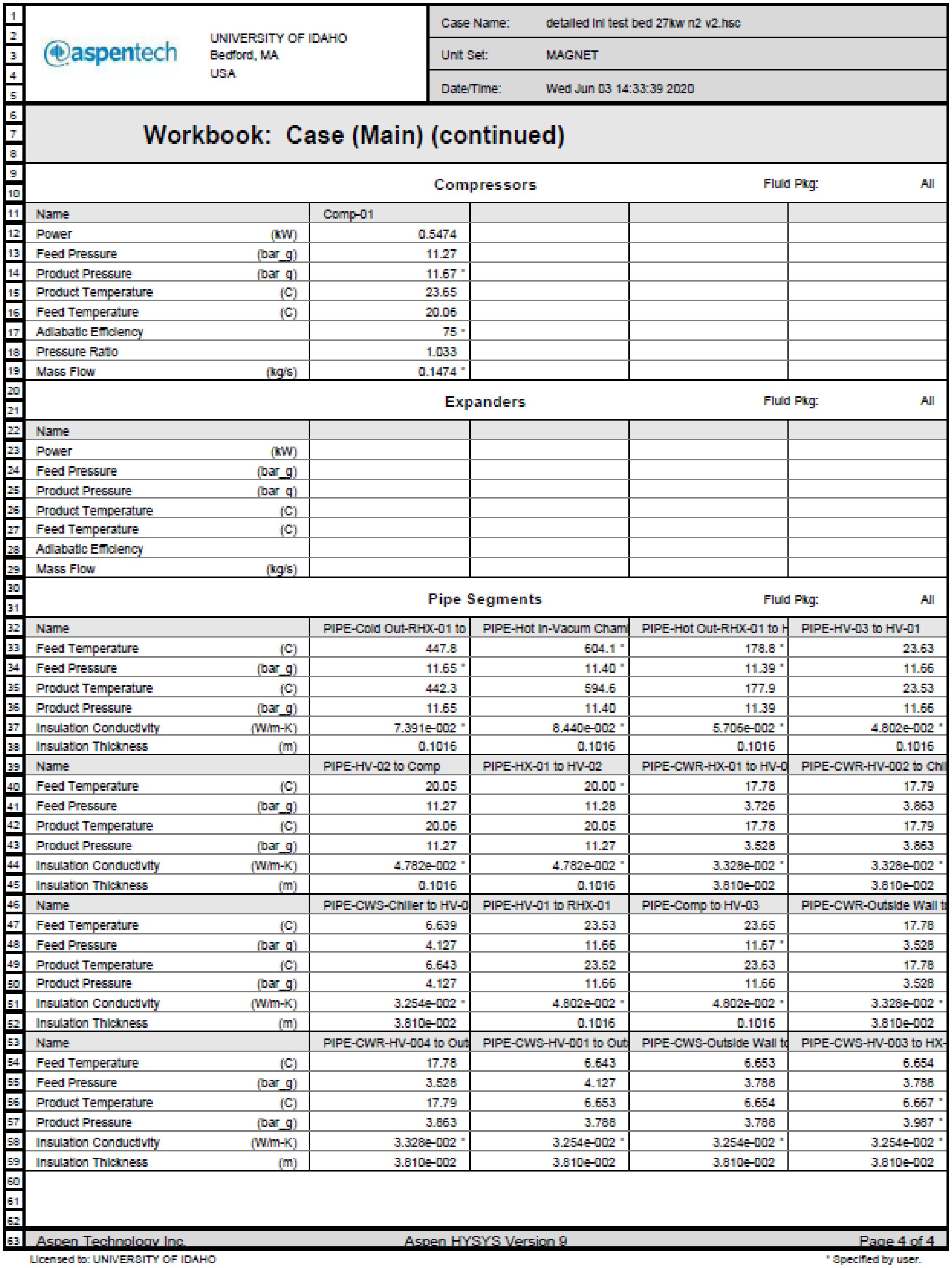

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Case Name:	detailed inl test bed 27kw n2 v2.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:33:39 2020

Workbook: Case (Main) (continued)

Compressors

Fluid Pkg: All

Name		Comp-01			
Power	(kW)	0.5474			
Feed Pressure	(bar_g)	11.27			
Product Pressure	(bar_g)	11.67 *			
Product Temperature	(C)	23.65			
Feed Temperature	(C)	20.06			
Adiabatic Efficiency		75 *			
Pressure Ratio		1.033			
Mass Flow	(kg/s)	0.1474 *			

Expanders

Fluid Pkg: All

Name					
Power	(kW)				
Feed Pressure	(bar_g)				
Product Pressure	(bar_g)				
Product Temperature	(C)				
Feed Temperature	(C)				
Adiabatic Efficiency					
Mass Flow	(kg/s)				

Pipe Segments

Fluid Pkg: All

Name		PIPE-Cold Out-RHX-01 to	PIPE-Hot In-Vacum Cham	PIPE-Hot Out-RHX-01 to H	PIPE-HV-03 to HV-01
Feed Temperature	(C)	447.8	604.1 *	178.8 *	23.63
Feed Pressure	(bar_g)	11.65 *	11.40 *	11.39 *	11.66
Product Temperature	(C)	442.3	594.6	177.9	23.53
Product Pressure	(bar_g)	11.65	11.40	11.39	11.66
Insulation Conductivity	(W/m-K)	7.391e-002 *	8.440e-002 *	5.706e-002 *	4.802e-002 *
Insulation Thickness	(m)	0.1016	0.1016	0.1016	0.1016
Name		PIPE-HV-02 to Comp	PIPE-HX-01 to HV-02	PIPE-CWR-HX-01 to HV-0	PIPE-CWR-HV-002 to Chi
Feed Temperature	(C)	20.05	20.00 *	17.78	17.79
Feed Pressure	(bar_g)	11.27	11.28	3.726	3.863
Product Temperature	(C)	20.06	20.05	17.78	17.79
Product Pressure	(bar_g)	11.27	11.27	3.528	3.863
Insulation Conductivity	(W/m-K)	4.782e-002 *	4.782e-002 *	3.328e-002 *	3.328e-002 *
Insulation Thickness	(m)	0.1016	0.1016	3.810e-002	3.810e-002
Name		PIPE-CWS-Chiller to HV-0	PIPE-HV-01 to RHX-01	PIPE-Comp to HV-03	PIPE-CWR-Outside Wall t
Feed Temperature	(C)	6.639	23.53	23.65	17.78
Feed Pressure	(bar_g)	4.127	11.66	11.67 *	3.528
Product Temperature	(C)	6.643	23.52	23.63	17.78
Product Pressure	(bar_g)	4.127	11.66	11.66	3.528
Insulation Conductivity	(W/m-K)	3.254e-002 *	4.802e-002 *	4.802e-002 *	3.328e-002 *
Insulation Thickness	(m)	3.810e-002	0.1016	0.1016	3.810e-002
Name		PIPE-CWR-HV-004 to Out	PIPE-CWS-HV-001 to Out	PIPE-CWS-Outside Wall t	PIPE-CWS-HV-003 to HX-
Feed Temperature	(C)	17.78	6.643	6.653	6.654
Feed Pressure	(bar_g)	3.528	4.127	3.788	3.788
Product Temperature	(C)	17.79	6.653	6.654	6.667 *
Product Pressure	(bar_g)	3.863	3.788	3.788	3.987 *
Insulation Conductivity	(W/m-K)	3.328e-002 *	3.254e-002 *	3.254e-002 *	3.254e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	3.810e-002	3.810e-002

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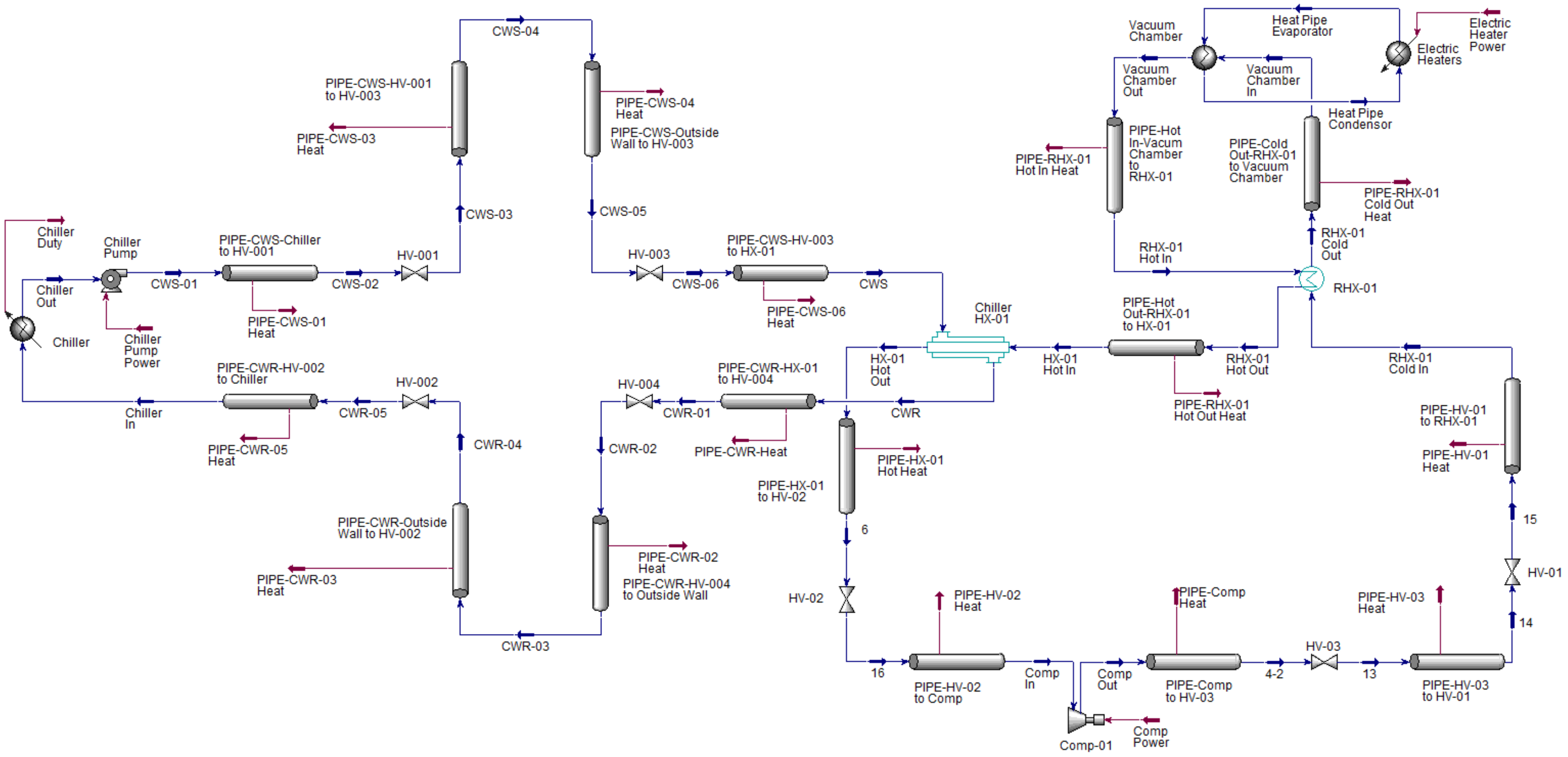
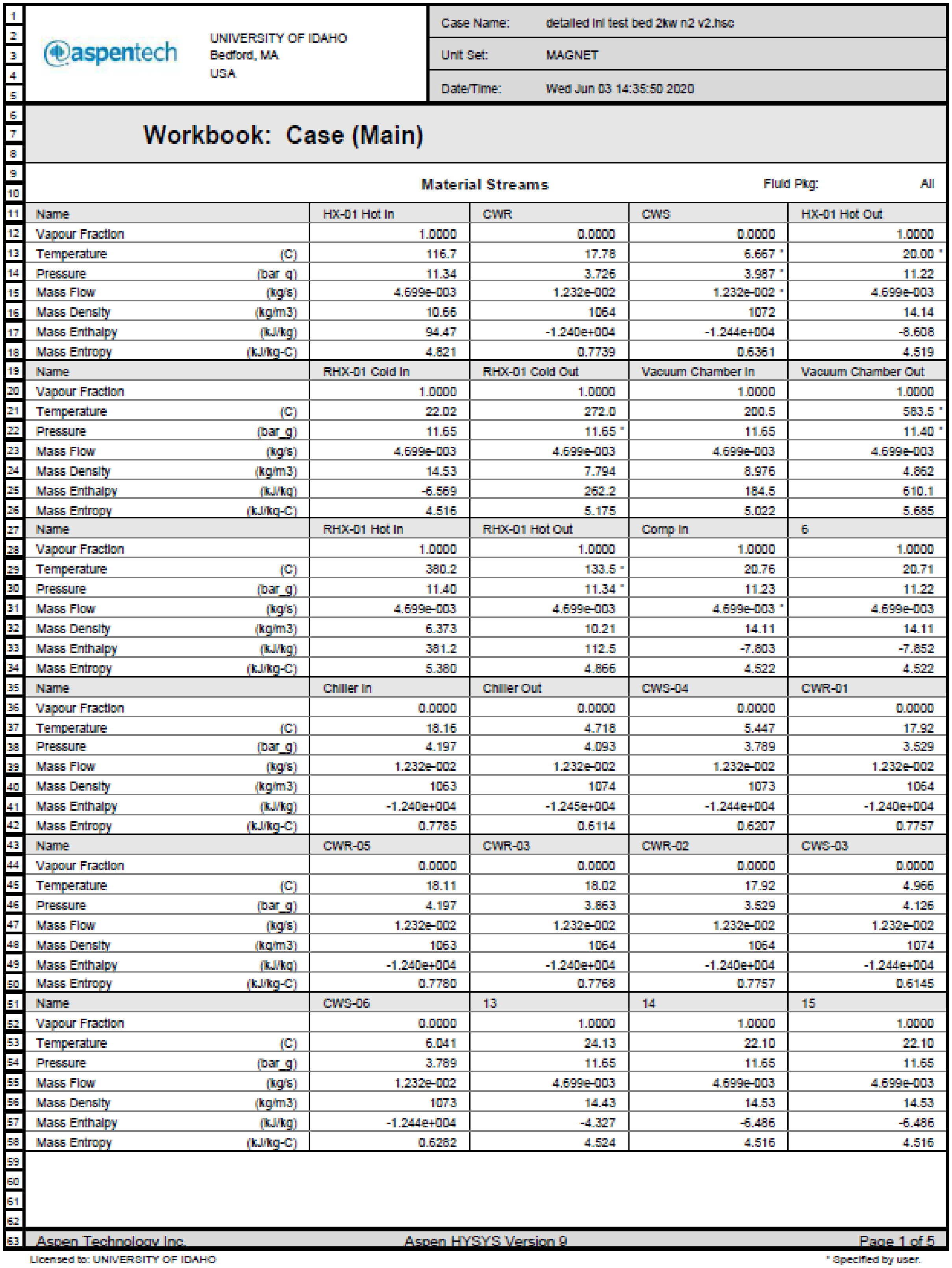
Aspen HYSYS Process Model of Microreactor AGile Non-nuclear Experimental Testbed with Heat Pipe Heat Exchanger using Nitrogen Operating at 600°C and 2 kW of Heat Pipe Power





UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed inl test bed 2kw n2 v2.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:35:50 2020

Workbook: Case (Main)

Material Streams Fluid Pkg: All

Name		HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Vapour Fraction		1.0000	0.0000	0.0000	1.0000
Temperature	(C)	116.7	17.78	6.667 *	20.00 *
Pressure	(bar_g)	11.34	3.726	3.987 *	11.22
Mass Flow	(kg/s)	4.699e-003	1.232e-002	1.232e-002 *	4.699e-003
Mass Density	(kg/m3)	10.66	1064	1072	14.14
Mass Enthalpy	(kJ/kg)	94.47	-1.240e+004	-1.244e+004	-8.608
Mass Entropy	(kJ/kg-C)	4.821	0.7739	0.6361	4.519
Name		RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Vapour Fraction		1.0000	1.0000	1.0000	1.0000
Temperature	(C)	22.02	272.0	200.5	583.5 *
Pressure	(bar_g)	11.65	11.65 *	11.65	11.40 *
Mass Flow	(kg/s)	4.699e-003	4.699e-003	4.699e-003	4.699e-003
Mass Density	(kg/m3)	14.53	7.794	8.976	4.862
Mass Enthalpy	(kJ/kg)	-6.569	262.2	184.5	610.1
Mass Entropy	(kJ/kg-C)	4.516	5.175	5.022	5.685
Name		RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Vapour Fraction		1.0000	1.0000	1.0000	1.0000
Temperature	(C)	380.2	133.5 *	20.76	20.71
Pressure	(bar_g)	11.40	11.34 *	11.23	11.22
Mass Flow	(kg/s)	4.699e-003	4.699e-003	4.699e-003 *	4.699e-003
Mass Density	(kg/m3)	6.373	10.21	14.11	14.11
Mass Enthalpy	(kJ/kg)	381.2	112.5	-7.803	-7.852
Mass Entropy	(kJ/kg-C)	5.380	4.866	4.522	4.522
Name		Chiller In	Chiller Out	CWS-04	CWR-01
Vapour Fraction		0.0000	0.0000	0.0000	0.0000
Temperature	(C)	18.16	4.718	5.447	17.92
Pressure	(bar_g)	4.197	4.093	3.789	3.529
Mass Flow	(kg/s)	1.232e-002	1.232e-002	1.232e-002	1.232e-002
Mass Density	(kg/m3)	1063	1074	1073	1064
Mass Enthalpy	(kJ/kg)	-1.240e+004	-1.245e+004	-1.244e+004	-1.240e+004
Mass Entropy	(kJ/kg-C)	0.7785	0.6114	0.6207	0.7757
Name		CWR-05	CWR-03	CWR-02	CWS-03
Vapour Fraction		0.0000	0.0000	0.0000	0.0000
Temperature	(C)	18.11	18.02	17.92	4.966
Pressure	(bar_g)	4.197	3.863	3.529	4.126
Mass Flow	(kg/s)	1.232e-002	1.232e-002	1.232e-002	1.232e-002
Mass Density	(kg/m3)	1063	1064	1064	1074
Mass Enthalpy	(kJ/kg)	-1.240e+004	-1.240e+004	-1.240e+004	-1.244e+004
Mass Entropy	(kJ/kg-C)	0.7780	0.7768	0.7757	0.6145
Name		CWS-06	13	14	15
Vapour Fraction		0.0000	1.0000	1.0000	1.0000
Temperature	(C)	6.041	24.13	22.10	22.10
Pressure	(bar_g)	3.789	11.65	11.65	11.65
Mass Flow	(kg/s)	1.232e-002	4.699e-003	4.699e-003	4.699e-003
Mass Density	(kg/m3)	1073	14.43	14.53	14.53
Mass Enthalpy	(kJ/kg)	-1.244e+004	-4.327	-6.486	-6.486
Mass Entropy	(kJ/kg-C)	0.6282	4.524	4.516	4.516

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Case Name:	detailed inl test bed 2kw n2 v2.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:35:50 2020

Workbook: Case (Main) (continued)

Material Streams (continued)

Fluid Pkg: All

Name		16	Comp Out	4-2	Heat Pipe Condensor
Vapour Fraction		1.0000	1.0000	1.0000	0.0000 *
Temperature	(C)	20.71	24.60	24.13	650.0
Pressure	(bar_g)	11.22	11.65 *	11.65	-0.9475
Mass Flow	(kg/s)	4.699e-003	4.699e-003	4.699e-003	4.866e-004
Mass Density	(kg/m3)	14.11	14.40	14.43	799.6
Mass Enthalpy	(kJ/kg)	-7.852	-3.831	-4.327	-5902
Mass Entropy	(kJ/kg-C)	4.522	4.525	4.524	53.39
Name		**CWS-01**	**CWS-02**	**CWR-04**	**CWS-05**
Vapour Fraction		0.0000	0.0000	0.0000	0.0000
Temperature	(C)	4.718	4.966	18.11	6.041
Pressure	(bar_g)	4.126	4.126	4.197	3.789
Mass Flow	(kg/s)	1.232e-002	1.232e-002	1.232e-002	1.232e-002
Mass Density	(kg/m3)	1074	1074	1063	1073
Mass Enthalpy	(kJ/kg)	-1.245e+004	-1.244e+004	-1.240e+004	-1.244e+004
Mass Entropy	(kJ/kg-C)	0.6114	0.6145	0.7780	0.6282
Name		**Heat Pipe Evaporator**			
Vapour Fraction		1.0000 *			
Temperature	(C)	650.0 *			
Pressure	(bar_g)	-0.9475			
Mass Flow	(kg/s)	4.866e-004			
Mass Density	(kg/m3)	1.972e-002			
Mass Enthalpy	(kJ/kg)	-1791			
Mass Entropy	(kJ/kg-C)	58.21			

Compositions

Fluid Pkg: All

Name	HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Master Comp Mass Frac (Nitrogen)	1.0000 *	***	***	1.0000
Master Comp Mass Frac (EGlycol)	***	0.4073	0.4073	***
Master Comp Mass Frac (H2O)	***	0.5927	0.5927	***
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	**RHX-01 Cold In**	**RHX-01 Cold Out**	**Vacuum Chamber In**	**Vacuum Chamber Out**
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	**RHX-01 Hot In**	**RHX-01 Hot Out**	**Comp In**	**6**
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000 *	1.0000
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	**Chiller In**	**Chiller Out**	**CWS-04**	**CWR-01**
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (EGlycol)	0.4073 *	0.4073	0.4073	0.4073
Master Comp Mass Frac (H2O)	0.5927 *	0.5927	0.5927	0.5927
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	**CWR-05**	**CWR-03**	**CWR-02**	**CWS-03**
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (EGlycol)	0.4073	0.4073	0.4073	0.4073
Master Comp Mass Frac (H2O)	0.5927	0.5927	0.5927	0.5927
Master Comp Mass Frac (Sodium*)	***	***	***	***

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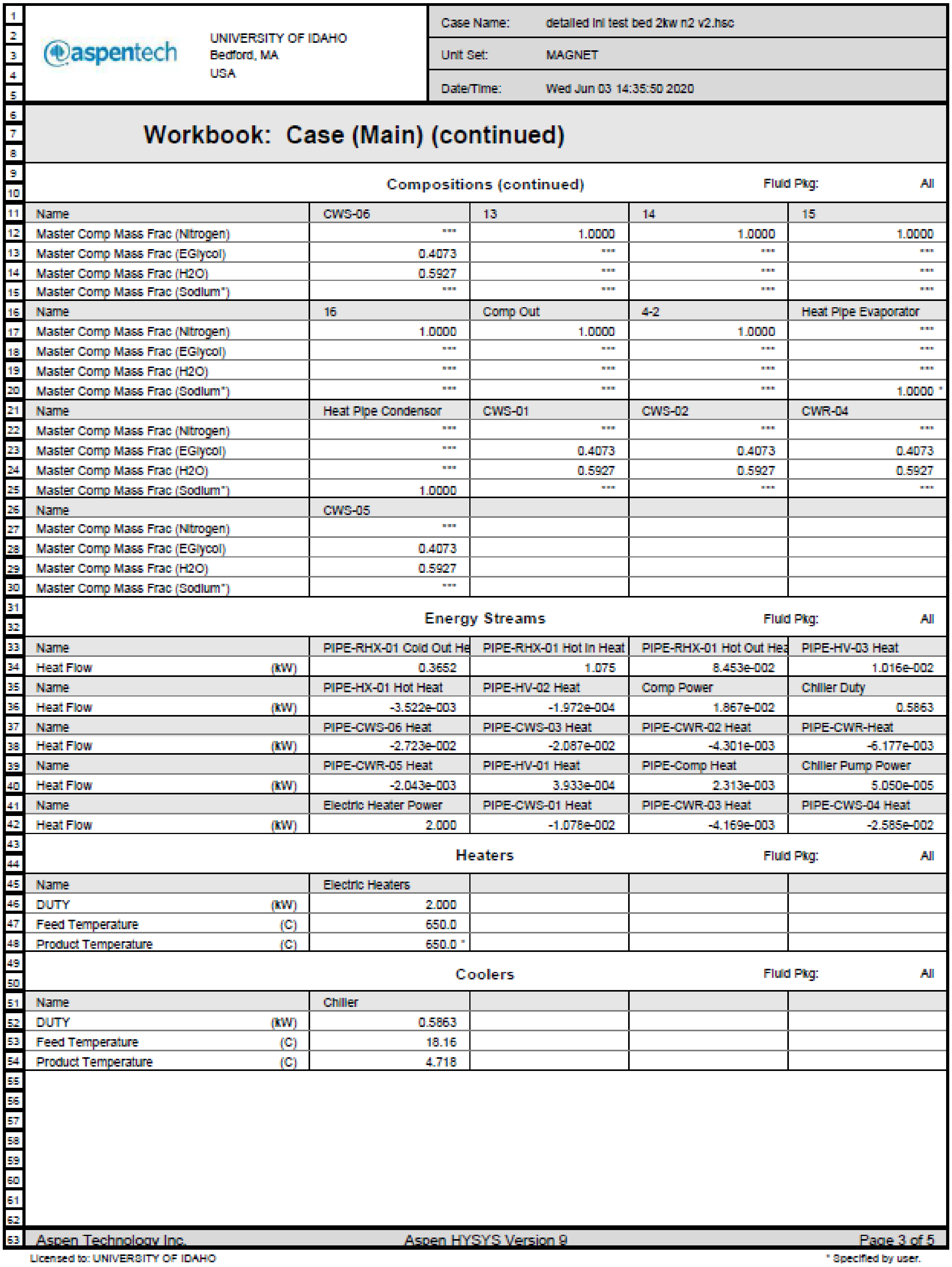

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Case Name:	detailed inl test bed 2kw n2 v2.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:35:50 2020

Workbook: Case (Main) (continued)

Compositions (continued)

Fluid Pkg: All

Name	CWS-06	13	14	15
Master Comp Mass Frac (Nitrogen)	***	1.0000	1.0000	1.0000
Master Comp Mass Frac (EGlycol)	0.4073	***	***	***
Master Comp Mass Frac (H2O)	0.5927	***	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	***
Name	16	Comp Out	4-2	Heat Pipe Evaporator
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000	***
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Master Comp Mass Frac (Sodium*)	***	***	***	1.0000 *
Name	Heat Pipe Condensor	CWS-01	CWS-02	CWR-04
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (EGlycol)	***	0.4073	0.4073	0.4073
Master Comp Mass Frac (H2O)	***	0.5927	0.5927	0.5927
Master Comp Mass Frac (Sodium*)	1.0000	***	***	***
Name	CWS-05			
Master Comp Mass Frac (Nitrogen)	***			
Master Comp Mass Frac (EGlycol)	0.4073			
Master Comp Mass Frac (H2O)	0.5927			
Master Comp Mass Frac (Sodium*)	***			

Energy Streams

Fluid Pkg: All

Name	PIPE-RHX-01 Cold Out He	PIPE-RHX-01 Hot In Heat	PIPE-RHX-01 Hot Out Hea	PIPE-HV-03 Heat
Heat Flow (kW)	0.3652	1.075	8.453e-002	1.016e-002
Name	PIPE-HX-01 Hot Heat	PIPE-HV-02 Heat	Comp Power	Chiller Duty
Heat Flow (kW)	-3.522e-003	-1.972e-004	1.867e-002	0.5863
Name	PIPE-CWS-06 Heat	PIPE-CWS-03 Heat	PIPE-CWR-02 Heat	PIPE-CWR-Heat
Heat Flow (kW)	-2.723e-002	-2.087e-002	-4.301e-003	-6.177e-003
Name	PIPE-CWR-05 Heat	PIPE-HV-01 Heat	PIPE-Comp Heat	Chiller Pump Power
Heat Flow (kW)	-2.043e-003	3.933e-004	2.313e-003	5.050e-005
Name	Electric Heater Power	PIPE-CWS-01 Heat	PIPE-CWR-03 Heat	PIPE-CWS-04 Heat
Heat Flow (kW)	2.000	-1.078e-002	-4.169e-003	-2.585e-002

Heaters

Fluid Pkg: All

Name	Electric Heaters			
DUTY (kW)	2.000			
Feed Temperature (C)	650.0			
Product Temperature (C)	650.0 *			

Coolers

Fluid Pkg: All

Name	Chiller			
DUTY (kW)	0.5863			
Feed Temperature (C)	18.16			
Product Temperature (C)	4.716			

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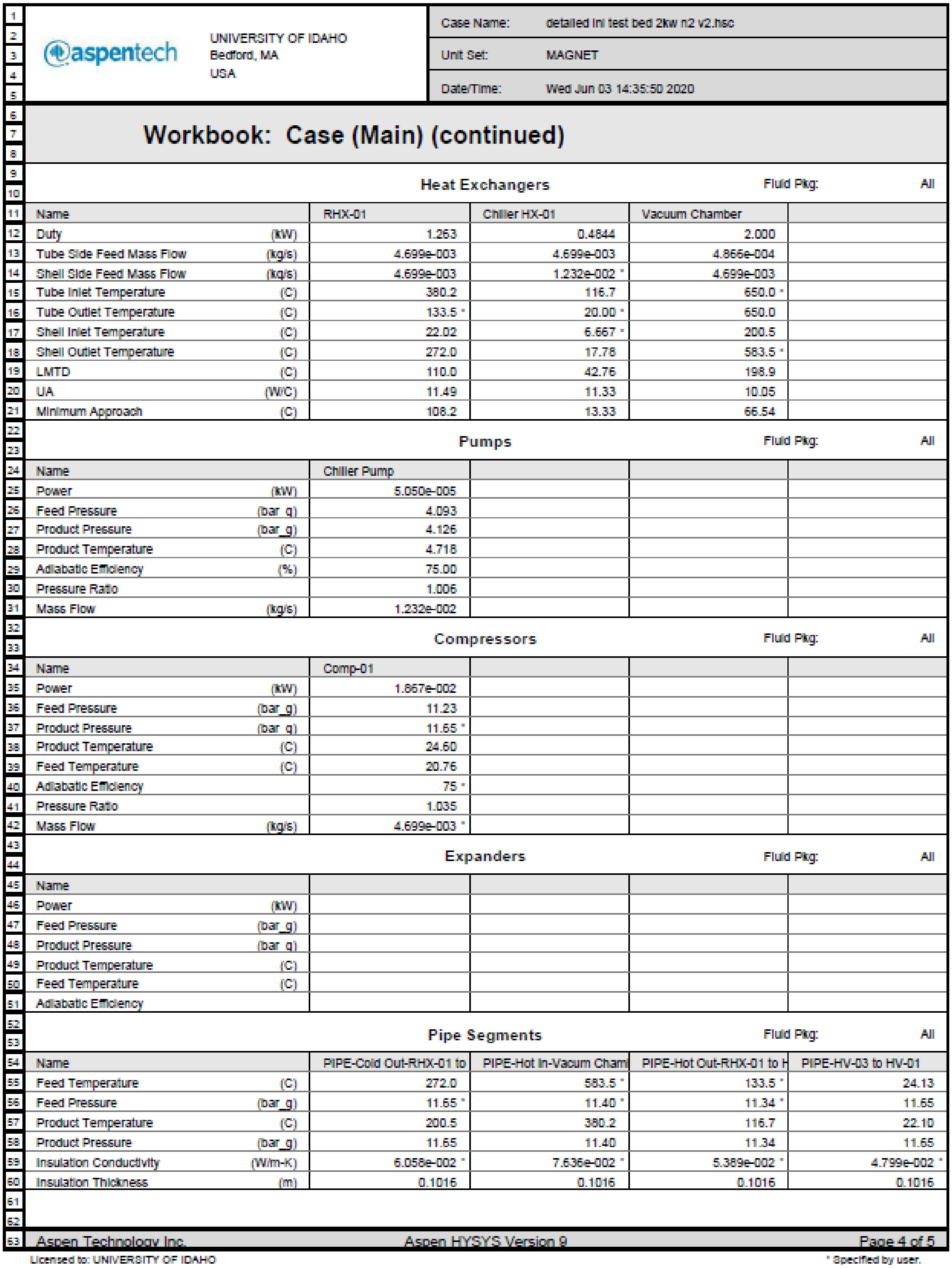

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Case Name:	detailed inl test bed 2kw n2 v2.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:35:50 2020

Workbook: Case (Main) (continued)

Heat Exchangers

Fluid Pkg: All

Name	RHX-01	Chiller HX-01	Vacuum Chamber	
Duty (kW)	1.263	0.4844	2.000	
Tube Side Feed Mass Flow (kg/s)	4.699e-003	4.699e-003	4.866e-004	
Shell Side Feed Mass Flow (kg/s)	4.699e-003	1.232e-002 *	4.699e-003	
Tube Inlet Temperature (C)	380.2	116.7	650.0 *	
Tube Outlet Temperature (C)	133.5 *	20.00 *	650.0	
Shell Inlet Temperature (C)	22.02	6.667 *	200.5	
Shell Outlet Temperature (C)	272.0	17.78	583.5 *	
LMTD (C)	110.0	42.76	198.9	
UA (W/C)	11.49	11.33	10.05	
Minimum Approach (C)	108.2	13.33	66.54	

Pumps

Fluid Pkg: All

Name	Chiller Pump			
Power (kW)	5.050e-005			
Feed Pressure (bar_g)	4.093			
Product Pressure (bar_g)	4.126			
Product Temperature (C)	4.718			
Adiabatic Efficiency (%)	75.00			
Pressure Ratio	1.006			
Mass Flow (kg/s)	1.232e-002			

Compressors

Fluid Pkg: All

Name	Comp-01			
Power (kW)	1.867e-002			
Feed Pressure (bar_g)	11.23			
Product Pressure (bar_g)	11.65 *			
Product Temperature (C)	24.60			
Feed Temperature (C)	20.76			
Adiabatic Efficiency	75 *			
Pressure Ratio	1.035			
Mass Flow (kg/s)	4.699e-003 *			

Expanders

Fluid Pkg: All

Name				
Power (kW)				
Feed Pressure (bar_g)				
Product Pressure (bar_g)				
Product Temperature (C)				
Feed Temperature (C)				
Adiabatic Efficiency				

Pipe Segments

Fluid Pkg: All

Name	PIPE-Cold Out-RHX-01 to	PIPE-Hot In-Vacum Cham	PIPE-Hot Out-RHX-01 to H	PIPE-HV-03 to HV-01
Feed Temperature (C)	272.0	583.5 *	133.5 *	24.13
Feed Pressure (bar_g)	11.65 *	11.40 *	11.34 *	11.65
Product Temperature (C)	200.5	380.2	116.7	22.10
Product Pressure (bar_g)	11.65	11.40	11.34	11.65
Insulation Conductivity (W/m-K)	6.058e-002 *	7.636e-002 *	5.389e-002 *	4.799e-002 *
Insulation Thickness (m)	0.1016	0.1016	0.1016	0.1016

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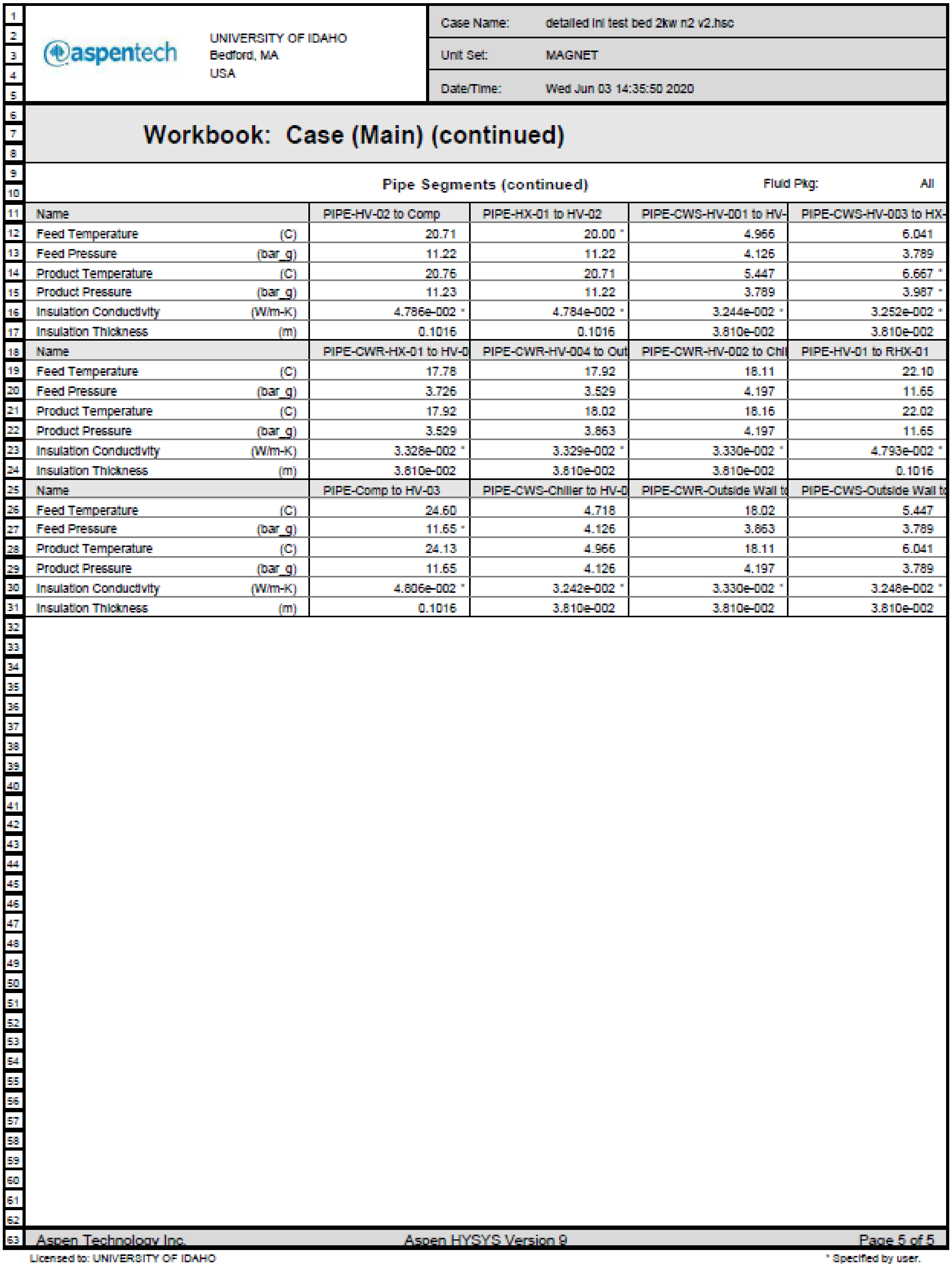

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Case Name: detailed inl test bed 2kw n2 v2.hsc

Unit Set: MAGNET

Date/Time: Wed Jun 03 14:35:50 2020

Workbook: Case (Main) (continued)

Pipe Segments (continued)

Fluid Pkg: All

Name		PIPE-HV-02 to Comp	PIPE-HX-01 to HV-02	PIPE-CWS-HV-001 to HV-	PIPE-CWS-HV-003 to HX-
Feed Temperature	(C)	20.71	20.00 *	4.966	6.041
Feed Pressure	(bar_g)	11.22	11.22	4.126	3.789
Product Temperature	(C)	20.76	20.71	5.447	6.667 *
Product Pressure	(bar_g)	11.23	11.22	3.789	3.987 *
Insulation Conductivity	(W/m-K)	4.786e-002 *	4.784e-002 *	3.244e-002 *	3.252e-002 *
Insulation Thickness	(m)	0.1016	0.1016	3.810e-002	3.810e-002
Name		PIPE-CWR-HX-01 to HV-0	PIPE-CWR-HV-004 to Out	PIPE-CWR-HV-002 to Chil	PIPE-HV-01 to RHX-01
Feed Temperature	(C)	17.78	17.92	18.11	22.10
Feed Pressure	(bar_g)	3.726	3.529	4.197	11.65
Product Temperature	(C)	17.92	18.02	18.16	22.02
Product Pressure	(bar_g)	3.529	3.863	4.197	11.65
Insulation Conductivity	(W/m-K)	3.328e-002 *	3.329e-002 *	3.330e-002 *	4.793e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	3.810e-002	0.1016
Name		PIPE-Comp to HV-03	PIPE-CWS-Chiller to HV-0	PIPE-CWR-Outside Wall to	PIPE-CWS-Outside Wall to
Feed Temperature	(C)	24.60	4.718	18.02	5.447
Feed Pressure	(bar_g)	11.65 *	4.126	3.863	3.789
Product Temperature	(C)	24.13	4.966	18.11	6.041
Product Pressure	(bar_g)	11.65	4.126	4.197	3.789
Insulation Conductivity	(W/m-K)	4.806e-002 *	3.242e-002 *	3.330e-002 *	3.248e-002 *
Insulation Thickness	(m)	0.1016	3.810e-002	3.810e-002	3.810e-002

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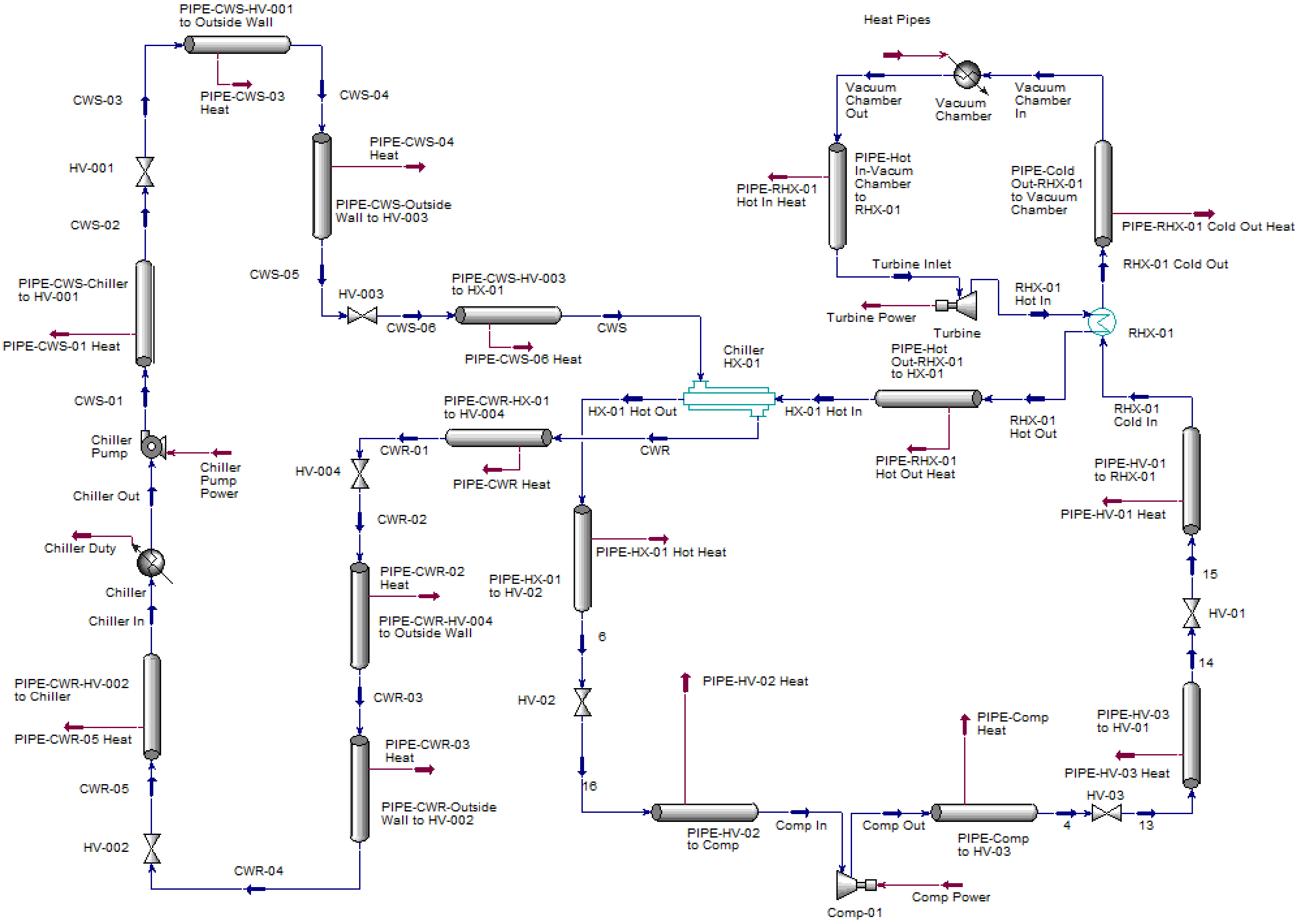
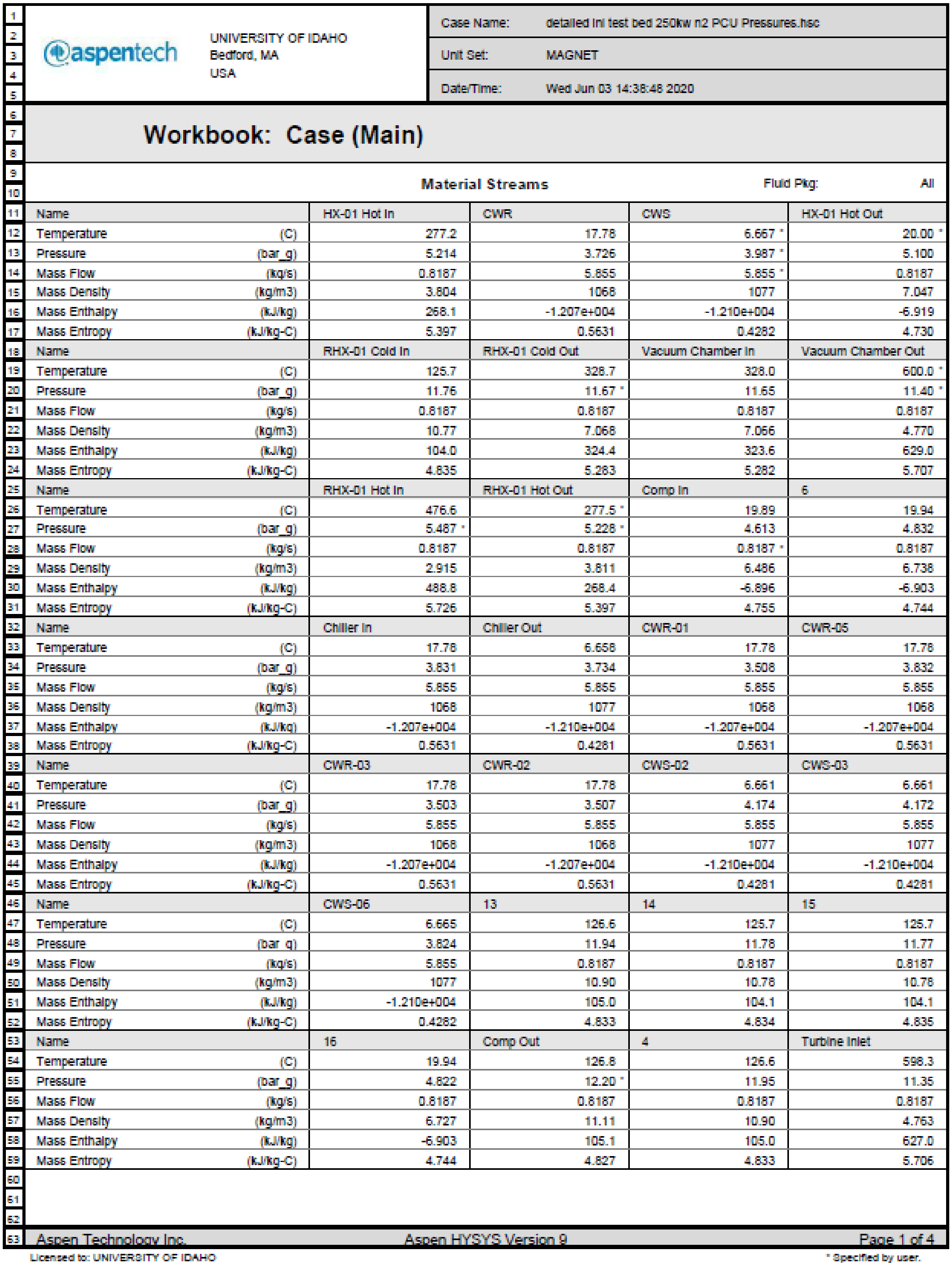
Appendix C: Aspen HYSYS Models for the Microreactor AGile Non-nuclear Experimental Testbed PCU Units

Aspen HYSYS Process Model of Microreactor AGile Non-nuclear Experimental Testbed with PCU using Nitrogen Operating at 600°C and 250 kW of Heat Pipe Power





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Case Name:	detailed inl test bed 250kw n2 PCU Pressures.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:38:48 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Temperature	(C)	277.2	17.78	6.667 *	20.00 *
Pressure	(bar_g)	5.214	3.726	3.987 *	5.100
Mass Flow	(kg/s)	0.8187	5.855	5.855 *	0.8187
Mass Density	(kg/m3)	3.804	1068	1077	7.047
Mass Enthalpy	(kJ/kg)	268.1	-1.207e+004	-1.210e+004	-6.919
Mass Entropy	(kJ/kg-C)	5.397	0.5631	0.4282	4.730
Name		RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Temperature	(C)	125.7	328.7	328.0	600.0 *
Pressure	(bar_g)	11.76	11.67 *	11.65	11.40 *
Mass Flow	(kg/s)	0.8187	0.8187	0.8187	0.8187
Mass Density	(kg/m3)	10.77	7.068	7.066	4.770
Mass Enthalpy	(kJ/kg)	104.0	324.4	323.6	629.0
Mass Entropy	(kJ/kg-C)	4.835	5.283	5.282	5.707
Name		RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Temperature	(C)	476.6	277.5 *	19.89	19.94
Pressure	(bar_g)	5.487 *	5.228 *	4.613	4.832
Mass Flow	(kg/s)	0.8187	0.8187	0.8187 *	0.8187
Mass Density	(kg/m3)	2.915	3.811	6.486	6.738
Mass Enthalpy	(kJ/kg)	488.8	268.4	-6.896	-6.903
Mass Entropy	(kJ/kg-C)	5.726	5.397	4.755	4.744
Name		Chiller In	Chiller Out	CWR-01	CWR-05
Temperature	(C)	17.78	6.658	17.78	17.78
Pressure	(bar_g)	3.831	3.734	3.508	3.832
Mass Flow	(kg/s)	5.855	5.855	5.855	5.855
Mass Density	(kg/m3)	1068	1077	1068	1068
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.210e+004	-1.207e+004	-1.207e+004
Mass Entropy	(kJ/kg-C)	0.5631	0.4281	0.5631	0.5631
Name		CWR-03	CWR-02	CWS-02	CWS-03
Temperature	(C)	17.78	17.78	6.661	6.661
Pressure	(bar_g)	3.503	3.507	4.174	4.172
Mass Flow	(kg/s)	5.855	5.855	5.855	5.855
Mass Density	(kg/m3)	1068	1068	1077	1077
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.207e+004	-1.210e+004	-1.210e+004
Mass Entropy	(kJ/kg-C)	0.5631	0.5631	0.4281	0.4281
Name		CWS-06	13	14	15
Temperature	(C)	6.665	126.6	125.7	125.7
Pressure	(bar_g)	3.824	11.94	11.78	11.77
Mass Flow	(kg/s)	5.855	0.8187	0.8187	0.8187
Mass Density	(kg/m3)	1077	10.90	10.78	10.78
Mass Enthalpy	(kJ/kg)	-1.210e+004	105.0	104.1	104.1
Mass Entropy	(kJ/kg-C)	0.4282	4.833	4.834	4.835
Name		16	Comp Out	4	Turbine Inlet
Temperature	(C)	19.94	126.8	126.6	598.3
Pressure	(bar_g)	4.822	12.20 *	11.95	11.35
Mass Flow	(kg/s)	0.8187	0.8187	0.8187	0.8187
Mass Density	(kg/m3)	6.727	11.11	10.90	4.763
Mass Enthalpy	(kJ/kg)	-6.903	105.1	105.0	627.0
Mass Entropy	(kJ/kg-C)	4.744	4.827	4.833	5.706

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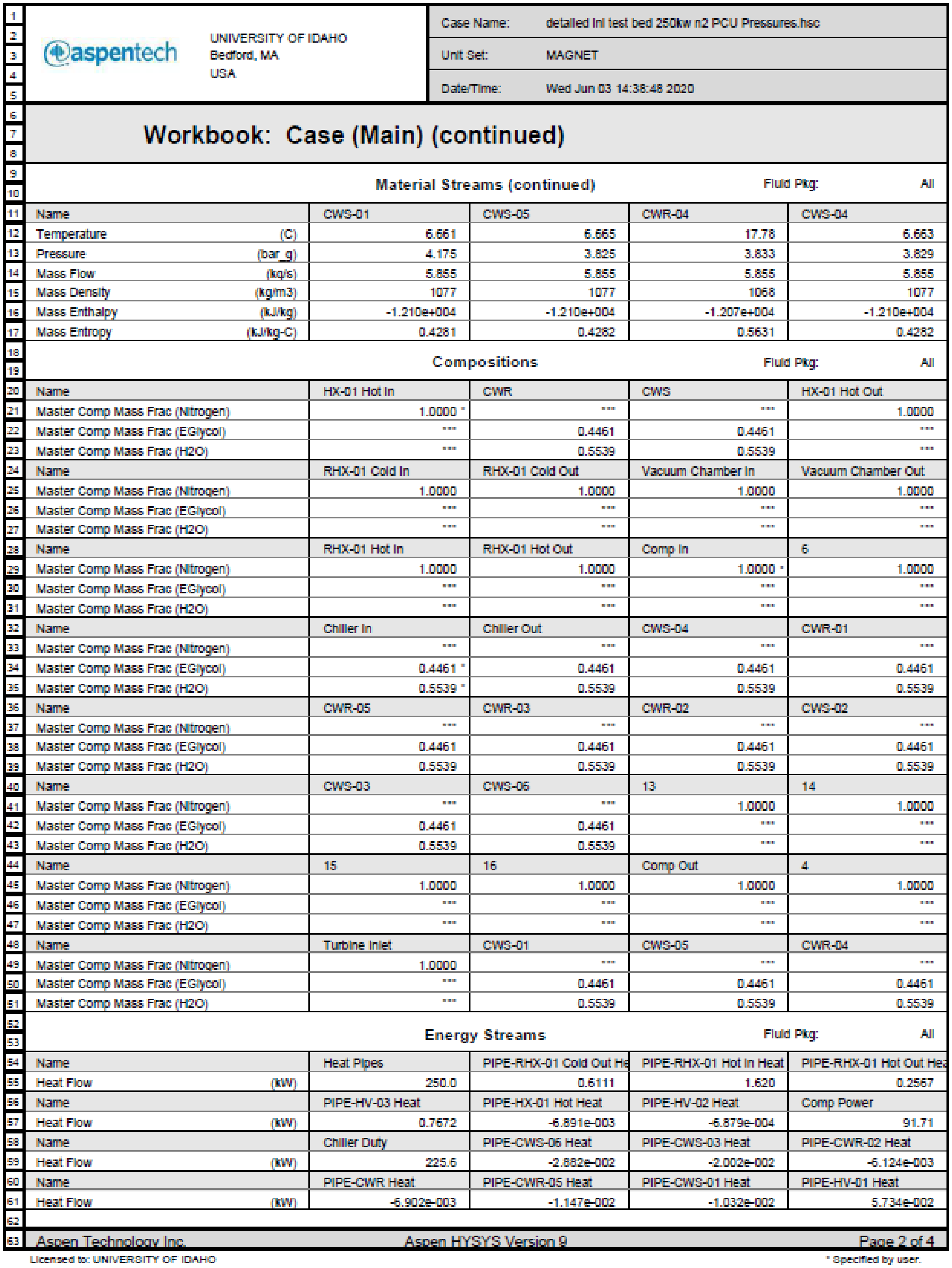

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Case Name:	detailed inl test bed 250kw n2 PCU Pressures.hsc
Unit Set:	MAGNET
Date/Time:	Wed Jun 03 14:38:48 2020

Workbook: Case (Main) (continued)

Material Streams (continued)

Fluid Pkg: All

Name	CWS-01	CWS-05	CWR-04	CWS-04
Temperature (C)	6.661	6.665	17.78	6.663
Pressure (bar_g)	4.175	3.825	3.833	3.829
Mass Flow (kg/s)	5.855	5.855	5.855	5.855
Mass Density (kg/m3)	1077	1077	1068	1077
Mass Enthalpy (kJ/kg)	-1.210e+004	-1.210e+004	-1.207e+004	-1.210e+004
Mass Entropy (kJ/kg-C)	0.4281	0.4282	0.5631	0.4282

Compositions

Fluid Pkg: All

Name	HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Master Comp Mass Frac (Nitrogen)	1.0000 *	***	***	1.0000
Master Comp Mass Frac (EGlycol)	***	0.4461	0.4461	***
Master Comp Mass Frac (H2O)	***	0.5539	0.5539	***
Name	RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Name	RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000 *	1.0000
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Name	Chiller In	Chiller Out	CWS-04	CWR-01
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (EGlycol)	0.4461 *	0.4461	0.4461	0.4461
Master Comp Mass Frac (H2O)	0.5539 *	0.5539	0.5539	0.5539
Name	CWR-05	CWR-03	CWR-02	CWS-02
Master Comp Mass Frac (Nitrogen)	***	***	***	***
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	0.4461	0.4461
Master Comp Mass Frac (H2O)	0.5539	0.5539	0.5539	0.5539
Name	CWS-03	CWS-06	13	14
Master Comp Mass Frac (Nitrogen)	***	***	1.0000	1.0000
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	***	***
Master Comp Mass Frac (H2O)	0.5539	0.5539	***	***
Name	15	16	Comp Out	4
Master Comp Mass Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Name	Turbine Inlet	CWS-01	CWS-05	CWR-04
Master Comp Mass Frac (Nitrogen)	1.0000	***	***	***
Master Comp Mass Frac (EGlycol)	***	0.4461	0.4461	0.4461
Master Comp Mass Frac (H2O)	***	0.5539	0.5539	0.5539

Energy Streams

Fluid Pkg: All

Name	Heat Pipes	PIPE-RHX-01 Cold Out He	PIPE-RHX-01 Hot In Heat	PIPE-RHX-01 Hot Out Hea
Heat Flow (kW)	250.0	0.6111	1.620	0.2567
Name	PIPE-HV-03 Heat	PIPE-HX-01 Hot Heat	PIPE-HV-02 Heat	Comp Power
Heat Flow (kW)	0.7672	-6.891e-003	-6.879e-004	91.71
Name	Chiller Duty	PIPE-CWS-06 Heat	PIPE-CWS-03 Heat	PIPE-CWR-02 Heat
Heat Flow (kW)	225.6	-2.882e-002	-2.002e-002	-6.124e-003
Name	PIPE-CWR Heat	PIPE-CWR-05 Heat	PIPE-CWS-01 Heat	PIPE-HV-01 Heat
Heat Flow (kW)	-6.902e-003	-1.147e-002	-1.032e-002	5.734e-002

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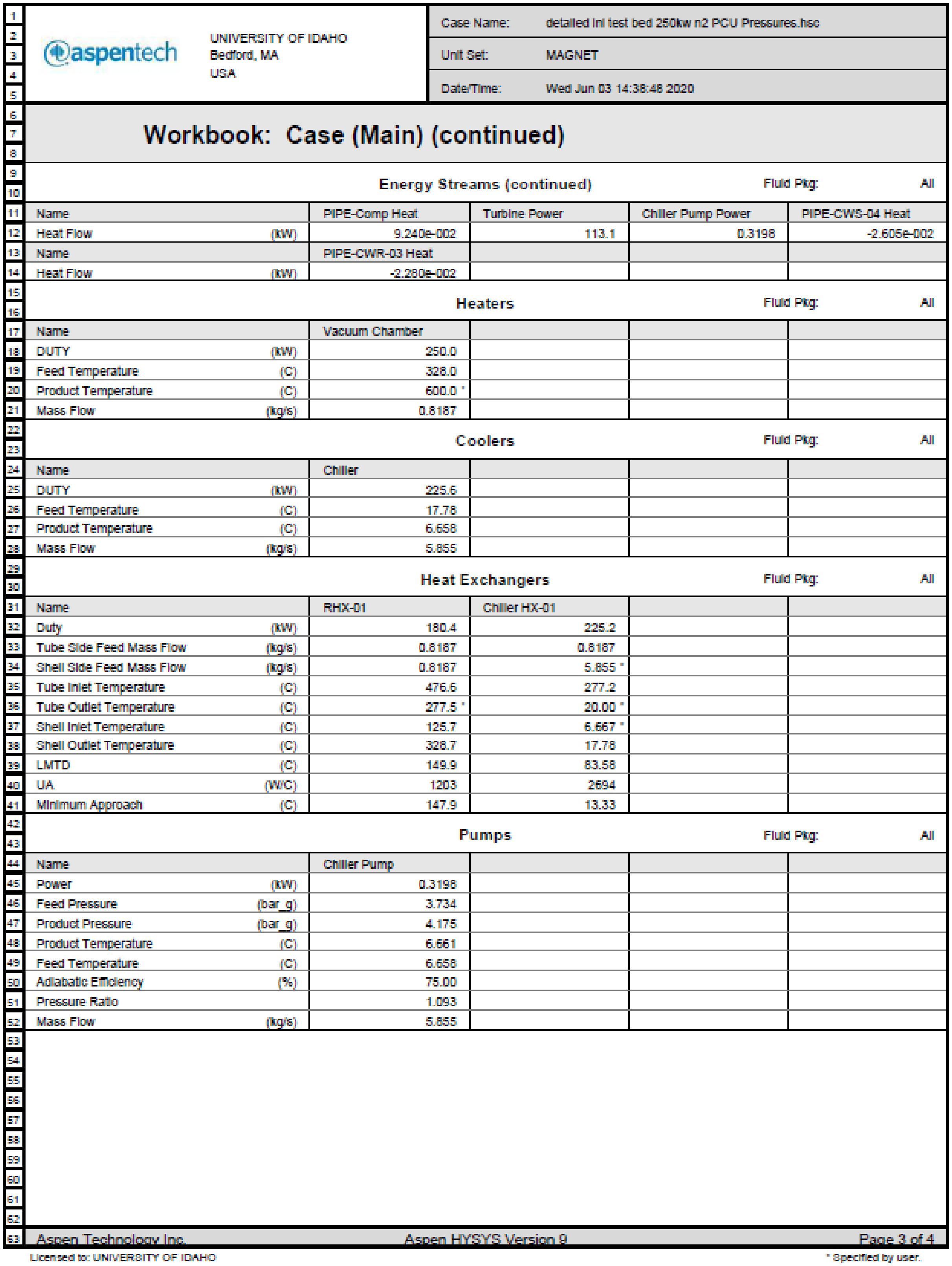

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Case Name: detailed inl test bed 250kw n2 PCU Pressures.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:38:48 2020

Workbook: Case (Main) (continued)

Energy Streams (continued)

Fluid Pkg: All

Name		PIPE-Comp Heat	Turbine Power	Chiller Pump Power	PIPE-CWS-04 Heat
Heat Flow	(kW)	9.240e-002	113.1	0.3198	-2.605e-002
Name		PIPE-CWR-03 Heat			
Heat Flow	(kW)	-2.280e-002			

Heaters

Fluid Pkg: All

Name		Vacuum Chamber			
DUTY	(kW)	250.0			
Feed Temperature	(C)	328.0			
Product Temperature	(C)	600.0 *			
Mass Flow	(kg/s)	0.8167			

Coolers

Fluid Pkg: All

Name		Chiller			
DUTY	(kW)	225.6			
Feed Temperature	(C)	17.78			
Product Temperature	(C)	6.658			
Mass Flow	(kg/s)	5.855			

Heat Exchangers

Fluid Pkg: All

Name		RHX-01	Chiller HX-01		
Duty	(kW)	180.4	225.2		
Tube Side Feed Mass Flow	(kg/s)	0.8167	0.8167		
Shell Side Feed Mass Flow	(kg/s)	0.8167	5.855 *		
Tube Inlet Temperature	(C)	476.6	277.2		
Tube Outlet Temperature	(C)	277.5 *	20.00 *		
Shell Inlet Temperature	(C)	125.7	6.667 *		
Shell Outlet Temperature	(C)	328.7	17.78		
LMTD	(C)	149.9	83.58		
UA	(W/C)	1203	2694		
Minimum Approach	(C)	147.9	13.33		

Pumps

Fluid Pkg: All

Name		Chiller Pump			
Power	(kW)	0.3198			
Feed Pressure	(bar_g)	3.734			
Product Pressure	(bar_g)	4.175			
Product Temperature	(C)	6.661			
Feed Temperature	(C)	6.658			
Adiabatic Efficiency	(%)	75.00			
Pressure Ratio		1.093			
Mass Flow	(kg/s)	5.855			

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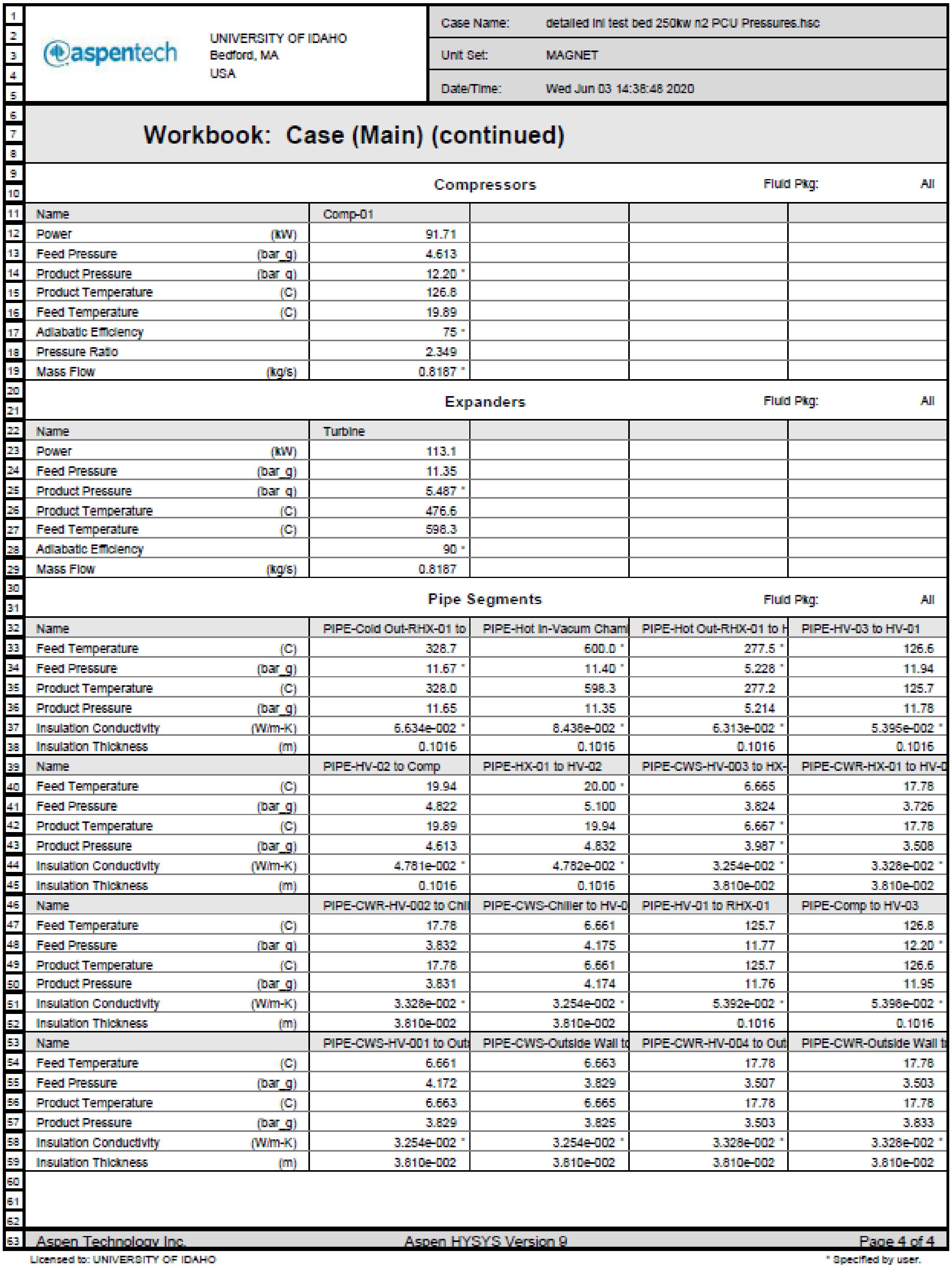

UNIVERSITY OF IDAHO Bedford, MA USA	Case Name: detailed inl test bed 250kw n2 PCU Pressures.hsc
	Unit Set: MAGNET
	Date/Time: Wed Jun 03 14:38:48 2020

Workbook: Case (Main) (continued)

Compressors

Fluid Pkg: All

Name		Comp-01			
Power	(kW)	91.71			
Feed Pressure	(bar_g)	4.613			
Product Pressure	(bar_g)	12.20 *			
Product Temperature	(C)	126.8			
Feed Temperature	(C)	19.89			
Adiabatic Efficiency		75 *			
Pressure Ratio		2.349			
Mass Flow	(kg/s)	0.8187 *			

Expanders

Fluid Pkg: All

Name		Turbine			
Power	(kW)	113.1			
Feed Pressure	(bar_g)	11.35			
Product Pressure	(bar_g)	5.487 *			
Product Temperature	(C)	476.6			
Feed Temperature	(C)	598.3			
Adiabatic Efficiency		90 *			
Mass Flow	(kg/s)	0.8187			

Pipe Segments

Fluid Pkg: All

Name		PIPE-Cold Out-RHX-01 to	PIPE-Hot In-Vacum Chaml	PIPE-Hot Out-RHX-01 to H	PIPE-HV-03 to HV-01
Feed Temperature	(C)	328.7	600.0 *	277.5 *	126.6
Feed Pressure	(bar_g)	11.67 *	11.40 *	5.228 *	11.94
Product Temperature	(C)	328.0	598.3	277.2	125.7
Product Pressure	(bar_g)	11.65	11.35	5.214	11.78
Insulation Conductivity	(W/m-K)	6.634e-002 *	8.438e-002 *	6.313e-002 *	5.395e-002 *
Insulation Thickness	(m)	0.1016	0.1016	0.1016	0.1016
Name		PIPE-HV-02 to Comp	PIPE-HX-01 to HV-02	PIPE-CWS-HV-003 to HX-	PIPE-CWR-HX-01 to HV-0
Feed Temperature	(C)	19.94	20.00 *	6.665	17.78
Feed Pressure	(bar_g)	4.822	5.100	3.824	3.726
Product Temperature	(C)	19.89	19.94	6.667 *	17.78
Product Pressure	(bar_g)	4.613	4.832	3.987 *	3.508
Insulation Conductivity	(W/m-K)	4.781e-002 *	4.782e-002 *	3.254e-002 *	3.328e-002 *
Insulation Thickness	(m)	0.1016	0.1016	3.810e-002	3.810e-002
Name		PIPE-CWR-HV-002 to Chil	PIPE-CWS-Chiller to HV-0	PIPE-HV-01 to RHX-01	PIPE-Comp to HV-03
Feed Temperature	(C)	17.78	6.661	125.7	126.8
Feed Pressure	(bar_g)	3.832	4.175	11.77	12.20 *
Product Temperature	(C)	17.78	6.661	125.7	126.6
Product Pressure	(bar_g)	3.831	4.174	11.76	11.95
Insulation Conductivity	(W/m-K)	3.328e-002 *	3.254e-002 *	5.392e-002 *	5.398e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	0.1016	0.1016
Name		PIPE-CWS-HV-001 to Out	PIPE-CWS-Outside Wall to	PIPE-CWR-HV-004 to Out	PIPE-CWR-Outside Wall t
Feed Temperature	(C)	6.661	6.663	17.78	17.78
Feed Pressure	(bar_g)	4.172	3.829	3.507	3.503
Product Temperature	(C)	6.663	6.665	17.78	17.78
Product Pressure	(bar_g)	3.829	3.825	3.503	3.833
Insulation Conductivity	(W/m-K)	3.254e-002 *	3.254e-002 *	3.328e-002 *	3.328e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	3.810e-002	3.810e-002

Aspen Technology Inc. Aspen HYSYS Version 9 Page 4 of 4

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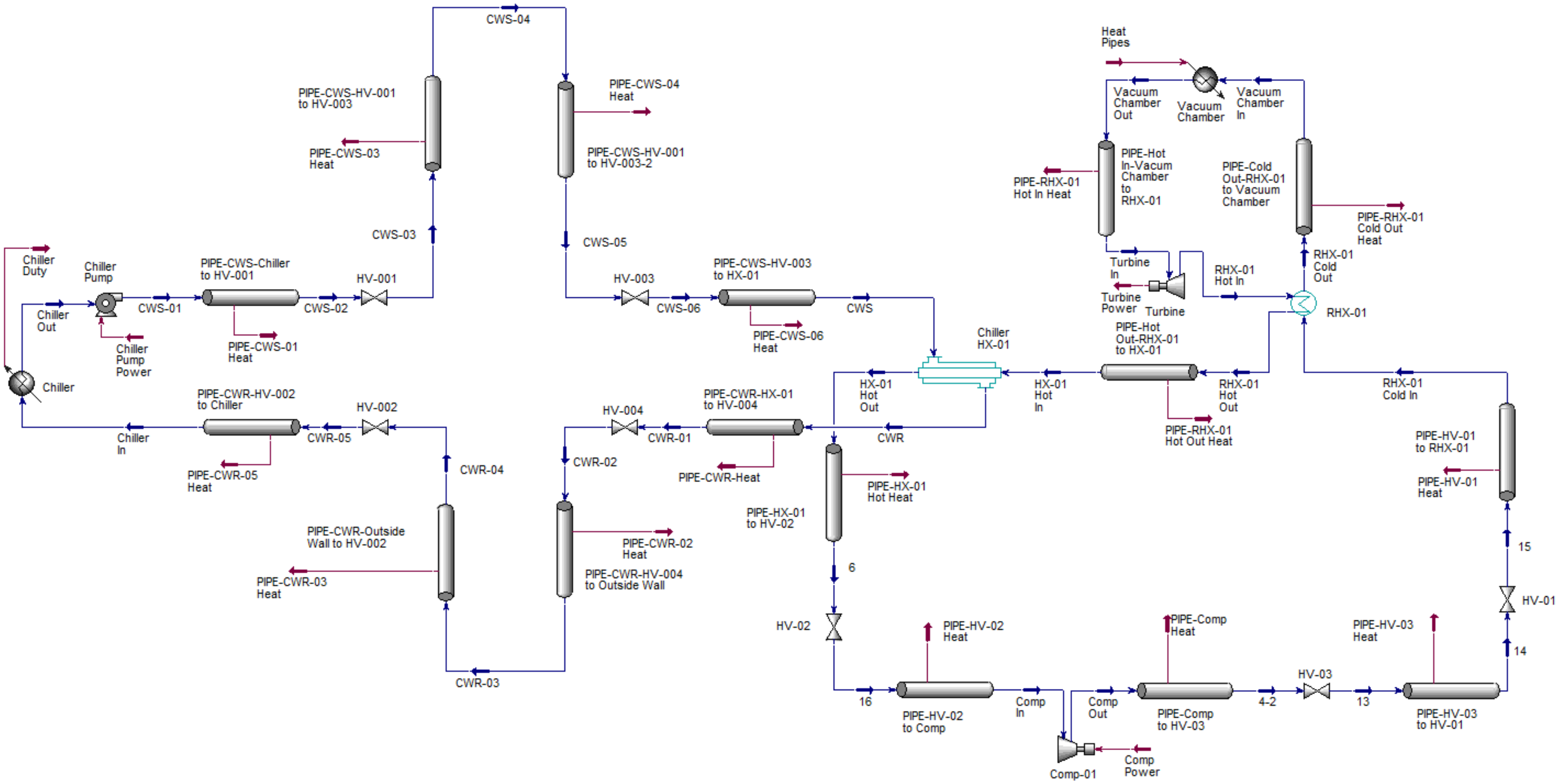
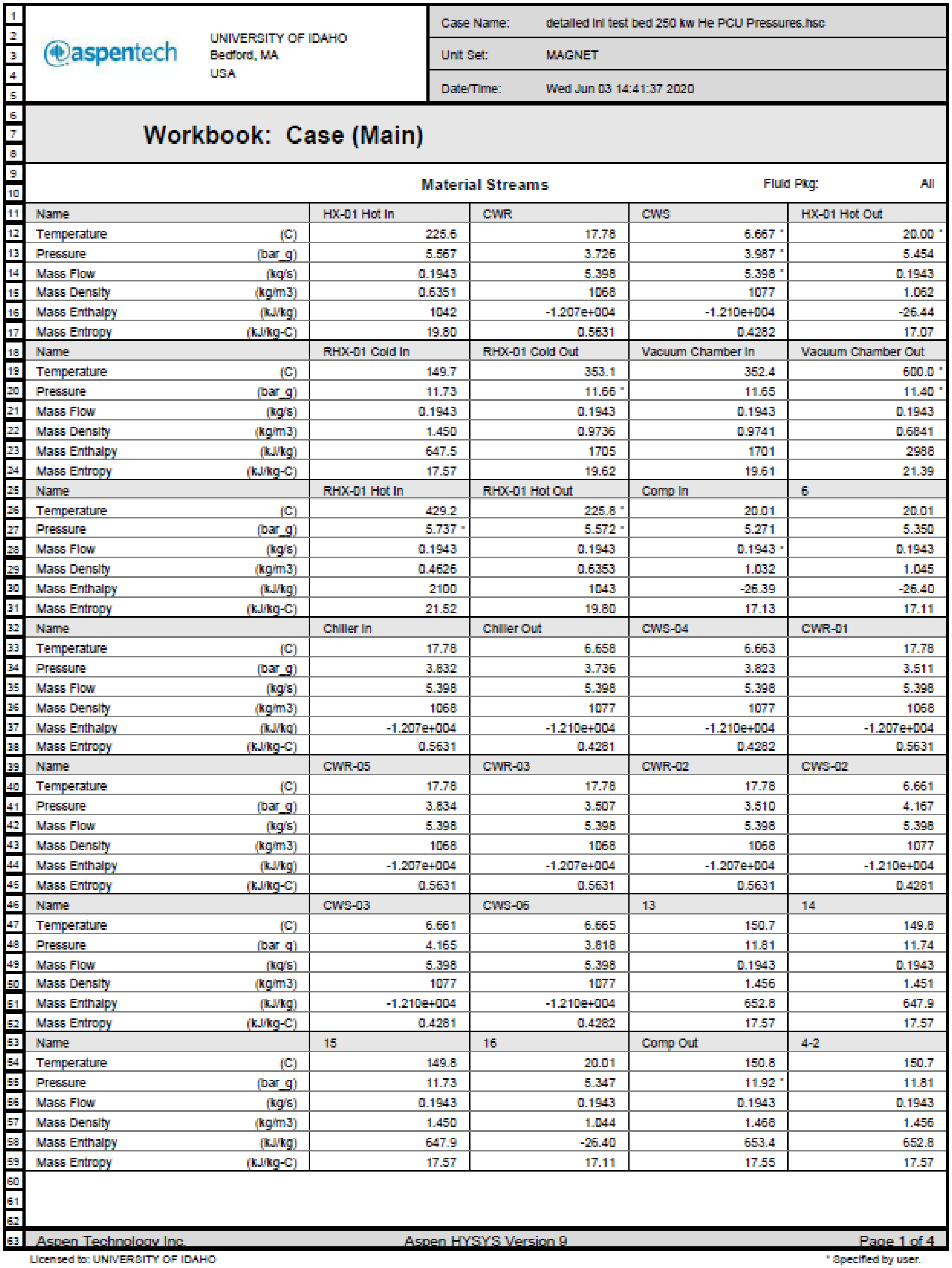
Aspen HYSYS Process Model of Microreactor AGile Non-nuclear Experimental Testbed with PCU using Helium Operating at 600°C and 250 kW of Heat Pipe Power





UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed inl test bed 250 kw He PCU Pressures.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:41:37 2020

Workbook: Case (Main)

Material Streams Fluid Pkg: All

Name		HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Temperature	(C)	225.6	17.78	6.667 *	20.00 *
Pressure	(bar_g)	5.567	3.726	3.987 *	5.454
Mass Flow	(kg/s)	0.1943	5.398	5.398 *	0.1943
Mass Density	(kg/m3)	0.6351	1068	1077	1.062
Mass Enthalpy	(kJ/kg)	1042	-1.207e+004	-1.210e+004	-26.44
Mass Entropy	(kJ/kg-C)	19.80	0.5631	0.4282	17.07
Name		**RHX-01 Cold In**	**RHX-01 Cold Out**	**Vacuum Chamber In**	**Vacuum Chamber Out**
Temperature	(C)	149.7	353.1	352.4	600.0 *
Pressure	(bar_g)	11.73	11.66 *	11.65	11.40 *
Mass Flow	(kg/s)	0.1943	0.1943	0.1943	0.1943
Mass Density	(kg/m3)	1.450	0.9736	0.9741	0.6841
Mass Enthalpy	(kJ/kg)	647.5	1705	1701	2988
Mass Entropy	(kJ/kg-C)	17.57	19.62	19.61	21.39
Name		**RHX-01 Hot In**	**RHX-01 Hot Out**	**Comp In**	**6**
Temperature	(C)	429.2	225.8 *	20.01	20.01
Pressure	(bar_g)	5.737 *	5.572 *	5.271	5.350
Mass Flow	(kg/s)	0.1943	0.1943	0.1943 *	0.1943
Mass Density	(kg/m3)	0.4626	0.6353	1.032	1.045
Mass Enthalpy	(kJ/kg)	2100	1043	-26.39	-26.40
Mass Entropy	(kJ/kg-C)	21.52	19.80	17.13	17.11
Name		**Chiller In**	**Chiller Out**	**CWS-04**	**CWR-01**
Temperature	(C)	17.78	6.658	6.663	17.78
Pressure	(bar_g)	3.832	3.736	3.823	3.511
Mass Flow	(kg/s)	5.398	5.398	5.398	5.398
Mass Density	(kg/m3)	1068	1077	1077	1068
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.210e+004	-1.210e+004	-1.207e+004
Mass Entropy	(kJ/kg-C)	0.5631	0.4281	0.4282	0.5631
Name		**CWR-05**	**CWR-03**	**CWR-02**	**CWS-02**
Temperature	(C)	17.78	17.78	17.78	6.661
Pressure	(bar_g)	3.834	3.507	3.510	4.167
Mass Flow	(kg/s)	5.398	5.398	5.398	5.398
Mass Density	(kg/m3)	1068	1068	1068	1077
Mass Enthalpy	(kJ/kg)	-1.207e+004	-1.207e+004	-1.207e+004	-1.210e+004
Mass Entropy	(kJ/kg-C)	0.5631	0.5631	0.5631	0.4281
Name		**CWS-03**	**CWS-06**	**13**	**14**
Temperature	(C)	6.661	6.665	150.7	149.8
Pressure	(bar_g)	4.165	3.818	11.81	11.74
Mass Flow	(kg/s)	5.398	5.398	0.1943	0.1943
Mass Density	(kg/m3)	1077	1077	1.456	1.451
Mass Enthalpy	(kJ/kg)	-1.210e+004	-1.210e+004	652.8	647.9
Mass Entropy	(kJ/kg-C)	0.4281	0.4282	17.57	17.57
Name		**15**	**16**	**Comp Out**	**4-2**
Temperature	(C)	149.8	20.01	150.8	150.7
Pressure	(bar_g)	11.73	5.347	11.92 *	11.81
Mass Flow	(kg/s)	0.1943	0.1943	0.1943	0.1943
Mass Density	(kg/m3)	1.450	1.044	1.468	1.456
Mass Enthalpy	(kJ/kg)	647.9	-26.40	653.4	652.8
Mass Entropy	(kJ/kg-C)	17.57	17.11	17.55	17.57

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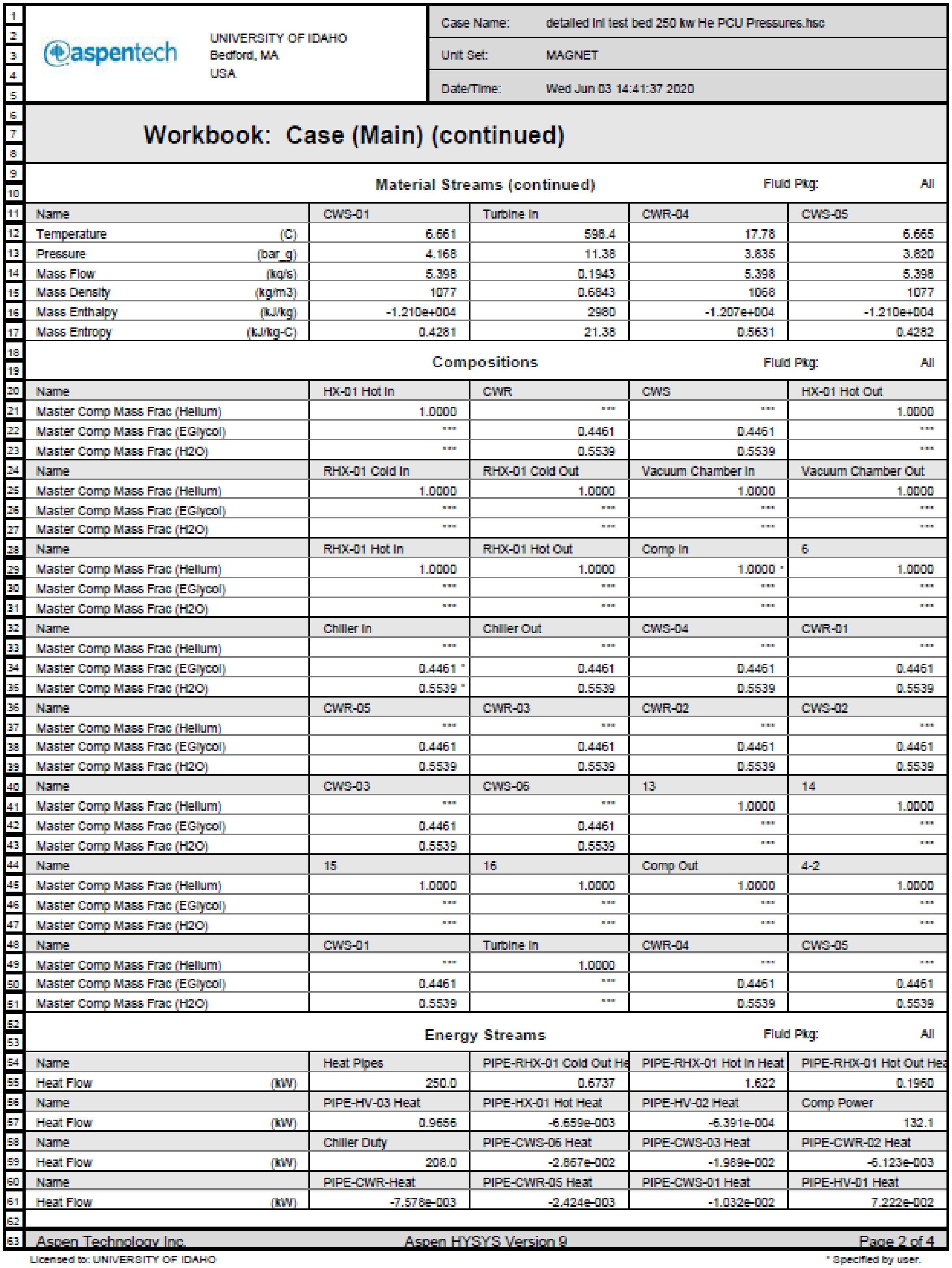

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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed inl test bed 250 kw He PCU Pressures.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:41:37 2020

Workbook: Case (Main) (continued)

Material Streams (continued)

Fluid Pkg: All

Name	CWS-01	Turbine In	CWR-04	CWS-05
Temperature (C)	6.661	598.4	17.78	6.665
Pressure (bar_g)	4.168	11.38	3.835	3.820
Mass Flow (kg/s)	5.398	0.1943	5.398	5.398
Mass Density (kg/m3)	1077	0.6843	1068	1077
Mass Enthalpy (kJ/kg)	-1.210e+004	2980	-1.207e+004	-1.210e+004
Mass Entropy (kJ/kg-C)	0.4281	21.38	0.5631	0.4282

Compositions

Fluid Pkg: All

Name	HX-01 Hot In	CWR	CWS	HX-01 Hot Out
Master Comp Mass Frac (Helium)	1.0000	***	***	1.0000
Master Comp Mass Frac (EGlycol)	***	0.4461	0.4461	***
Master Comp Mass Frac (H2O)	***	0.5539	0.5539	***
Name	RHX-01 Cold In	RHX-01 Cold Out	Vacuum Chamber In	Vacuum Chamber Out
Master Comp Mass Frac (Helium)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Name	RHX-01 Hot In	RHX-01 Hot Out	Comp In	6
Master Comp Mass Frac (Helium)	1.0000	1.0000	1.0000 *	1.0000
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Name	Chiller In	Chiller Out	CWS-04	CWR-01
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (EGlycol)	0.4461 *	0.4461	0.4461	0.4461
Master Comp Mass Frac (H2O)	0.5539 *	0.5539	0.5539	0.5539
Name	CWR-05	CWR-03	CWR-02	CWS-02
Master Comp Mass Frac (Helium)	***	***	***	***
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	0.4461	0.4461
Master Comp Mass Frac (H2O)	0.5539	0.5539	0.5539	0.5539
Name	CWS-03	CWS-06	13	14
Master Comp Mass Frac (Helium)	***	***	1.0000	1.0000
Master Comp Mass Frac (EGlycol)	0.4461	0.4461	***	***
Master Comp Mass Frac (H2O)	0.5539	0.5539	***	***
Name	15	16	Comp Out	4-2
Master Comp Mass Frac (Helium)	1.0000	1.0000	1.0000	1.0000
Master Comp Mass Frac (EGlycol)	***	***	***	***
Master Comp Mass Frac (H2O)	***	***	***	***
Name	CWS-01	Turbine In	CWR-04	CWS-05
Master Comp Mass Frac (Helium)	***	1.0000	***	***
Master Comp Mass Frac (EGlycol)	0.4461	***	0.4461	0.4461
Master Comp Mass Frac (H2O)	0.5539	***	0.5539	0.5539

Energy Streams

Fluid Pkg: All

Name	Heat Pipes	PIPE-RHX-01 Cold Out He	PIPE-RHX-01 Hot In Heat	PIPE-RHX-01 Hot Out Hea
Heat Flow (kW)	250.0	0.6737	1.622	0.1960
Name	PIPE-HV-03 Heat	PIPE-HX-01 Hot Heat	PIPE-HV-02 Heat	Comp Power
Heat Flow (kW)	0.9656	-6.659e-003	-6.391e-004	132.1
Name	Chiller Duty	PIPE-CWS-06 Heat	PIPE-CWS-03 Heat	PIPE-CWR-02 Heat
Heat Flow (kW)	208.0	-2.867e-002	-1.989e-002	-6.123e-003
Name	PIPE-CWR-Heat	PIPE-CWR-05 Heat	PIPE-CWS-01 Heat	PIPE-HV-01 Heat
Heat Flow (kW)	-7.578e-003	-2.424e-003	-1.032e-002	7.222e-002

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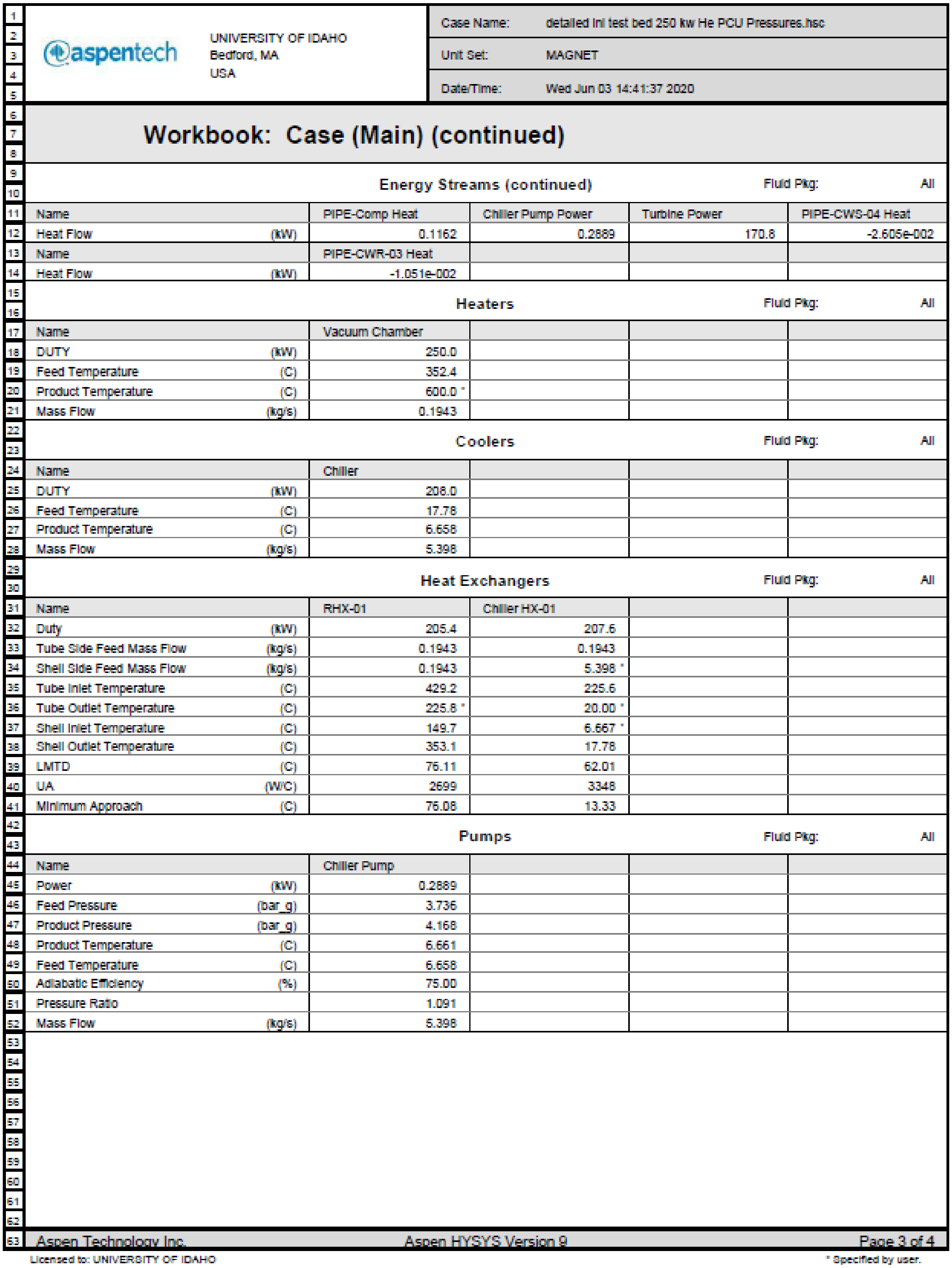

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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed inl test bed 250 kw He PCU Pressures.hsc
Unit Set: MAGNET
Date/Time: Wed Jun 03 14:41:37 2020

Workbook: Case (Main) (continued)

Energy Streams (continued)

Fluid Pkg: All

Name		PIPE-Comp Heat	Chiller Pump Power	Turbine Power	PIPE-CWS-04 Heat
Heat Flow	(kW)	0.1162	0.2889	170.8	-2.605e-002
Name		PIPE-CWR-03 Heat			
Heat Flow	(kW)	-1.051e-002			

Heaters

Fluid Pkg: All

Name		Vacuum Chamber			
DUTY	(kW)	250.0			
Feed Temperature	(C)	352.4			
Product Temperature	(C)	600.0 *			
Mass Flow	(kg/s)	0.1943			

Coolers

Fluid Pkg: All

Name		Chiller			
DUTY	(kW)	208.0			
Feed Temperature	(C)	17.78			
Product Temperature	(C)	6.658			
Mass Flow	(kg/s)	5.398			

Heat Exchangers

Fluid Pkg: All

Name		RHX-01	Chiller HX-01		
Duty	(kW)	205.4	207.6		
Tube Side Feed Mass Flow	(kg/s)	0.1943	0.1943		
Shell Side Feed Mass Flow	(kg/s)	0.1943	5.398 *		
Tube Inlet Temperature	(C)	429.2	225.6		
Tube Outlet Temperature	(C)	225.8 *	20.00 *		
Shell Inlet Temperature	(C)	149.7	6.667 *		
Shell Outlet Temperature	(C)	353.1	17.78		
LMTD	(C)	76.11	62.01		
UA	(W/C)	2699	3348		
Minimum Approach	(C)	76.08	13.33		

Pumps

Fluid Pkg: All

Name		Chiller Pump			
Power	(kW)	0.2889			
Feed Pressure	(bar_g)	3.736			
Product Pressure	(bar_g)	4.168			
Product Temperature	(C)	6.661			
Feed Temperature	(C)	6.658			
Adiabatic Efficiency	(%)	75.00			
Pressure Ratio		1.091			
Mass Flow	(kg/s)	5.398			

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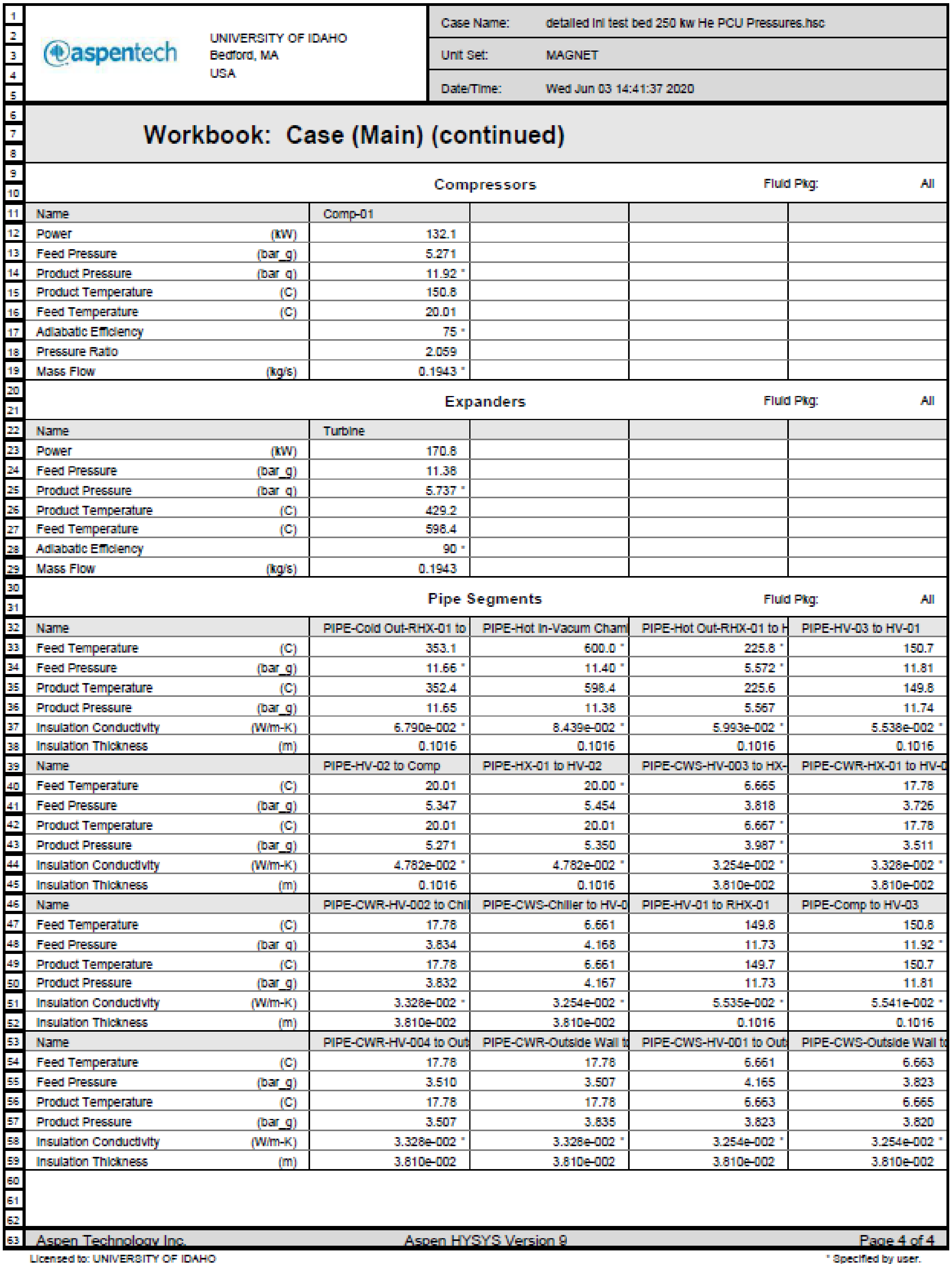

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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: detailed inl test bed 250 kw He PCU Pressures.hsc

Unit Set: MAGNET

Date/Time: Wed Jun 03 14:41:37 2020

Workbook: Case (Main) (continued)

Compressors

Fluid Pkg: All

Name		Comp-01			
Power	(kW)	132.1			
Feed Pressure	(bar_g)	5.271			
Product Pressure	(bar_g)	11.92 *			
Product Temperature	(C)	150.8			
Feed Temperature	(C)	20.01			
Adiabatic Efficiency		75 *			
Pressure Ratio		2.059			
Mass Flow	(kg/s)	0.1943 *			

Expanders

Fluid Pkg: All

Name		Turbine			
Power	(kW)	170.8			
Feed Pressure	(bar_g)	11.38			
Product Pressure	(bar_g)	5.737 *			
Product Temperature	(C)	429.2			
Feed Temperature	(C)	598.4			
Adiabatic Efficiency		90 *			
Mass Flow	(kg/s)	0.1943			

Pipe Segments

Fluid Pkg: All

Name		PIPE-Cold Out-RHX-01 to	PIPE-Hot In-Vacum Chaml	PIPE-Hot Out-RHX-01 to H	PIPE-HV-03 to HV-01
Feed Temperature	(C)	353.1	600.0 *	225.8 *	150.7
Feed Pressure	(bar_g)	11.66 *	11.40 *	5.572 *	11.81
Product Temperature	(C)	352.4	598.4	225.6	149.8
Product Pressure	(bar_g)	11.65	11.38	5.567	11.74
Insulation Conductivity	(W/m-K)	6.790e-002 *	8.439e-002 *	5.993e-002 *	5.538e-002 *
Insulation Thickness	(m)	0.1016	0.1016	0.1016	0.1016
Name		PIPE-HV-02 to Comp	PIPE-HX-01 to HV-02	PIPE-CWS-HV-003 to HX-	PIPE-CWR-HX-01 to HV-0
Feed Temperature	(C)	20.01	20.00 *	6.665	17.78
Feed Pressure	(bar_g)	5.347	5.454	3.818	3.726
Product Temperature	(C)	20.01	20.01	6.667 *	17.78
Product Pressure	(bar_g)	5.271	5.350	3.987 *	3.511
Insulation Conductivity	(W/m-K)	4.782e-002 *	4.782e-002 *	3.254e-002 *	3.328e-002 *
Insulation Thickness	(m)	0.1016	0.1016	3.810e-002	3.810e-002
Name		PIPE-CWR-HV-002 to Chil	PIPE-CWS-Chiller to HV-0	PIPE-HV-01 to RHX-01	PIPE-Comp to HV-03
Feed Temperature	(C)	17.78	6.661	149.8	150.8
Feed Pressure	(bar_g)	3.834	4.168	11.73	11.92 *
Product Temperature	(C)	17.78	6.661	149.7	150.7
Product Pressure	(bar_g)	3.832	4.167	11.73	11.81
Insulation Conductivity	(W/m-K)	3.328e-002 *	3.254e-002 *	5.535e-002 *	5.541e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	0.1016	0.1016
Name		PIPE-CWR-HV-004 to Out	PIPE-CWR-Outside Wall t	PIPE-CWS-HV-001 to Out	PIPE-CWS-Outside Wall t
Feed Temperature	(C)	17.78	17.78	6.661	6.663
Feed Pressure	(bar_g)	3.510	3.507	4.165	3.823
Product Temperature	(C)	17.78	17.78	6.663	6.665
Product Pressure	(bar_g)	3.507	3.835	3.823	3.820
Insulation Conductivity	(W/m-K)	3.328e-002 *	3.328e-002 *	3.254e-002 *	3.254e-002 *
Insulation Thickness	(m)	3.810e-002	3.810e-002	3.810e-002	3.810e-002

Aspen Technology Inc. Aspen HYSYS Version 9 Page 4 of 4

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Appendix D: Pipe Insulation Data Sheet

MAGNET Gas Pipe Insulation Data Sheet (Johns Manville, 2019)

Johns Manville
A Berkshire Hathaway Company

INDUSTRIAL INSULATION

THERMO-1200™
CALCIUM SILICATE PIPE & BLOCK INSULATION

DATA SHEET

THERMO-1200™

Thermo-1200™ is a water resistant, Type I calcium silicate pipe and block insulation, designed for applications that operate at temperatures up to 1200°F (650°C).

BENEFITS

Water Resistant*: Thermo-1200™ is the only North American calcium silicate insulation available that is water resistant. The insulation is engineered to withstand a heavy rainfall (1¼" of rain/ hour) for up to 20 minutes without absorbing more than 15% of its weight in water. This will allow contractors to install the insulation without immediately applying the jacketing afterward, offering more time and flexibility in the installation process than has traditionally been available.

Inhibits Corrosion: A proprietary corrosion inhibitor, called XOX Corrosion Inhibitor®, is integral to the chemical makeup of Thermo-1200™. XOX Corrosion Inhibitor helps protect against corrosion under insulation (CUI) and makes Thermo-1200™ one of the least corrosive thermal insulations available.

Durable: Thermo-1200™ is a cementitious insulation with exceptional compressive strength (>100 psi/690kPa), making it ideal for applications where mechanical abuse is likely. The inorganic binder will hold its shape and maintain the physical integrity of the insulation, even past 450°F, the point at which most organic binders burn off.

Extended Life Cycle: When properly installed and maintained, Thermo-1200's superior physical strength and inorganic binders can provide an insulation lifespan of up to 25 years or more.

FEATURES

- Non-combustible, cementitious insulation
- Temperature range: Ambient to 1200°F
- Asbestos, lead, and mercury-free

APPLICATIONS

In addition to water resistance, Thermo-1200™ offers superior durability and compressive strength. This is coupled with high-temperature, corrosion-inhibiting performance, making it ideal for the following applications:
Pipe and Equipment:
- Chemical Processing
- Power Generation
- Petroleum Refining

QUALITY STATEMENT

Johns Manville industrial products are designed, manufactured and tested to strict quality standards in our own facilities. This, along with third party auditing is your assurance that this product delivers consistently high quality.

FIRE SAFETY

Surface Burning Characteristics. When tested in accordance with ASTM E84 and UL 723, Thermo-1200™ has flame spread/smoke developed ratings of 0/0.

Non-Combustible. When tested in accordance with ASTM E136 as defined by NFPA 101.

ISO 9000 CERTIFICATION

Thermo-1200™ is manufactured and tested in our own facilities under implemented Quality Management Systems which are certified to be in accordance with ISO 9001quality standards. This certification, along with regular, independent third-party auditing of our plant and records for compliance, is your assurance that this product consistently delivers high quality performance.

PRODUCT CERTIFICATION

When ordering material to comply with any government specification or any other listed specification, a statement of that fact must appear on the purchase order. Government regulations and other listed specifications require specific lot testing, and prohibit the certification of compliance after shipment has been made. There may be additional charges associated with specification compliance testing. Please refer to JM-IND-CSP-3 for Certification Procedures and Charges. Call customer service for more information (1-800-866-3234).

**Thermo-1200™ water resistant calcium silicate is not hydrophobic. Thermo-1200™ is designed to be able to withstand short periods of rainfall without absorbing water in excess. The volume of water absorption depends on the duration of exposure and the amount of rainfall. The insulation is not meant to withstand extreme weather conditions without jacketing. While this new water resistant feature can be helpful during prolonged field installations, it is nevertheless recommended that an installer weatherproof and jacket the thermal insulation as soon as it is feasibly possible. Should water enter the system, the corrosion inhibitors will still activate to continue to help combat corrosion at a chemical level, and once the system reaches operating temperatures, the water will vaporize and leave the system.*

IND- 303 10/16/19 (Replaces IND-300 05/28/19)

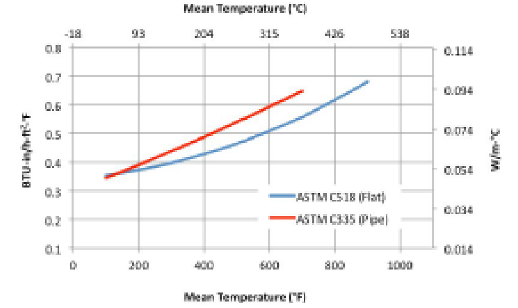
INDUSTRIAL INSULATION

THERMO-1200™

CALCIUM SILICATE PIPE & BLOCK INSULATION

DATA SHEET

THERMAL CONDUCTIVITY



Mean Temperature		100	200	300	400	500	600	700
	°C	38	93	149	204	260	316	371
ASTM C335 (Pipe)	Btu • in/(hr • ft² • °F)	.344	.389	.437	.486	.538	.591	.647
	W/m • °C	.050	.056	.063	.070	.078	.085	.093
ASTM C518 (Flat)	Btu • in/(hr • ft² • °F)	.355	.373	.397	.428	.465	.509	.559
	W/m • °C	.051	.054	.057	.062	.067	.073	.081

* Thermo-1200 Insulation is tested in accordance with ASTM C518 and ASTM C335.

AVAILABLE FORMS & SIZES

Insulation Form: Round Surfaces	**Pipe Size (in)**	**Pipe Size (mm)**
Pipe Insulation	½-24	15-600
Quad Segments	20-37	500-925
Hex Pipe Covering (Ruston Plant Only)	38-52	950-1300
3-V Scored Block Width: 12"/305mm Length: 36"/914mm	30 minimum	750 minimum
Curved Segments	30-126	762 - 3200
Beveled Lags	126 and higher	3200 and higher
Insulation Form: Flat Surfaces	**Insulation Size (in)**	**Insulation Size (mm)**
Flat Block	Width: 6 and 12 Length: 36	Width: 152 and 305 Length: 914

SPECIFICATION COMPLIANCE

ASTM C165 Compressive Strength	>100psi (690kPa) 5% compression
ASTM C203 Flexural Strength	>50psi (450kPa)
ASTM C302 Density (Dry) Average	<15pcf (240kg/m³)
ASTM C356 Linear Shrinkage	<2.0% after 24hr Soaking period at 1200°F (650°C)
ASTM C421 Abrasion Resistance Weight Loss by Tumbling	After the first 10min <20% After the second 10min<40%
ASTM C447 Maximum Service Temperature	1200°F (650°C)
ASTM C533, Type I Material Specification	Passes
ASTM C665 Corrosivity to Steel	Passes
ASTM C795/C871/C692 Corrosion: Austenitic Stainless Steel	Passes
ASTM C1338 Fungi Resistant	Passes
ASTM C1617 Corrosion	Passes (<DI Water)
ASTM E84 Surface Burning Characteristics	Flame Spread: 0 Smoke Developed: 0
ASTM E136 Non-Combustible	Passes
NRC Reg. Guide 1.36	Passes
MIL-I-24244	Passes
MIL-I-2781 1200°F (650°C) [Pipe] Military Specification	Passes
MIL-PRF-2819 Class 2 to 1200°F (650°C) [Block] Military Specification	Passes

3-V SCORED BLOCK APPLICATION GUIDE

Minimum Diameter			
Insulation Thickness		Triple Scored	
in	mm	in	mm
1½	38	30	762
2	51	40	1016
2½	64	50	1270
3	76	60	1524

Johns Manville
717 17th St.
Denver, CO 80202
(800) 866-3234
JM.com

Technical specifications as shown in this literature are intended to be used as general guidelines only. Please refer to the Safety Data Sheet and product label prior to using this product. The physical and chemical properties of the Thermo-1200™ listed herein represent typical, average values obtained in accordance with accepted test methods and are subject to normal manufacturing variations. They are supplied as a technical service and are subject to change without notice. Any references to numerical flame spread or smoke developed ratings are not intended to reflect hazards presented by these or any other materials under actual fire conditions. Check with the Regional Sales Office nearest you for current information.

All Johns Manville products are sold subject to Johns Manville's standard Terms and Conditions, which includes a Limited Warranty and Limitation of Remedy. For a copy of the Johns Manville standard Terms and Conditions or for information on other Johns Manville thermal insulation and systems, visit www.jm.com/terms-conditions or call (800)654-3103.

IND- 303 10/16/19 (Replaces IND-300 05/28/19)

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MAGNET Outside Chiller Loop Pipe Insulation Data Sheet (Owen Corning, 2017)

OWENS CORNING®

SSL II® WITH ASJ MAX FIBERGLAS™ PIPE INSULATION

FIBERGLASS INSULATION

Description

Owens Corning® SSL II® with ASJ Max Fiberglas™ Pipe Insulation is molded of heavy density resin bonded inorganic glass fibers that come in one-piece, 36" (914mm) long, hinged sections. The insulation is tailored to fit for copper and iron pipe applications.

Features

- ASJ Max is an all-service-jacket with a polymer film exterior surface that is smooth, durable, cleanable, wrinkle-resistant, resists water staining and doesn't support mold or mildew growth[1]
- ASJ Max can resist short durations of water exposure that may occur during construction
- SSL II® Positive Closure System is an advanced double adhesion that fastens and installs with no need for staples or mastic
- Insulation is tailored to fit with:
  - FlexCore technology to compress over copper and some small-bore iron pipes and fittings, saving time by eliminating the need to fillet
  - RigidCore technology for fast and easy fabrication on larger pipes
- The product has a maximum operating temperature of 1,000°F (538°C) (with heat-up schedule)
- The product does not contain Polybromodiphenyl ethers (PBDE) (penta-, octa-, or deca-brominated diphenyl)

[1] ASJ Max jacket does not support mold growth as tested in accordance with ASTM C1338.

Physical Properties

PROPERTY	TEST METHOD	VALUE
Density (size dependent)	ASTM C302	3.5 to 5.5 pcf
Operating Temperature Range[2]	ASTM C411	0°F to 1,000°F (-18°C to 538°C)
Water Vapor Sorption	ASTM C1104	Less than 5% by weight
Corrosion	ASTM C665	Pass – steel, copper, and aluminum
Corrosion	ASTM C1617	Pass – steel
Jacket Temperature Limitation	ASTM C1136	-20°F to 150°F (-29°C to 66°C)
Jacket Permeance	ASTM E96, Proc. A	0.01 perm
Burst Strength, min	ASTM D774/D774M	100 psi
Composite Surface Burning Characteristics[3]	UL 723, ASTM E84 or CAN/ULC-S201	Flame Spread 25 Smoke Developed 50

[2] With heat-up schedule when operating temperatures between 850°F and 1,000°F.

[3] The surface burning characteristics of these products have been determined in accordance with UL 723, ASTM E84 or CAN/ULC-S102. Values are reported to the nearest 5 rating.

Standards, Codes Compliance

- ASTM C547, Mineral Fiber Pipe Insulation: Type I, Grade A; and Type IV, Grade B
- ASTM C585, Inner and Outer Diameters of Thermal Insulation for Nominal Sizes of Pipe and Tubing
- ASTM C1136, Flexible Low Permeance Vapor Retarders for Thermal Insulation: Types I, II, III, IV, X
- UL Labeled for Flame Spread Index of 25 or less and Smoke Developed Index of 50 and is fully building code compliant
- UL Listed and Labeled for use over PVC and other polymer pipes UL Category BSMP
- ASTM C795, Thermal Insulation for Use in Contact with Austenitic Stainless Steel[4]
- Nuclear Regulatory Commission Guide 1.36, Non-Metallic Thermal Insulation[4]
- MIL-PRF-22344E, Insulation, Pipe, Thermal, Fibrous Glass
- MIL-DTL-32585, Type I, Form 4, Facing A
- MIL-DTL-24244D (Ships) Insulation Material with Special Corrosion, Chloride, and Fluoride Requirements[4]
- NFPA 90A and 90B

[4] Preproduction qualification testing complete and on file. Chemical analysis of each production lot required for total conformance. Certification needs to be specified at time of order.

Applications

- Used to insulate iron, copper, PVC and other polymer pipes with operating temperatures between 0°F (-18°C) to 1,000°F (538°C) in commercial & institutional buildings, and industrial facilities
- When temperatures are above 650°F (454°C), maximum installed insulation thickness shall be no greater than 6" as a single layer or nested
- Rated per ASTM C547, Type I, Grade A - Pipe insulation can be installed on in-service/hot pipes with an operating temperature up to 850°F (454°C)
- Rated per ASTM C547, Type IV, Grade B - When operating temperatures will be between 850°F (454°C) to a 1,000°F (538°C) a heat-up schedule needs to be followed per the Installation Instructions, Pub No. 10021355
- When installed outdoors, an additional weather-protective jacket is required

Thermal Conductivity

MEAN TEMP °F	K BTU•IN/HR•FT^2•°F	MEAN TEMP °C	λ W/M•°C
50	0.22	10	0.032
75	0.23	25	0.034
100	0.24	50	0.037
150	0.27	100	0.043
200	0.29	125	0.047
250	0.32	150	0.051
300	0.35	175	0.056
350	0.39	200	0.062
400	0.43	225	0.068
450	0.48	250	0.075
500	0.54	275	0.082

Apparent thermal conductivity values determined in accordance with ASTM practice C1045 with data obtained by ASTM Test Method C335. Values are nominal, subject to normal testing and manufacturing tolerances.

Thickness to Prevent Surface Condensation

Owens Corning® ASJ Max Jacket for up to 16" NPS (400mm DN), in. (mm)[5,6]

AMBIENT TEMP		RELATIVE HUMIDITY	SYSTEM OPERATING TEMPERATURES					
°F	(°C)		35°F	(2°C)	45°F	(7°C)	55°F	(13°C)
110	(43)	70%	1	(25)	1	(25)	1	(25)
		80%	$1\frac{1}{2}$	(38)	$1\frac{1}{2}$	(38)	$1\frac{1}{2}$	(38)
		90%	$3\frac{1}{2}$	(89)	$3\frac{1}{2}$	(89)	3	(76)
100	(38)	70%	1	(25)	1	(25)	1	(25)
		80%	$1\frac{1}{2}$	(38)	$1\frac{1}{2}$	(38)	1	(25)
		90%	$3\frac{1}{2}$	(89)	3	(76)	$2\frac{1}{2}$	(64)
90	(32)	70%	1	(25)	1	(25)	1	(25)
		80%	$1\frac{1}{2}$	(38)	1	(25)	1	(25)
		90%	$3\frac{1}{2}$	(89)	3	(76)	$2\frac{1}{2}$	(64)
80	(27)	80%	$1\frac{1}{2}$	(38)	1	(25)	1	(25)
		90%	3	(76)	$2\frac{1}{2}$	(64)	2	(51)
70	(21)	80%	1	(25)	1	(25)	1	(25)
		90%	$2\frac{1}{2}$	(64)	2	(51)	1	(25)

[5] Calculations estimated using NAIMA 3E Plus version 4.0 software. Fixed design conditions: Steel Horizontal Piping, 16" NPS, 0 mph wind speed, Outer Surface Jacket Emittance of 0.9.

[6] Thermal conductivity values used in these calculations are subject to normal manufacturing tolerances.

Availability

Our Fiberglas™ Pipe Insulation portfolio is available in thicknesses up to 5". Contact your local Owens Corning Area Sales Manager for product availability.

Refer to Pipe Insulation Sizing Manual for more information: Pub. No. 10018078.

Installation

Ambient application temperatures are from 25°F (-4°C) to 110°F (43°C).

For complete installation instructions and recommendations see "Fiberglas™ Pipe Insulation Installation Instructions" (Pub. No. 10021355).

Environmental and Sustainability

Owens Corning is a worldwide leader in building material systems, insulation and composite solutions, delivering a broad range of high-quality products and services. Owens Corning is committed to driving sustainability by delivering solutions, transforming markets and enhancing lives. More information can be found at www.owenscorning.com.

Certifications and Sustainable Features

- Certified by SCS Global Services to contain an average of 53% recycled glass content, 31% pre-consumer and 22% post-consumer
- For faced products: GREENGUARD Certified products are certified to GREENGUARD standards for low chemical emissions into indoor air during product usage. For more information, visit ul.com/gg
- Environmental Product Declaration (EPD) has been certified by UL Environment
- Material Health Certificate from Cradle to Cradle Products Innovation Institute or Health Product Declarations available

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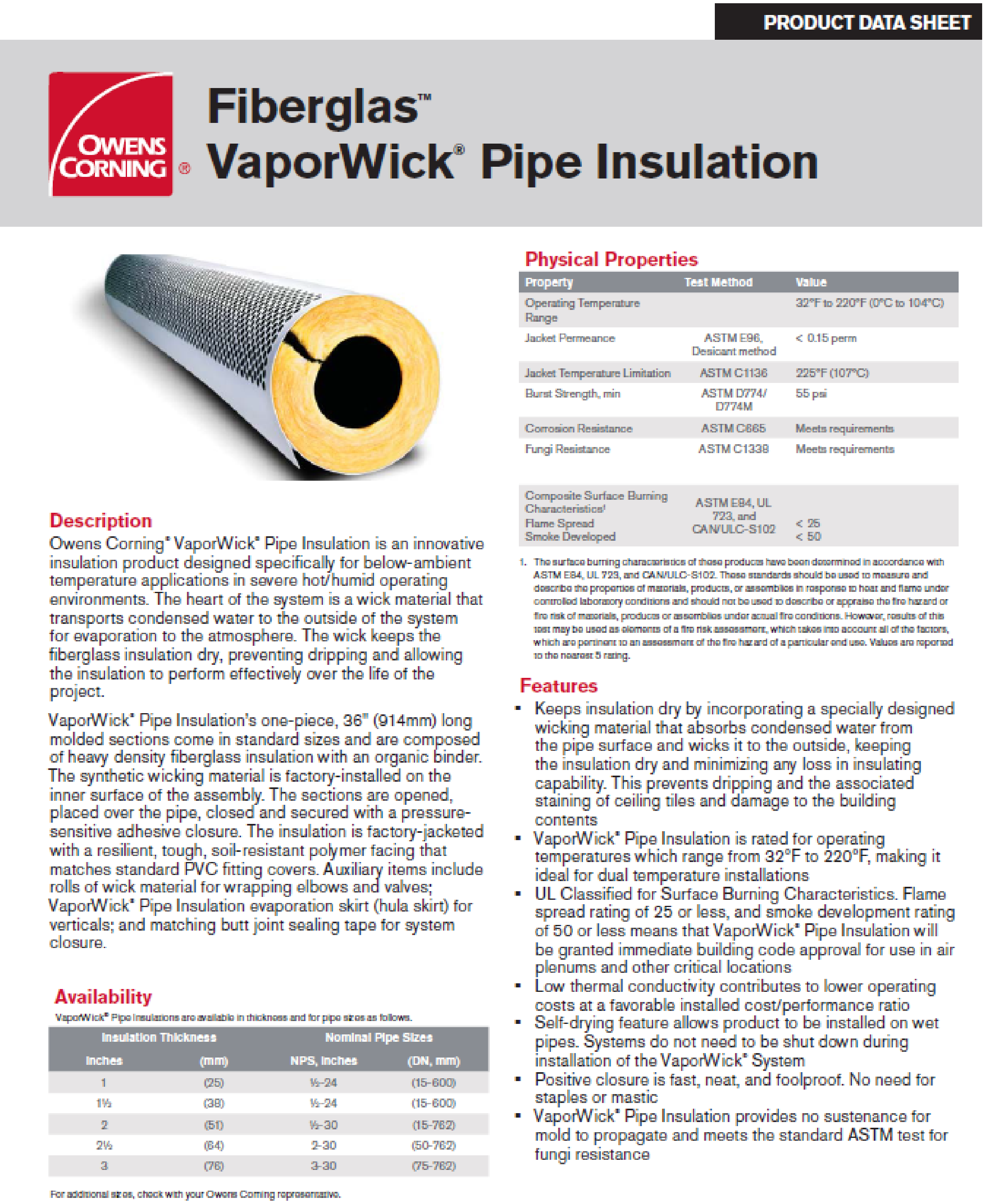
MAGNET Inside Insulation Chiller Loop Pipe Data Sheet (Owen Corning, 2017)



PRODUCT DATA SHEET

OWENS CORNING®

Fiberglas™ VaporWick® Pipe Insulation

Description

Owens Corning® VaporWick® Pipe Insulation is an innovative insulation product designed specifically for below-ambient temperature applications in severe hot/humid operating environments. The heart of the system is a wick material that transports condensed water to the outside of the system for evaporation to the atmosphere. The wick keeps the fiberglass insulation dry, preventing dripping and allowing the insulation to perform effectively over the life of the project.

VaporWick® Pipe Insulation's one-piece, 36" (914mm) long molded sections come in standard sizes and are composed of heavy density fiberglass insulation with an organic binder. The synthetic wicking material is factory-installed on the inner surface of the assembly. The sections are opened, placed over the pipe, closed and secured with a pressure-sensitive adhesive closure. The insulation is factory-jacketed with a resilient, tough, soil-resistant polymer facing that matches standard PVC fitting covers. Auxiliary items include rolls of wick material for wrapping elbows and valves; VaporWick® Pipe Insulation evaporation skirt (hula skirt) for verticals; and matching butt joint sealing tape for system closure.

Availability

VaporWick® Pipe Insulations are available in thickness and for pipe sizes as follows.

Insulation Thickness		Nominal Pipe Sizes	
Inches	(mm)	NPS, Inches	(DN, mm)
1	(25)	½-24	(15-600)
1½	(38)	½-24	(15-600)
2	(51)	½-30	(15-762)
2½	(64)	2-30	(50-762)
3	(76)	3-30	(75-762)

For additional sizes, check with your Owens Corning representative.

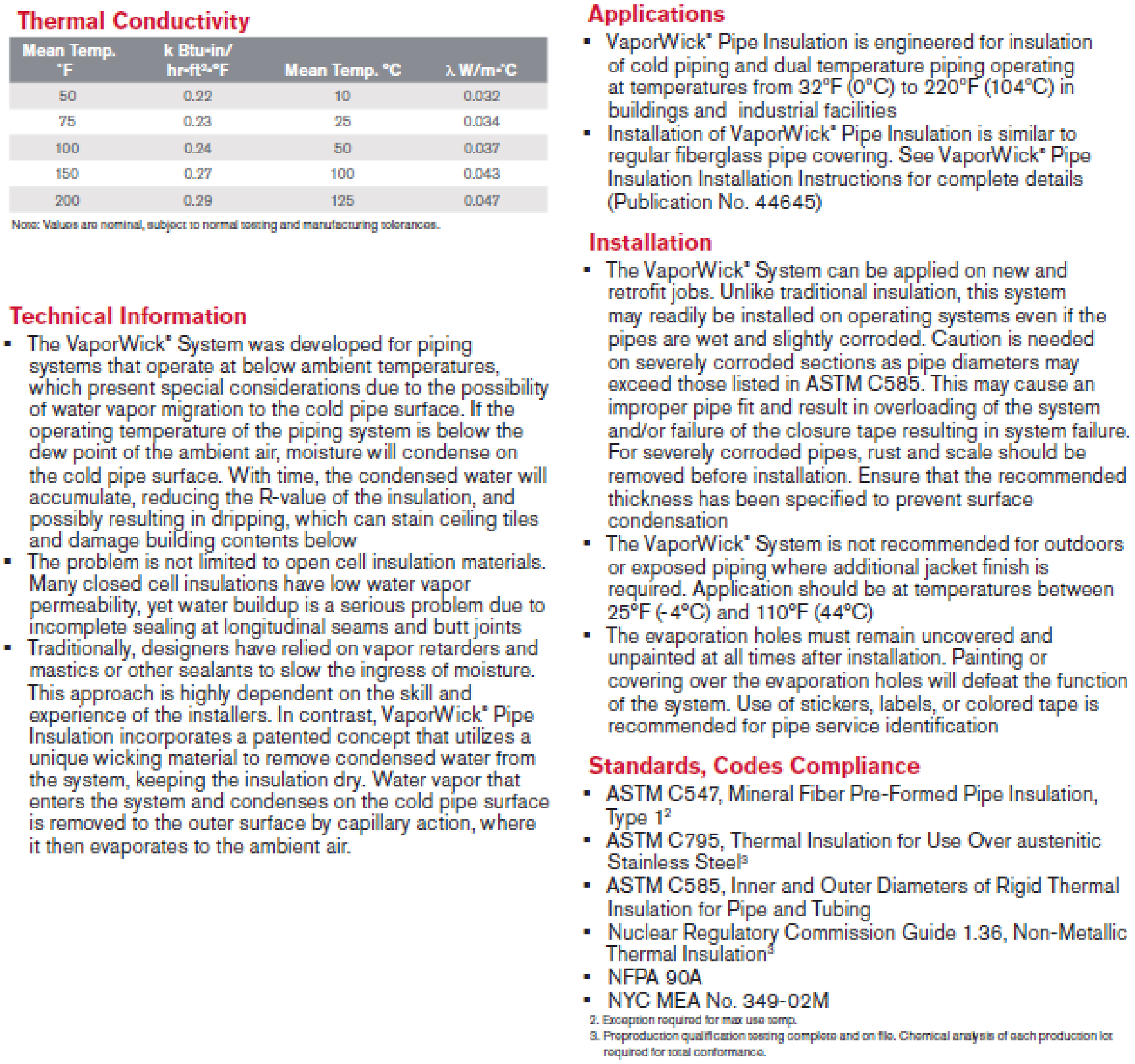
Physical Properties

Property	Test Method	Value
Operating Temperature Range		32°F to 220°F (0°C to 104°C)
Jacket Permeance	ASTM E96, Desicant method	< 0.15 perm
Jacket Temperature Limitation	ASTM C1136	225°F (107°C)
Burst Strength, min	ASTM D774/ D774M	55 psi
Corrosion Resistance	ASTM C665	Meets requirements
Fungi Resistance	ASTM C1338	Meets requirements
Composite Surface Burning Characteristics[1] Flame Spread Smoke Developed	ASTM E84, UL 723, and CAN/ULC-S102	 < 25 < 50

1. The surface burning characteristics of these products have been determined in accordance with ASTM E84, UL 723, and CAN/ULC-S102. These standards should be used to measure and describe the properties of materials, products, or assemblies in response to heat and flame under controlled laboratory conditions and should not be used to describe or appraise the fire hazard or fire risk of materials, products or assemblies under actual fire conditions. However, results of this test may be used as elements of a fire risk assessment, which takes into account all of the factors, which are pertinent to an assessment of the fire hazard of a particular end use. Values are reported to the nearest 5 rating.

Features

- Keeps insulation dry by incorporating a specially designed wicking material that absorbs condensed water from the pipe surface and wicks it to the outside, keeping the insulation dry and minimizing any loss in insulating capability. This prevents dripping and the associated staining of ceiling tiles and damage to the building contents
- VaporWick® Pipe Insulation is rated for operating temperatures which range from 32°F to 220°F, making it ideal for dual temperature installations
- UL Classified for Surface Burning Characteristics. Flame spread rating of 25 or less, and smoke development rating of 50 or less means that VaporWick® Pipe Insulation will be granted immediate building code approval for use in air plenums and other critical locations
- Low thermal conductivity contributes to lower operating costs at a favorable installed cost/performance ratio
- Self-drying feature allows product to be installed on wet pipes. Systems do not need to be shut down during installation of the VaporWick® System
- Positive closure is fast, neat, and foolproof. No need for staples or mastic
- VaporWick® Pipe Insulation provides no sustenance for mold to propagate and meets the standard ASTM test for fungi resistance



Thermal Conductivity

Mean Temp. °F	k Btu-in/hr-ft^2-°F	Mean Temp. °C	λ W/m-°C
50	0.22	10	0.032
75	0.23	25	0.034
100	0.24	50	0.037
150	0.27	100	0.043
200	0.29	125	0.047

Note: Values are nominal, subject to normal testing and manufacturing tolerances.

Technical Information

- The VaporWick® System was developed for piping systems that operate at below ambient temperatures, which present special considerations due to the possibility of water vapor migration to the cold pipe surface. If the operating temperature of the piping system is below the dew point of the ambient air, moisture will condense on the cold pipe surface. With time, the condensed water will accumulate, reducing the R-value of the insulation, and possibly resulting in dripping, which can stain ceiling tiles and damage building contents below
- The problem is not limited to open cell insulation materials. Many closed cell insulations have low water vapor permeability, yet water buildup is a serious problem due to incomplete sealing at longitudinal seams and butt joints
- Traditionally, designers have relied on vapor retarders and mastics or other sealants to slow the ingress of moisture. This approach is highly dependent on the skill and experience of the installers. In contrast, VaporWick® Pipe Insulation incorporates a patented concept that utilizes a unique wicking material to remove condensed water from the system, keeping the insulation dry. Water vapor that enters the system and condenses on the cold pipe surface is removed to the outer surface by capillary action, where it then evaporates to the ambient air.

Applications

- VaporWick® Pipe Insulation is engineered for insulation of cold piping and dual temperature piping operating at temperatures from 32°F (0°C) to 220°F (104°C) in buildings and industrial facilities
- Installation of VaporWick® Pipe Insulation is similar to regular fiberglass pipe covering. See VaporWick® Pipe Insulation Installation Instructions for complete details (Publication No. 44645)

Installation

- The VaporWick® System can be applied on new and retrofit jobs. Unlike traditional insulation, this system may readily be installed on operating systems even if the pipes are wet and slightly corroded. Caution is needed on severely corroded sections as pipe diameters may exceed those listed in ASTM C585. This may cause an improper pipe fit and result in overloading of the system and/or failure of the closure tape resulting in system failure. For severely corroded pipes, rust and scale should be removed before installation. Ensure that the recommended thickness has been specified to prevent surface condensation
- The VaporWick® System is not recommended for outdoors or exposed piping where additional jacket finish is required. Application should be at temperatures between 25°F (-4°C) and 110°F (44°C)
- The evaporation holes must remain uncovered and unpainted at all times after installation. Painting or covering over the evaporation holes will defeat the function of the system. Use of stickers, labels, or colored tape is recommended for pipe service identification

Standards, Codes Compliance

- ASTM C547, Mineral Fiber Pre-Formed Pipe Insulation, Type 1[2]
- ASTM C795, Thermal Insulation for Use Over austenitic Stainless Steel[3]
- ASTM C585, Inner and Outer Diameters of Rigid Thermal Insulation for Pipe and Tubing
- Nuclear Regulatory Commission Guide 1.36, Non-Metallic Thermal Insulation[3]
- NFPA 90A
- NYC MEA No. 349-02M

[2] Exception required for max use temp.

[3] Preproduction qualification testing complete and on file. Chemical analysis of each production lot required for total conformance.

Thickness To Prevent Surface Condensation

VaporWick® Pipe Insulation does not prevent surface condensation. Sufficient thickness must be selected to minimize condensation on the outer surface. Use the following table for guidance.

Fluid Temperature 35°F

Ambient Temp. °F	Relative Humidity %	Pipe Size, NPS								
		½"	1"	1½"	2"	4"	6"	8"	10"	12"
80	70	1	1	1	1	1	1	1	1	1
	80	1	1	1	1	1	1	1	1½	1½
	90	1½	1½	2	2	2	2	2½	2½	2½
90	70	1	1	1	1	1	1	1	1	1
	80	1	1	1	1	1	1½	1½	1½	1½
	90	2	2	2	2½	3	3	3	3	3½

Fluid Temperature 45°F

Ambient Temp. °F	Relative Humidity %	Pipe Size, NPS								
		½"	1"	1½"	2"	4"	6"	8"	10"	12"
80	70	1	1	1	1	1	1	1	1	1
	80	1	1	1	1	1	1	1	1	1
	90	1	1½	1½	1½	1½	2	2	2	2
90	70	1	1	1	1	1	1	1	1	1
	80	1	1	1	1	1	1	1	1	1
	90	1½	2	2	2	2½	2½	2½	2½	3

Fluid Temperature 55°F

Ambient Temp. °F	Relative Humidity %	Pipe Size, NPS								
		½"	1"	1½"	2"	4"	6"	8"	10"	12"
80	70	1	1	1	1	1	1	1	1	1
	80	1	1	1	1	1	1	1	1	1
	90	1	1	1	1	1½	1½	1½	1½	1½
90	70	1	1	1	1	1	1	1	1	1
	80	1	1	1	1	1	1	1	1	1
	90	1½	1½	1½	1½	2	2	2	2	2

Note: All thicknesses are in inches rounded up to the nearest available VaporWick® Pipe Insulation size.

Recommendations were developed using the NAIMA 3E Plus® computer program, assuming wind speed of 0 mph and outer jacket emittance of 0.9.

Environmental and Sustainability

Owens Corning is a worldwide leader in building material systems, insulation and composite solutions, delivering a broad range of high-quality products and services. Owens Corning is committed to driving sustainability by delivering solutions, transforming markets and enhancing lives. More information can be found at www.owenscorning.com.

Certifications and Sustainable Features

- Certified by SCS Global Services to contain a minimum of 53% recycled glass content, 31% pre-consumer and 22% post-consumer
- GREENGUARD Certified products are certified to GREENGUARD standards for low chemical emissions into indoor air during product usage. For more information, visit ul.com/gg
- Environmental Product Declaration (EPD) has been certified by UL Environment
- Material Health Certificate from Cradle to Cradle Products Innovation Institute

AVERAGE 53% RECYCLED CONTENT
31% PRE-CONSUMER
22% POST-CONSUMER

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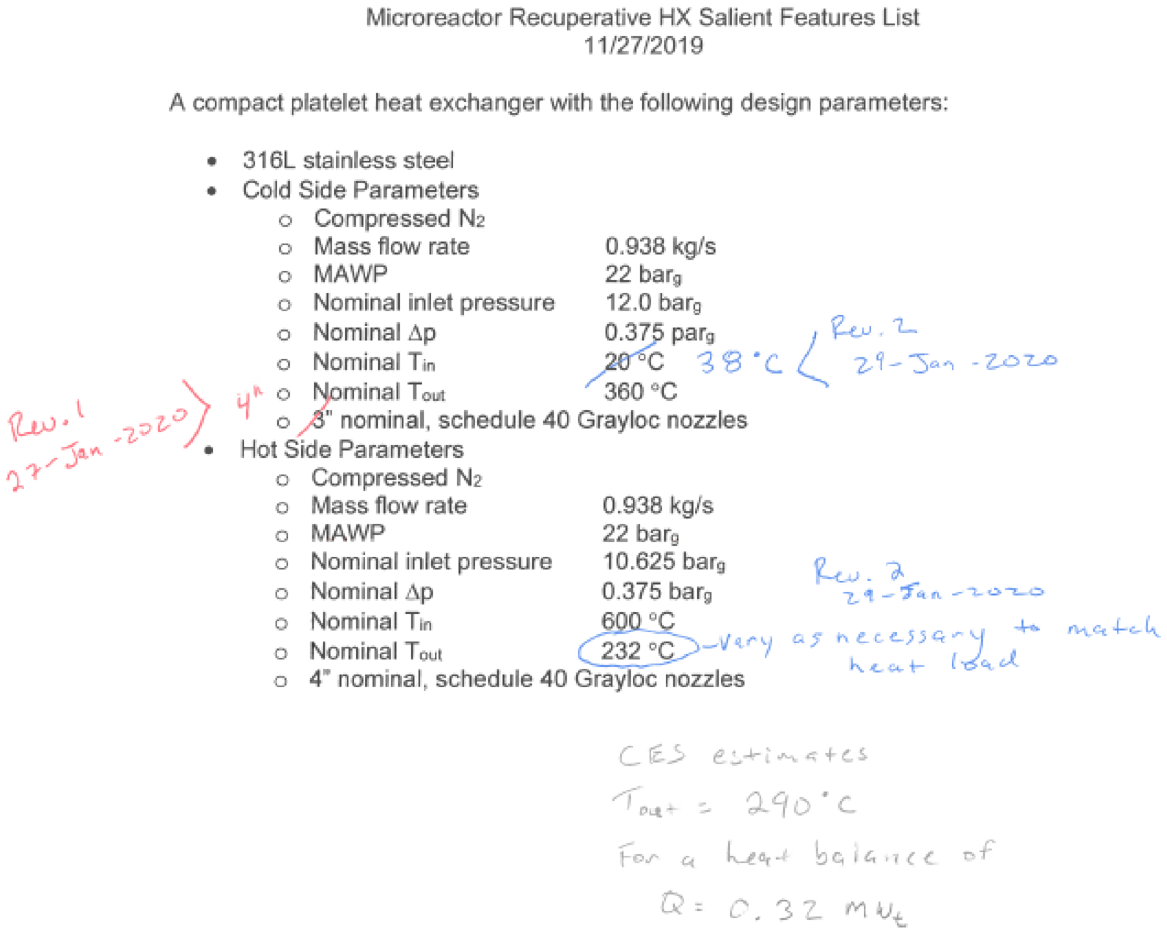
Appendix E: Recuperating Heat Exchanger Data

PCHE Recuperating Heat Exchanger Process Specifications



Microreactor Recuperative HX Salient Features List
11/27/2019

A compact platelet heat exchanger with the following design parameters:

- 316L stainless steel
- Cold Side Parameters
    - Compressed N_2
    - Mass flow rate 0.938 kg/s
    - MAWP 22 bar_g
    - Nominal inlet pressure 12.0 bar_g
    - Nominal Δp 0.375 par_g
    - Nominal T_{in} ~~20~~ °C 38 °C
    - Nominal T_{out} 360 °C
    - 4" ~~3~~" nominal, schedule 40 Grayloc nozzles
- Hot Side Parameters
    - Compressed N_2
    - Mass flow rate 0.938 kg/s
    - MAWP 22 bar_g
    - Nominal inlet pressure 10.625 bar_g
    - Nominal Δp 0.375 bar_g
    - Nominal T_{in} 600 °C
    - Nominal T_{out} 232 °C — Vary as necessary to match heat load
    - 4" nominal, schedule 40 Grayloc nozzles

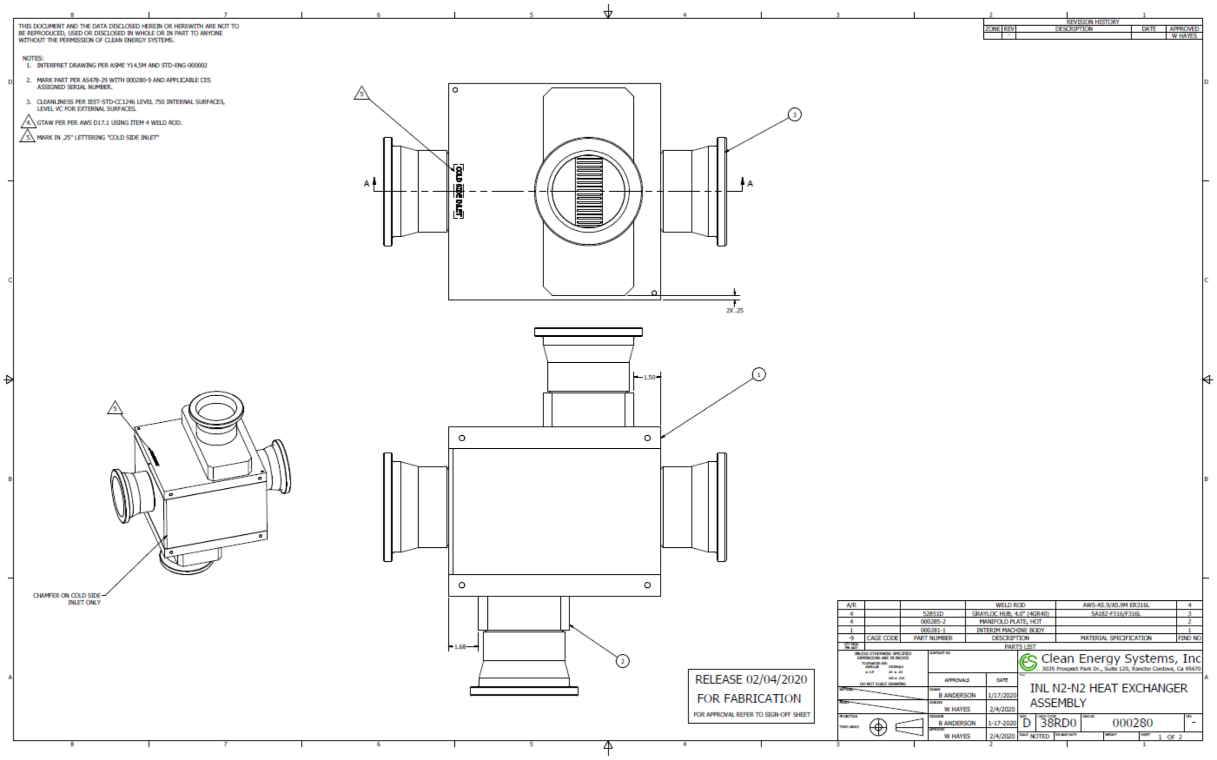
Rev. 2
29-Jan-2020

Rev. 1
27-Jan-2020

Rev. 2
29-Jan-2020

CES estimates
T_{out} = 290 °C
For a heat balance of
Q = 0.32 MW_t

Recuperating Heat Exchanger Outer Dimensions



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NOTES:

1. INTERPRET DRAWING PER ASME Y14.5M AND STD-ENG-000002
2. MARK PART PER AS478-29 WITH 000280-9 AND APPLICABLE CES ASSIGNED SERIAL NUMBER.
3. CLEANLINESS PER IEST-STD-CC1246 LEVEL 750 INTERNAL SURFACES, LEVEL VC FOR EXTERNAL SURFACES.
4. GTAW PER PER AWS D17.1 USING ITEM 4 WELD ROD.
5. MARK IN .25" LETTERING "COLD SIDE INLET"

REVISION HISTORY				
ZONE	REV	DESCRIPTION	DATE	APPROVED
	-			W HAYES

A/R			WELD ROD	AWS-A5.9/A5.9M ER316L	4
4		52851D	GRAYLOC HUB, 4.0" (4GR40)	SA182-F316/F316L	3
4		000285-2	MANIFOLD PLATE, HOT		2
1		000281-1	INTERIM MACHINE BODY		1
-9	CAGE CODE	PART NUMBER	DESCRIPTION	MATERIAL SPECIFICATION	FIND NO
	PARTS LIST				

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

DO NOT SCALE DRAWING

APPROVALS	DATE
B ANDERSON	1/17/2020
W HAYES	2/4/2020
B ANDERSON	1-17-2020
W HAYES	2/4/2020

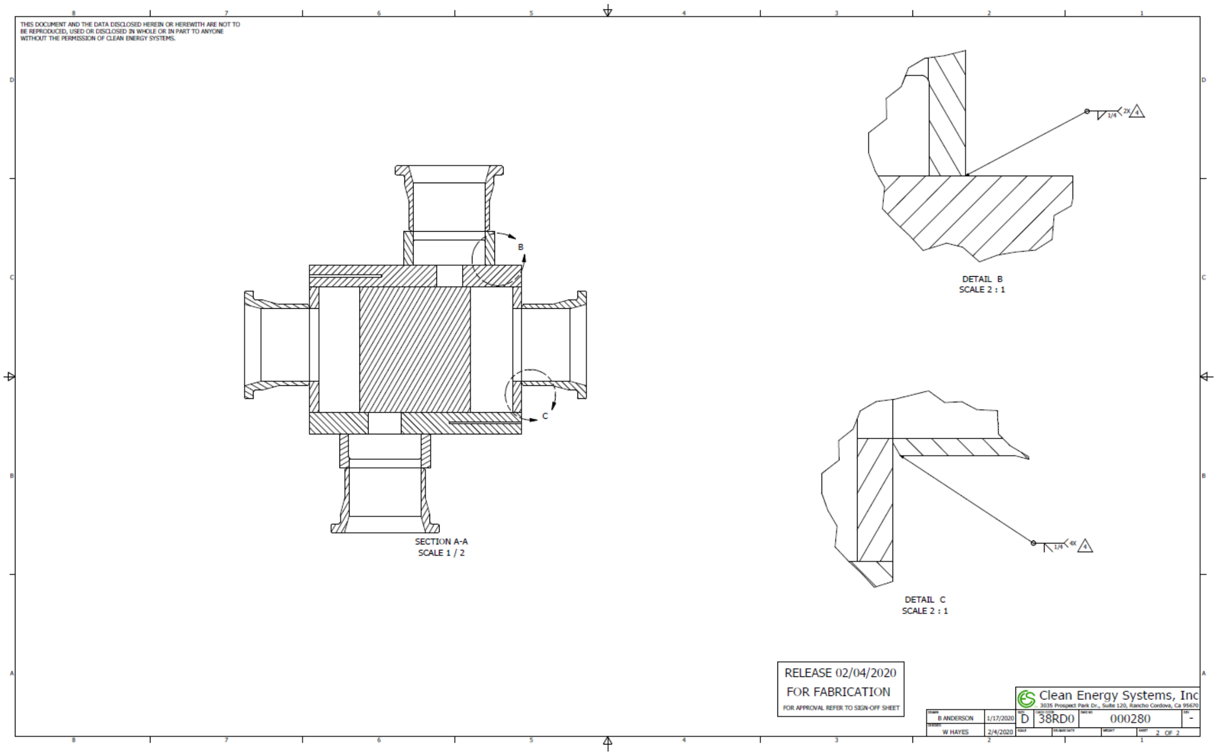
Clean Energy Systems, Inc
3035 Prospect Park Dr., Suite 120, Rancho Cordova, Ca 95670

INL N2-N2 HEAT EXCHANGER ASSEMBLY

D 38RD0 000280 -

NOTED 1 OF 2

RELEASE 02/04/2020
FOR FABRICATION
FOR APPROVAL REFER TO SIGN-OFF SHEET



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SECTION A-A
SCALE 1 / 2

DETAIL B
SCALE 2 : 1

DETAIL C
SCALE 2 : 1

RELEASE 02/04/2020
FOR FABRICATION
FOR APPROVAL REFER TO SIGN-OFF SHEET

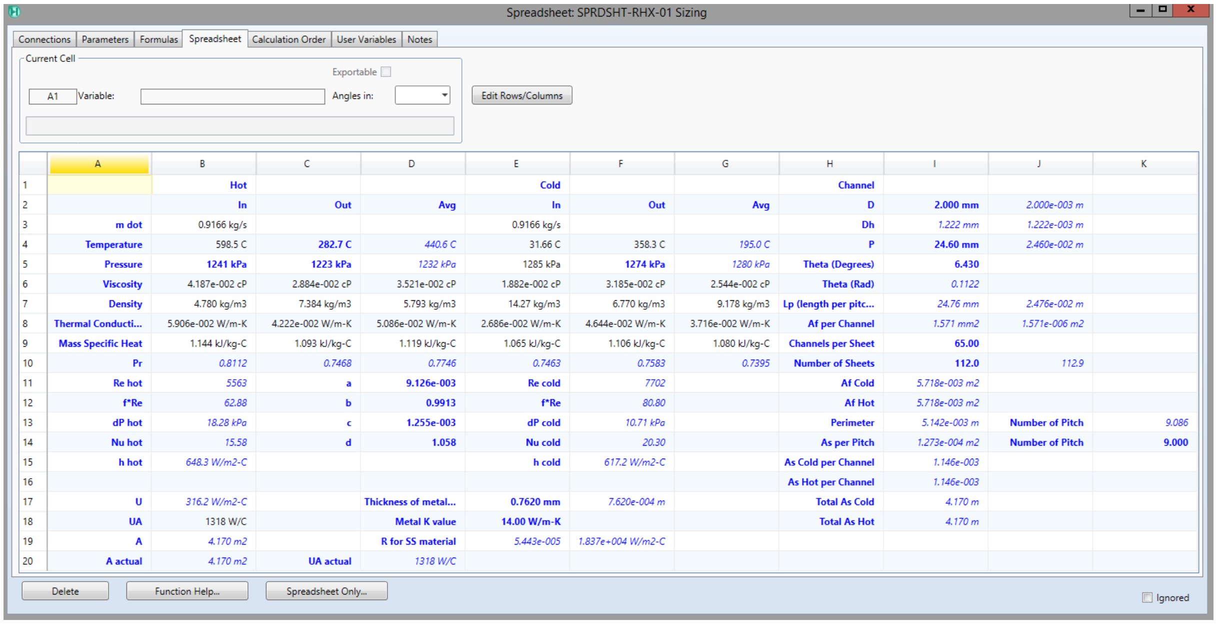
Clean Energy Systems, Inc
3035 Prospect Park Dr., Suite 120, Rancho Cordova, Ca 95670

B ANDERSON	1/17/2020
W HAYES	2/4/2020

D 38RD0 000280 -

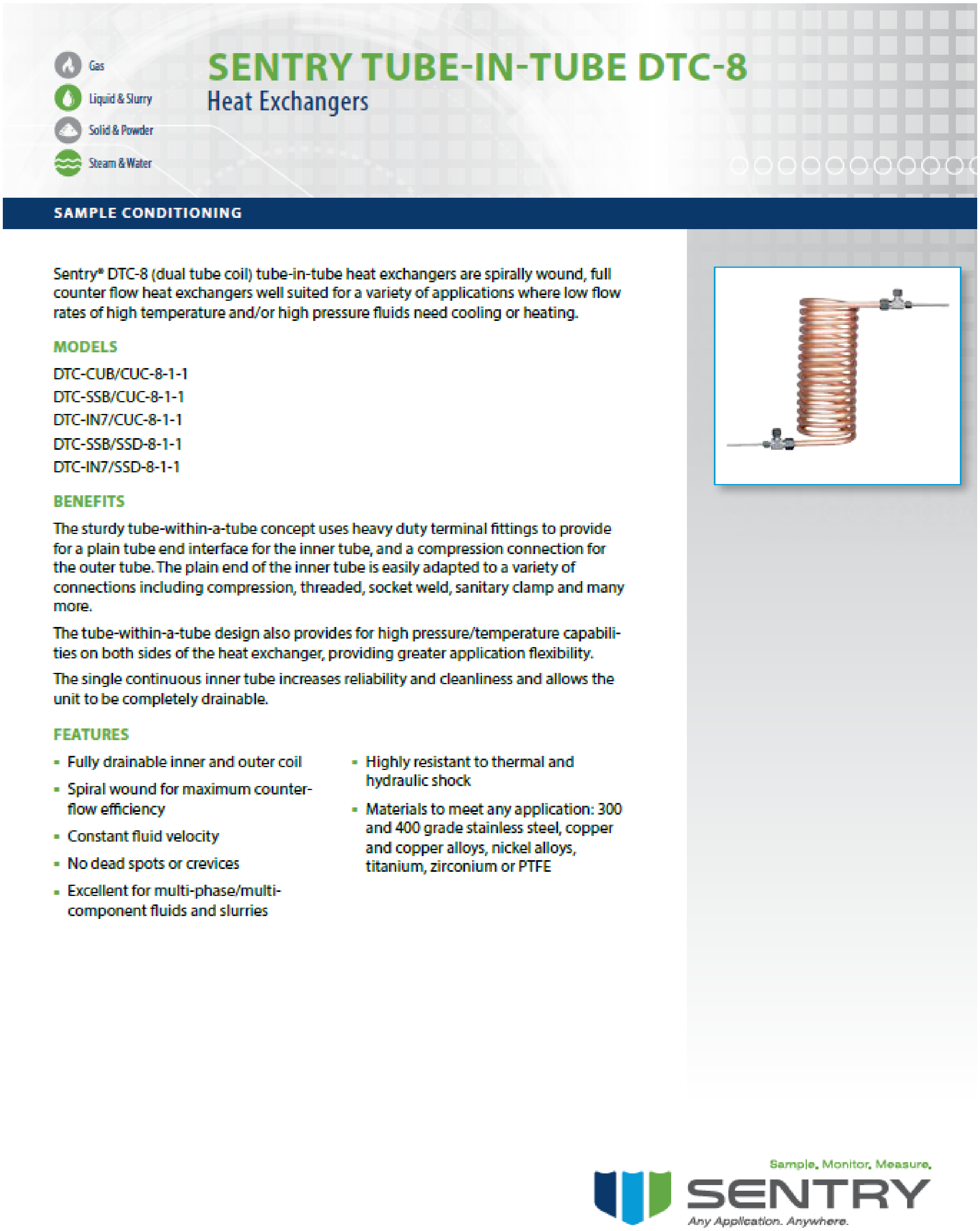
2 OF 2

Aspen HYSYS Spreadsheet of Recuperating Heat Exchanger Design Parameters



	A	B	C	D	E	F	G	H	I	J	K
1		Hot			Cold			Channel			
2		In	Out	Avg	In	Out	Avg	D	2.000 mm	2.000e-003 m	
3	m dot	0.9166 kg/s			0.9166 kg/s			Dh	1.222 mm	1.222e-003 m	
4	Temperature	598.5 C	282.7 C	440.6 C	31.66 C	358.3 C	195.0 C	P	24.60 mm	2.460e-002 m	
5	Pressure	1241 kPa	1223 kPa	1232 kPa	1285 kPa	1274 kPa	1280 kPa	Theta (Degrees)	6.430		
6	Viscosity	4.187e-002 cP	2.884e-002 cP	3.521e-002 cP	1.882e-002 cP	3.185e-002 cP	2.544e-002 cP	Theta (Rad)	0.1122		
7	Density	4.780 kg/m3	7.384 kg/m3	5.793 kg/m3	14.27 kg/m3	6.770 kg/m3	9.178 kg/m3	Lp (length per pitc...	24.76 mm	2.476e-002 m	
8	Thermal Conducti...	5.906e-002 W/m-K	4.222e-002 W/m-K	5.086e-002 W/m-K	2.686e-002 W/m-K	4.644e-002 W/m-K	3.716e-002 W/m-K	Af per Channel	1.571 mm2	1.571e-006 m2	
9	Mass Specific Heat	1.144 kJ/kg-C	1.093 kJ/kg-C	1.119 kJ/kg-C	1.065 kJ/kg-C	1.106 kJ/kg-C	1.080 kJ/kg-C	Channels per Sheet	65.00		
10	Pr	0.8112	0.7468	0.7746	0.7463	0.7583	0.7395	Number of Sheets	112.0	112.9	
11	Re hot	5563	a	9.126e-003	Re cold	7702		Af Cold	5.718e-003 m2		
12	f*Re	62.88	b	0.9913	f*Re	80.80		Af Hot	5.718e-003 m2		
13	dP hot	18.28 kPa	c	1.255e-003	dP cold	10.71 kPa		Perimeter	5.142e-003 m	Number of Pitch	9.086
14	Nu hot	15.58	d	1.058	Nu cold	20.30		As per Pitch	1.273e-004 m2	Number of Pitch	9.000
15	h hot	648.3 W/m2-C			h cold	617.2 W/m2-C		As Cold per Channel	1.146e-003		
16								As Hot per Channel	1.146e-003		
17	U	316.2 W/m2-C		Thickness of metal...	0.7620 mm	7.620e-004 m		Total As Cold	4.170 m		
18	UA	1318 W/C		Metal K value	14.00 W/m-K			Total As Hot	4.170 m		
19	A	4.170 m2		R for SS material	5.443e-005	1.837e+004 W/m2-C					
20	A actual	4.170 m2	UA actual	1318 W/C							

Sentry Tube-in-Tube Recuperating Heat Exchanger (Sentry, 2017)



Gas
Liquid & Slurry
Solid & Powder
Steam & Water

SENTRY TUBE-IN-TUBE DTC-8

Heat Exchangers

SAMPLE CONDITIONING

Sentry® DTC-8 (dual tube coil) tube-in-tube heat exchangers are spirally wound, full counter flow heat exchangers well suited for a variety of applications where low flow rates of high temperature and/or high pressure fluids need cooling or heating.

MODELS

DTC-CUB/CUC-8-1-1
DTC-SSB/CUC-8-1-1
DTC-IN7/CUC-8-1-1
DTC-SSB/SSD-8-1-1
DTC-IN7/SSD-8-1-1

BENEFITS

The sturdy tube-within-a-tube concept uses heavy duty terminal fittings to provide for a plain tube end interface for the inner tube, and a compression connection for the outer tube. The plain end of the inner tube is easily adapted to a variety of connections including compression, threaded, socket weld, sanitary clamp and many more.

The tube-within-a-tube design also provides for high pressure/temperature capabilities on both sides of the heat exchanger, providing greater application flexibility.

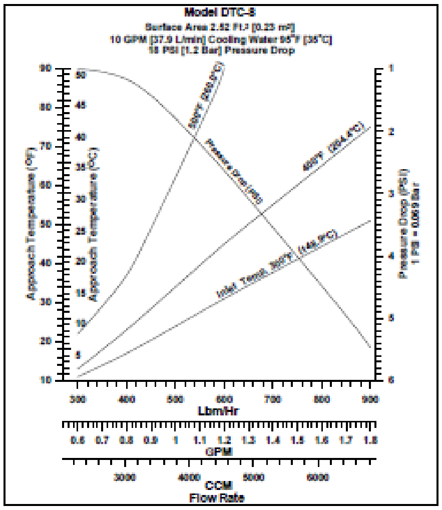
The single continuous inner tube increases reliability and cleanliness and allows the unit to be completely drainable.

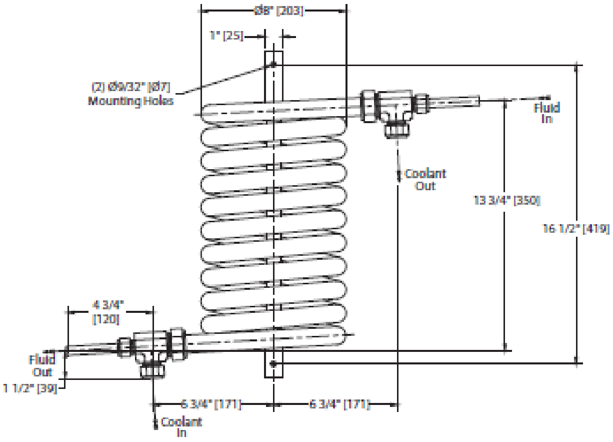
FEATURES

- Fully drainable inner and outer coil
- Spiral wound for maximum counter-flow efficiency
- Constant fluid velocity
- No dead spots or crevices
- Excellent for multi-phase/multi-component fluids and slurries
- Highly resistant to thermal and hydraulic shock
- Materials to meet any application: 300 and 400 grade stainless steel, copper and copper alloys, nickel alloys, titanium, zirconium or PTFE

Sample. Monitor. Measure.
SENTRY
Any Application. Anywhere.

SENTRY TUBE-IN-TUBE DTC-8 > HEAT EXCHANGERS > SAMPLE CONDITIONING





SPECIFICATIONS

models	inner tube design	outer tube design	inner tube material	outer tube material	heat transfer area	weight
DTC-CUB/CUC-8-1-1	1250 psi at 300°F (86 bar at 148°C)	700 psi at 300°F (48 bar at 148°C)	1/2 in OD copper	1 in OD copper	2.52 ft² (0.23 m²)	30 lb (13.6 kg)
DTC-SSB/CUC-8-1-1	2400 psi at 1000°F (165 bar at 537°C)	700 psi at 300°F (48 bar at 148°C)	1/2 in OD 316 SS	1 in OD copper	2.52 ft² (0.23 m²)	30 lb (13.6 kg)
DTC-IN7/CUC-8-1-1	4000 psi at 900°F (276 bar at 482°C)	700 psi at 300°F (48 bar at 148°C)	1/2 in OD Inconel®	1 in OD copper	2.52 ft² (0.23 m²)	30 lb (13.6 kg)
DTC-SSB/SSD-8-1-1	2400 psi at 1000°F (165 bar at 537°C)	2300 psi at 1000°F (158 bar at 537°C)	1/2 in OD 316 SS	1 in OD 316 SS	2.52 ft² (0.23 m²)	30 lb (13.6 kg)
DTC-IN7/SSD-8-1-1	4000 psi at 900°F (276 bar at 482°C)	2300 psi at 1000°F (158 bar at 537°C)	1/2 in OD Inconel®	1 in OD 316 SS	2.52 ft² (0.23 m²)	30 lb (13.6 kg)

sentry-equip.com

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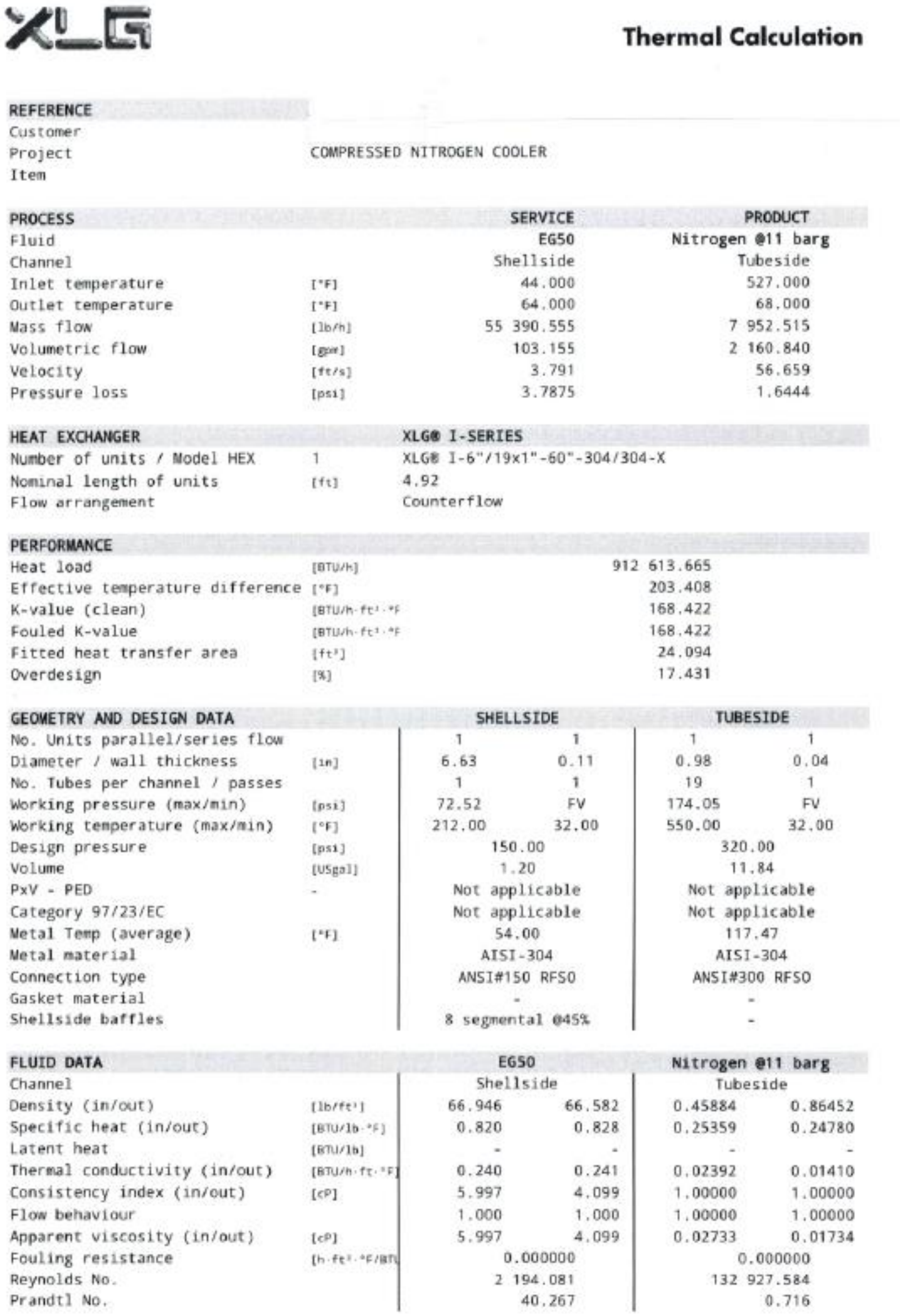
Appendix F: Chiller Heat Exchanger Data

Chiller Heat Exchanger Process Specifications



Thermal Calculation

REFERENCE	
Customer	
Project	COMPRESSED NITROGEN COOLER
Item	

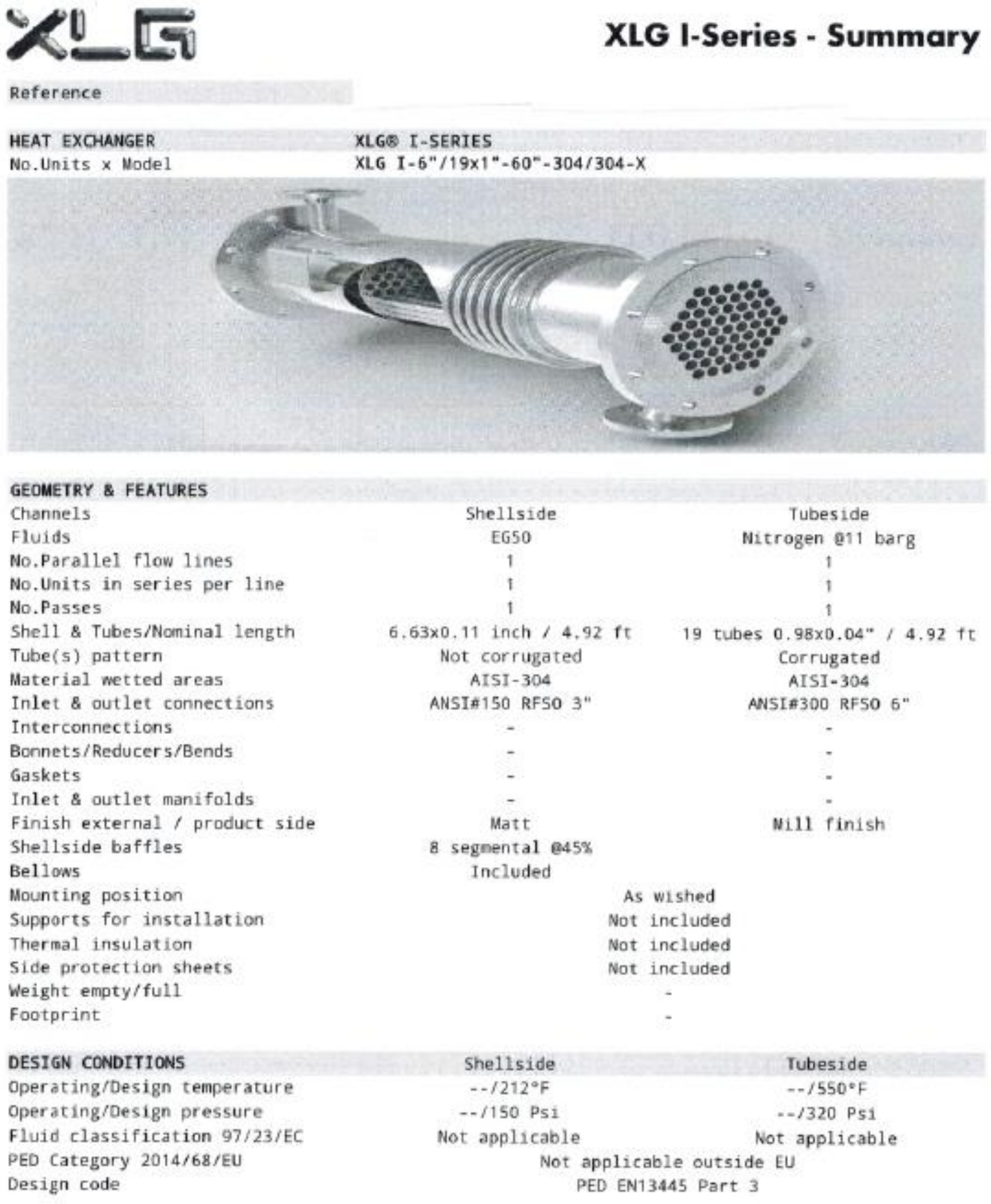
PROCESS		SERVICE	PRODUCT
Fluid		EG50	Nitrogen @11 barg
Channel		Shellside	Tubeside
Inlet temperature	[°F]	44.000	527.000
Outlet temperature	[°F]	64.000	68.000
Mass flow	[lb/h]	55 390.555	7 952.515
Volumetric flow	[gpm]	103.155	2 160.840
Velocity	[ft/s]	3.791	56.659
Pressure loss	[psi]	3.7875	1.6444

HEAT EXCHANGER		XLG® I-SERIES
Number of units / Model HEX	1	XLG® I-6"/19x1"-60"-304/304-X
Nominal length of units	[ft]	4.92
Flow arrangement		Counterflow

PERFORMANCE		
Heat load	[BTU/h]	912 613.665
Effective temperature difference	[°F]	203.408
K-value (clean)	[BTU/h·ft²·°F	168.422
Fouled K-value	[BTU/h·ft²·°F	168.422
Fitted heat transfer area	[ft²]	24.094
Overdesign	[%]	17.431

GEOMETRY AND DESIGN DATA		SHELLSIDE		TUBESIDE	
No. Units parallel/series flow		1	1	1	1
Diameter / wall thickness	[in]	6.63	0.11	0.98	0.04
No. Tubes per channel / passes		1	1	19	1
Working pressure (max/min)	[psi]	72.52	FV	174.05	FV
Working temperature (max/min)	[°F]	212.00	32.00	550.00	32.00
Design pressure	[psi]	150.00		320.00	
Volume	[USgal]	1.20		11.84	
PxV - PED	-	Not applicable		Not applicable	
Category 97/23/EC		Not applicable		Not applicable	
Metal Temp (average)	[°F]	54.00		117.47	
Metal material		AISI-304		AISI-304	
Connection type		ANSI#150 RFSO		ANSI#300 RFSO	
Gasket material		-		-	
Shellside baffles		8 segmental @45%		-	

FLUID DATA		EG50		Nitrogen @11 barg	
Channel		Shellside		Tubeside	
Density (in/out)	[lb/ft³]	66.946	66.582	0.45884	0.86452
Specific heat (in/out)	[BTU/lb·°F]	0.820	0.828	0.25359	0.24780
Latent heat	[BTU/lb]	-	-	-	-
Thermal conductivity (in/out)	[BTU/h·ft·°F]	0.240	0.241	0.02392	0.01410
Consistency index (in/out)	[cP]	5.997	4.099	1.00000	1.00000
Flow behaviour		1.000	1.000	1.00000	1.00000
Apparent viscosity (in/out)	[cP]	5.997	4.099	0.02733	0.01734
Fouling resistance	[h·ft²·°F/BT	0.000000		0.000000	
Reynolds No.		2 194.081		132 927.584	
Prandtl No.		40.267		0.716	



XLG I-Series - Summary

Reference

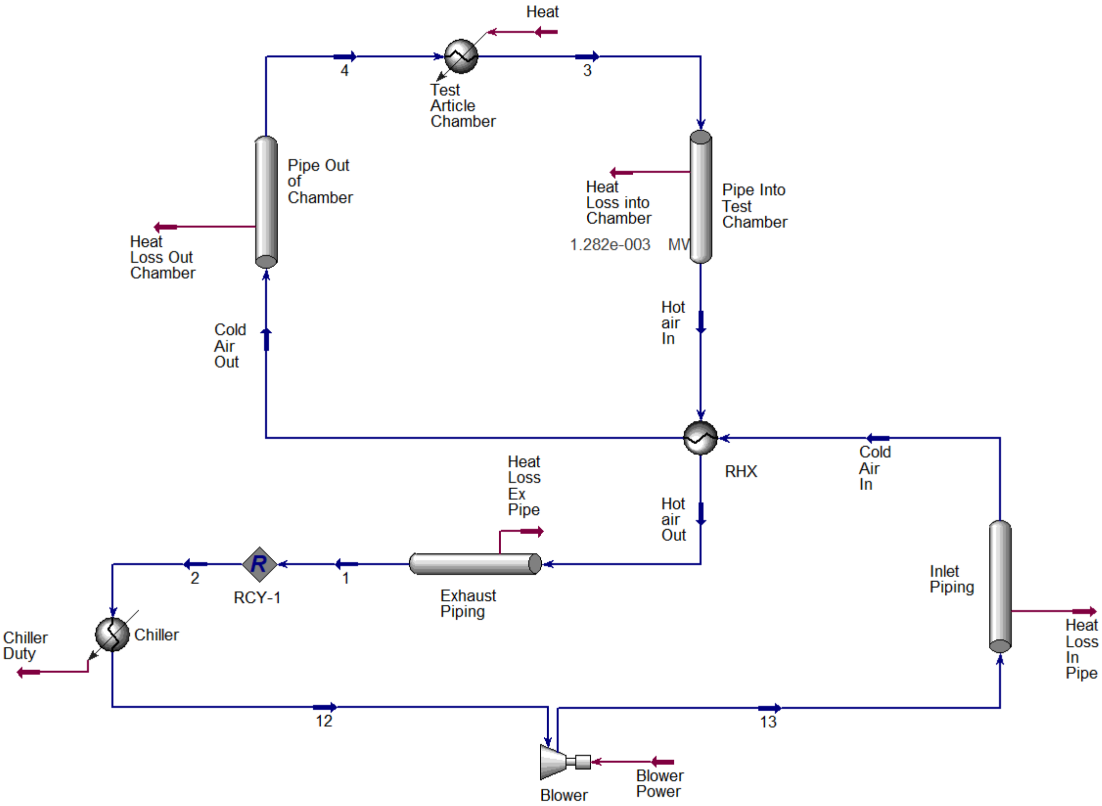
HEAT EXCHANGER	XLG® I-SERIES
No.Units x Model	XLG I-6"/19x1"-60"-304/304-X

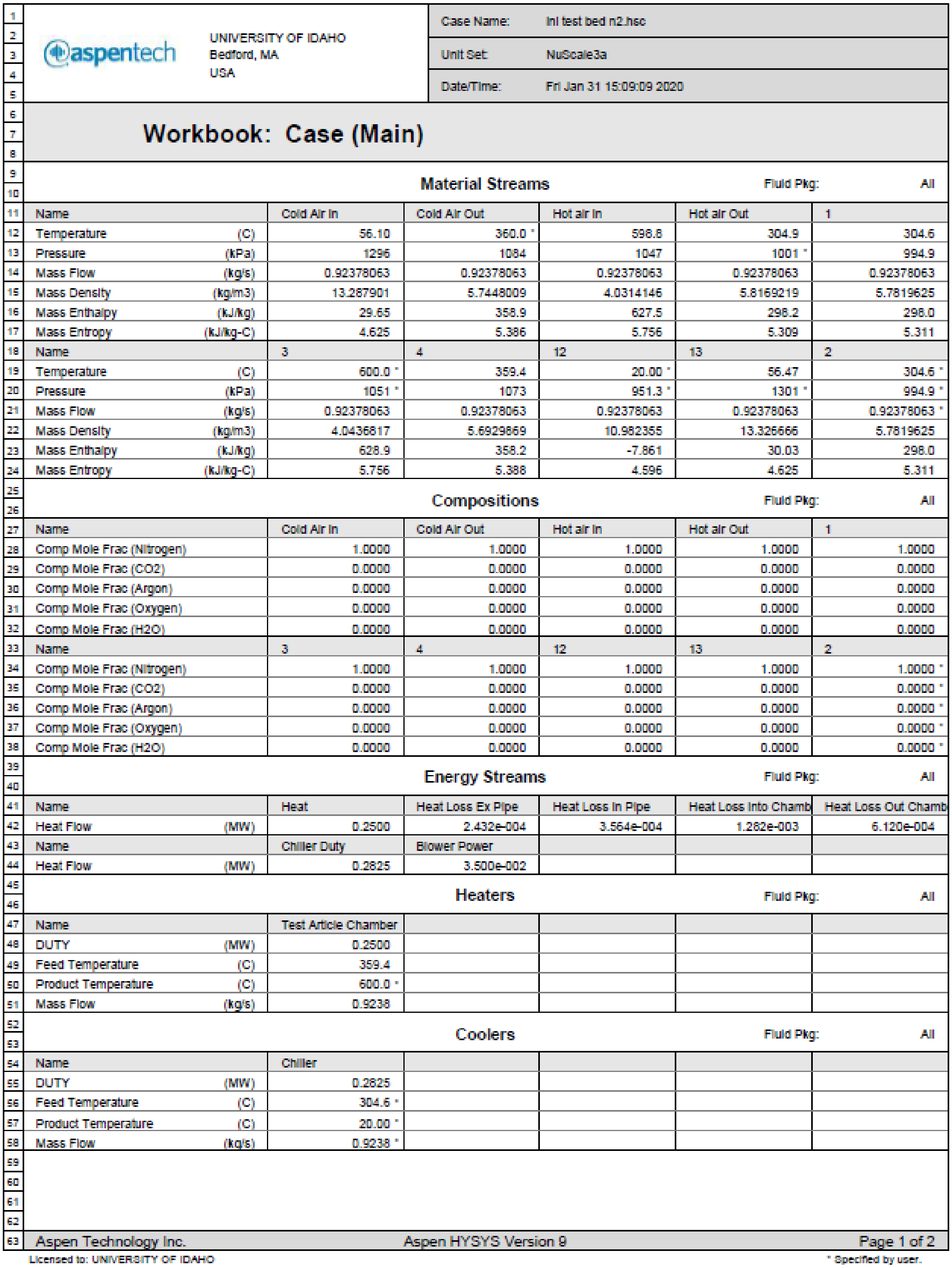
GEOMETRY & FEATURES		
Channels	Shellside	Tubeside
Fluids	EG50	Nitrogen @11 barg
No.Parallel flow lines	1	1
No.Units in series per line	1	1
No.Passes	1	1
Shell & Tubes/Nominal length	6.63x0.11 inch / 4.92 ft	19 tubes 0.98x0.04" / 4.92 ft
Tube(s) pattern	Not corrugated	Corrugated
Material wetted areas	AISI-304	AISI-304
Inlet & outlet connections	ANSI#150 RFSO 3"	ANSI#300 RFSO 6"
Interconnections	-	-
Bonnets/Reducers/Bends	-	-
Gaskets	-	-
Inlet & outlet manifolds	-	-
Finish external / product side	Matt	Mill finish
Shellside baffles	8 segmental @45%	
Bellows	Included	
Mounting position	As wished	
Supports for installation	Not included	
Thermal insulation	Not included	
Side protection sheets	Not included	
Weight empty/full	-	
Footprint	-	

DESIGN CONDITIONS	Shellside	Tubeside
Operating/Design temperature	--/212°F	--/550°F
Operating/Design pressure	--/150 Psi	--/320 Psi
Fluid classification 97/23/EC	Not applicable	Not applicable
PED Category 2014/68/EU	Not applicable outside EU	
Design code	PED EN13445 Part 3	

Appendix G: Aspen HYSYS Power Cycle Models for the Development of PCU Test Loop for Micro-Reactor Testbed

Aspen HYSYS Process Model of Micro AGile Non-nuclear Experimental Testbed with Nitrogen Operating at 600°C





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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: Inl test bed n2.hsc
Unit Set: NuScale3a
Date/Time: Fri Jan 31 15:09:09 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name	Cold Air In	Cold Air Out	Hot air In	Hot air Out	1
Temperature (C)	56.10	360.0 *	598.8	304.9	304.6
Pressure (kPa)	1296	1084	1047	1001 *	994.9
Mass Flow (kg/s)	0.92378063	0.92378063	0.92378063	0.92378063	0.92378063
Mass Density (kg/m3)	13.287901	5.7448009	4.0314146	5.8169219	5.7819625
Mass Enthalpy (kJ/kg)	29.65	358.9	627.5	298.2	298.0
Mass Entropy (kJ/kg-C)	4.625	5.386	5.756	5.309	5.311
Name	**3**	**4**	**12**	**13**	**2**
Temperature (C)	600.0 *	359.4	20.00 *	56.47	304.6 *
Pressure (kPa)	1051 *	1073	951.3 *	1301 *	994.9 *
Mass Flow (kg/s)	0.92378063	0.92378063	0.92378063	0.92378063	0.92378063 *
Mass Density (kg/m3)	4.0436817	5.6929869	10.982355	13.326666	5.7819625
Mass Enthalpy (kJ/kg)	628.9	358.2	-7.861	30.03	298.0
Mass Entropy (kJ/kg-C)	5.756	5.388	4.596	4.625	5.311

Compositions

Fluid Pkg: All

Name	Cold Air In	Cold Air Out	Hot air In	Hot air Out	1
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	0.0000
Name	**3**	**4**	**12**	**13**	**2**
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000	1.0000 *
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	0.0000 *
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	0.0000 *
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000 *
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	0.0000 *

Energy Streams

Fluid Pkg: All

Name	Heat	Heat Loss Ex Pipe	Heat Loss In Pipe	Heat Loss Into Chamb	Heat Loss Out Chamb
Heat Flow (MW)	0.2500	2.432e-004	3.564e-004	1.282e-003	6.120e-004
Name	**Chiller Duty**	**Blower Power**			
Heat Flow (MW)	0.2825	3.500e-002			

Heaters

Fluid Pkg: All

Name	Test Article Chamber				
DUTY (MW)	0.2500				
Feed Temperature (C)	359.4				
Product Temperature (C)	600.0 *				
Mass Flow (kg/s)	0.9238				

Coolers

Fluid Pkg: All

Name	Chiller				
DUTY (MW)	0.2825				
Feed Temperature (C)	304.6 *				
Product Temperature (C)	20.00 *				
Mass Flow (kg/s)	0.9238 *				

Aspen Technology Inc. Aspen HYSYS Version 9 Page 1 of 2

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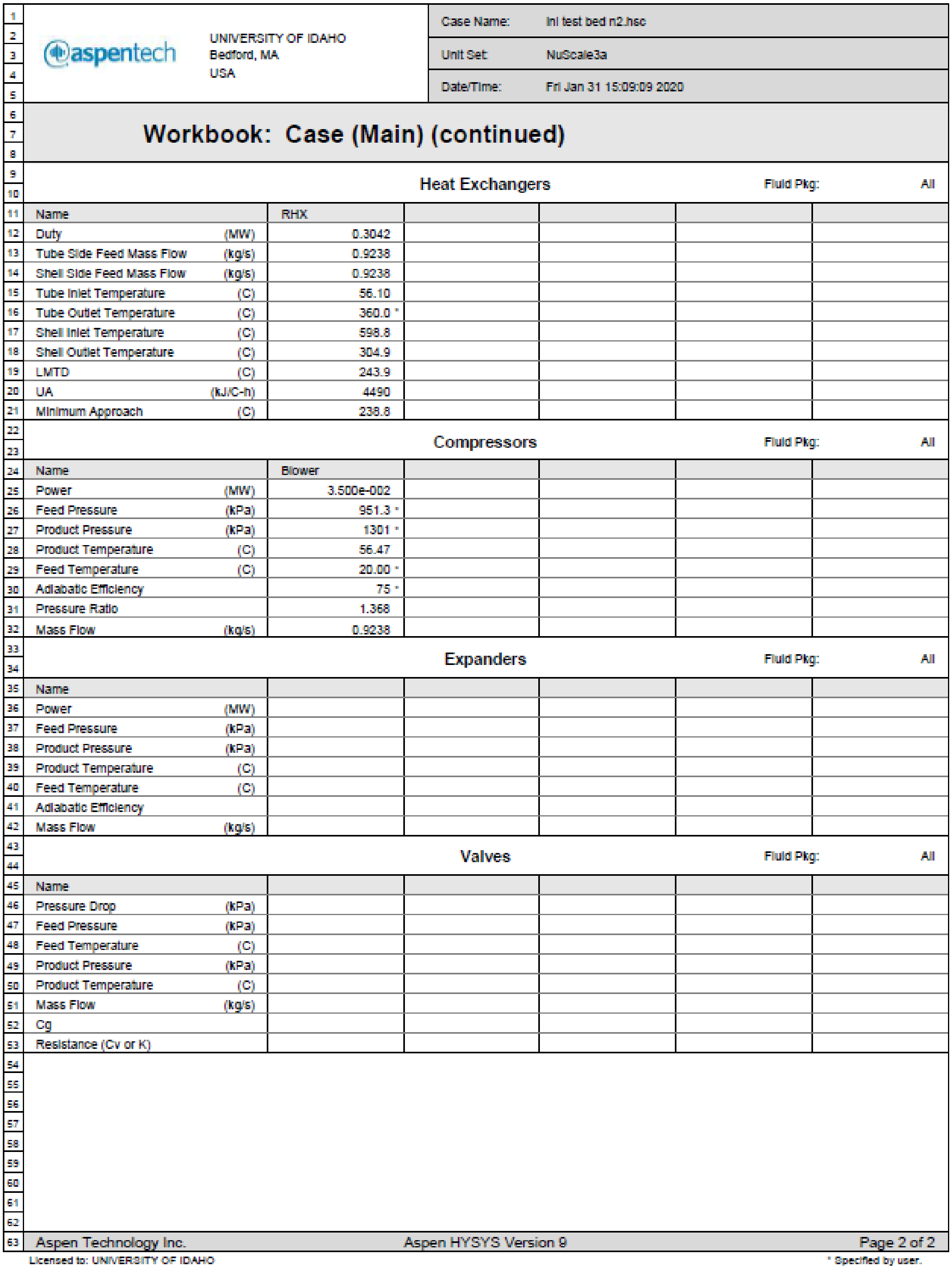

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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	Ini test bed n2.hsc
Unit Set:	NuScale3a
Date/Time:	Fri Jan 31 15:09:09 2020

Workbook: Case (Main) (continued)

Heat Exchangers

Fluid Pkg: All

Name		RHX				
Duty	(MW)	0.3042				
Tube Side Feed Mass Flow	(kg/s)	0.9238				
Shell Side Feed Mass Flow	(kg/s)	0.9238				
Tube Inlet Temperature	(C)	56.10				
Tube Outlet Temperature	(C)	360.0 *				
Shell Inlet Temperature	(C)	598.8				
Shell Outlet Temperature	(C)	304.9				
LMTD	(C)	243.9				
UA	(kJ/C-h)	4490				
Minimum Approach	(C)	238.8				

Compressors

Fluid Pkg: All

Name		Blower				
Power	(MW)	3.500e-002				
Feed Pressure	(kPa)	951.3 *				
Product Pressure	(kPa)	1301 *				
Product Temperature	(C)	56.47				
Feed Temperature	(C)	20.00 *				
Adiabatic Efficiency		75 *				
Pressure Ratio		1.368				
Mass Flow	(kg/s)	0.9238				

Expanders

Fluid Pkg: All

Name						
Power	(MW)					
Feed Pressure	(kPa)					
Product Pressure	(kPa)					
Product Temperature	(C)					
Feed Temperature	(C)					
Adiabatic Efficiency						
Mass Flow	(kg/s)					

Valves

Fluid Pkg: All

Name						
Pressure Drop	(kPa)					
Feed Pressure	(kPa)					
Feed Temperature	(C)					
Product Pressure	(kPa)					
Product Temperature	(C)					
Mass Flow	(kg/s)					
Cg						
Resistance (Cv or K)						

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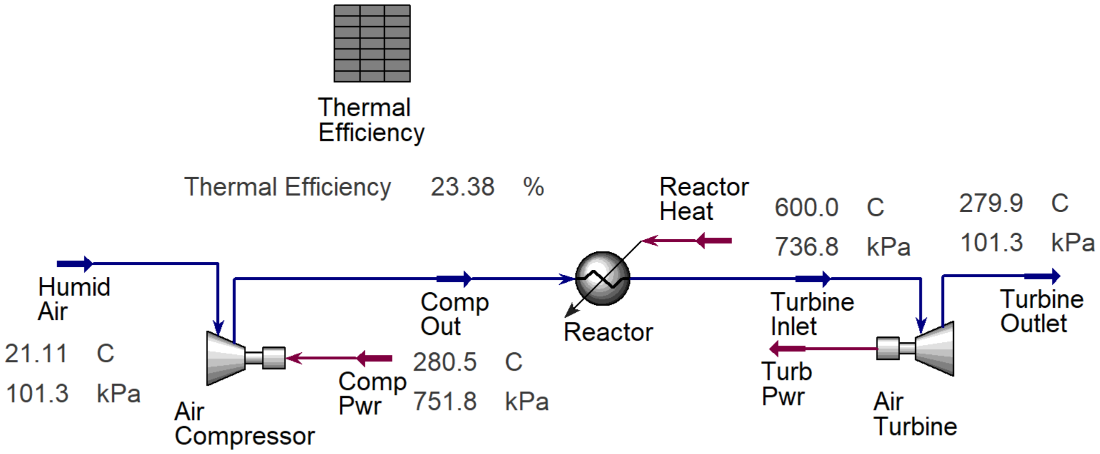
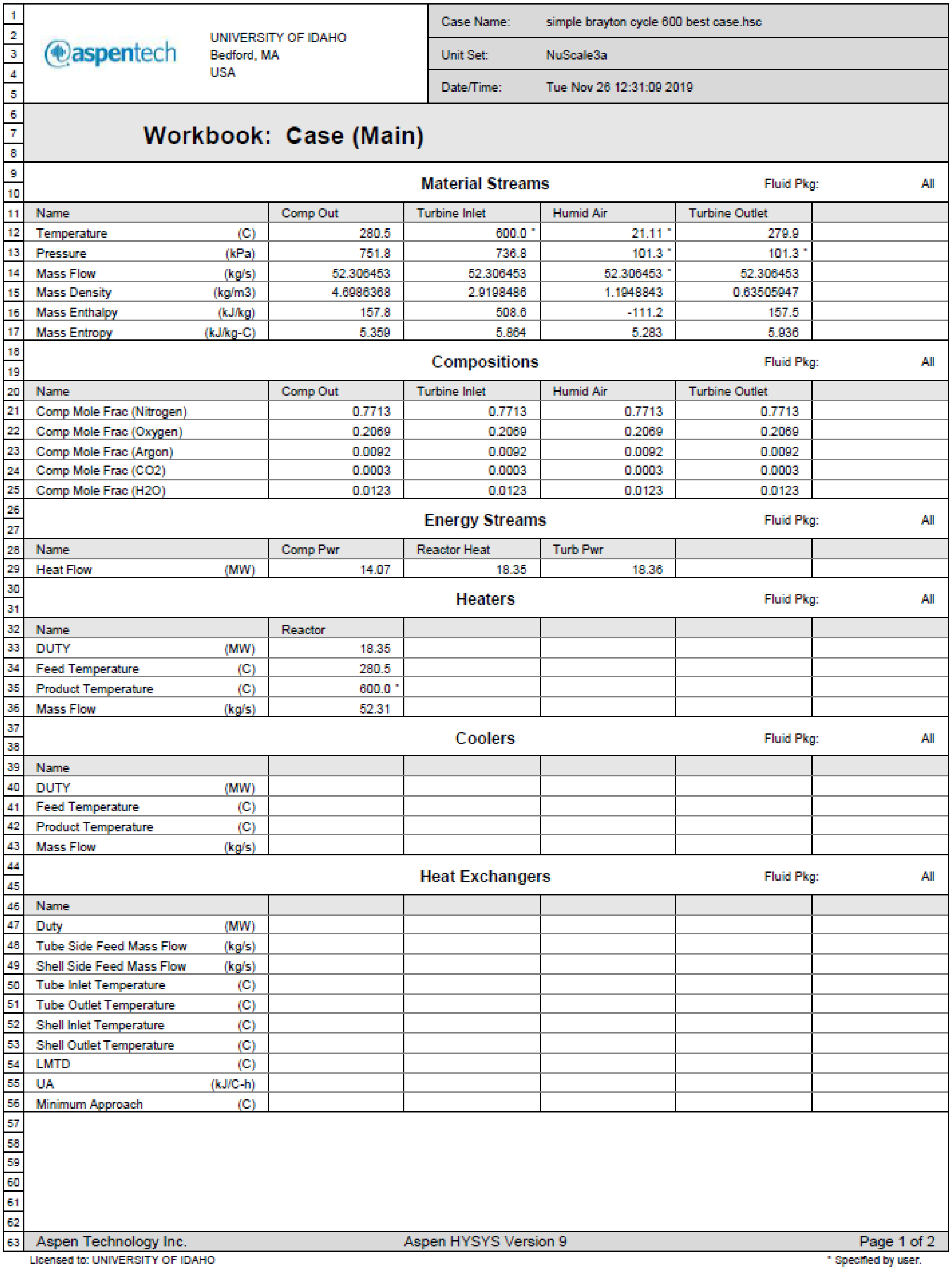
Air Brayton Open Cycle at 600°C Turbine Inlet Temperature with Compressor and Turbine Adiabatic Efficiencies of 85% and 90%





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Case Name:	simple brayton cycle 600 best case.hsc
Unit Set:	NuScale3a
Date/Time:	Tue Nov 26 12:31:09 2019

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Comp Out	Turbine Inlet	Humid Air	Turbine Outlet	
Temperature	(C)	280.5	600.0 *	21.11 *	279.9	
Pressure	(kPa)	751.8	736.8	101.3 *	101.3 *	
Mass Flow	(kg/s)	52.306453	52.306453	52.306453 *	52.306453	
Mass Density	(kg/m3)	4.6986368	2.9198486	1.1948843	0.63505947	
Mass Enthalpy	(kJ/kg)	157.8	508.6	-111.2	157.5	
Mass Entropy	(kJ/kg-C)	5.359	5.864	5.283	5.936	

Compositions

Fluid Pkg: All

Name	Comp Out	Turbine Inlet	Humid Air	Turbine Outlet	
Comp Mole Frac (Nitrogen)	0.7713	0.7713	0.7713	0.7713	
Comp Mole Frac (Oxygen)	0.2069	0.2069	0.2069	0.2069	
Comp Mole Frac (Argon)	0.0092	0.0092	0.0092	0.0092	
Comp Mole Frac (CO2)	0.0003	0.0003	0.0003	0.0003	
Comp Mole Frac (H2O)	0.0123	0.0123	0.0123	0.0123	

Energy Streams

Fluid Pkg: All

Name		Comp Pwr	Reactor Heat	Turb Pwr		
Heat Flow	(MW)	14.07	18.35	18.36		

Heaters

Fluid Pkg: All

Name		Reactor				
DUTY	(MW)	18.35				
Feed Temperature	(C)	280.5				
Product Temperature	(C)	600.0 *				
Mass Flow	(kg/s)	52.31				

Coolers

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

Heat Exchangers

Fluid Pkg: All

Name						
Duty	(MW)					
Tube Side Feed Mass Flow	(kg/s)					
Shell Side Feed Mass Flow	(kg/s)					
Tube Inlet Temperature	(C)					
Tube Outlet Temperature	(C)					
Shell Inlet Temperature	(C)					
Shell Outlet Temperature	(C)					
LMTD	(C)					
UA	(kJ/C-h)					
Minimum Approach	(C)					

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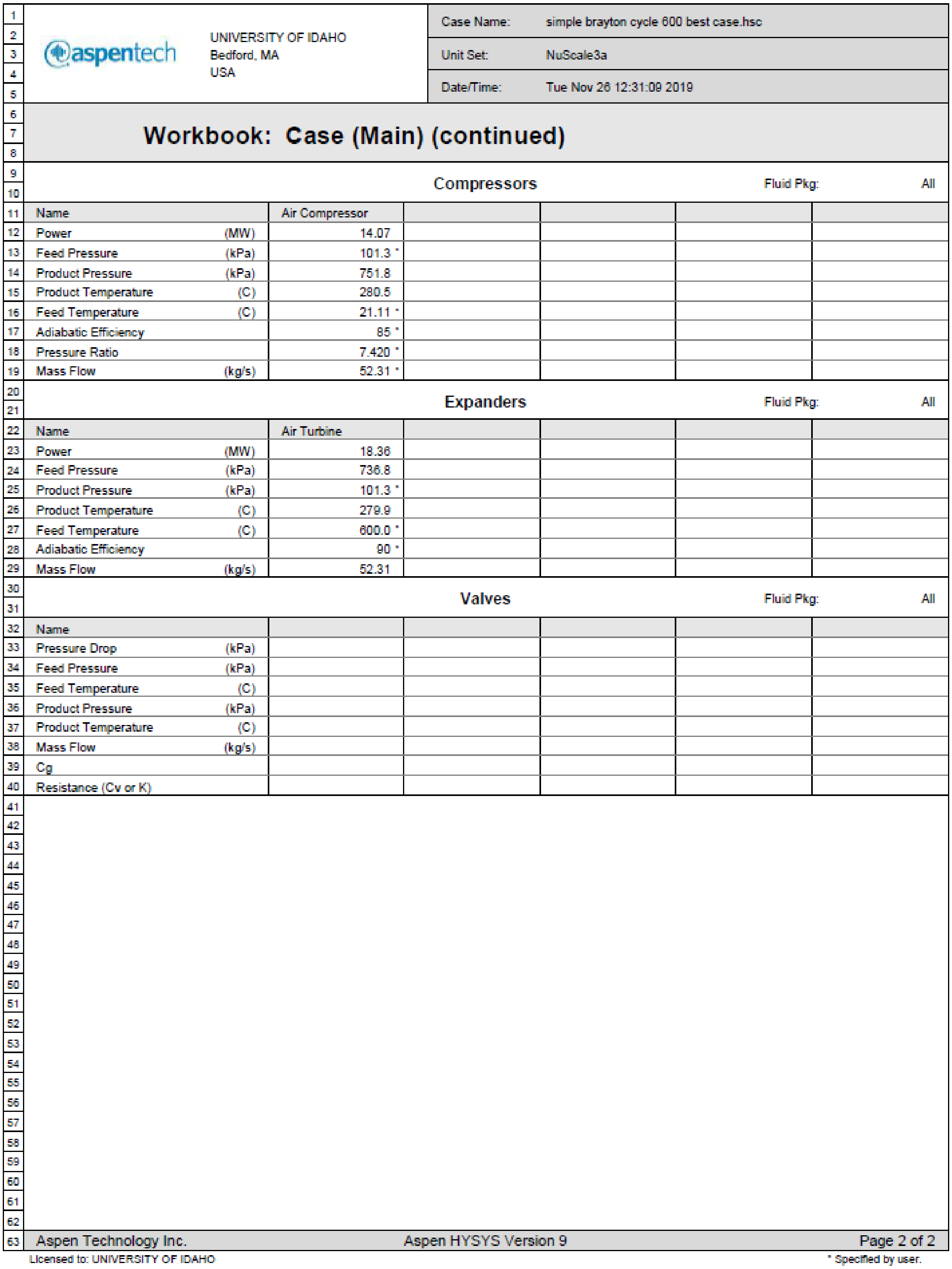

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USA

Case Name:	simple brayton cycle 600 best case.hsc
Unit Set:	NuScale3a
Date/Time:	Tue Nov 26 12:31:09 2019

Workbook: Case (Main) (continued)

Compressors

Fluid Pkg: All

Name		Air Compressor				
Power	(MW)	14.07				
Feed Pressure	(kPa)	101.3 *				
Product Pressure	(kPa)	751.8				
Product Temperature	(C)	280.5				
Feed Temperature	(C)	21.11 *				
Adiabatic Efficiency		85 *				
Pressure Ratio		7.420 *				
Mass Flow	(kg/s)	52.31 *				

Expanders

Fluid Pkg: All

Name		Air Turbine				
Power	(MW)	18.36				
Feed Pressure	(kPa)	736.8				
Product Pressure	(kPa)	101.3 *				
Product Temperature	(C)	279.9				
Feed Temperature	(C)	600.0 *				
Adiabatic Efficiency		90 *				
Mass Flow	(kg/s)	52.31				

Valves

Fluid Pkg: All

Name						
Pressure Drop	(kPa)					
Feed Pressure	(kPa)					
Feed Temperature	(C)					
Product Pressure	(kPa)					
Product Temperature	(C)					
Mass Flow	(kg/s)					
Cg						
Resistance (Cv or K)						

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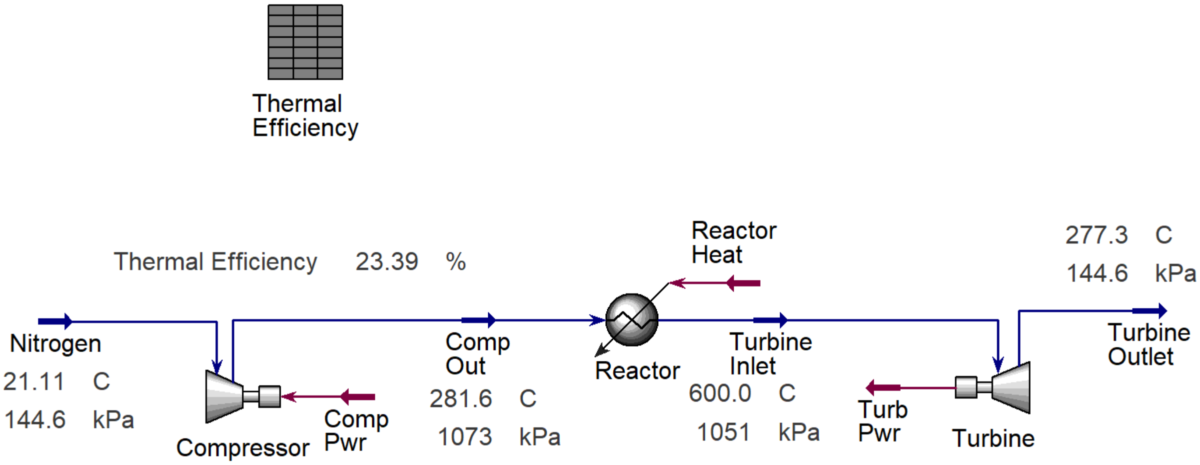
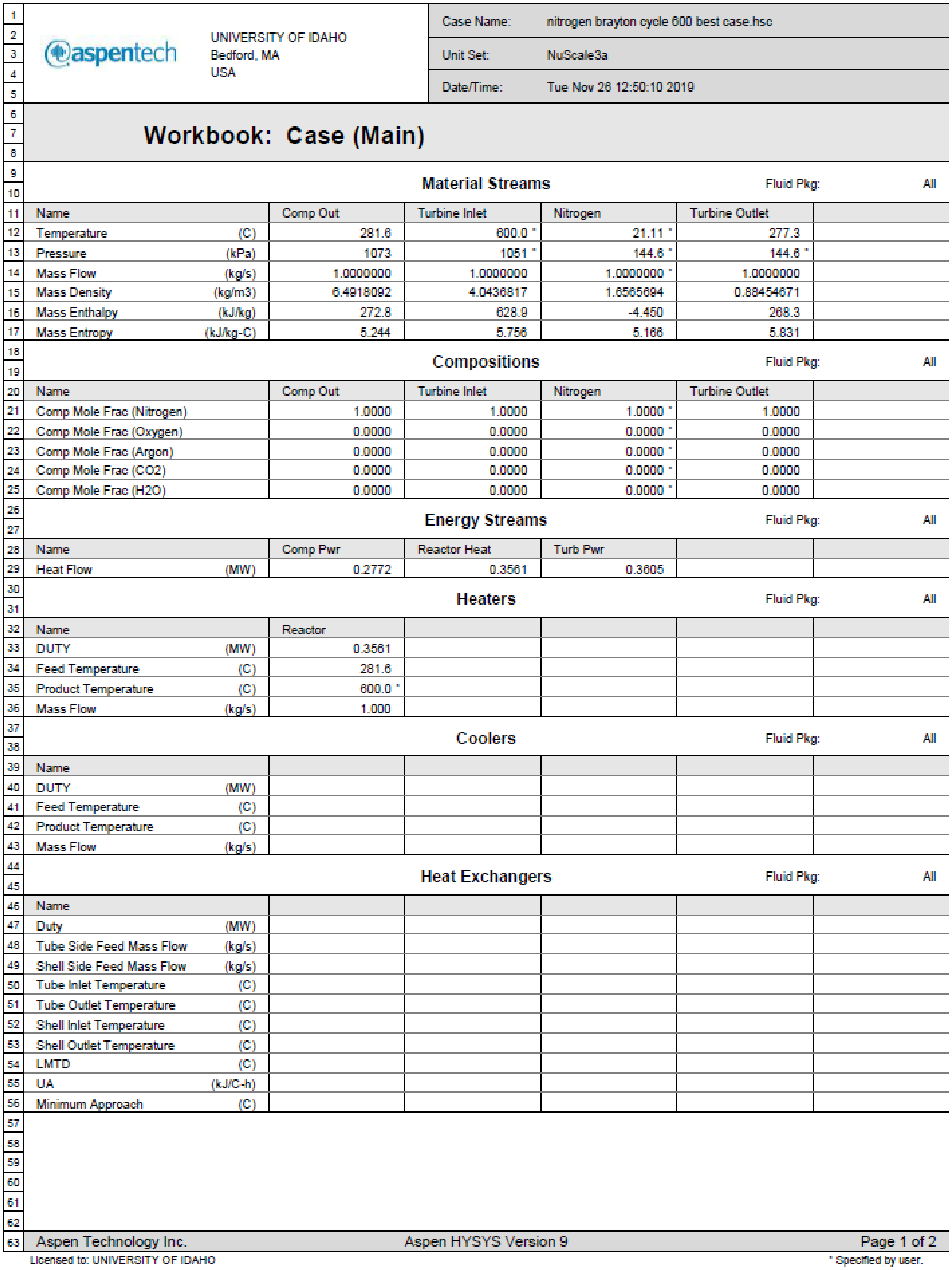
Nitrogen Brayton Cycle at 600°C Turbine Inlet Temperature with Compressor and Turbine Adiabatic Efficiencies of 85% and 90%





UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: nitrogen brayton cycle 600 best case.hsc
Unit Set: NuScale3a
Date/Time: Tue Nov 26 12:50:10 2019

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Comp Out	Turbine Inlet	Nitrogen	Turbine Outlet	
Temperature	(C)	281.6	600.0 *	21.11 *	277.3	
Pressure	(kPa)	1073	1051 *	144.6 *	144.6 *	
Mass Flow	(kg/s)	1.0000000	1.0000000	1.0000000 *	1.0000000	
Mass Density	(kg/m3)	6.4918092	4.0436817	1.6565694	0.88454671	
Mass Enthalpy	(kJ/kg)	272.8	628.9	-4.450	268.3	
Mass Entropy	(kJ/kg-C)	5.244	5.756	5.166	5.831	

Compositions

Fluid Pkg: All

Name	Comp Out	Turbine Inlet	Nitrogen	Turbine Outlet	
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000 *	1.0000	
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000 *	0.0000	
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000 *	0.0000	
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000 *	0.0000	
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000 *	0.0000	

Energy Streams

Fluid Pkg: All

Name		Comp Pwr	Reactor Heat	Turb Pwr		
Heat Flow	(MW)	0.2772	0.3561	0.3605		

Heaters

Fluid Pkg: All

Name		Reactor				
DUTY	(MW)	0.3561				
Feed Temperature	(C)	281.6				
Product Temperature	(C)	600.0 *				
Mass Flow	(kg/s)	1.000				

Coolers

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

Heat Exchangers

Fluid Pkg: All

Name						
Duty	(MW)					
Tube Side Feed Mass Flow	(kg/s)					
Shell Side Feed Mass Flow	(kg/s)					
Tube Inlet Temperature	(C)					
Tube Outlet Temperature	(C)					
Shell Inlet Temperature	(C)					
Shell Outlet Temperature	(C)					
LMTD	(C)					
UA	(kJ/C-h)					
Minimum Approach	(C)					

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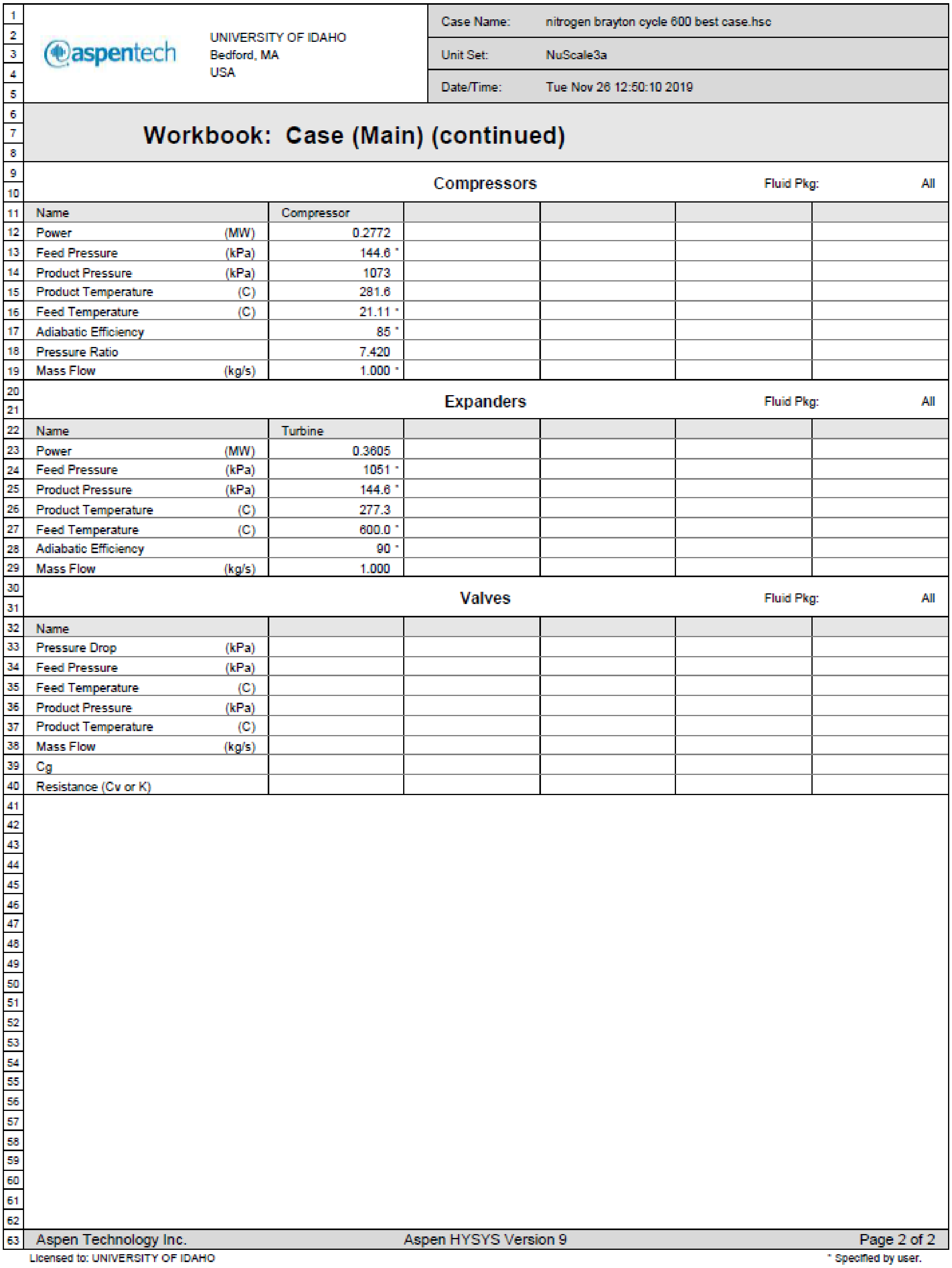

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	nitrogen brayton cycle 600 best case.hsc
Unit Set:	NuScale3a
Date/Time:	Tue Nov 26 12:50:10 2019

Workbook: Case (Main) (continued)

Compressors

Fluid Pkg: All

Name		Compressor				
Power	(MW)	0.2772				
Feed Pressure	(kPa)	144.6 *				
Product Pressure	(kPa)	1073				
Product Temperature	(C)	281.6				
Feed Temperature	(C)	21.11 *				
Adiabatic Efficiency		85 *				
Pressure Ratio		7.420				
Mass Flow	(kg/s)	1.000 *				

Expanders

Fluid Pkg: All

Name		Turbine				
Power	(MW)	0.3605				
Feed Pressure	(kPa)	1051 *				
Product Pressure	(kPa)	144.6 *				
Product Temperature	(C)	277.3				
Feed Temperature	(C)	600.0 *				
Adiabatic Efficiency		90 *				
Mass Flow	(kg/s)	1.000				

Valves

Fluid Pkg: All

Name						
Pressure Drop	(kPa)					
Feed Pressure	(kPa)					
Feed Temperature	(C)					
Product Pressure	(kPa)					
Product Temperature	(C)					
Mass Flow	(kg/s)					
Cg						
Resistance (Cv or K)						

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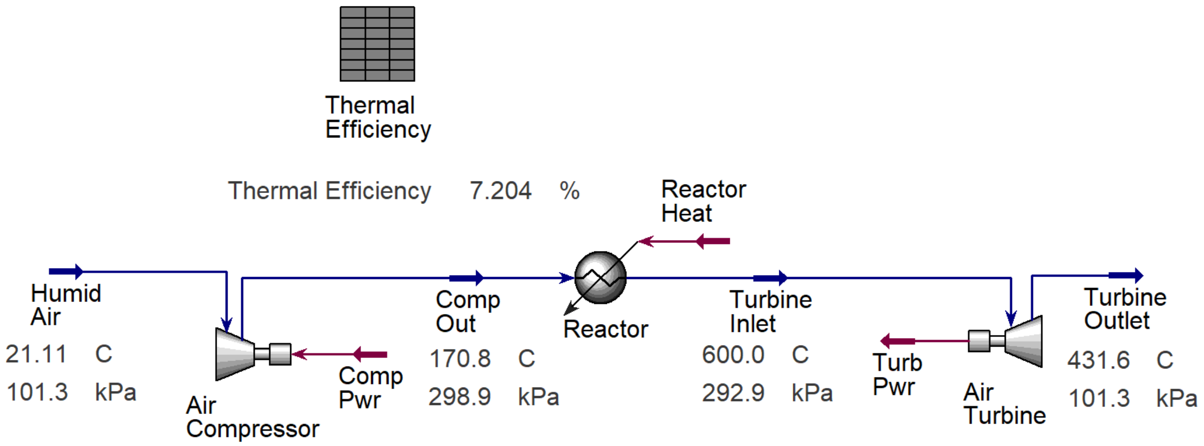
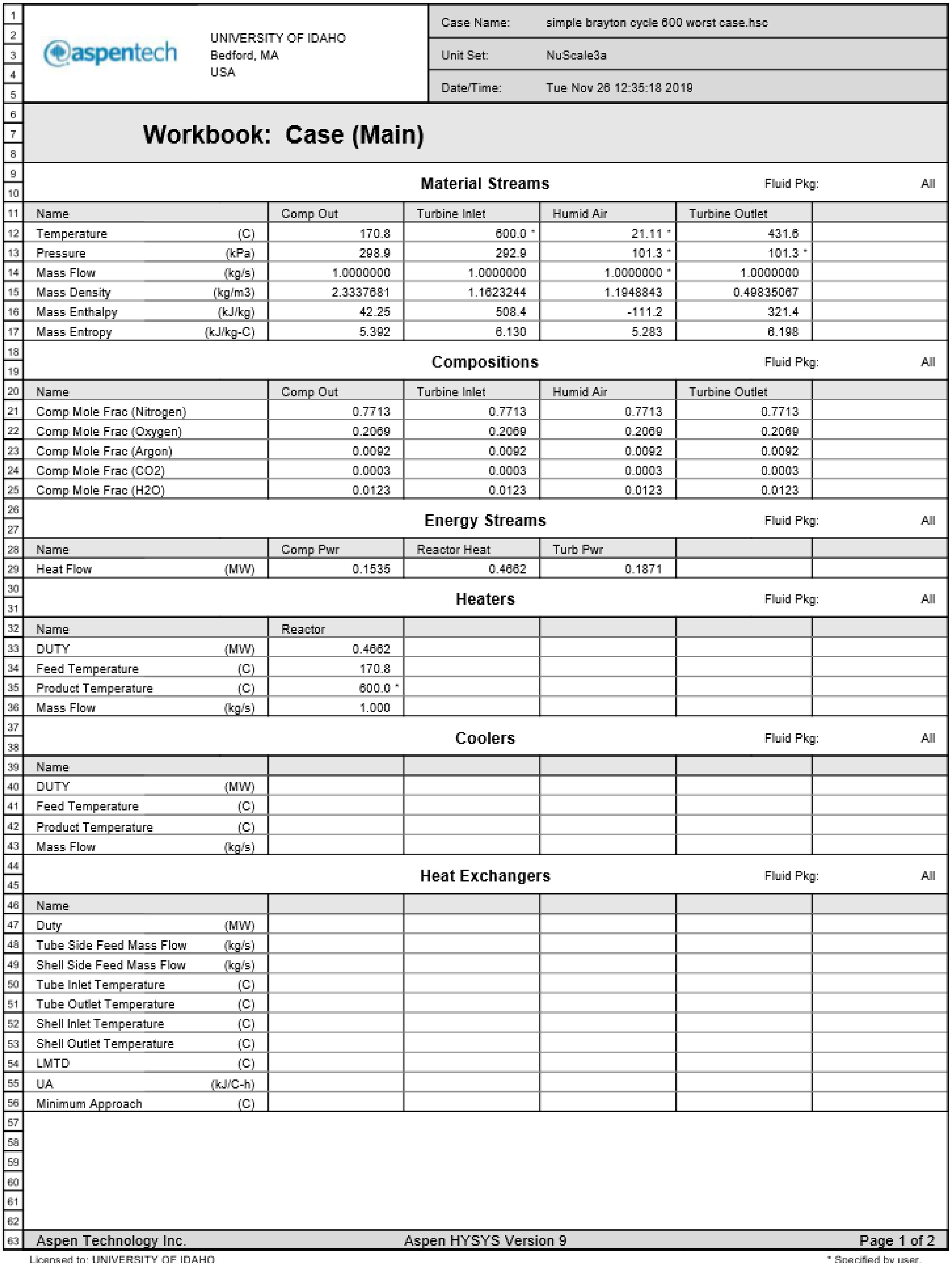
Air Brayton Open Cycle at 600°C Turbine Inlet Temperature with Compressor and Turbine Adiabatic Efficiencies of 70% and 80%





UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	simple brayton cycle 600 worst case.hsc
Unit Set:	NuScale3a
Date/Time:	Tue Nov 26 12:35:18 2019

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Comp Out	Turbine Inlet	Humid Air	Turbine Outlet	
Temperature	(C)	170.8	600.0 *	21.11 *	431.6	
Pressure	(kPa)	298.9	292.9	101.3 *	101.3 *	
Mass Flow	(kg/s)	1.0000000	1.0000000	1.0000000 *	1.0000000	
Mass Density	(kg/m3)	2.3337681	1.1623244	1.1948843	0.49835067	
Mass Enthalpy	(kJ/kg)	42.25	508.4	-111.2	321.4	
Mass Entropy	(kJ/kg-C)	5.392	6.130	5.283	6.198	

Compositions

Fluid Pkg: All

Name	Comp Out	Turbine Inlet	Humid Air	Turbine Outlet	
Comp Mole Frac (Nitrogen)	0.7713	0.7713	0.7713	0.7713	
Comp Mole Frac (Oxygen)	0.2069	0.2069	0.2069	0.2069	
Comp Mole Frac (Argon)	0.0092	0.0092	0.0092	0.0092	
Comp Mole Frac (CO2)	0.0003	0.0003	0.0003	0.0003	
Comp Mole Frac (H2O)	0.0123	0.0123	0.0123	0.0123	

Energy Streams

Fluid Pkg: All

Name		Comp Pwr	Reactor Heat	Turb Pwr		
Heat Flow	(MW)	0.1535	0.4662	0.1871		

Heaters

Fluid Pkg: All

Name		Reactor				
DUTY	(MW)	0.4662				
Feed Temperature	(C)	170.8				
Product Temperature	(C)	600.0 *				
Mass Flow	(kg/s)	1.000				

Coolers

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

Heat Exchangers

Fluid Pkg: All

Name						
Duty	(MW)					
Tube Side Feed Mass Flow	(kg/s)					
Shell Side Feed Mass Flow	(kg/s)					
Tube Inlet Temperature	(C)					
Tube Outlet Temperature	(C)					
Shell Inlet Temperature	(C)					
Shell Outlet Temperature	(C)					
LMTD	(C)					
UA	(kJ/C-h)					
Minimum Approach	(C)					

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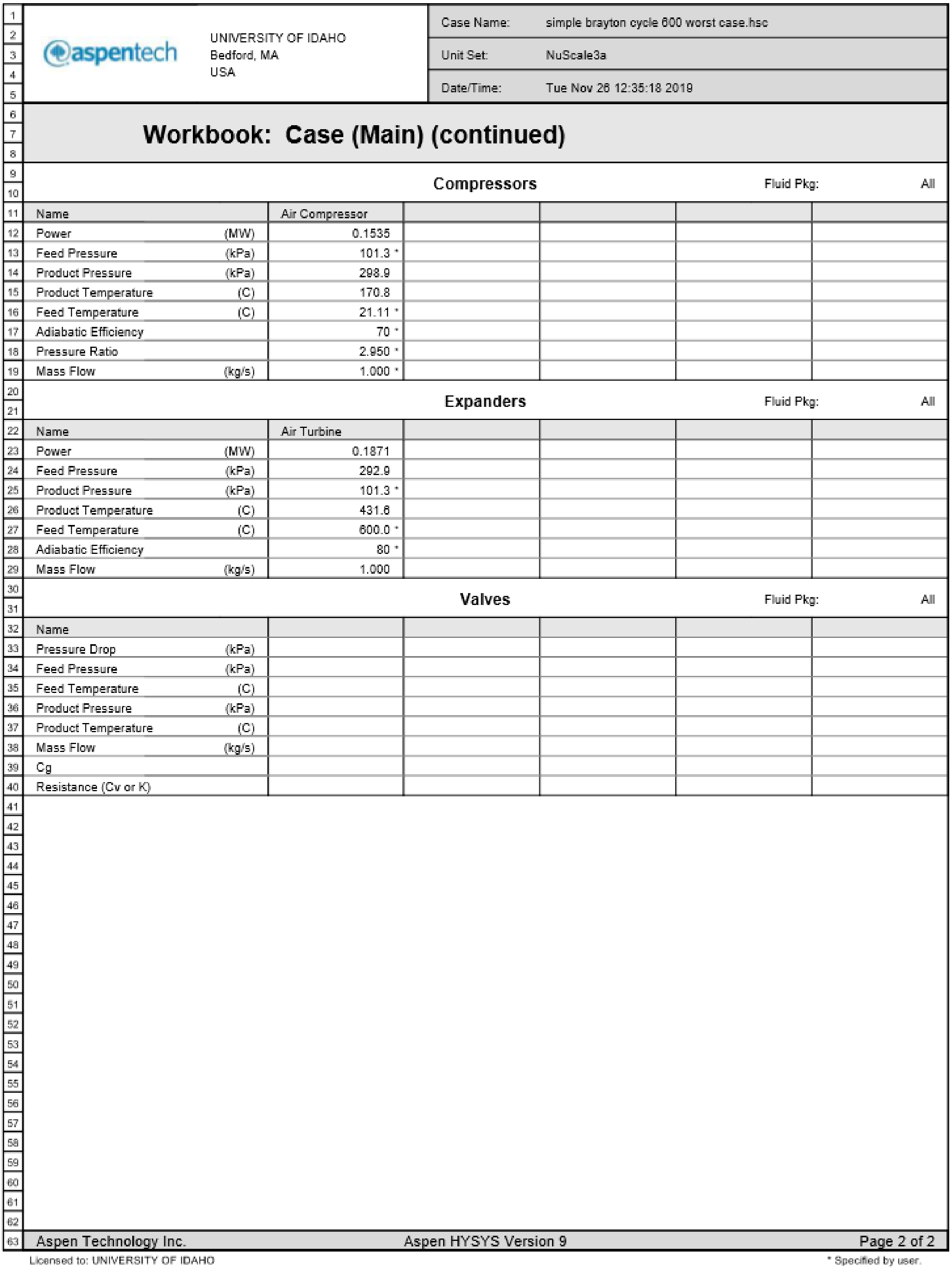

UNIVERSITY OF IDAHO Bedford, MA USA	Case Name:	simple brayton cycle 600 worst case.hsc
	Unit Set:	NuScale3a
	Date/Time:	Tue Nov 26 12:35:18 2019

Workbook: Case (Main) (continued)

Compressors

Fluid Pkg: All

Name		Air Compressor				
Power	(MW)	0.1535				
Feed Pressure	(kPa)	101.3 *				
Product Pressure	(kPa)	298.9				
Product Temperature	(C)	170.8				
Feed Temperature	(C)	21.11 *				
Adiabatic Efficiency		70 *				
Pressure Ratio		2.950 *				
Mass Flow	(kg/s)	1.000 *				

Expanders

Fluid Pkg: All

Name		Air Turbine				
Power	(MW)	0.1871				
Feed Pressure	(kPa)	292.9				
Product Pressure	(kPa)	101.3 *				
Product Temperature	(C)	431.6				
Feed Temperature	(C)	600.0 *				
Adiabatic Efficiency		80 *				
Mass Flow	(kg/s)	1.000				

Valves

Fluid Pkg: All

Name						
Pressure Drop	(kPa)					
Feed Pressure	(kPa)					
Feed Temperature	(C)					
Product Pressure	(kPa)					
Product Temperature	(C)					
Mass Flow	(kg/s)					
Cg						
Resistance (Cv or K)						

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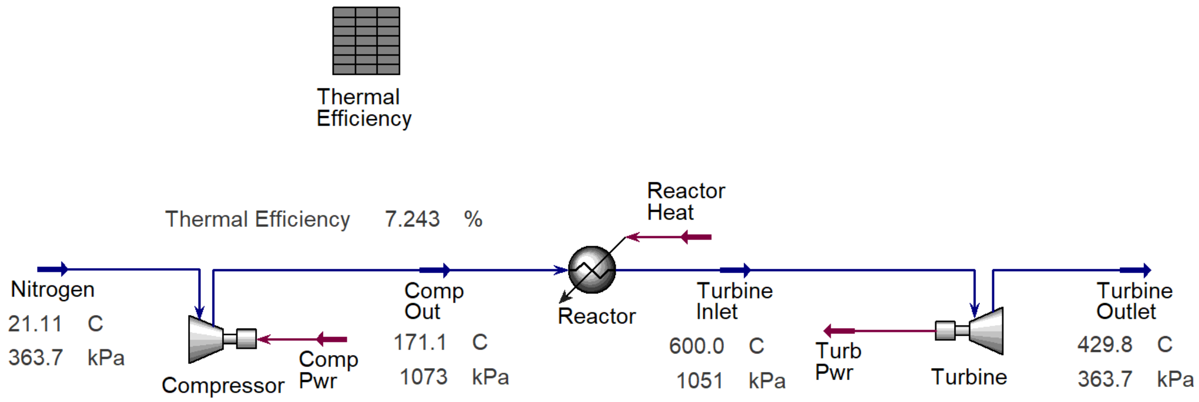
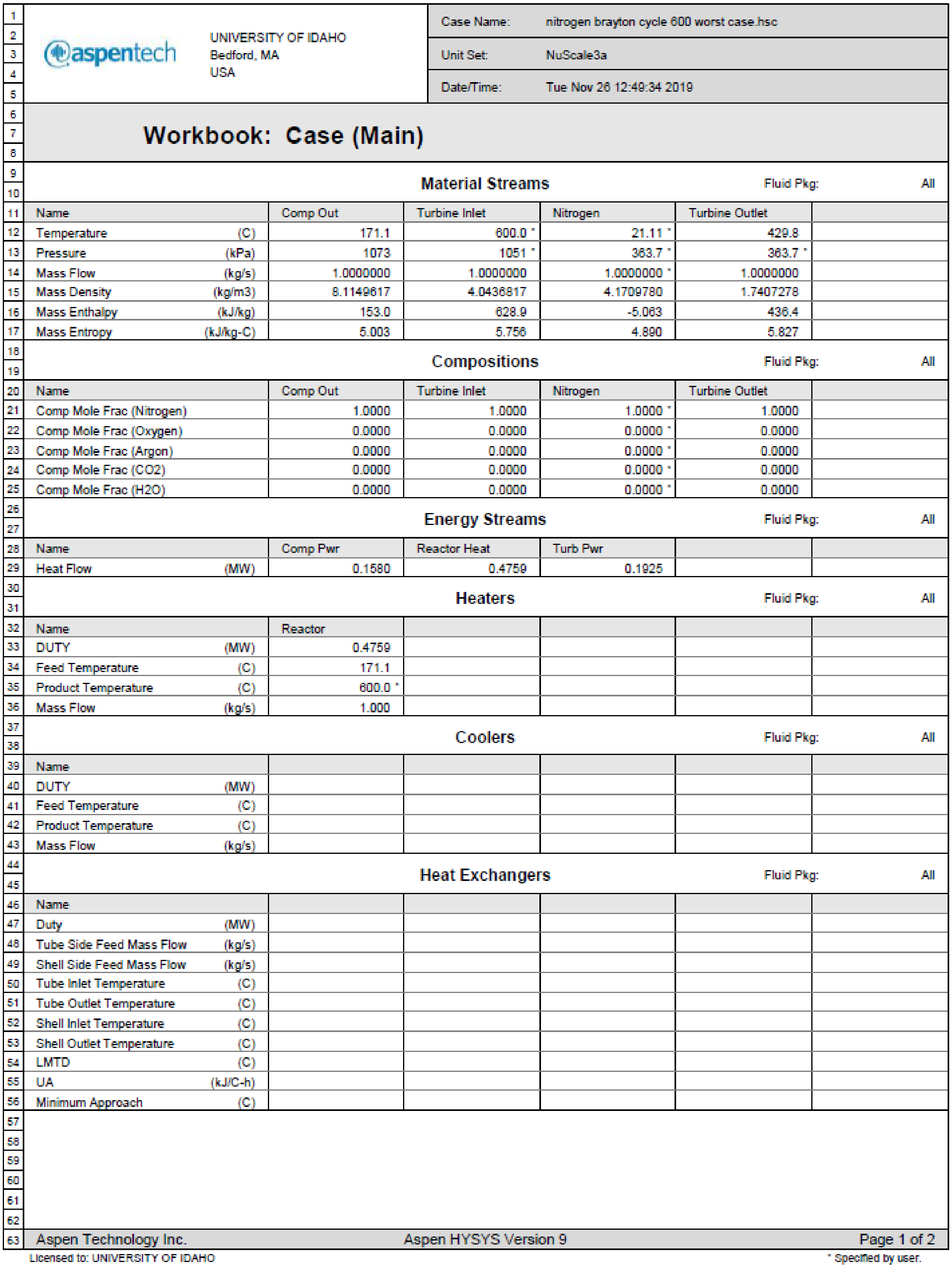
Nitrogen Brayton Open Cycle at 600°C Turbine Inlet Temperature with Compressor and Turbine Adiabatic Efficiencies of 70% and 80%





UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	nitrogen brayton cycle 600 worst case.hsc
Unit Set:	NuScale3a
Date/Time:	Tue Nov 26 12:49:34 2019

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Comp Out	Turbine Inlet	Nitrogen	Turbine Outlet	
Temperature	(C)	171.1	600.0 *	21.11 *	429.8	
Pressure	(kPa)	1073	1051 *	363.7 *	363.7 *	
Mass Flow	(kg/s)	1.0000000	1.0000000	1.0000000 *	1.0000000	
Mass Density	(kg/m3)	8.1149617	4.0436817	4.1709780	1.7407278	
Mass Enthalpy	(kJ/kg)	153.0	628.9	-5.063	436.4	
Mass Entropy	(kJ/kg-C)	5.003	5.756	4.890	5.827	

Compositions

Fluid Pkg: All

Name	Comp Out	Turbine Inlet	Nitrogen	Turbine Outlet	
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000 *	1.0000	
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000 *	0.0000	
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000 *	0.0000	
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000 *	0.0000	
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000 *	0.0000	

Energy Streams

Fluid Pkg: All

Name		Comp Pwr	Reactor Heat	Turb Pwr		
Heat Flow	(MW)	0.1580	0.4759	0.1925		

Heaters

Fluid Pkg: All

Name		Reactor				
DUTY	(MW)	0.4759				
Feed Temperature	(C)	171.1				
Product Temperature	(C)	600.0 *				
Mass Flow	(kg/s)	1.000				

Coolers

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

Heat Exchangers

Fluid Pkg: All

Name						
Duty	(MW)					
Tube Side Feed Mass Flow	(kg/s)					
Shell Side Feed Mass Flow	(kg/s)					
Tube Inlet Temperature	(C)					
Tube Outlet Temperature	(C)					
Shell Inlet Temperature	(C)					
Shell Outlet Temperature	(C)					
LMTD	(C)					
UA	(kJ/C-h)					
Minimum Approach	(C)					

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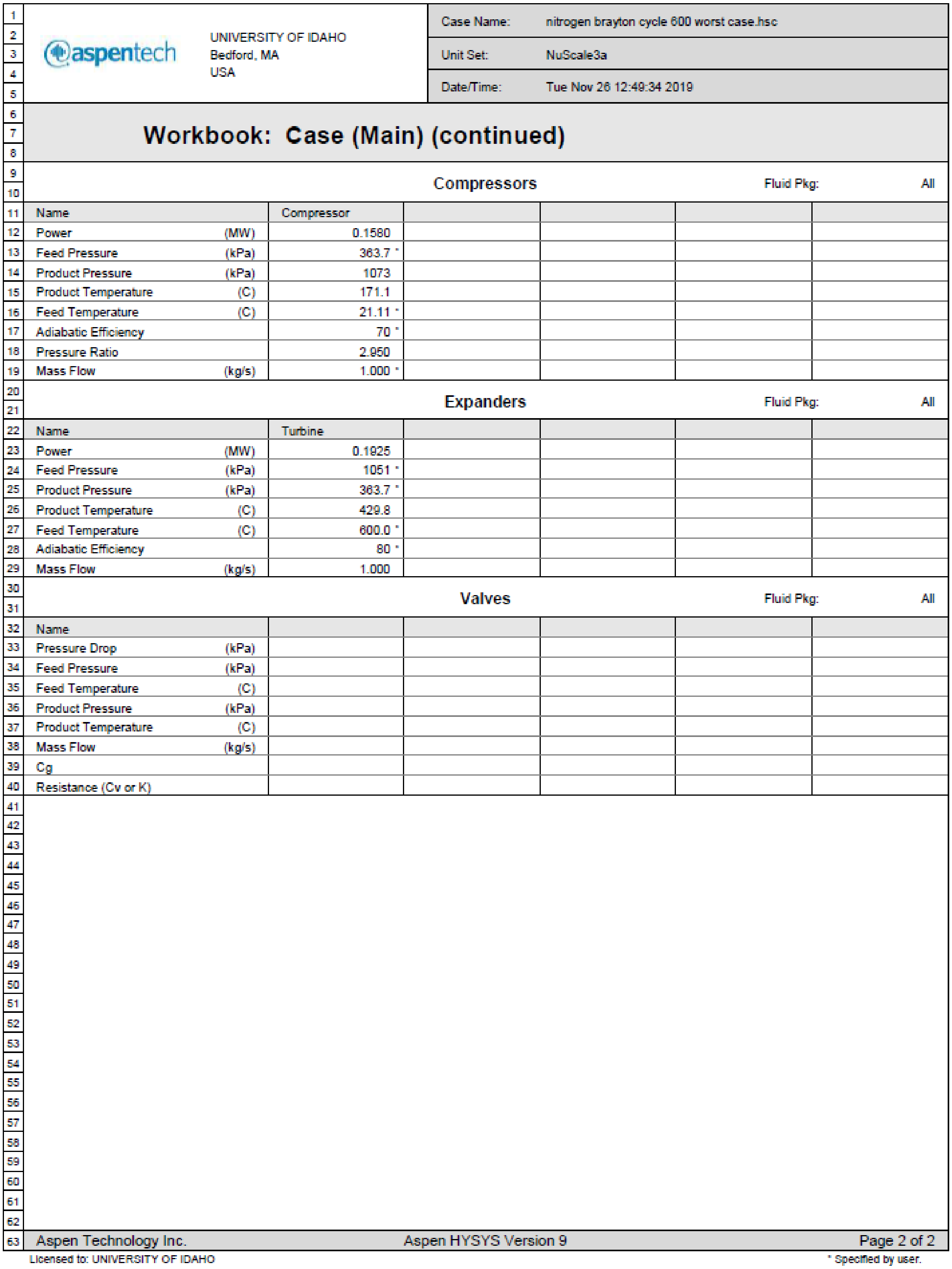

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: nitrogen brayton cycle 600 worst case.hsc
Unit Set: NuScale3a
Date/Time: Tue Nov 26 12:49:34 2019

Workbook: Case (Main) (continued)

Compressors

Fluid Pkg: All

Name	Compressor				
Power (MW)	0.1580				
Feed Pressure (kPa)	363.7 *				
Product Pressure (kPa)	1073				
Product Temperature (C)	171.1				
Feed Temperature (C)	21.11 *				
Adiabatic Efficiency	70 *				
Pressure Ratio	2.950				
Mass Flow (kg/s)	1.000 *				

Expanders

Fluid Pkg: All

Name	Turbine				
Power (MW)	0.1925				
Feed Pressure (kPa)	1051 *				
Product Pressure (kPa)	363.7 *				
Product Temperature (C)	429.8				
Feed Temperature (C)	600.0 *				
Adiabatic Efficiency	80 *				
Mass Flow (kg/s)	1.000				

Valves

Fluid Pkg: All

Name					
Pressure Drop (kPa)					
Feed Pressure (kPa)					
Feed Temperature (C)					
Product Pressure (kPa)					
Product Temperature (C)					
Mass Flow (kg/s)					
Cg					
Resistance (Cv or K)					

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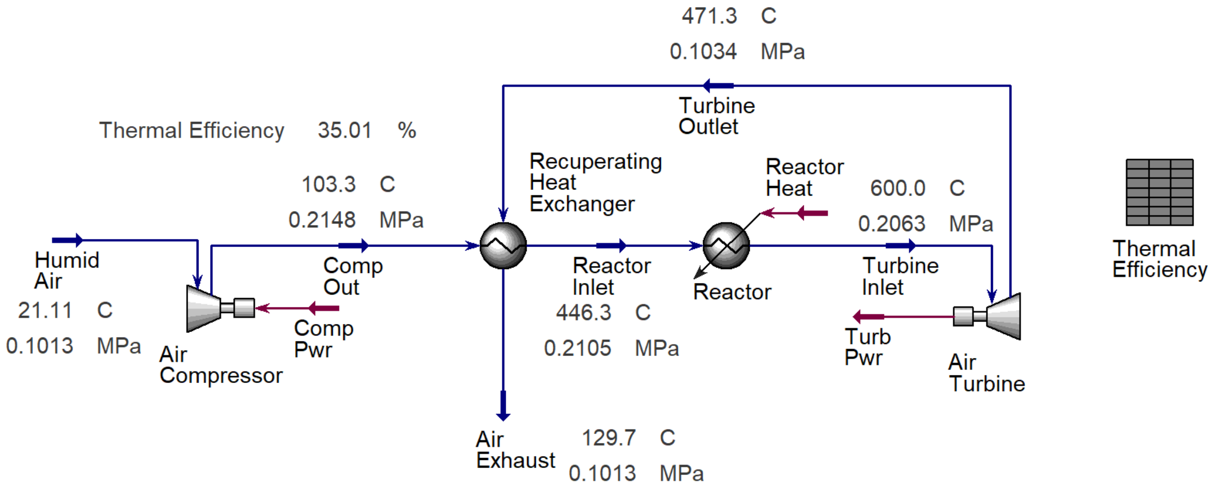
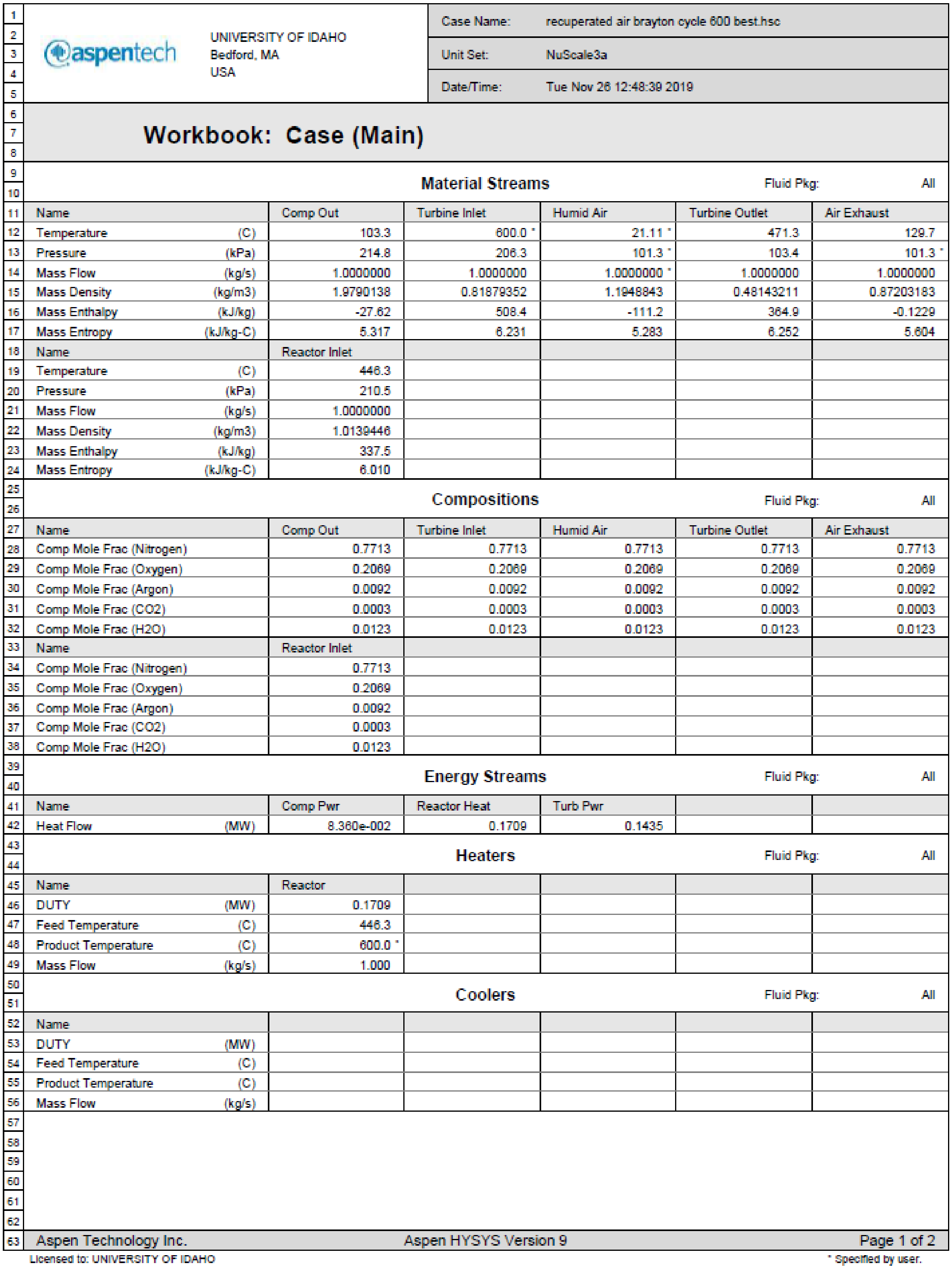
Recuperated Air Brayton Open Cycle at 600°C Turbine Inlet Temperature with Compressor and Turbine Adiabatic Efficiencies of 85% and 90%





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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: recuperated air brayton cycle 600 best.hsc
Unit Set: NuScale3a
Date/Time: Tue Nov 26 12:48:39 2019

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Comp Out	Turbine Inlet	Humid Air	Turbine Outlet	Air Exhaust
Temperature	(C)	103.3	600.0 *	21.11 *	471.3	129.7
Pressure	(kPa)	214.8	206.3	101.3 *	103.4	101.3 *
Mass Flow	(kg/s)	1.0000000	1.0000000	1.0000000 *	1.0000000	1.0000000
Mass Density	(kg/m3)	1.9790138	0.81879352	1.1948843	0.48143211	0.87203183
Mass Enthalpy	(kJ/kg)	-27.62	508.4	-111.2	364.9	-0.1229
Mass Entropy	(kJ/kg-C)	5.317	6.231	5.283	6.252	5.604
Name		Reactor Inlet				
Temperature	(C)	446.3				
Pressure	(kPa)	210.5				
Mass Flow	(kg/s)	1.0000000				
Mass Density	(kg/m3)	1.0139446				
Mass Enthalpy	(kJ/kg)	337.5				
Mass Entropy	(kJ/kg-C)	6.010				

Compositions

Fluid Pkg: All

Name	Comp Out	Turbine Inlet	Humid Air	Turbine Outlet	Air Exhaust
Comp Mole Frac (Nitrogen)	0.7713	0.7713	0.7713	0.7713	0.7713
Comp Mole Frac (Oxygen)	0.2069	0.2069	0.2069	0.2069	0.2069
Comp Mole Frac (Argon)	0.0092	0.0092	0.0092	0.0092	0.0092
Comp Mole Frac (CO2)	0.0003	0.0003	0.0003	0.0003	0.0003
Comp Mole Frac (H2O)	0.0123	0.0123	0.0123	0.0123	0.0123
Name	Reactor Inlet				
Comp Mole Frac (Nitrogen)	0.7713				
Comp Mole Frac (Oxygen)	0.2069				
Comp Mole Frac (Argon)	0.0092				
Comp Mole Frac (CO2)	0.0003				
Comp Mole Frac (H2O)	0.0123				

Energy Streams

Fluid Pkg: All

Name		Comp Pwr	Reactor Heat	Turb Pwr		
Heat Flow	(MW)	8.360e-002	0.1709	0.1435		

Heaters

Fluid Pkg: All

Name		Reactor				
DUTY	(MW)	0.1709				
Feed Temperature	(C)	446.3				
Product Temperature	(C)	600.0 *				
Mass Flow	(kg/s)	1.000				

Coolers

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

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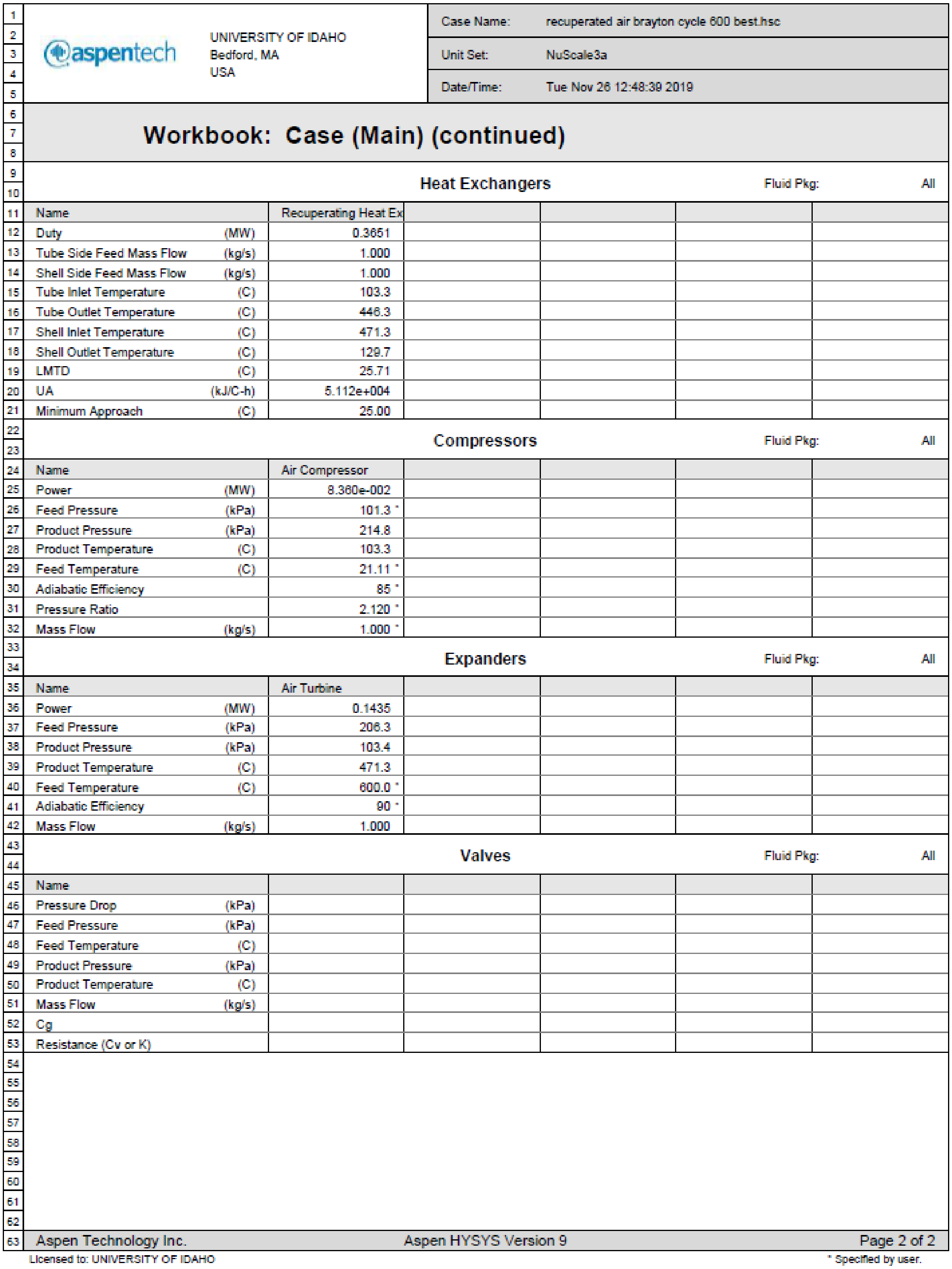

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	recuperated air brayton cycle 600 best.hsc
Unit Set:	NuScale3a
Date/Time:	Tue Nov 26 12:48:39 2019

Workbook: Case (Main) (continued)

Heat Exchangers

Fluid Pkg: All

Name		Recuperating Heat Ex				
Duty	(MW)	0.3651				
Tube Side Feed Mass Flow	(kg/s)	1.000				
Shell Side Feed Mass Flow	(kg/s)	1.000				
Tube Inlet Temperature	(C)	103.3				
Tube Outlet Temperature	(C)	446.3				
Shell Inlet Temperature	(C)	471.3				
Shell Outlet Temperature	(C)	129.7				
LMTD	(C)	25.71				
UA	(kJ/C-h)	5.112e+004				
Minimum Approach	(C)	25.00				

Compressors

Fluid Pkg: All

Name		Air Compressor				
Power	(MW)	8.360e-002				
Feed Pressure	(kPa)	101.3 *				
Product Pressure	(kPa)	214.8				
Product Temperature	(C)	103.3				
Feed Temperature	(C)	21.11 *				
Adiabatic Efficiency		85 *				
Pressure Ratio		2.120 *				
Mass Flow	(kg/s)	1.000 *				

Expanders

Fluid Pkg: All

Name		Air Turbine				
Power	(MW)	0.1435				
Feed Pressure	(kPa)	206.3				
Product Pressure	(kPa)	103.4				
Product Temperature	(C)	471.3				
Feed Temperature	(C)	600.0 *				
Adiabatic Efficiency		90 *				
Mass Flow	(kg/s)	1.000				

Valves

Fluid Pkg: All

Name						
Pressure Drop	(kPa)					
Feed Pressure	(kPa)					
Feed Temperature	(C)					
Product Pressure	(kPa)					
Product Temperature	(C)					
Mass Flow	(kg/s)					
Cg						
Resistance (Cv or K)						

Aspen Technology Inc. Aspen HYSYS Version 9 Page 2 of 2

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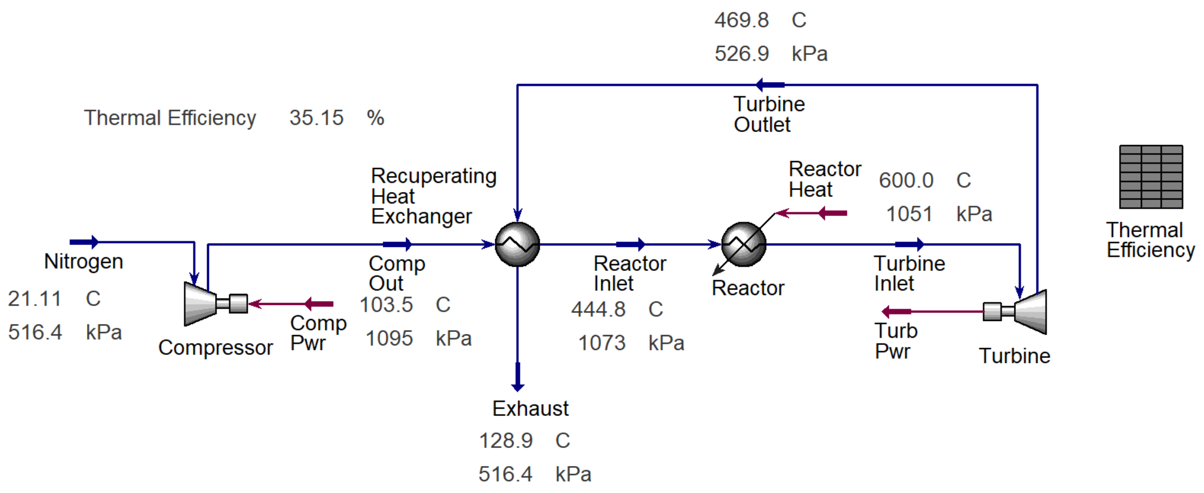
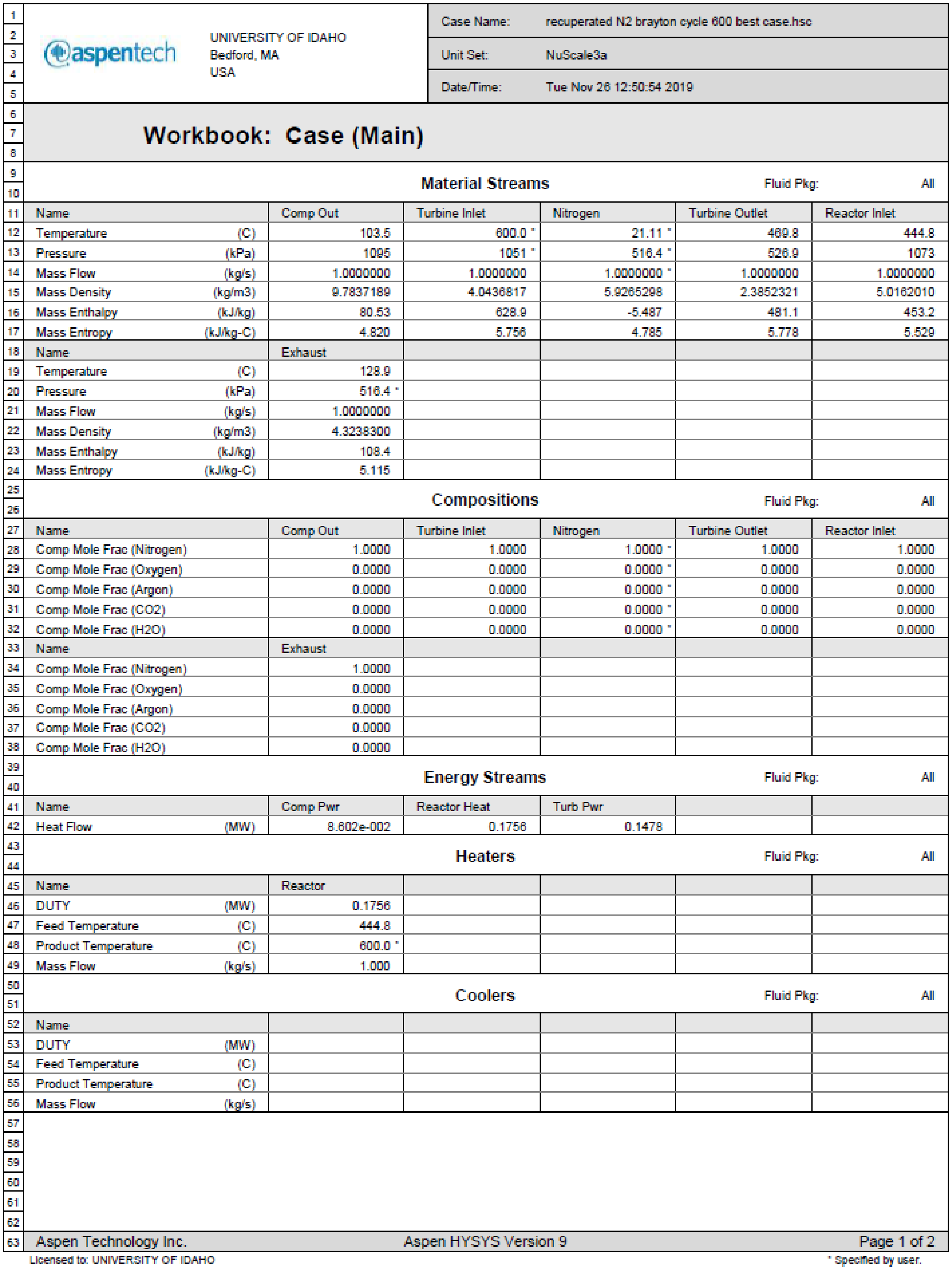
Recuperated Nitrogen Brayton Open Cycle at 600°C Turbine Inlet Temperature with Compressor and Turbine Adiabatic Efficiencies of 85% and 90%





aspentech

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	recuperated N2 brayton cycle 600 best case.hsc
Unit Set:	NuScale3a
Date/Time:	Tue Nov 26 12:50:54 2019

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Comp Out	Turbine Inlet	Nitrogen	Turbine Outlet	Reactor Inlet
Temperature	(C)	103.5	600.0 *	21.11 *	469.8	444.8
Pressure	(kPa)	1095	1051 *	516.4 *	526.9	1073
Mass Flow	(kg/s)	1.0000000	1.0000000	1.0000000 *	1.0000000	1.0000000
Mass Density	(kg/m3)	9.7837189	4.0436817	5.9265298	2.3852321	5.0162010
Mass Enthalpy	(kJ/kg)	80.53	628.9	-5.487	481.1	453.2
Mass Entropy	(kJ/kg-C)	4.820	5.756	4.785	5.778	5.529
Name		Exhaust				
Temperature	(C)	128.9				
Pressure	(kPa)	516.4 *				
Mass Flow	(kg/s)	1.0000000				
Mass Density	(kg/m3)	4.3238300				
Mass Enthalpy	(kJ/kg)	108.4				
Mass Entropy	(kJ/kg-C)	5.115				

Compositions

Fluid Pkg: All

Name	Comp Out	Turbine Inlet	Nitrogen	Turbine Outlet	Reactor Inlet
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000 *	1.0000	1.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000 *	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000 *	0.0000	0.0000
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000 *	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000 *	0.0000	0.0000
Name	Exhaust				
Comp Mole Frac (Nitrogen)	1.0000				
Comp Mole Frac (Oxygen)	0.0000				
Comp Mole Frac (Argon)	0.0000				
Comp Mole Frac (CO2)	0.0000				
Comp Mole Frac (H2O)	0.0000				

Energy Streams

Fluid Pkg: All

Name		Comp Pwr	Reactor Heat	Turb Pwr		
Heat Flow	(MW)	8.602e-002	0.1756	0.1478		

Heaters

Fluid Pkg: All

Name		Reactor				
DUTY	(MW)	0.1756				
Feed Temperature	(C)	444.8				
Product Temperature	(C)	600.0 *				
Mass Flow	(kg/s)	1.000				

Coolers

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

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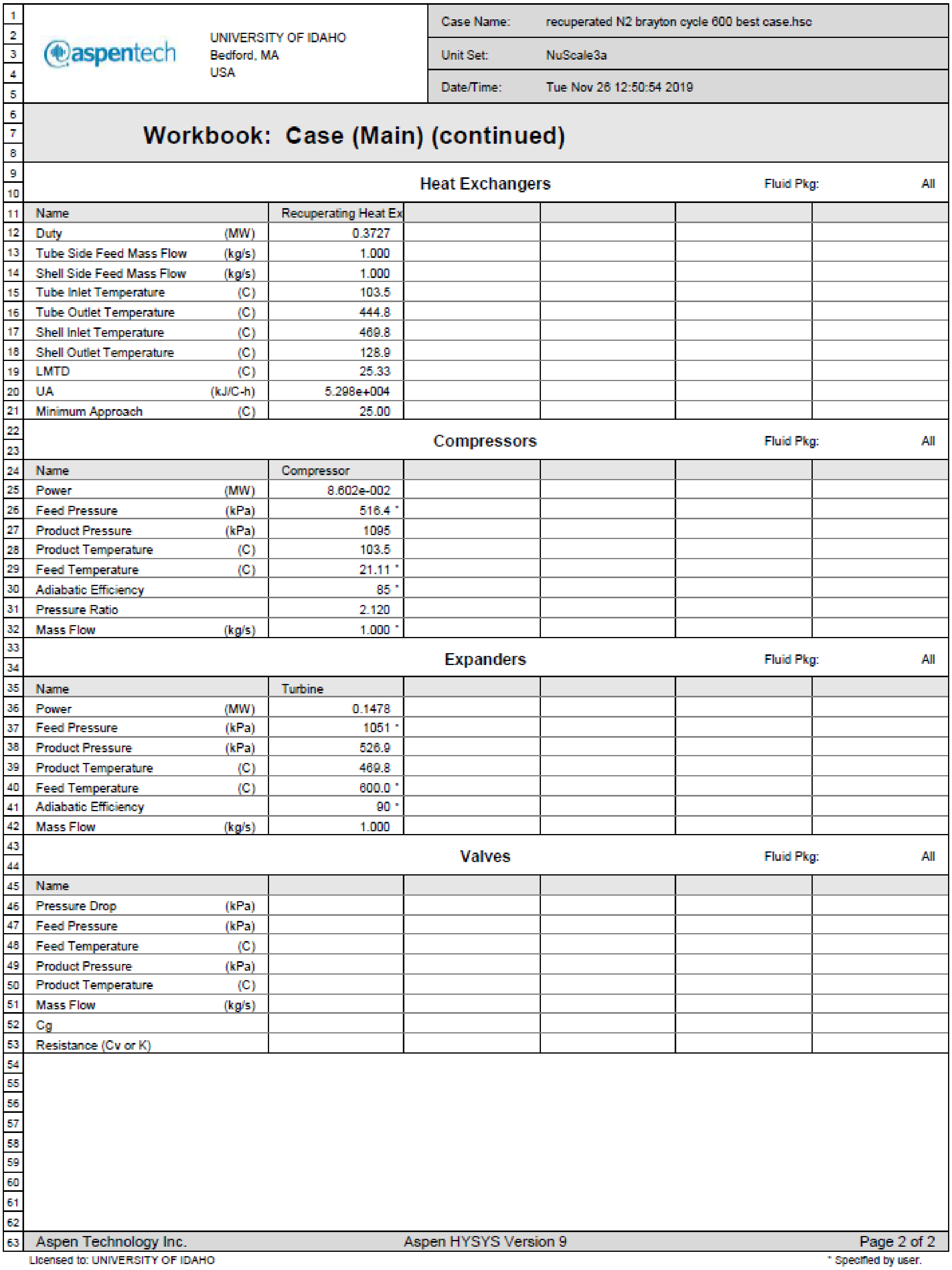

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	recuperated N2 brayton cycle 600 best case.hsc
Unit Set:	NuScale3a
Date/Time:	Tue Nov 26 12:50:54 2019

Workbook: Case (Main) (continued)

Heat Exchangers

Fluid Pkg: All

Name		Recuperating Heat Ex				
Duty	(MW)	0.3727				
Tube Side Feed Mass Flow	(kg/s)	1.000				
Shell Side Feed Mass Flow	(kg/s)	1.000				
Tube Inlet Temperature	(C)	103.5				
Tube Outlet Temperature	(C)	444.8				
Shell Inlet Temperature	(C)	469.8				
Shell Outlet Temperature	(C)	128.9				
LMTD	(C)	25.33				
UA	(kJ/C-h)	5.298e+004				
Minimum Approach	(C)	25.00				

Compressors

Fluid Pkg: All

Name		Compressor				
Power	(MW)	8.602e-002				
Feed Pressure	(kPa)	516.4 *				
Product Pressure	(kPa)	1095				
Product Temperature	(C)	103.5				
Feed Temperature	(C)	21.11 *				
Adiabatic Efficiency		85 *				
Pressure Ratio		2.120				
Mass Flow	(kg/s)	1.000 *				

Expanders

Fluid Pkg: All

Name		Turbine				
Power	(MW)	0.1478				
Feed Pressure	(kPa)	1051 *				
Product Pressure	(kPa)	526.9				
Product Temperature	(C)	469.8				
Feed Temperature	(C)	600.0 *				
Adiabatic Efficiency		90 *				
Mass Flow	(kg/s)	1.000				

Valves

Fluid Pkg: All

Name						
Pressure Drop	(kPa)					
Feed Pressure	(kPa)					
Feed Temperature	(C)					
Product Pressure	(kPa)					
Product Temperature	(C)					
Mass Flow	(kg/s)					
Cg						
Resistance (Cv or K)						

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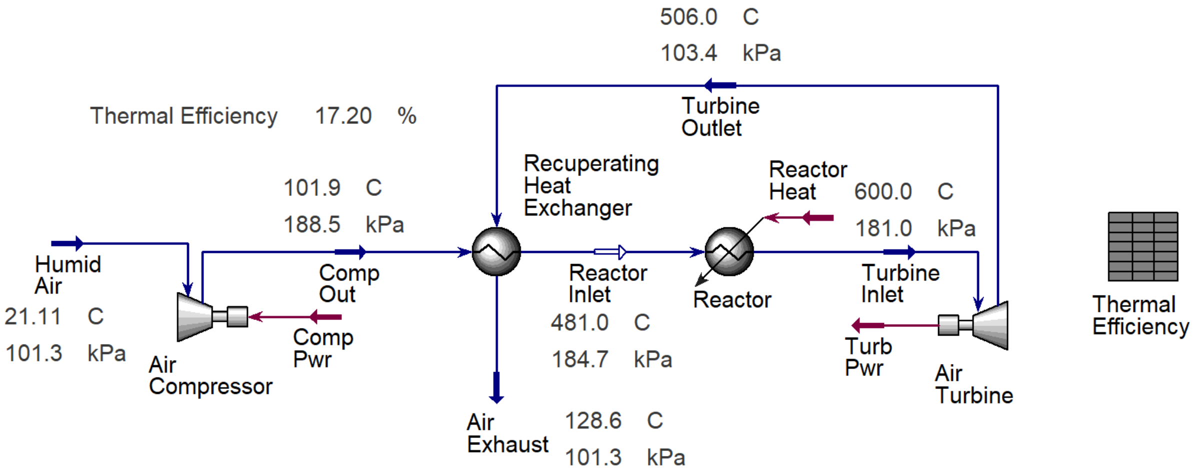
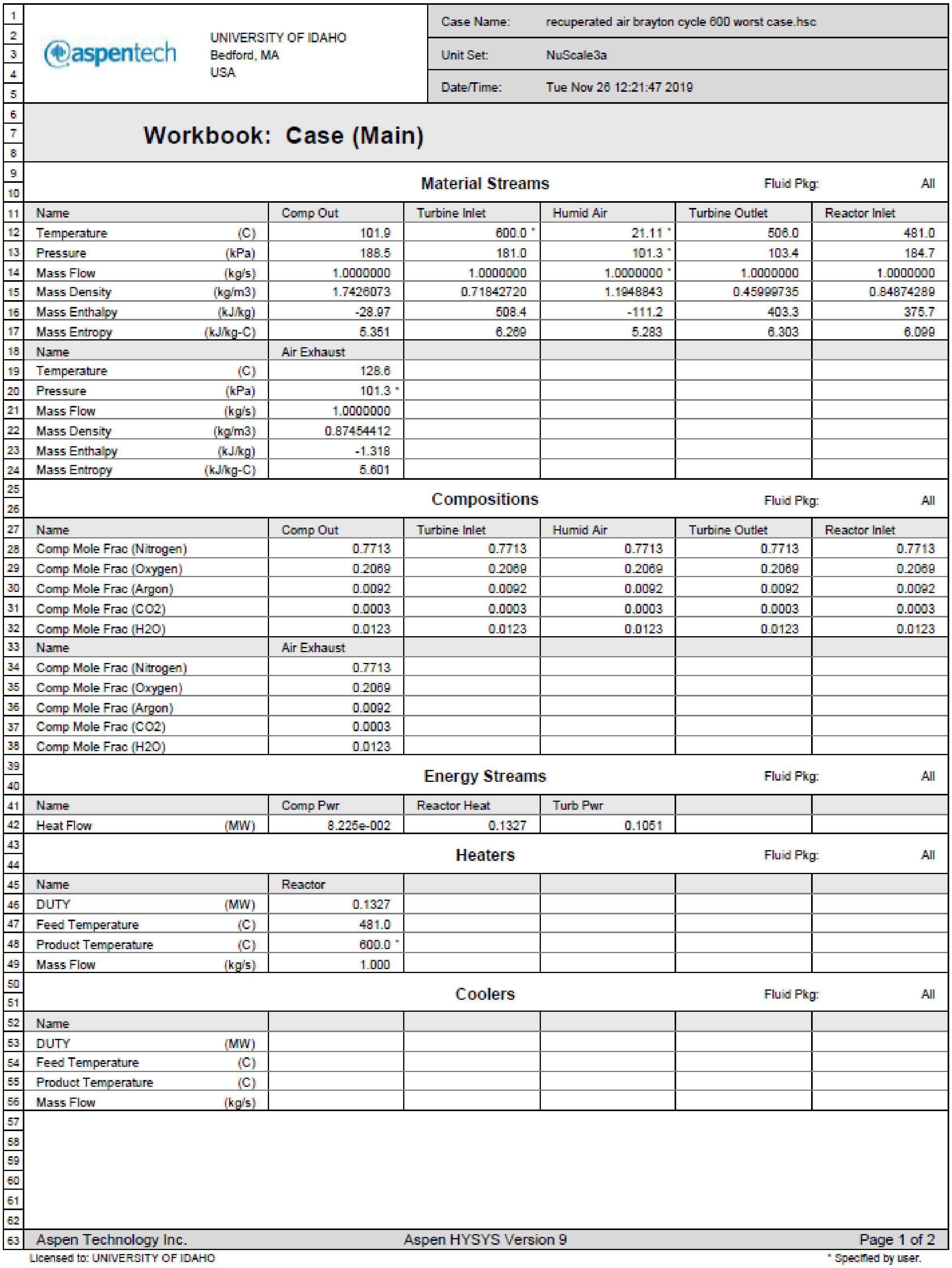
Recuperated Air Brayton Open Cycle at 600°C Turbine Inlet Temperature with Compressor and Turbine Adiabatic Efficiencies of 70% and 80%





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Bedford, MA
USA

Case Name:	recuperated air brayton cycle 600 worst case.hsc
Unit Set:	NuScale3a
Date/Time:	Tue Nov 26 12:21:47 2019

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Comp Out	Turbine Inlet	Humid Air	Turbine Outlet	Reactor Inlet
Temperature	(C)	101.9	600.0 *	21.11 *	506.0	481.0
Pressure	(kPa)	188.5	181.0	101.3 *	103.4	184.7
Mass Flow	(kg/s)	1.0000000	1.0000000	1.0000000 *	1.0000000	1.0000000
Mass Density	(kg/m3)	1.7426073	0.71842720	1.1948843	0.45999735	0.84874289
Mass Enthalpy	(kJ/kg)	-28.97	508.4	-111.2	403.3	375.7
Mass Entropy	(kJ/kg-C)	5.351	6.269	5.283	6.303	6.099
Name		Air Exhaust				
Temperature	(C)	128.6				
Pressure	(kPa)	101.3 *				
Mass Flow	(kg/s)	1.0000000				
Mass Density	(kg/m3)	0.87454412				
Mass Enthalpy	(kJ/kg)	-1.318				
Mass Entropy	(kJ/kg-C)	5.601				

Compositions

Fluid Pkg: All

Name	Comp Out	Turbine Inlet	Humid Air	Turbine Outlet	Reactor Inlet
Comp Mole Frac (Nitrogen)	0.7713	0.7713	0.7713	0.7713	0.7713
Comp Mole Frac (Oxygen)	0.2069	0.2069	0.2069	0.2069	0.2069
Comp Mole Frac (Argon)	0.0092	0.0092	0.0092	0.0092	0.0092
Comp Mole Frac (CO2)	0.0003	0.0003	0.0003	0.0003	0.0003
Comp Mole Frac (H2O)	0.0123	0.0123	0.0123	0.0123	0.0123
Name	Air Exhaust				
Comp Mole Frac (Nitrogen)	0.7713				
Comp Mole Frac (Oxygen)	0.2069				
Comp Mole Frac (Argon)	0.0092				
Comp Mole Frac (CO2)	0.0003				
Comp Mole Frac (H2O)	0.0123				

Energy Streams

Fluid Pkg: All

Name		Comp Pwr	Reactor Heat	Turb Pwr		
Heat Flow	(MW)	8.225e-002	0.1327	0.1051		

Heaters

Fluid Pkg: All

Name		Reactor				
DUTY	(MW)	0.1327				
Feed Temperature	(C)	481.0				
Product Temperature	(C)	600.0 *				
Mass Flow	(kg/s)	1.000				

Coolers

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

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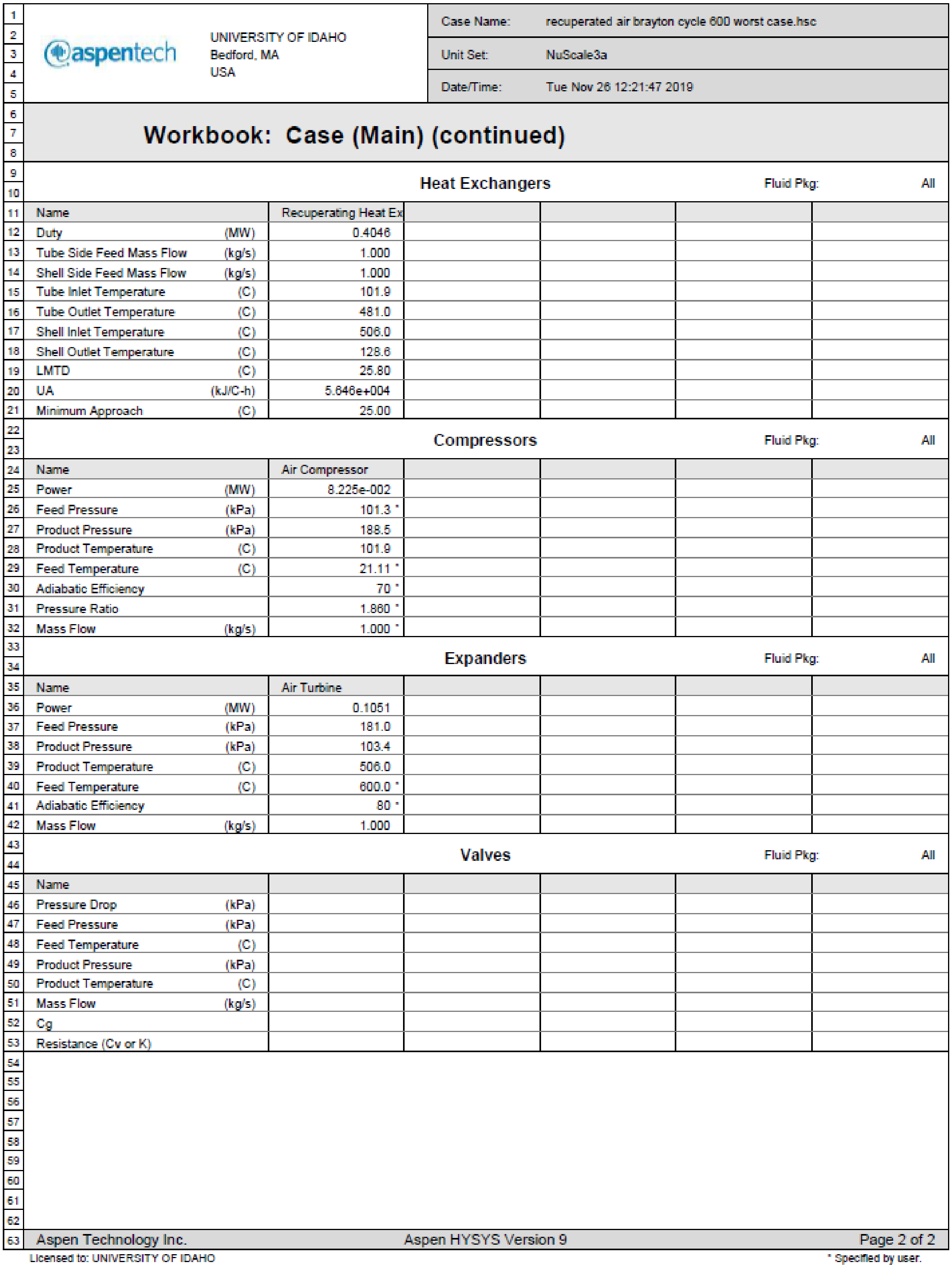

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Bedford, MA
USA

Case Name: recuperated air brayton cycle 600 worst case.hsc
Unit Set: NuScale3a
Date/Time: Tue Nov 26 12:21:47 2019

Workbook: Case (Main) (continued)

Heat Exchangers

Fluid Pkg: All

Name		Recuperating Heat Ex				
Duty	(MW)	0.4046				
Tube Side Feed Mass Flow	(kg/s)	1.000				
Shell Side Feed Mass Flow	(kg/s)	1.000				
Tube Inlet Temperature	(C)	101.9				
Tube Outlet Temperature	(C)	481.0				
Shell Inlet Temperature	(C)	506.0				
Shell Outlet Temperature	(C)	128.6				
LMTD	(C)	25.80				
UA	(kJ/C-h)	5.646e+004				
Minimum Approach	(C)	25.00				

Compressors

Fluid Pkg: All

Name		Air Compressor				
Power	(MW)	8.225e-002				
Feed Pressure	(kPa)	101.3 *				
Product Pressure	(kPa)	188.5				
Product Temperature	(C)	101.9				
Feed Temperature	(C)	21.11 *				
Adiabatic Efficiency		70 *				
Pressure Ratio		1.860 *				
Mass Flow	(kg/s)	1.000 *				

Expanders

Fluid Pkg: All

Name		Air Turbine				
Power	(MW)	0.1051				
Feed Pressure	(kPa)	181.0				
Product Pressure	(kPa)	103.4				
Product Temperature	(C)	506.0				
Feed Temperature	(C)	600.0 *				
Adiabatic Efficiency		80 *				
Mass Flow	(kg/s)	1.000				

Valves

Fluid Pkg: All

Name						
Pressure Drop	(kPa)					
Feed Pressure	(kPa)					
Feed Temperature	(C)					
Product Pressure	(kPa)					
Product Temperature	(C)					
Mass Flow	(kg/s)					
Cg						
Resistance (Cv or K)						

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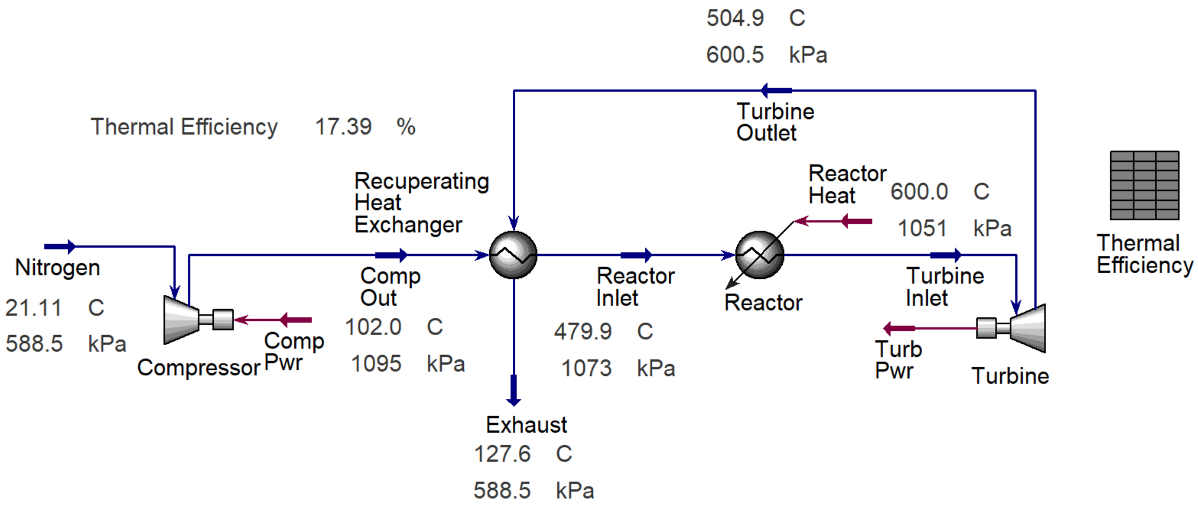
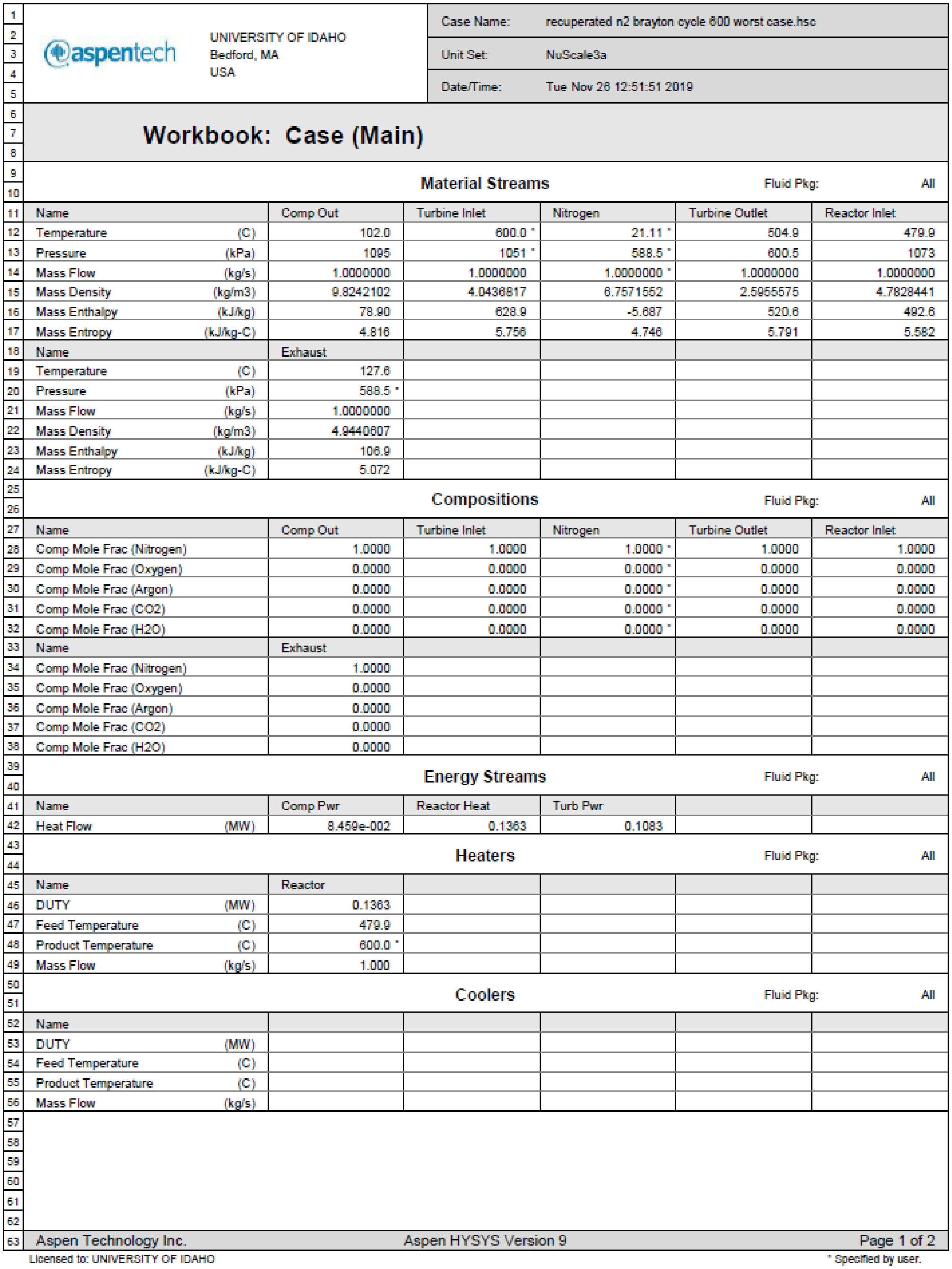
Recuperated Nitrogen Brayton Open Cycle at 600°C Turbine Inlet Temperature with Compressor and Turbine Adiabatic Efficiencies of 70% and 80%





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USA

Case Name: recuperated n2 brayton cycle 600 worst case.hsc
Unit Set: NuScale3a
Date/Time: Tue Nov 26 12:51:51 2019

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Comp Out	Turbine Inlet	Nitrogen	Turbine Outlet	Reactor Inlet
Temperature	(C)	102.0	600.0 *	21.11 *	504.9	479.9
Pressure	(kPa)	1095	1051 *	588.5 *	600.5	1073
Mass Flow	(kg/s)	1.0000000	1.0000000	1.0000000 *	1.0000000	1.0000000
Mass Density	(kg/m3)	9.8242102	4.0436817	6.7571552	2.5955575	4.7828441
Mass Enthalpy	(kJ/kg)	78.90	628.9	-5.687	520.6	492.6
Mass Entropy	(kJ/kg-C)	4.816	5.756	4.746	5.791	5.582

Name		Exhaust
Temperature	(C)	127.6
Pressure	(kPa)	588.5 *
Mass Flow	(kg/s)	1.0000000
Mass Density	(kg/m3)	4.9440607
Mass Enthalpy	(kJ/kg)	106.9
Mass Entropy	(kJ/kg-C)	5.072

Compositions

Fluid Pkg: All

Name	Comp Out	Turbine Inlet	Nitrogen	Turbine Outlet	Reactor Inlet
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000 *	1.0000	1.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000 *	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000 *	0.0000	0.0000
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000 *	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000 *	0.0000	0.0000

Name	Exhaust
Comp Mole Frac (Nitrogen)	1.0000
Comp Mole Frac (Oxygen)	0.0000
Comp Mole Frac (Argon)	0.0000
Comp Mole Frac (CO2)	0.0000
Comp Mole Frac (H2O)	0.0000

Energy Streams

Fluid Pkg: All

Name		Comp Pwr	Reactor Heat	Turb Pwr
Heat Flow	(MW)	8.459e-002	0.1363	0.1083

Heaters

Fluid Pkg: All

Name		Reactor
DUTY	(MW)	0.1363
Feed Temperature	(C)	479.9
Product Temperature	(C)	600.0 *
Mass Flow	(kg/s)	1.000

Coolers

Fluid Pkg: All

Name	
DUTY	(MW)
Feed Temperature	(C)
Product Temperature	(C)
Mass Flow	(kg/s)

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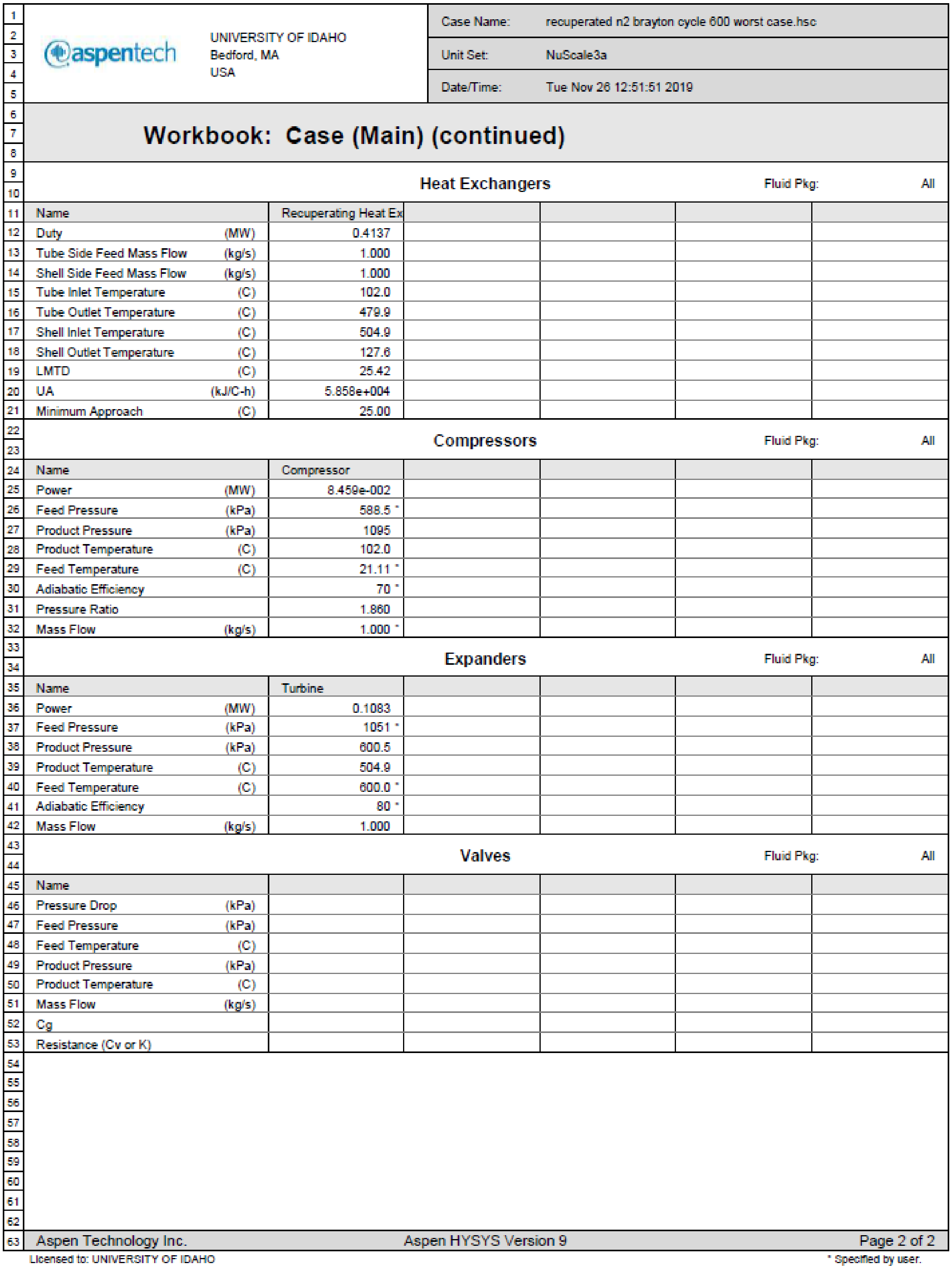

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Bedford, MA
USA

Case Name:	recuperated n2 brayton cycle 600 worst case.hsc
Unit Set:	NuScale3a
Date/Time:	Tue Nov 26 12:51:51 2019

Workbook: Case (Main) (continued)

Heat Exchangers

Fluid Pkg: All

Name		Recuperating Heat Ex				
Duty	(MW)	0.4137				
Tube Side Feed Mass Flow	(kg/s)	1.000				
Shell Side Feed Mass Flow	(kg/s)	1.000				
Tube Inlet Temperature	(C)	102.0				
Tube Outlet Temperature	(C)	479.9				
Shell Inlet Temperature	(C)	504.9				
Shell Outlet Temperature	(C)	127.6				
LMTD	(C)	25.42				
UA	(kJ/C-h)	5.858e+004				
Minimum Approach	(C)	25.00				

Compressors

Fluid Pkg: All

Name		Compressor				
Power	(MW)	8.459e-002				
Feed Pressure	(kPa)	588.5 *				
Product Pressure	(kPa)	1095				
Product Temperature	(C)	102.0				
Feed Temperature	(C)	21.11 *				
Adiabatic Efficiency		70 *				
Pressure Ratio		1.860				
Mass Flow	(kg/s)	1.000 *				

Expanders

Fluid Pkg: All

Name		Turbine				
Power	(MW)	0.1083				
Feed Pressure	(kPa)	1051 *				
Product Pressure	(kPa)	600.5				
Product Temperature	(C)	504.9				
Feed Temperature	(C)	600.0 *				
Adiabatic Efficiency		80 *				
Mass Flow	(kg/s)	1.000				

Valves

Fluid Pkg: All

Name						
Pressure Drop	(kPa)					
Feed Pressure	(kPa)					
Feed Temperature	(C)					
Product Pressure	(kPa)					
Product Temperature	(C)					
Mass Flow	(kg/s)					
Cg						
Resistance (Cv or K)						

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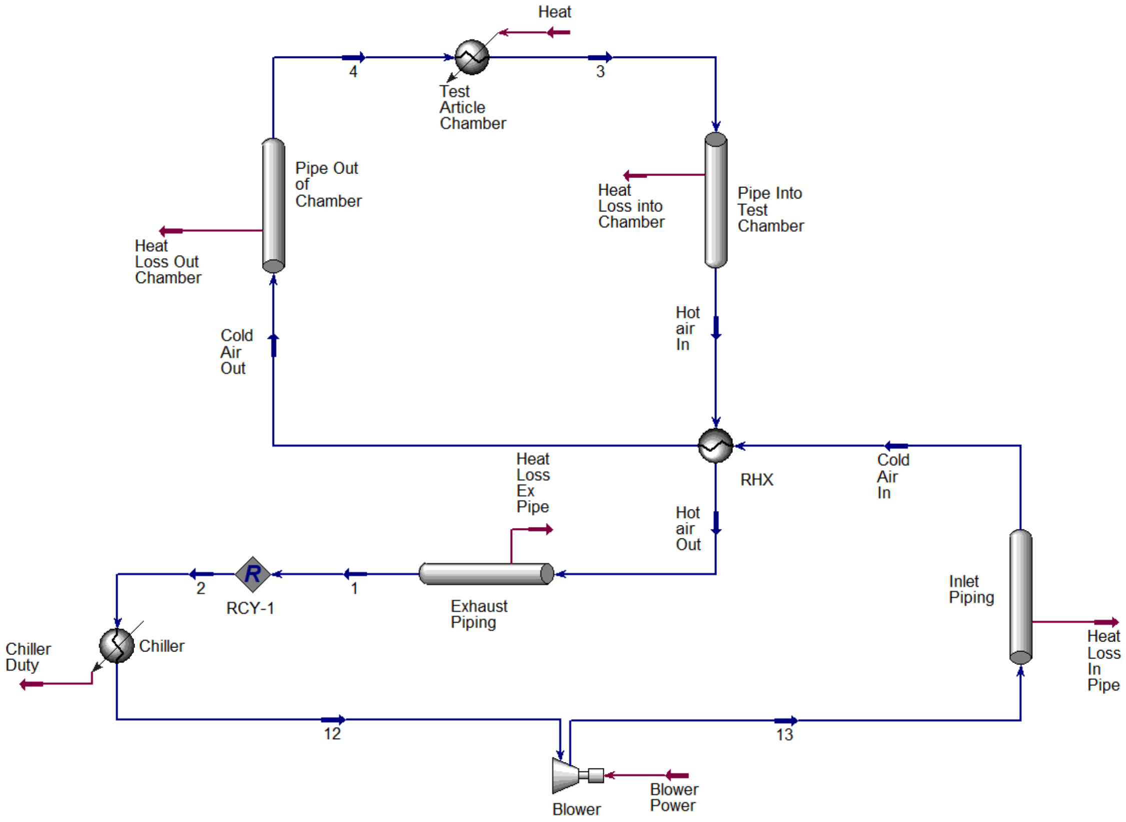
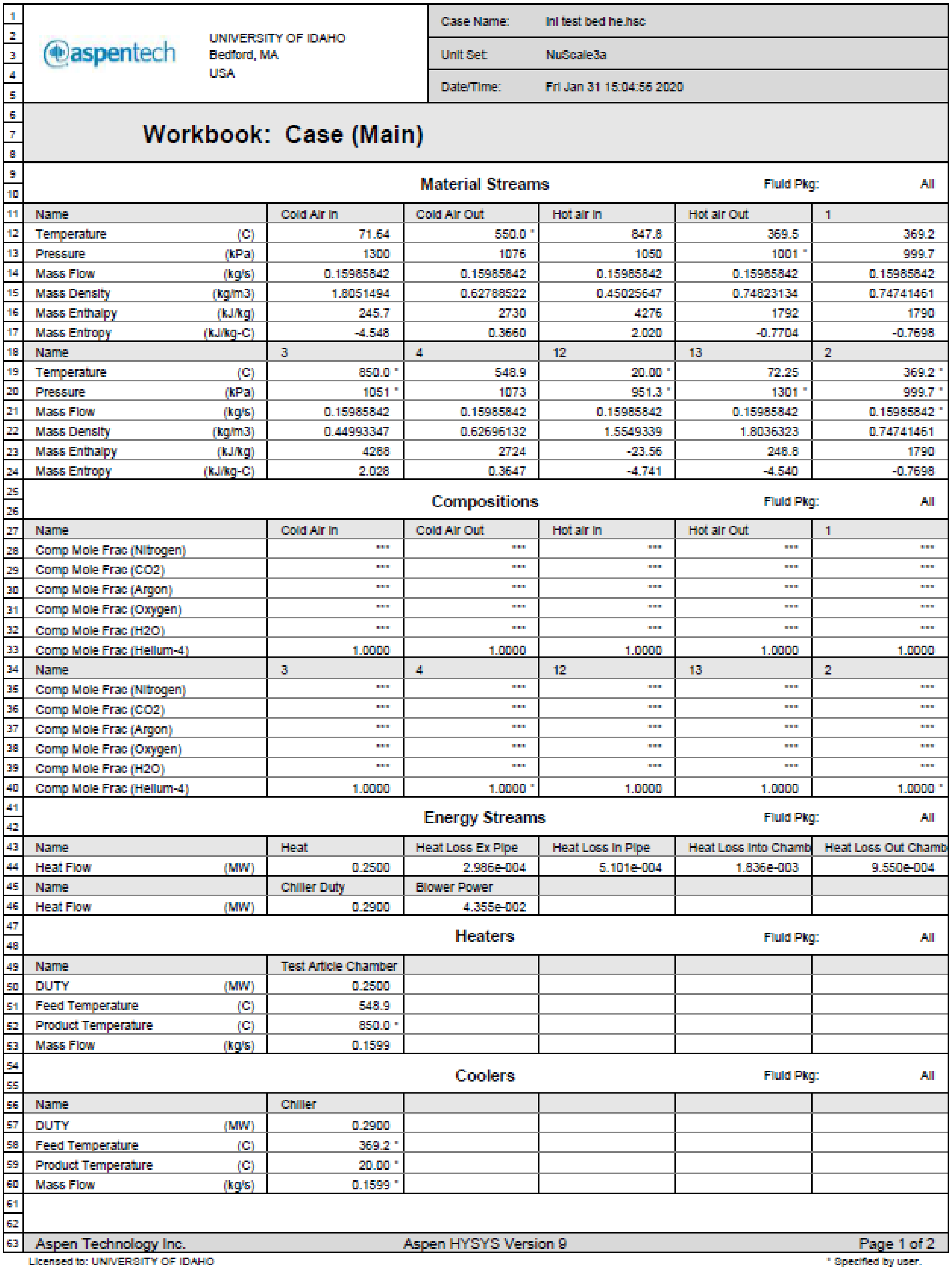
Aspen HYSYS Process Model of Micro AGile Non-nuclear Experimental Testbed with Helium Operating at 850°C





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USA

Case Name:	lnl test bed he.hsc
Unit Set:	NuScale3a
Date/Time:	Fri Jan 31 15:04:56 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Cold Air In	Cold Air Out	Hot air In	Hot air Out	1
Temperature	(C)	71.64	550.0 *	847.8	369.5	369.2
Pressure	(kPa)	1300	1076	1050	1001 *	999.7
Mass Flow	(kg/s)	0.15985842	0.15985842	0.15985842	0.15985842	0.15985842
Mass Density	(kg/m3)	1.8051494	0.62788522	0.45025647	0.74823134	0.74741461
Mass Enthalpy	(kJ/kg)	245.7	2730	4276	1792	1790
Mass Entropy	(kJ/kg-C)	-4.548	0.3660	2.020	-0.7704	-0.7698
Name		**3**	**4**	**12**	**13**	**2**
Temperature	(C)	850.0 *	548.9	20.00 *	72.25	369.2 *
Pressure	(kPa)	1051 *	1073	951.3 *	1301 *	999.7 *
Mass Flow	(kg/s)	0.15985842	0.15985842	0.15985842	0.15985842	0.15985842 *
Mass Density	(kg/m3)	0.44993347	0.62696132	1.5549339	1.8036323	0.74741461
Mass Enthalpy	(kJ/kg)	4288	2724	-23.56	248.8	1790
Mass Entropy	(kJ/kg-C)	2.028	0.3647	-4.741	-4.540	-0.7698

Compositions

Fluid Pkg: All

Name	Cold Air In	Cold Air Out	Hot air In	Hot air Out	1
Comp Mole Frac (Nitrogen)	***	***	***	***	***
Comp Mole Frac (CO2)	***	***	***	***	***
Comp Mole Frac (Argon)	***	***	***	***	***
Comp Mole Frac (Oxygen)	***	***	***	***	***
Comp Mole Frac (H2O)	***	***	***	***	***
Comp Mole Frac (Helium-4)	1.0000	1.0000	1.0000	1.0000	1.0000
Name	**3**	**4**	**12**	**13**	**2**
Comp Mole Frac (Nitrogen)	***	***	***	***	***
Comp Mole Frac (CO2)	***	***	***	***	***
Comp Mole Frac (Argon)	***	***	***	***	***
Comp Mole Frac (Oxygen)	***	***	***	***	***
Comp Mole Frac (H2O)	***	***	***	***	***
Comp Mole Frac (Helium-4)	1.0000	1.0000 *	1.0000	1.0000	1.0000 *

Energy Streams

Fluid Pkg: All

Name		Heat	Heat Loss Ex Pipe	Heat Loss In Pipe	Heat Loss Into Chamb	Heat Loss Out Chamb
Heat Flow	(MW)	0.2500	2.986e-004	5.101e-004	1.836e-003	9.550e-004
Name		**Chiller Duty**	**Blower Power**			
Heat Flow	(MW)	0.2900	4.355e-002			

Heaters

Fluid Pkg: All

Name		Test Article Chamber				
DUTY	(MW)	0.2500				
Feed Temperature	(C)	548.9				
Product Temperature	(C)	850.0 *				
Mass Flow	(kg/s)	0.1599				

Coolers

Fluid Pkg: All

Name		Chiller				
DUTY	(MW)	0.2900				
Feed Temperature	(C)	369.2 *				
Product Temperature	(C)	20.00 *				
Mass Flow	(kg/s)	0.1599 *				

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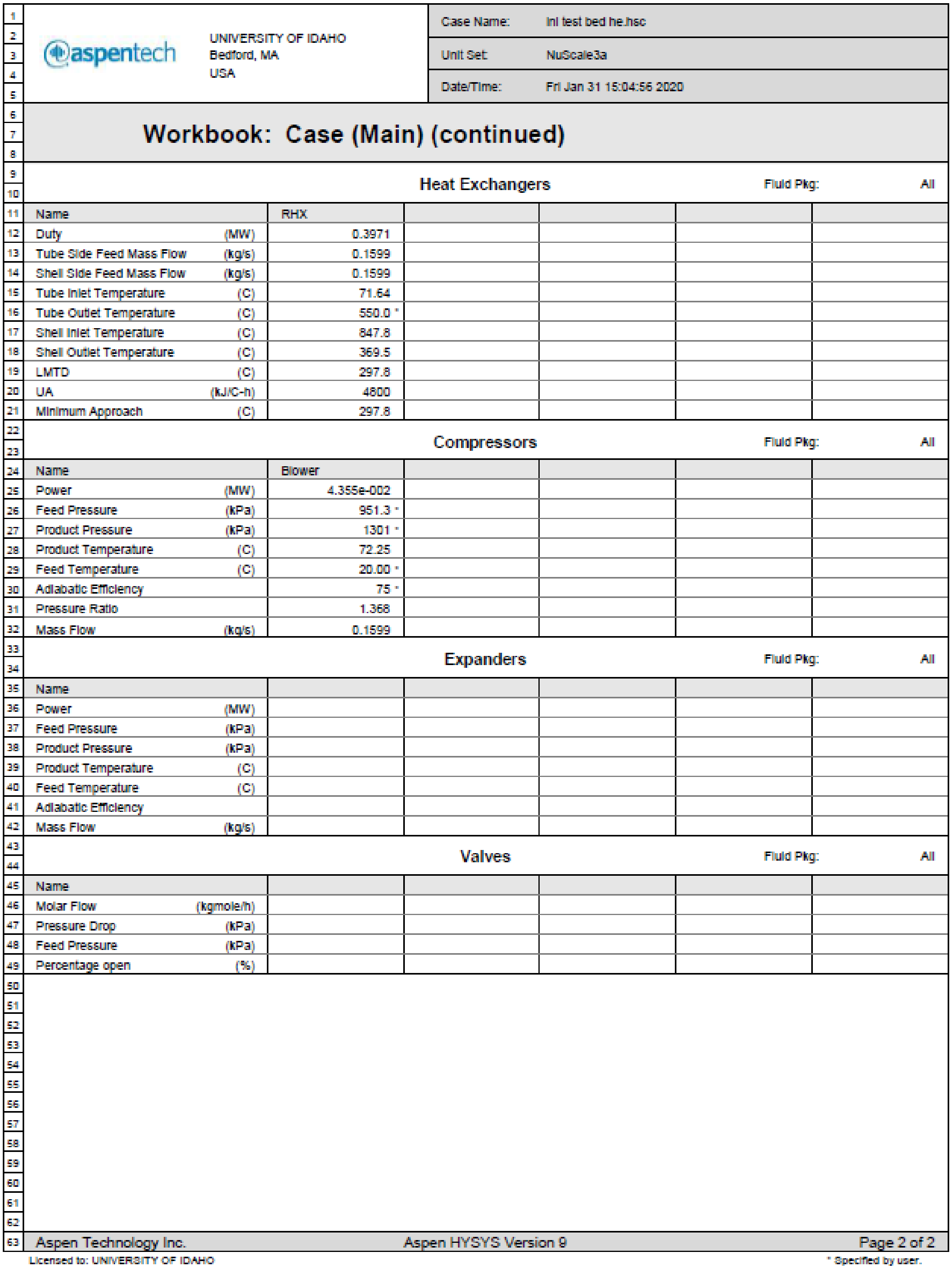

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Bedford, MA
USA

Case Name: inl test bed he.hsc
Unit Set: NuScale3a
Date/Time: Fri Jan 31 15:04:56 2020

Workbook: Case (Main) (continued)

Heat Exchangers

Fluid Pkg: All

Name	RHX				
Duty (MW)	0.3971				
Tube Side Feed Mass Flow (kg/s)	0.1599				
Shell Side Feed Mass Flow (kg/s)	0.1599				
Tube Inlet Temperature (C)	71.64				
Tube Outlet Temperature (C)	550.0 *				
Shell Inlet Temperature (C)	847.8				
Shell Outlet Temperature (C)	369.5				
LMTD (C)	297.8				
UA (kJ/C-h)	4800				
Minimum Approach (C)	297.8				

Compressors

Fluid Pkg: All

Name	Blower				
Power (MW)	4.355e-002				
Feed Pressure (kPa)	951.3 *				
Product Pressure (kPa)	1301 *				
Product Temperature (C)	72.25				
Feed Temperature (C)	20.00 *				
Adiabatic Efficiency	75 *				
Pressure Ratio	1.368				
Mass Flow (kg/s)	0.1599				

Expanders

Fluid Pkg: All

Name					
Power (MW)					
Feed Pressure (kPa)					
Product Pressure (kPa)					
Product Temperature (C)					
Feed Temperature (C)					
Adiabatic Efficiency					
Mass Flow (kg/s)					

Valves

Fluid Pkg: All

Name					
Molar Flow (kgmole/h)					
Pressure Drop (kPa)					
Feed Pressure (kPa)					
Percentage open (%)					

Aspen Technology Inc. Aspen HYSYS Version 9 Page 2 of 2

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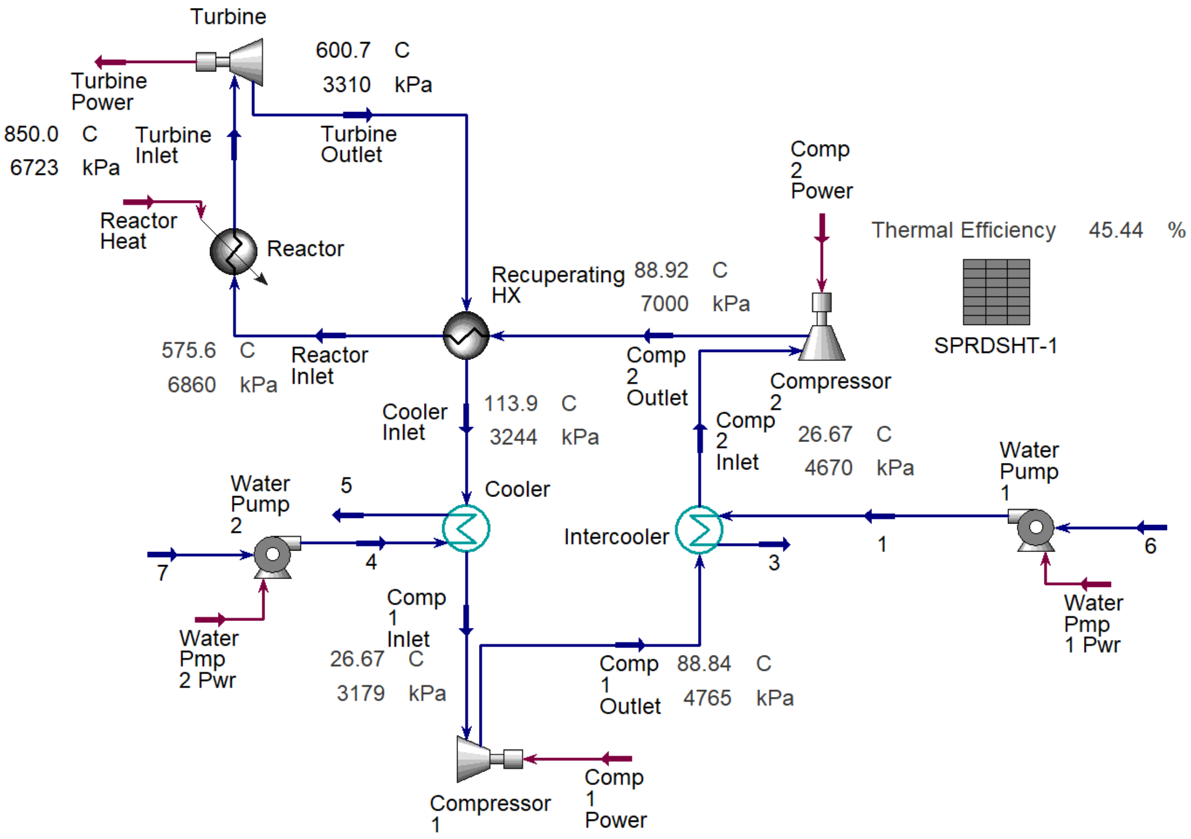
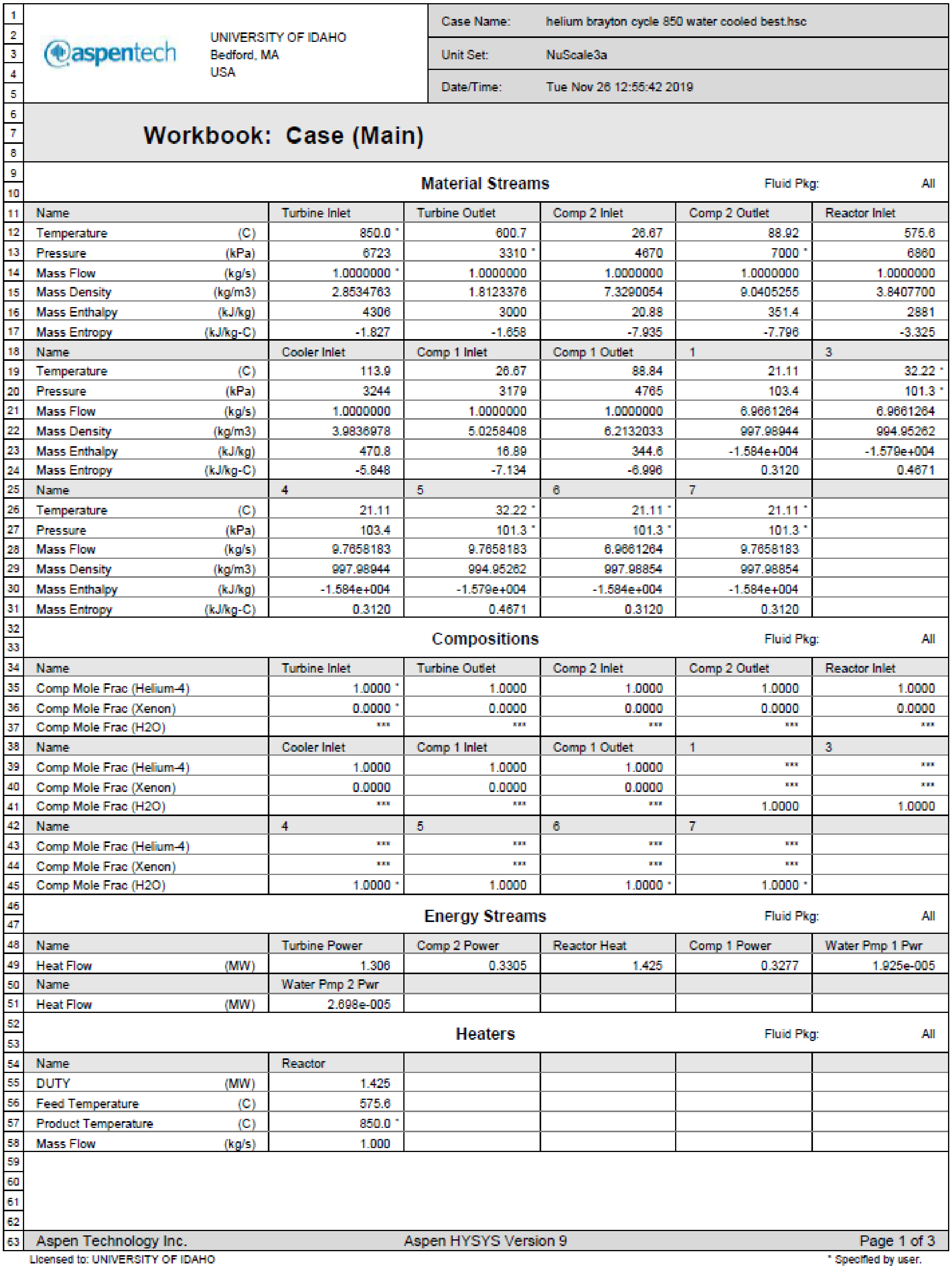
Recuperated Helium Brayton Open Cycle at 850°C Turbine Inlet Temperature with Compressor and Turbine Adiabatic Efficiencies of 85% and 90% and Compressor 2 Outlet Pressure of 7 MPa





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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: helium brayton cycle 850 water cooled best.hsc

Unit Set: NuScale3a

Date/Time: Tue Nov 26 12:55:42 2019

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Turbine Inlet	Turbine Outlet	Comp 2 Inlet	Comp 2 Outlet	Reactor Inlet
Temperature	(C)	850.0 *	600.7	26.67	88.92	575.6
Pressure	(kPa)	6723	3310 *	4670	7000 *	6860
Mass Flow	(kg/s)	1.0000000 *	1.0000000	1.0000000	1.0000000	1.0000000
Mass Density	(kg/m3)	2.8534763	1.8123376	7.3290054	9.0405255	3.8407700
Mass Enthalpy	(kJ/kg)	4306	3000	20.88	351.4	2881
Mass Entropy	(kJ/kg-C)	-1.827	-1.658	-7.935	-7.796	-3.325
Name		**Cooler Inlet**	**Comp 1 Inlet**	**Comp 1 Outlet**	**1**	**3**
Temperature	(C)	113.9	26.67	88.84	21.11	32.22 *
Pressure	(kPa)	3244	3179	4765	103.4	101.3 *
Mass Flow	(kg/s)	1.0000000	1.0000000	1.0000000	6.9661264	6.9661264
Mass Density	(kg/m3)	3.9836978	5.0258408	6.2132033	997.98944	994.95262
Mass Enthalpy	(kJ/kg)	470.8	16.89	344.6	-1.584e+004	-1.579e+004
Mass Entropy	(kJ/kg-C)	-5.848	-7.134	-6.996	0.3120	0.4671
Name		**4**	**5**	**6**	**7**	
Temperature	(C)	21.11	32.22 *	21.11 *	21.11 *	
Pressure	(kPa)	103.4	101.3 *	101.3 *	101.3 *	
Mass Flow	(kg/s)	9.7658183	9.7658183	6.9661264	9.7658183	
Mass Density	(kg/m3)	997.98944	994.95262	997.98854	997.98854	
Mass Enthalpy	(kJ/kg)	-1.584e+004	-1.579e+004	-1.584e+004	-1.584e+004	
Mass Entropy	(kJ/kg-C)	0.3120	0.4671	0.3120	0.3120	

Compositions

Fluid Pkg: All

Name	Turbine Inlet	Turbine Outlet	Comp 2 Inlet	Comp 2 Outlet	Reactor Inlet
Comp Mole Frac (Helium-4)	1.0000 *	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (Xenon)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	***	***	***	***	***
Name	**Cooler Inlet**	**Comp 1 Inlet**	**Comp 1 Outlet**	**1**	**3**
Comp Mole Frac (Helium-4)	1.0000	1.0000	1.0000	***	***
Comp Mole Frac (Xenon)	0.0000	0.0000	0.0000	***	***
Comp Mole Frac (H2O)	***	***	***	1.0000	1.0000
Name	**4**	**5**	**6**	**7**	
Comp Mole Frac (Helium-4)	***	***	***	***	
Comp Mole Frac (Xenon)	***	***	***	***	
Comp Mole Frac (H2O)	1.0000 *	1.0000	1.0000 *	1.0000 *	

Energy Streams

Fluid Pkg: All

Name		Turbine Power	Comp 2 Power	Reactor Heat	Comp 1 Power	Water Pmp 1 Pwr
Heat Flow	(MW)	1.306	0.3305	1.425	0.3277	1.925e-005
Name		**Water Pmp 2 Pwr**				
Heat Flow	(MW)	2.698e-005				

Heaters

Fluid Pkg: All

Name		Reactor				
DUTY	(MW)	1.425				
Feed Temperature	(C)	575.6				
Product Temperature	(C)	850.0 *				
Mass Flow	(kg/s)	1.000				

Aspen Technology Inc. Aspen HYSYS Version 9 Page 1 of 3

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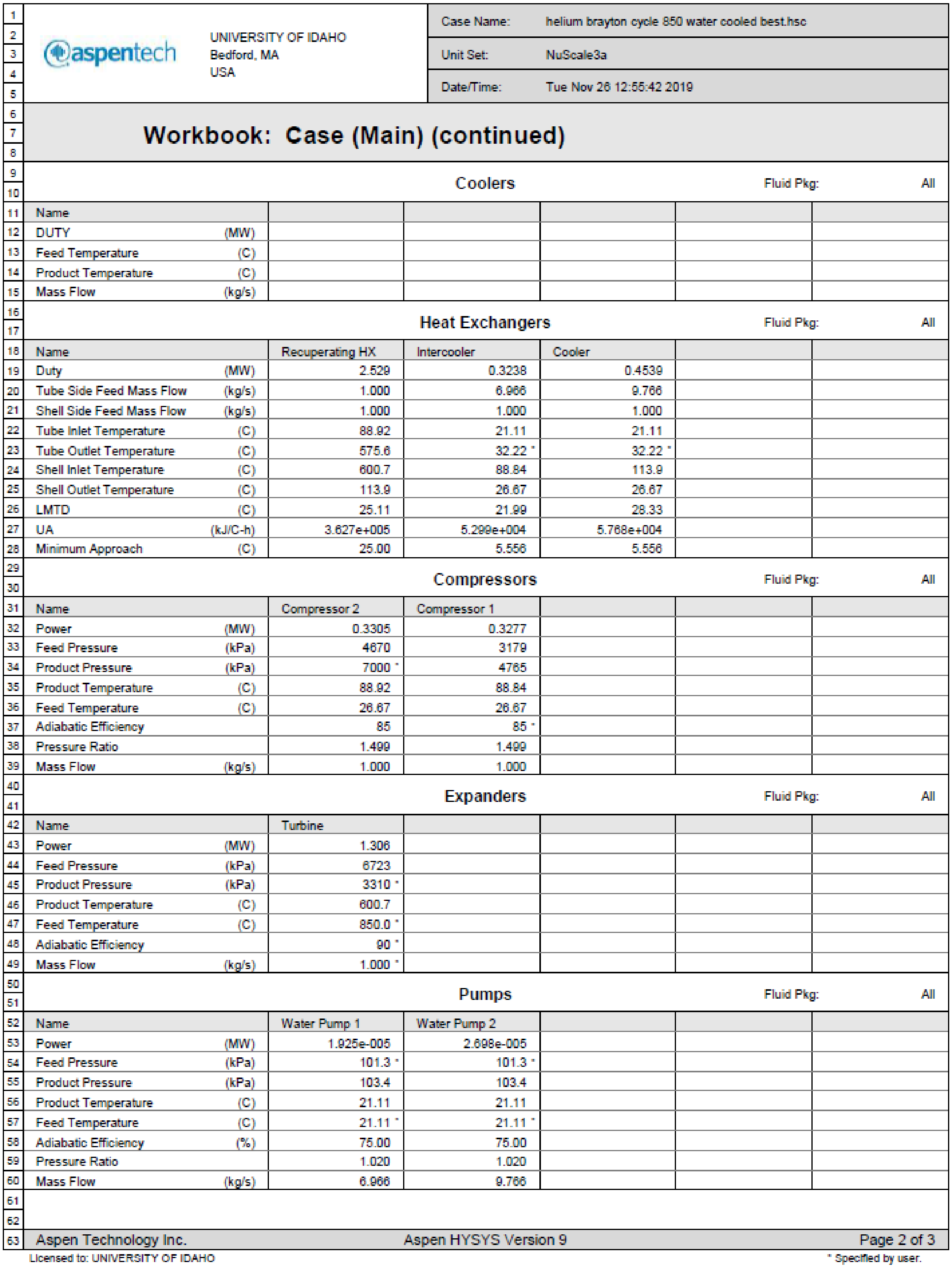

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Bedford, MA
USA

Case Name: helium brayton cycle 850 water cooled best.hsc
Unit Set: NuScale3a
Date/Time: Tue Nov 26 12:55:42 2019

Workbook: Case (Main) (continued)

Coolers

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

Heat Exchangers

Fluid Pkg: All

Name		Recuperating HX	Intercooler	Cooler		
Duty	(MW)	2.529	0.3238	0.4539		
Tube Side Feed Mass Flow	(kg/s)	1.000	6.966	9.766		
Shell Side Feed Mass Flow	(kg/s)	1.000	1.000	1.000		
Tube Inlet Temperature	(C)	88.92	21.11	21.11		
Tube Outlet Temperature	(C)	575.6	32.22 *	32.22 *		
Shell Inlet Temperature	(C)	600.7	88.84	113.9		
Shell Outlet Temperature	(C)	113.9	26.67	26.67		
LMTD	(C)	25.11	21.99	28.33		
UA	(kJ/C-h)	3.627e+005	5.299e+004	5.768e+004		
Minimum Approach	(C)	25.00	5.556	5.556		

Compressors

Fluid Pkg: All

Name		Compressor 2	Compressor 1			
Power	(MW)	0.3305	0.3277			
Feed Pressure	(kPa)	4670	3179			
Product Pressure	(kPa)	7000 *	4765			
Product Temperature	(C)	88.92	88.84			
Feed Temperature	(C)	26.67	26.67			
Adiabatic Efficiency		85	85 *			
Pressure Ratio		1.499	1.499			
Mass Flow	(kg/s)	1.000	1.000			

Expanders

Fluid Pkg: All

Name		Turbine				
Power	(MW)	1.306				
Feed Pressure	(kPa)	6723				
Product Pressure	(kPa)	3310 *				
Product Temperature	(C)	600.7				
Feed Temperature	(C)	850.0 *				
Adiabatic Efficiency		90 *				
Mass Flow	(kg/s)	1.000 *				

Pumps

Fluid Pkg: All

Name		Water Pump 1	Water Pump 2			
Power	(MW)	1.925e-005	2.698e-005			
Feed Pressure	(kPa)	101.3 *	101.3 *			
Product Pressure	(kPa)	103.4	103.4			
Product Temperature	(C)	21.11	21.11			
Feed Temperature	(C)	21.11 *	21.11 *			
Adiabatic Efficiency	(%)	75.00	75.00			
Pressure Ratio		1.020	1.020			
Mass Flow	(kg/s)	6.966	9.766			

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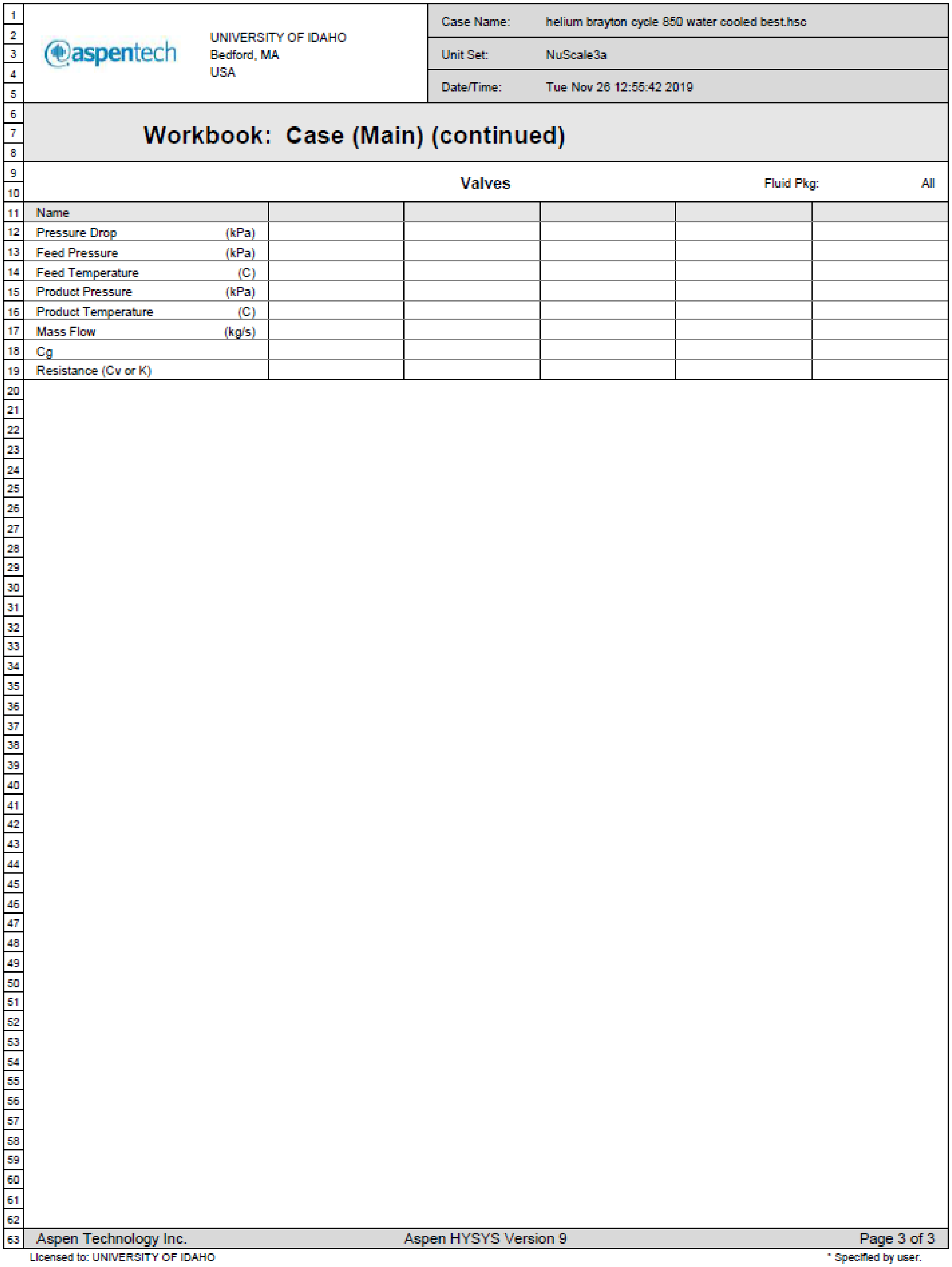

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USA

Case Name:	helium brayton cycle 850 water cooled best.hsc
Unit Set:	NuScale3a
Date/Time:	Tue Nov 26 12:55:42 2019

Workbook: Case (Main) (continued)

Valves

Fluid Pkg: All

Name					
Pressure Drop (kPa)					
Feed Pressure (kPa)					
Feed Temperature (C)					
Product Pressure (kPa)					
Product Temperature (C)					
Mass Flow (kg/s)					
Cg					
Resistance (Cv or K)					

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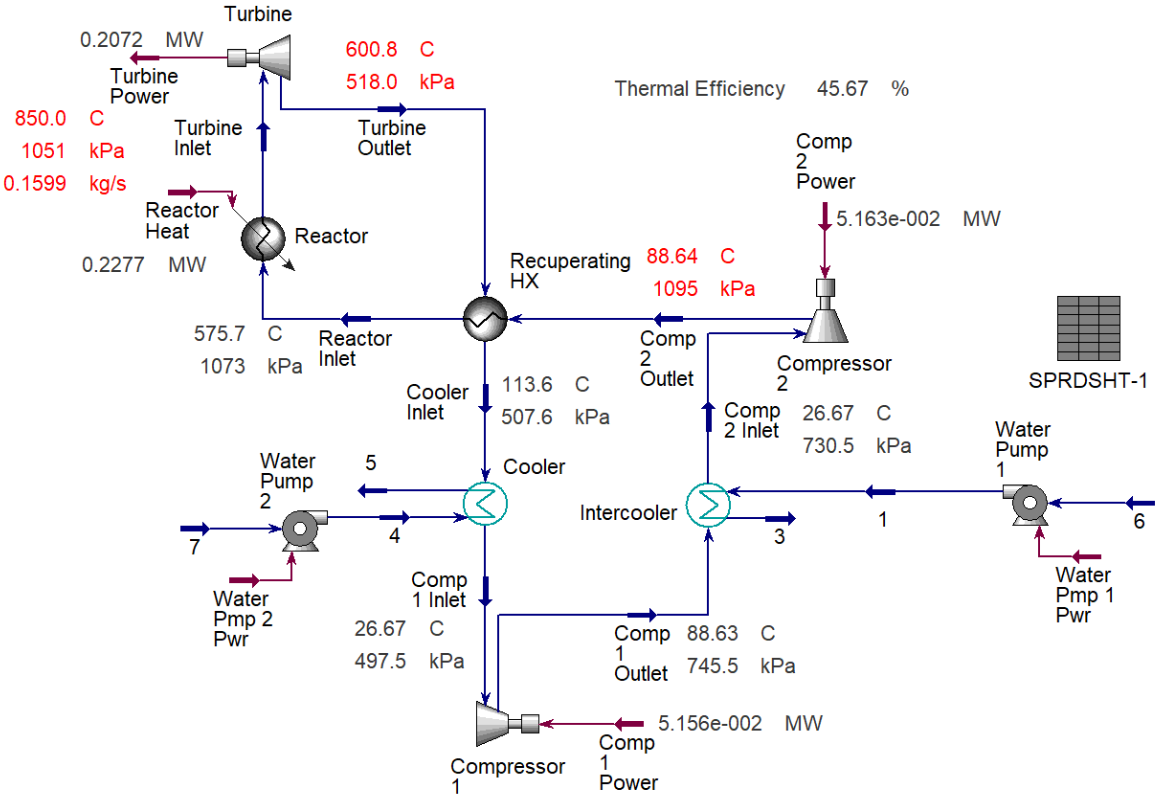
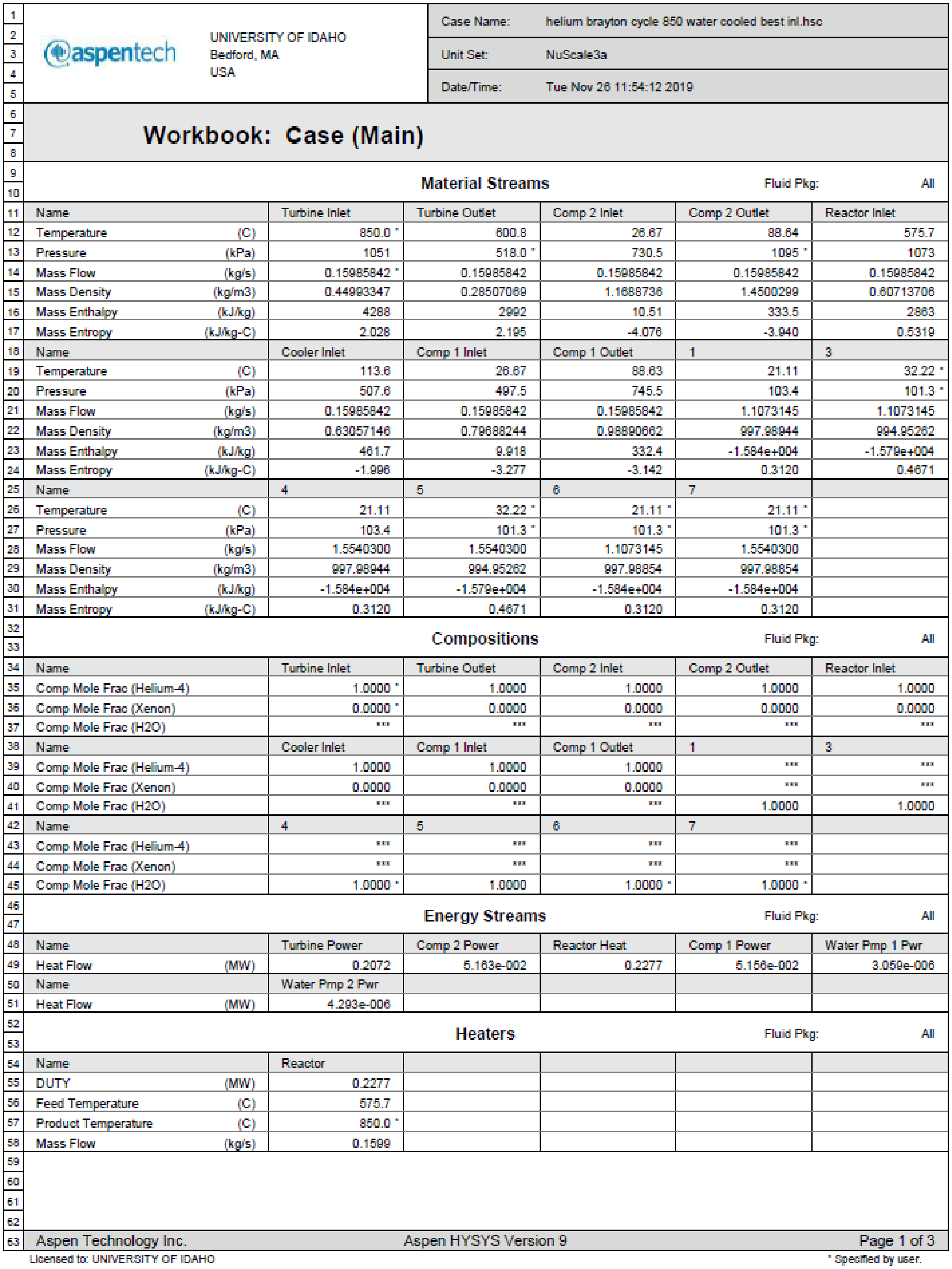
Recuperated Helium Brayton Open Cycle at 850°C Turbine Inlet Temperature with Compressor and Turbine Adiabatic Efficiencies of 85% and 90% and Turbine Inlet Pressure of 1051 kPa





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Case Name: helium brayton cycle 850 water cooled best inl.hsc

Unit Set: NuScale3a

Date/Time: Tue Nov 26 11:54:12 2019

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name	Turbine Inlet	Turbine Outlet	Comp 2 Inlet	Comp 2 Outlet	Reactor Inlet
Temperature (C)	850.0 *	600.8	26.67	88.64	575.7
Pressure (kPa)	1051	518.0 *	730.5	1095 *	1073
Mass Flow (kg/s)	0.15985842 *	0.15985842	0.15985842	0.15985842	0.15985842
Mass Density (kg/m3)	0.44993347	0.28507069	1.1688736	1.4500299	0.60713706
Mass Enthalpy (kJ/kg)	4288	2992	10.51	333.5	2863
Mass Entropy (kJ/kg-C)	2.028	2.195	-4.076	-3.940	0.5319
Name	Cooler Inlet	Comp 1 Inlet	Comp 1 Outlet	1	3
Temperature (C)	113.6	26.67	88.63	21.11	32.22 *
Pressure (kPa)	507.6	497.5	745.5	103.4	101.3 *
Mass Flow (kg/s)	0.15985842	0.15985842	0.15985842	1.1073145	1.1073145
Mass Density (kg/m3)	0.63057146	0.79688244	0.98890662	997.98944	994.95262
Mass Enthalpy (kJ/kg)	461.7	9.918	332.4	-1.584e+004	-1.579e+004
Mass Entropy (kJ/kg-C)	-1.996	-3.277	-3.142	0.3120	0.4671
Name	4	5	6	7	
Temperature (C)	21.11	32.22 *	21.11 *	21.11 *	
Pressure (kPa)	103.4	101.3 *	101.3 *	101.3 *	
Mass Flow (kg/s)	1.5540300	1.5540300	1.1073145	1.5540300	
Mass Density (kg/m3)	997.98944	994.95262	997.98854	997.98854	
Mass Enthalpy (kJ/kg)	-1.584e+004	-1.579e+004	-1.584e+004	-1.584e+004	
Mass Entropy (kJ/kg-C)	0.3120	0.4671	0.3120	0.3120	

Compositions

Fluid Pkg: All

Name	Turbine Inlet	Turbine Outlet	Comp 2 Inlet	Comp 2 Outlet	Reactor Inlet
Comp Mole Frac (Helium-4)	1.0000 *	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (Xenon)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	***	***	***	***	***
Name	Cooler Inlet	Comp 1 Inlet	Comp 1 Outlet	1	3
Comp Mole Frac (Helium-4)	1.0000	1.0000	1.0000	***	***
Comp Mole Frac (Xenon)	0.0000	0.0000	0.0000	***	***
Comp Mole Frac (H2O)	***	***	***	1.0000	1.0000
Name	4	5	6	7	
Comp Mole Frac (Helium-4)	***	***	***	***	
Comp Mole Frac (Xenon)	***	***	***	***	
Comp Mole Frac (H2O)	1.0000 *	1.0000	1.0000 *	1.0000 *	

Energy Streams

Fluid Pkg: All

Name	Turbine Power	Comp 2 Power	Reactor Heat	Comp 1 Power	Water Pmp 1 Pwr
Heat Flow (MW)	0.2072	5.163e-002	0.2277	5.156e-002	3.059e-006
Name	Water Pmp 2 Pwr				
Heat Flow (MW)	4.293e-006				

Heaters

Fluid Pkg: All

Name	Reactor				
DUTY (MW)	0.2277				
Feed Temperature (C)	575.7				
Product Temperature (C)	850.0 *				
Mass Flow (kg/s)	0.1599				

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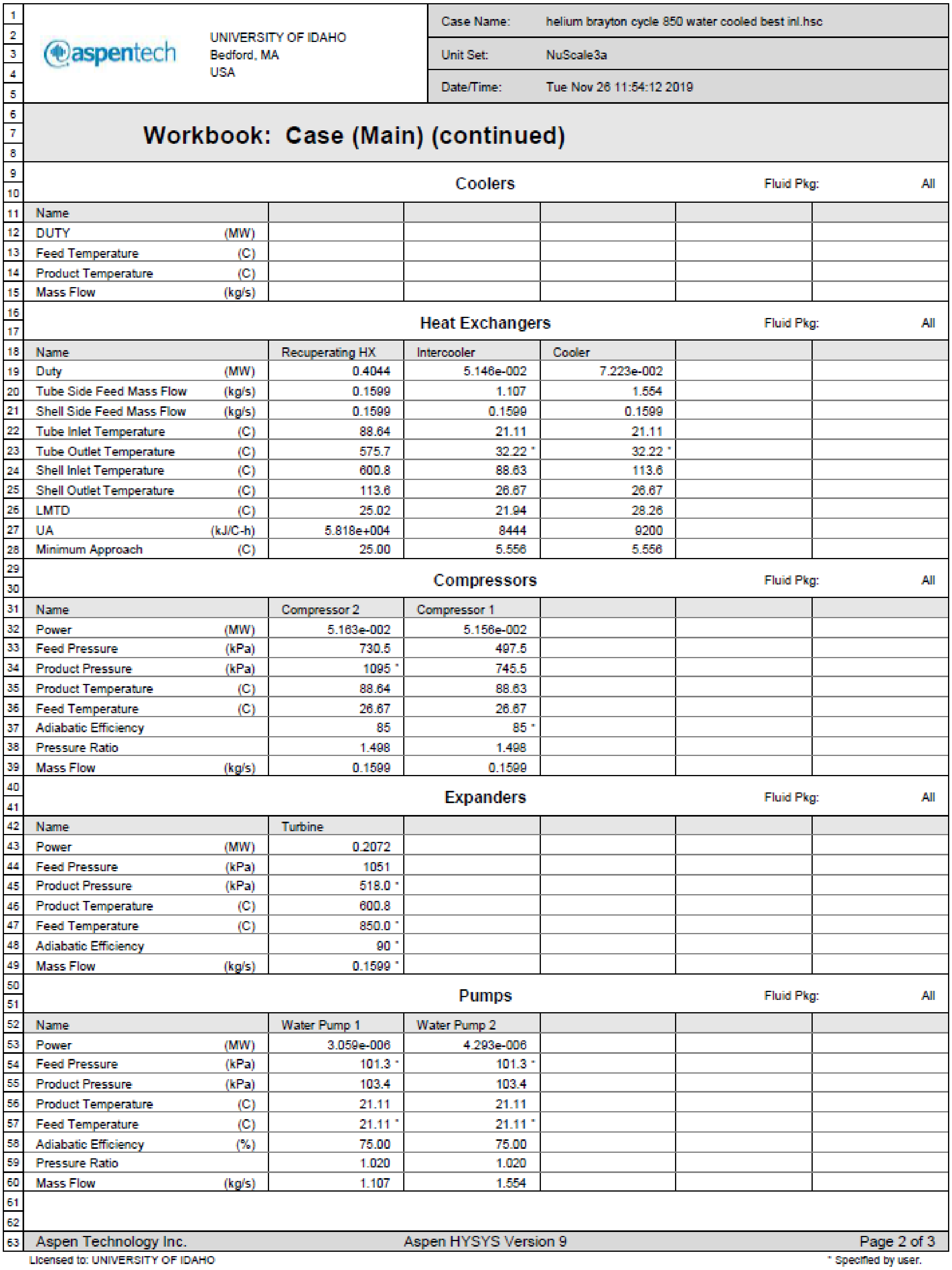

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	helium brayton cycle 850 water cooled best inl.hsc
Unit Set:	NuScale3a
Date/Time:	Tue Nov 26 11:54:12 2019

Workbook: Case (Main) (continued)

Coolers

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

Heat Exchangers

Fluid Pkg: All

Name		Recuperating HX	Intercooler	Cooler		
Duty	(MW)	0.4044	5.146e-002	7.223e-002		
Tube Side Feed Mass Flow	(kg/s)	0.1599	1.107	1.554		
Shell Side Feed Mass Flow	(kg/s)	0.1599	0.1599	0.1599		
Tube Inlet Temperature	(C)	88.64	21.11	21.11		
Tube Outlet Temperature	(C)	575.7	32.22 *	32.22 *		
Shell Inlet Temperature	(C)	600.8	88.63	113.6		
Shell Outlet Temperature	(C)	113.6	26.67	26.67		
LMTD	(C)	25.02	21.94	28.26		
UA	(kJ/C-h)	5.818e+004	8444	9200		
Minimum Approach	(C)	25.00	5.556	5.556		

Compressors

Fluid Pkg: All

Name		Compressor 2	Compressor 1			
Power	(MW)	5.163e-002	5.156e-002			
Feed Pressure	(kPa)	730.5	497.5			
Product Pressure	(kPa)	1095 *	745.5			
Product Temperature	(C)	88.64	88.63			
Feed Temperature	(C)	26.67	26.67			
Adiabatic Efficiency		85	85 *			
Pressure Ratio		1.498	1.498			
Mass Flow	(kg/s)	0.1599	0.1599			

Expanders

Fluid Pkg: All

Name		Turbine				
Power	(MW)	0.2072				
Feed Pressure	(kPa)	1051				
Product Pressure	(kPa)	518.0 *				
Product Temperature	(C)	600.8				
Feed Temperature	(C)	850.0 *				
Adiabatic Efficiency		90 *				
Mass Flow	(kg/s)	0.1599 *				

Pumps

Fluid Pkg: All

Name		Water Pump 1	Water Pump 2			
Power	(MW)	3.059e-006	4.293e-006			
Feed Pressure	(kPa)	101.3 *	101.3 *			
Product Pressure	(kPa)	103.4	103.4			
Product Temperature	(C)	21.11	21.11			
Feed Temperature	(C)	21.11 *	21.11 *			
Adiabatic Efficiency	(%)	75.00	75.00			
Pressure Ratio		1.020	1.020			
Mass Flow	(kg/s)	1.107	1.554			

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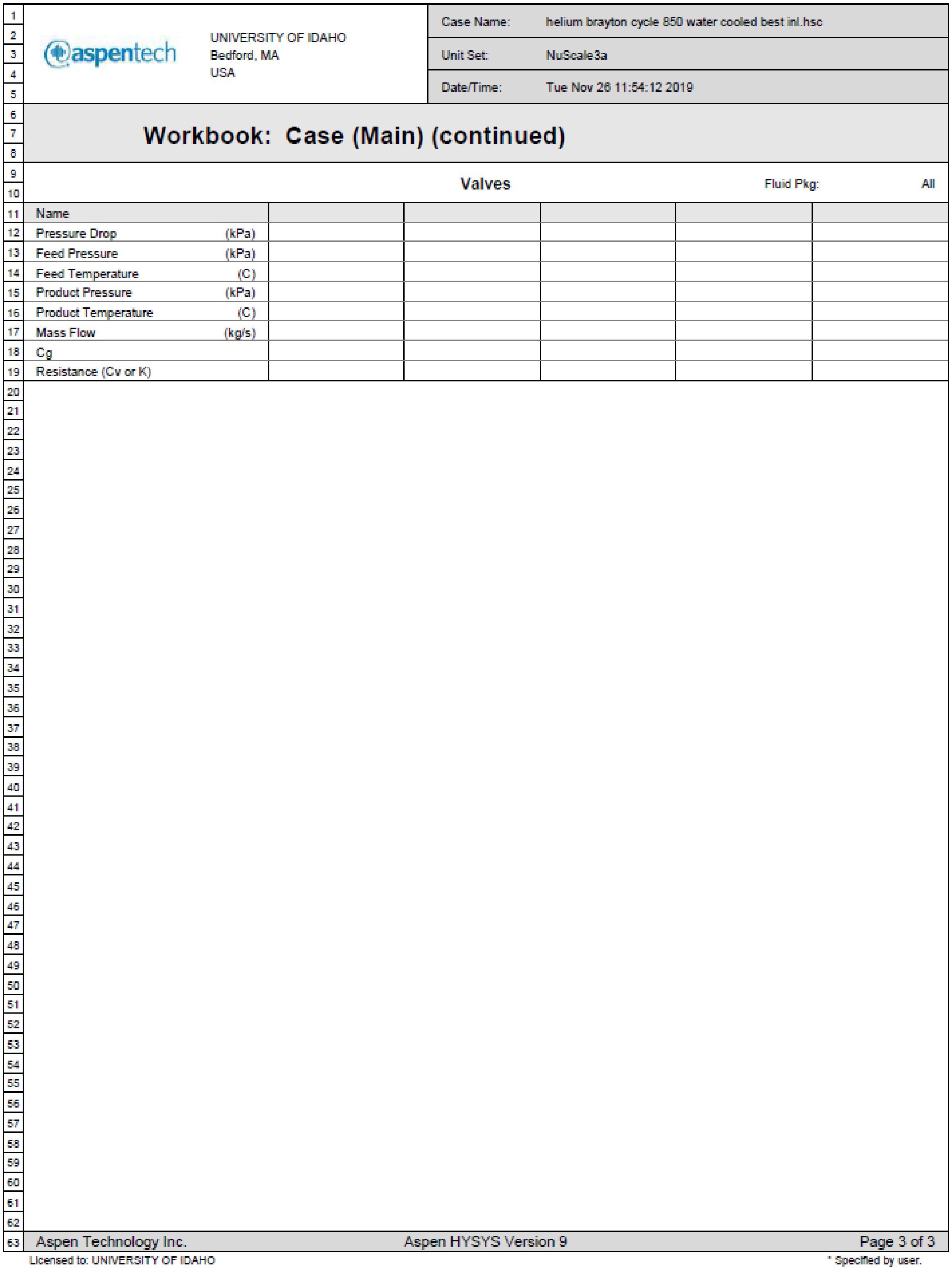

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USA

Case Name:	helium brayton cycle 850 water cooled best inl.hsc
Unit Set:	NuScale3a
Date/Time:	Tue Nov 26 11:54:12 2019

Workbook: Case (Main) (continued)

Valves Fluid Pkg: All

Name						
Pressure Drop	(kPa)					
Feed Pressure	(kPa)					
Feed Temperature	(C)					
Product Pressure	(kPa)					
Product Temperature	(C)					
Mass Flow	(kg/s)					
Cg						
Resistance (Cv or K)						

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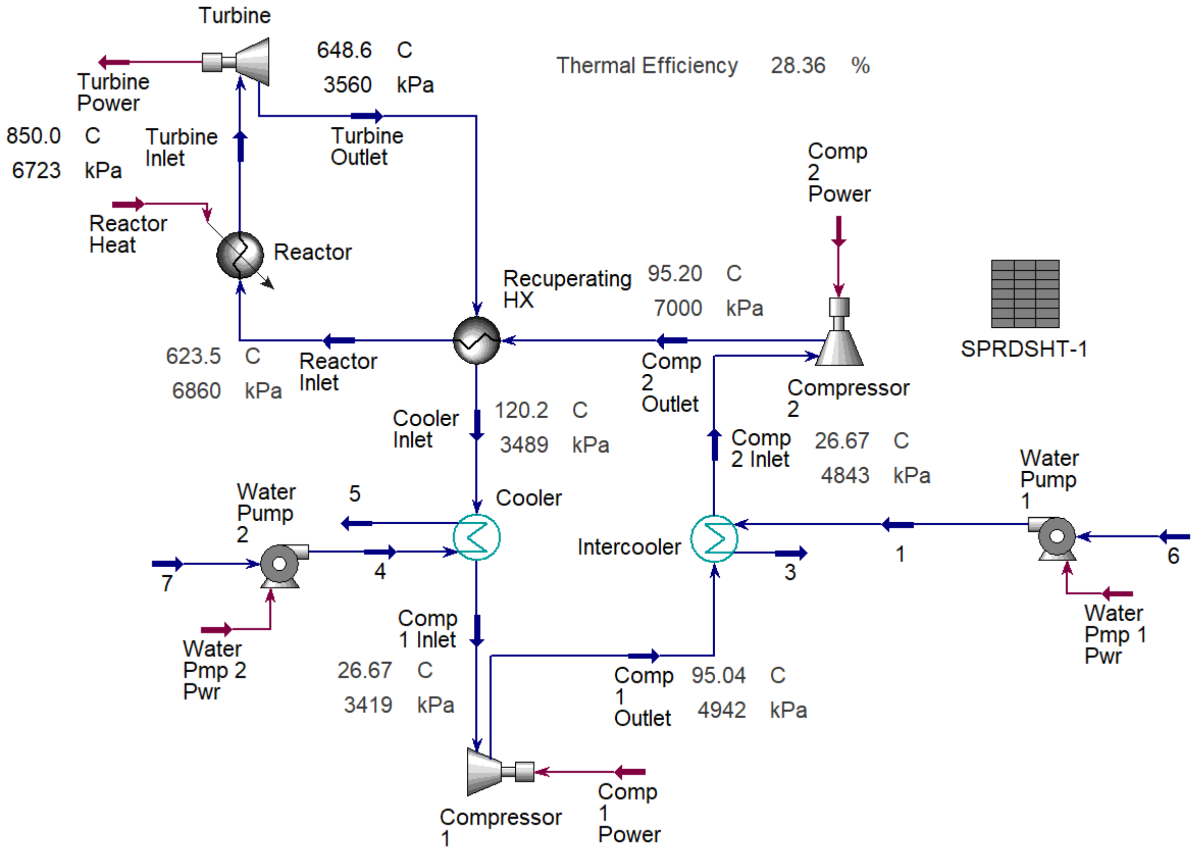
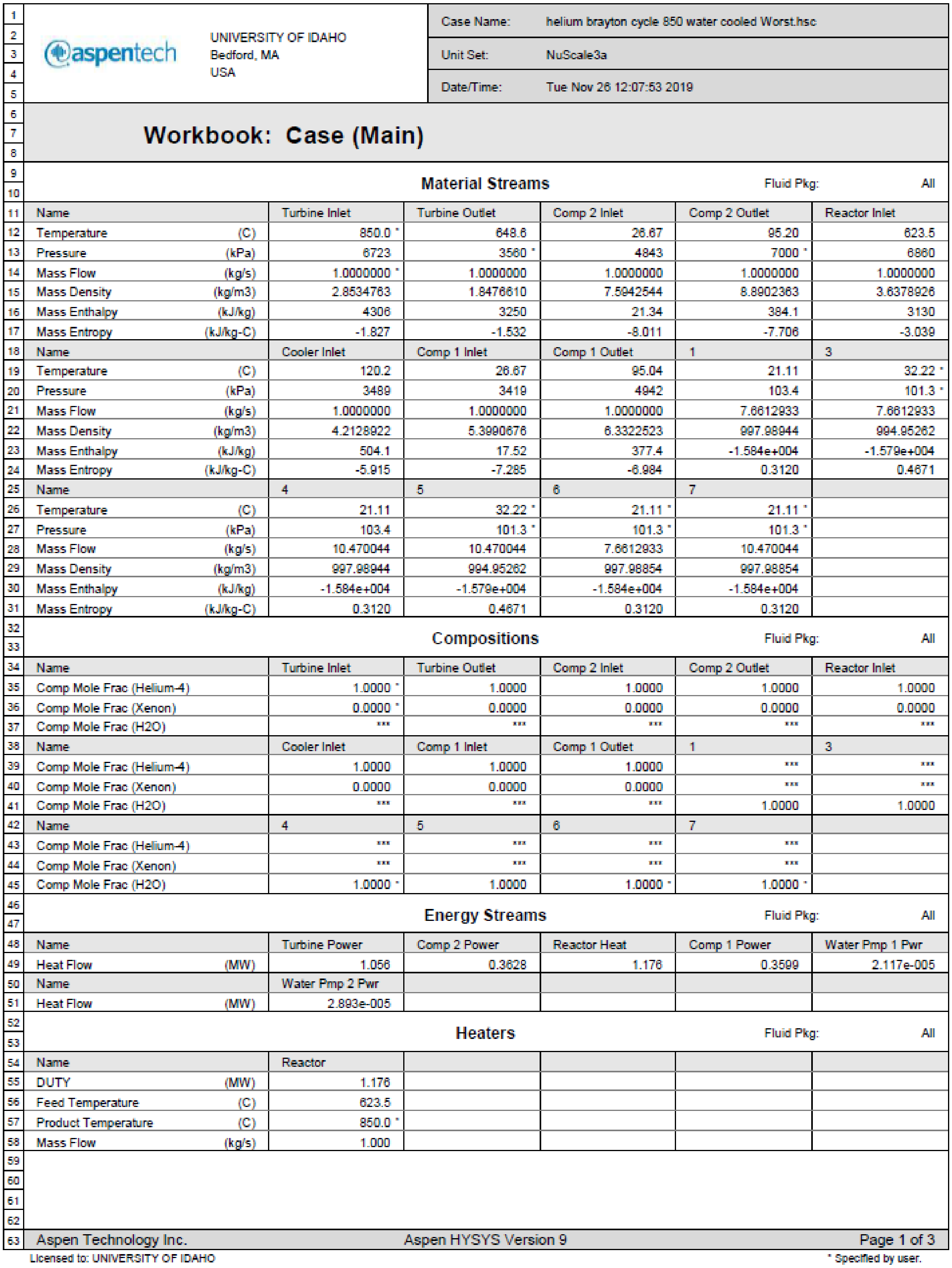
Recuperated Helium Brayton Open Cycle at 850°C Turbine Inlet Temperature with Compressor and Turbine Adiabatic Efficiencies of 70% and 80% and Compressor 2 Outlet Pressure of 7 MPa





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Case Name: helium brayton cycle 850 water cooled Worst.hsc
Unit Set: NuScale3a
Date/Time: Tue Nov 26 12:07:53 2019

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Turbine Inlet	Turbine Outlet	Comp 2 Inlet	Comp 2 Outlet	Reactor Inlet
Temperature	(C)	850.0 *	648.6	26.67	95.20	623.5
Pressure	(kPa)	6723	3560 *	4843	7000 *	6860
Mass Flow	(kg/s)	1.0000000 *	1.0000000	1.0000000	1.0000000	1.0000000
Mass Density	(kg/m3)	2.8534763	1.8476610	7.5942544	8.8902363	3.6378926
Mass Enthalpy	(kJ/kg)	4306	3250	21.34	384.1	3130
Mass Entropy	(kJ/kg-C)	-1.827	-1.532	-8.011	-7.706	-3.039
Name		Cooler Inlet	Comp 1 Inlet	Comp 1 Outlet	1	3
Temperature	(C)	120.2	26.67	95.04	21.11	32.22 *
Pressure	(kPa)	3489	3419	4942	103.4	101.3 *
Mass Flow	(kg/s)	1.0000000	1.0000000	1.0000000	7.6612933	7.6612933
Mass Density	(kg/m3)	4.2128922	5.3990676	6.3322523	997.98944	994.95262
Mass Enthalpy	(kJ/kg)	504.1	17.52	377.4	-1.584e+004	-1.579e+004
Mass Entropy	(kJ/kg-C)	-5.915	-7.285	-6.984	0.3120	0.4671
Name		4	5	6	7	
Temperature	(C)	21.11	32.22 *	21.11 *	21.11 *	
Pressure	(kPa)	103.4	101.3 *	101.3 *	101.3 *	
Mass Flow	(kg/s)	10.470044	10.470044	7.6612933	10.470044	
Mass Density	(kg/m3)	997.98944	994.95262	997.98854	997.98854	
Mass Enthalpy	(kJ/kg)	-1.584e+004	-1.579e+004	-1.584e+004	-1.584e+004	
Mass Entropy	(kJ/kg-C)	0.3120	0.4671	0.3120	0.3120	

Compositions

Fluid Pkg: All

Name	Turbine Inlet	Turbine Outlet	Comp 2 Inlet	Comp 2 Outlet	Reactor Inlet
Comp Mole Frac (Helium-4)	1.0000 *	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (Xenon)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	***	***	***	***	***
Name	Cooler Inlet	Comp 1 Inlet	Comp 1 Outlet	1	3
Comp Mole Frac (Helium-4)	1.0000	1.0000	1.0000	***	***
Comp Mole Frac (Xenon)	0.0000	0.0000	0.0000	***	***
Comp Mole Frac (H2O)	***	***	***	1.0000	1.0000
Name	4	5	6	7	
Comp Mole Frac (Helium-4)	***	***	***	***	
Comp Mole Frac (Xenon)	***	***	***	***	
Comp Mole Frac (H2O)	1.0000 *	1.0000	1.0000 *	1.0000 *	

Energy Streams

Fluid Pkg: All

Name		Turbine Power	Comp 2 Power	Reactor Heat	Comp 1 Power	Water Pmp 1 Pwr
Heat Flow	(MW)	1.056	0.3628	1.176	0.3599	2.117e-005
Name		Water Pmp 2 Pwr				
Heat Flow	(MW)	2.893e-005				

Heaters

Fluid Pkg: All

Name		Reactor				
DUTY	(MW)	1.176				
Feed Temperature	(C)	623.5				
Product Temperature	(C)	850.0 *				
Mass Flow	(kg/s)	1.000				

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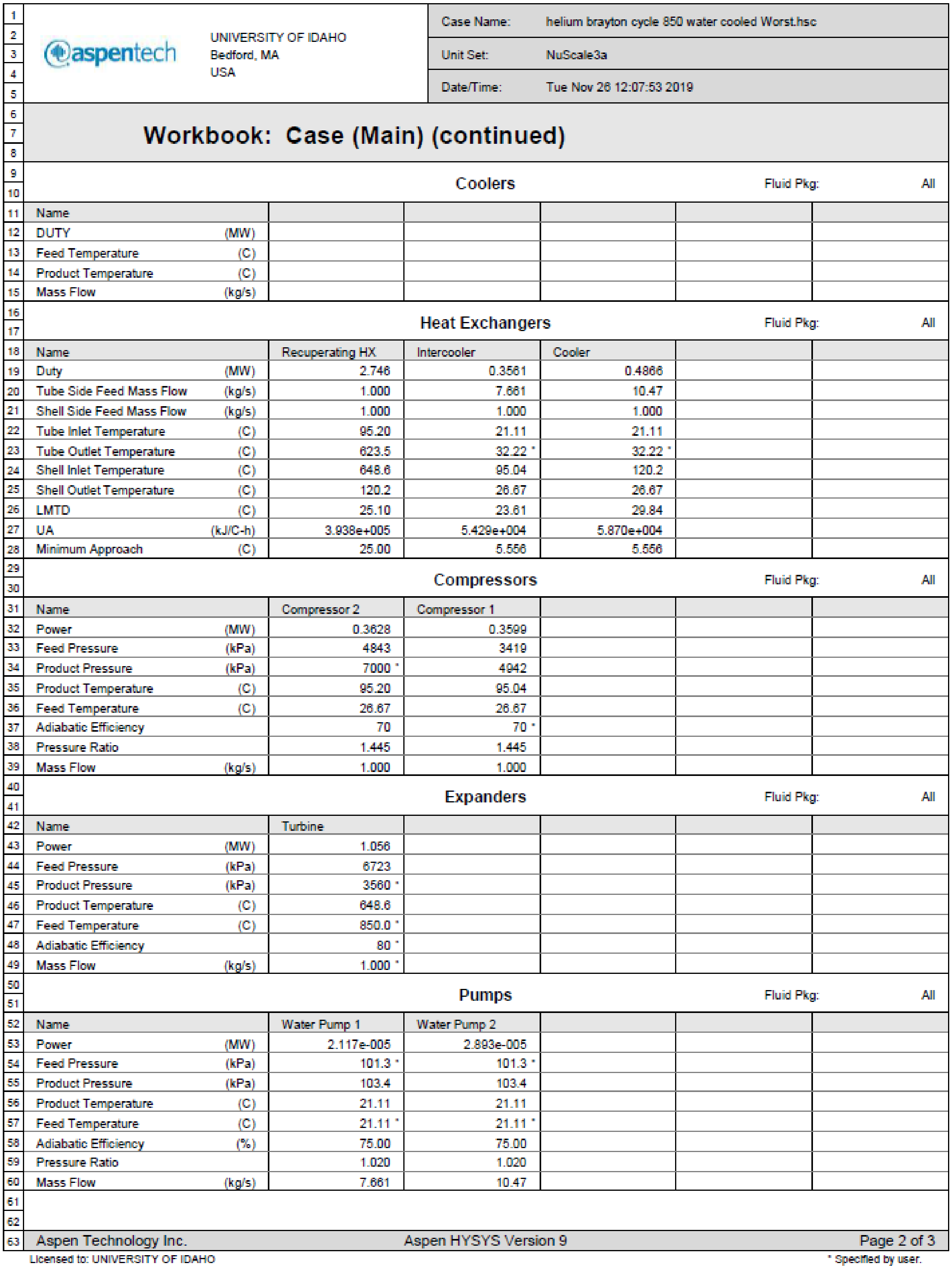

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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: helium brayton cycle 850 water cooled Worst.hsc
Unit Set: NuScale3a
Date/Time: Tue Nov 26 12:07:53 2019

Workbook: Case (Main) (continued)

Coolers

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

Heat Exchangers

Fluid Pkg: All

Name		Recuperating HX	Intercooler	Cooler		
Duty	(MW)	2.746	0.3561	0.4866		
Tube Side Feed Mass Flow	(kg/s)	1.000	7.661	10.47		
Shell Side Feed Mass Flow	(kg/s)	1.000	1.000	1.000		
Tube Inlet Temperature	(C)	95.20	21.11	21.11		
Tube Outlet Temperature	(C)	623.5	32.22 *	32.22 *		
Shell Inlet Temperature	(C)	648.6	95.04	120.2		
Shell Outlet Temperature	(C)	120.2	26.67	26.67		
LMTD	(C)	25.10	23.61	29.84		
UA	(kJ/C-h)	3.938e+005	5.429e+004	5.870e+004		
Minimum Approach	(C)	25.00	5.556	5.556		

Compressors

Fluid Pkg: All

Name		Compressor 2	Compressor 1			
Power	(MW)	0.3628	0.3599			
Feed Pressure	(kPa)	4843	3419			
Product Pressure	(kPa)	7000 *	4942			
Product Temperature	(C)	95.20	95.04			
Feed Temperature	(C)	26.67	26.67			
Adiabatic Efficiency		70	70 *			
Pressure Ratio		1.445	1.445			
Mass Flow	(kg/s)	1.000	1.000			

Expanders

Fluid Pkg: All

Name		Turbine				
Power	(MW)	1.056				
Feed Pressure	(kPa)	6723				
Product Pressure	(kPa)	3560 *				
Product Temperature	(C)	648.6				
Feed Temperature	(C)	850.0 *				
Adiabatic Efficiency		80 *				
Mass Flow	(kg/s)	1.000 *				

Pumps

Fluid Pkg: All

Name		Water Pump 1	Water Pump 2			
Power	(MW)	2.117e-005	2.893e-005			
Feed Pressure	(kPa)	101.3 *	101.3 *			
Product Pressure	(kPa)	103.4	103.4			
Product Temperature	(C)	21.11	21.11			
Feed Temperature	(C)	21.11 *	21.11 *			
Adiabatic Efficiency	(%)	75.00	75.00			
Pressure Ratio		1.020	1.020			
Mass Flow	(kg/s)	7.661	10.47			

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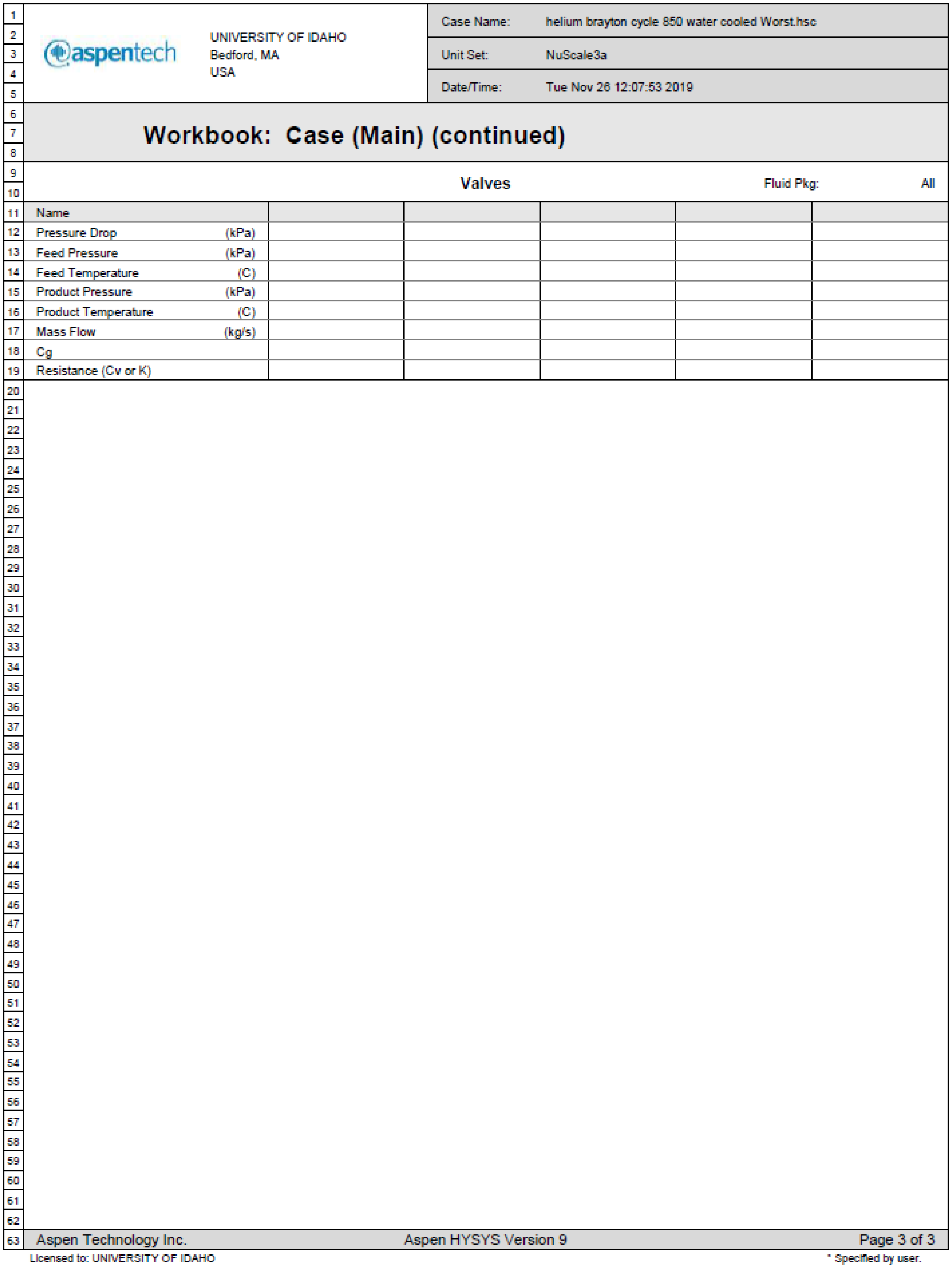

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	helium brayton cycle 850 water cooled Worst.hsc
Unit Set:	NuScale3a
Date/Time:	Tue Nov 26 12:07:53 2019

Workbook: Case (Main) (continued)

Valves

Fluid Pkg: All

Name					
Pressure Drop (kPa)					
Feed Pressure (kPa)					
Feed Temperature (C)					
Product Pressure (kPa)					
Product Temperature (C)					
Mass Flow (kg/s)					
Cg					
Resistance (Cv or K)					

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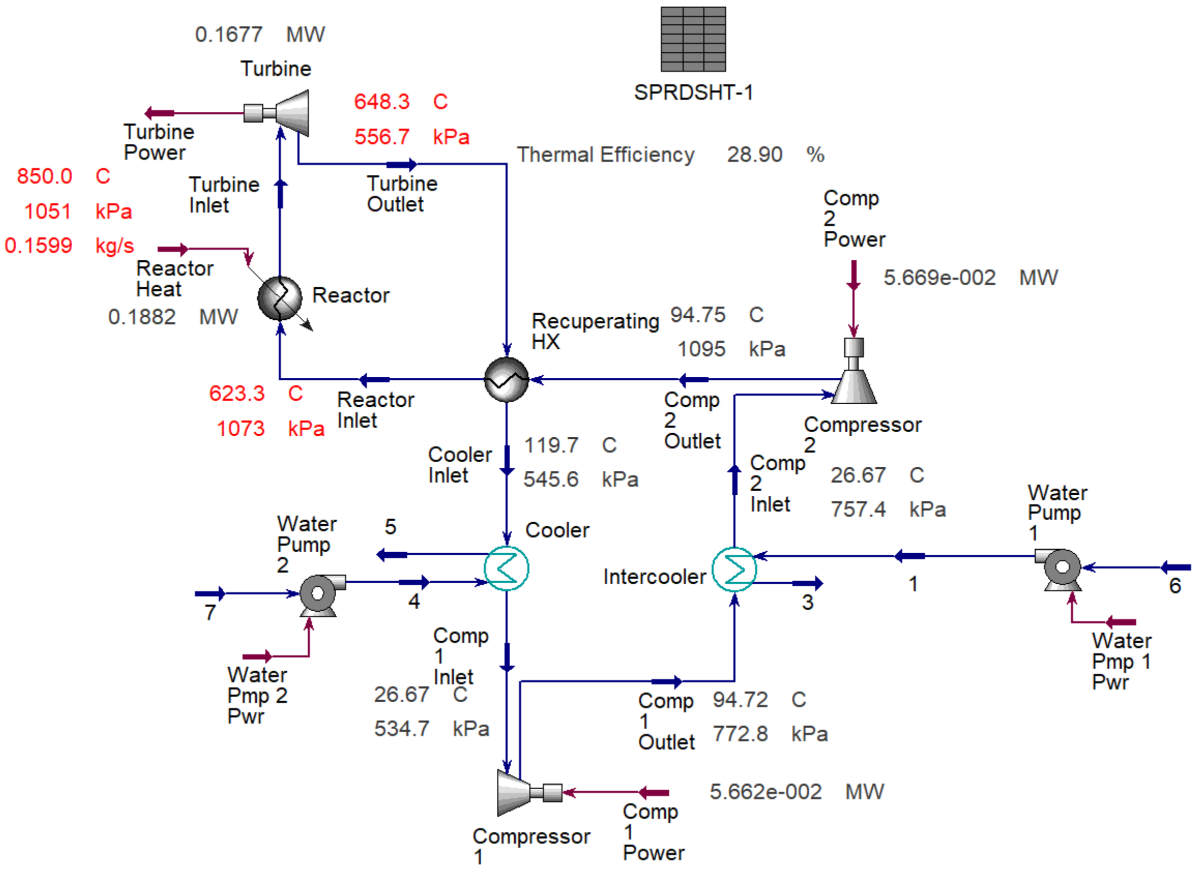
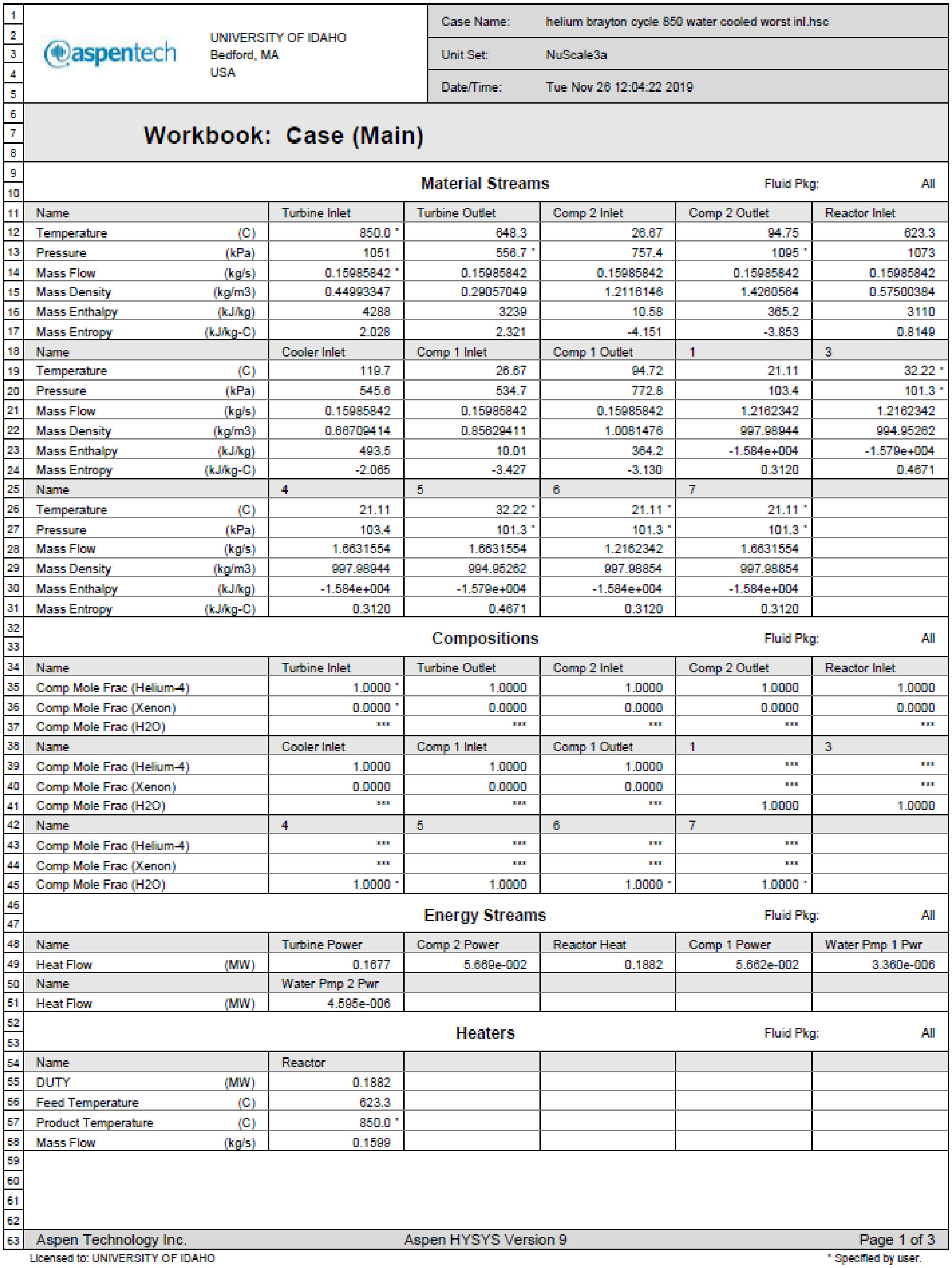
Recuperated Helium Brayton Open Cycle at 850°C Turbine Inlet Temperature with Compressor and Turbine Adiabatic Efficiencies of 70% and 80% and Turbine Inlet Pressure of 1051 kPa





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USA

Case Name: helium brayton cycle 850 water cooled worst inl.hsc

Unit Set: NuScale3a

Date/Time: Tue Nov 26 12:04:22 2019

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Turbine Inlet	Turbine Outlet	Comp 2 Inlet	Comp 2 Outlet	Reactor Inlet
Temperature	(C)	850.0 *	648.3	26.67	94.75	623.3
Pressure	(kPa)	1051	556.7 *	757.4	1095 *	1073
Mass Flow	(kg/s)	0.15985842 *	0.15985842	0.15985842	0.15985842	0.15985842
Mass Density	(kg/m3)	0.44993347	0.29057049	1.2116146	1.4260564	0.57500384
Mass Enthalpy	(kJ/kg)	4288	3239	10.58	365.2	3110
Mass Entropy	(kJ/kg-C)	2.028	2.321	-4.151	-3.853	0.8149
Name		**Cooler Inlet**	**Comp 1 Inlet**	**Comp 1 Outlet**	**1**	**3**
Temperature	(C)	119.7	26.67	94.72	21.11	32.22 *
Pressure	(kPa)	545.6	534.7	772.8	103.4	101.3 *
Mass Flow	(kg/s)	0.15985842	0.15985842	0.15985842	1.2162342	1.2162342
Mass Density	(kg/m3)	0.66709414	0.85629411	1.0081476	997.98944	994.95262
Mass Enthalpy	(kJ/kg)	493.5	10.01	364.2	-1.584e+004	-1.579e+004
Mass Entropy	(kJ/kg-C)	-2.065	-3.427	-3.130	0.3120	0.4671
Name		**4**	**5**	**6**	**7**	
Temperature	(C)	21.11	32.22 *	21.11 *	21.11 *	
Pressure	(kPa)	103.4	101.3 *	101.3 *	101.3 *	
Mass Flow	(kg/s)	1.6631554	1.6631554	1.2162342	1.6631554	
Mass Density	(kg/m3)	997.98944	994.95262	997.98854	997.98854	
Mass Enthalpy	(kJ/kg)	-1.584e+004	-1.579e+004	-1.584e+004	-1.584e+004	
Mass Entropy	(kJ/kg-C)	0.3120	0.4671	0.3120	0.3120	

Compositions

Fluid Pkg: All

Name	Turbine Inlet	Turbine Outlet	Comp 2 Inlet	Comp 2 Outlet	Reactor Inlet
Comp Mole Frac (Helium-4)	1.0000 *	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (Xenon)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	***	***	***	***	***
Name	**Cooler Inlet**	**Comp 1 Inlet**	**Comp 1 Outlet**	**1**	**3**
Comp Mole Frac (Helium-4)	1.0000	1.0000	1.0000	***	***
Comp Mole Frac (Xenon)	0.0000	0.0000	0.0000	***	***
Comp Mole Frac (H2O)	***	***	***	1.0000	1.0000
Name	**4**	**5**	**6**	**7**	
Comp Mole Frac (Helium-4)	***	***	***	***	
Comp Mole Frac (Xenon)	***	***	***	***	
Comp Mole Frac (H2O)	1.0000 *	1.0000	1.0000 *	1.0000 *	

Energy Streams

Fluid Pkg: All

Name		Turbine Power	Comp 2 Power	Reactor Heat	Comp 1 Power	Water Pmp 1 Pwr
Heat Flow	(MW)	0.1677	5.669e-002	0.1882	5.662e-002	3.360e-006
Name		**Water Pmp 2 Pwr**				
Heat Flow	(MW)	4.595e-006				

Heaters

Fluid Pkg: All

Name		Reactor				
DUTY	(MW)	0.1882				
Feed Temperature	(C)	623.3				
Product Temperature	(C)	850.0 *				
Mass Flow	(kg/s)	0.1599				

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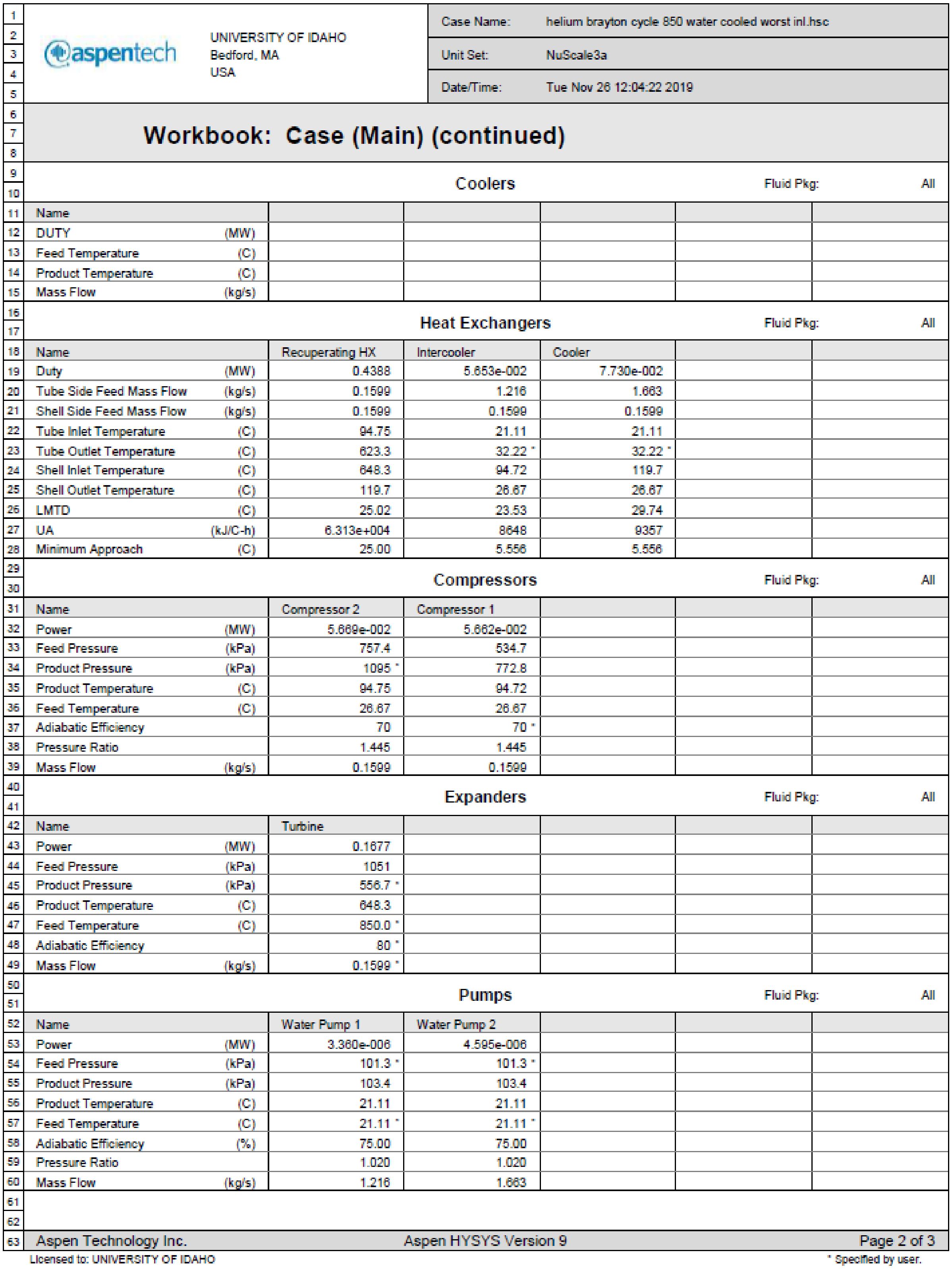

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: helium brayton cycle 850 water cooled worst inl.hsc
Unit Set: NuScale3a
Date/Time: Tue Nov 26 12:04:22 2019

Workbook: Case (Main) (continued)

Coolers

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

Heat Exchangers

Fluid Pkg: All

Name		Recuperating HX	Intercooler	Cooler		
Duty	(MW)	0.4388	5.653e-002	7.730e-002		
Tube Side Feed Mass Flow	(kg/s)	0.1599	1.216	1.663		
Shell Side Feed Mass Flow	(kg/s)	0.1599	0.1599	0.1599		
Tube Inlet Temperature	(C)	94.75	21.11	21.11		
Tube Outlet Temperature	(C)	623.3	32.22 *	32.22 *		
Shell Inlet Temperature	(C)	648.3	94.72	119.7		
Shell Outlet Temperature	(C)	119.7	26.67	26.67		
LMTD	(C)	25.02	23.53	29.74		
UA	(kJ/C-h)	6.313e+004	8648	9357		
Minimum Approach	(C)	25.00	5.556	5.556		

Compressors

Fluid Pkg: All

Name		Compressor 2	Compressor 1			
Power	(MW)	5.669e-002	5.662e-002			
Feed Pressure	(kPa)	757.4	534.7			
Product Pressure	(kPa)	1095 *	772.8			
Product Temperature	(C)	94.75	94.72			
Feed Temperature	(C)	26.67	26.67			
Adiabatic Efficiency		70	70 *			
Pressure Ratio		1.445	1.445			
Mass Flow	(kg/s)	0.1599	0.1599			

Expanders

Fluid Pkg: All

Name		Turbine				
Power	(MW)	0.1677				
Feed Pressure	(kPa)	1051				
Product Pressure	(kPa)	556.7 *				
Product Temperature	(C)	648.3				
Feed Temperature	(C)	850.0 *				
Adiabatic Efficiency		80 *				
Mass Flow	(kg/s)	0.1599 *				

Pumps

Fluid Pkg: All

Name		Water Pump 1	Water Pump 2			
Power	(MW)	3.360e-006	4.595e-006			
Feed Pressure	(kPa)	101.3 *	101.3 *			
Product Pressure	(kPa)	103.4	103.4			
Product Temperature	(C)	21.11	21.11			
Feed Temperature	(C)	21.11 *	21.11 *			
Adiabatic Efficiency	(%)	75.00	75.00			
Pressure Ratio		1.020	1.020			
Mass Flow	(kg/s)	1.216	1.663			

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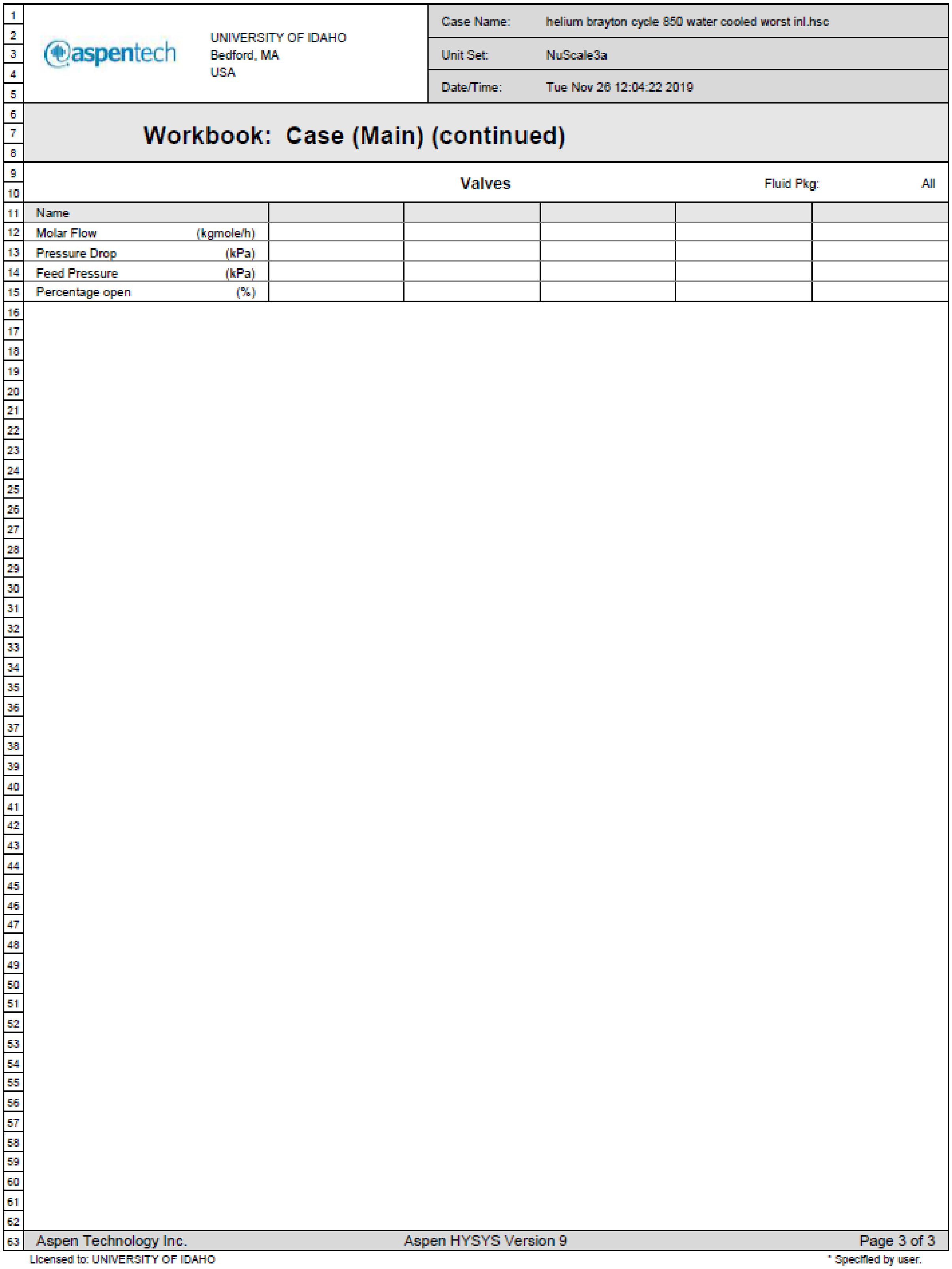

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Bedford, MA
USA

Case Name:	helium brayton cycle 850 water cooled worst inl.hsc
Unit Set:	NuScale3a
Date/Time:	Tue Nov 26 12:04:22 2019

Workbook: Case (Main) (continued)

Valves

Fluid Pkg: All

Name						
Molar Flow	(kgmole/h)					
Pressure Drop	(kPa)					
Feed Pressure	(kPa)					
Percentage open	(%)					

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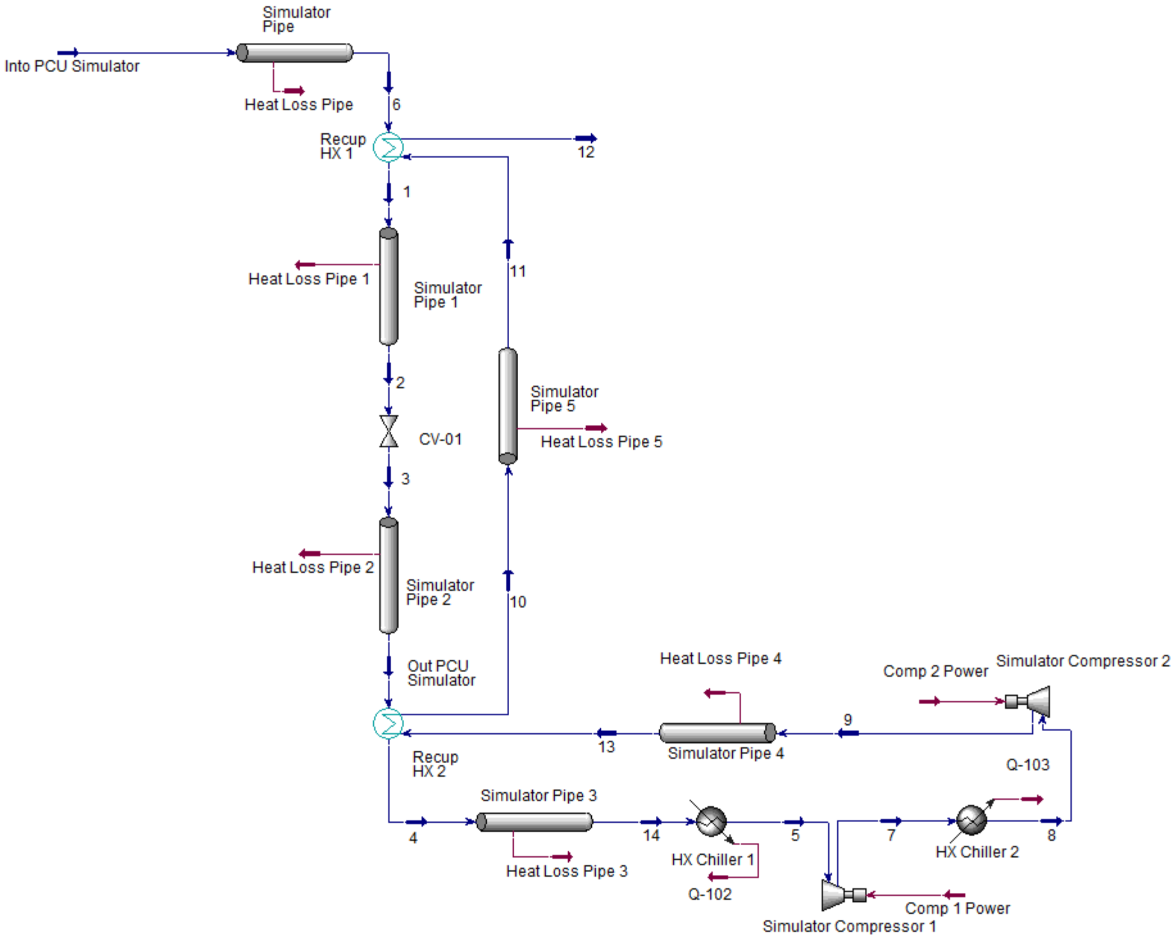
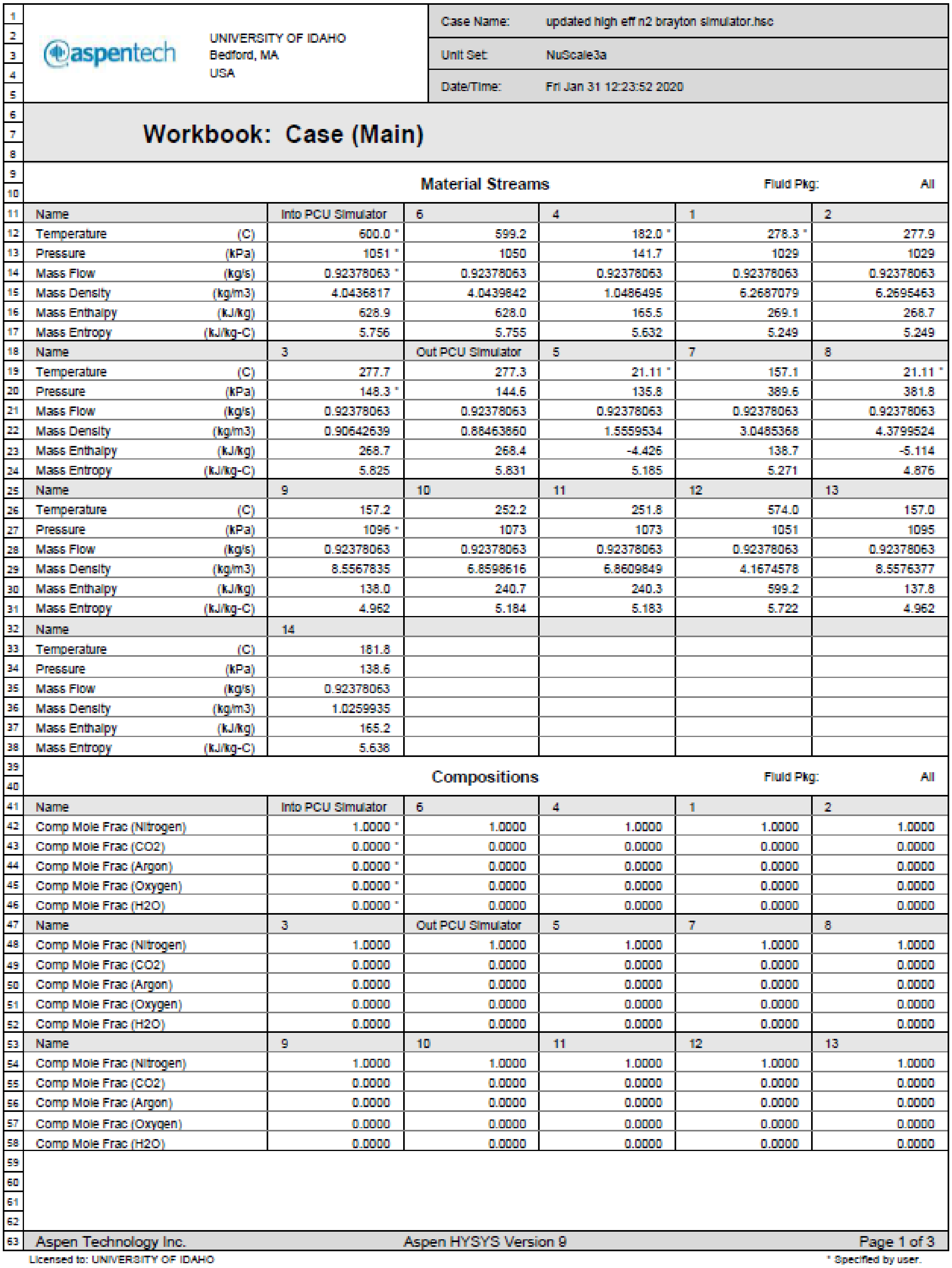
Appendix H: Aspen HYSYS Models for Sizing of the PCU Simulator

Modified Simple Nitrogen Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 85% and 90%





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USA

Case Name: updated high eff n2 brayton simulator.hsc

Unit Set: NuScale3a

Date/Time: Fri Jan 31 12:23:52 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name	Into PCU Simulator	6	4	1	2
Temperature (C)	600.0 *	599.2	182.0 *	278.3 *	277.9
Pressure (kPa)	1051 *	1050	141.7	1029	1029
Mass Flow (kg/s)	0.92378063 *	0.92378063	0.92378063	0.92378063	0.92378063
Mass Density (kg/m3)	4.0436817	4.0439842	1.0486495	6.2687079	6.2695463
Mass Enthalpy (kJ/kg)	628.9	628.0	165.5	269.1	268.7
Mass Entropy (kJ/kg-C)	5.756	5.755	5.632	5.249	5.249

Name	3	Out PCU Simulator	5	7	8
Temperature (C)	277.7	277.3	21.11 *	157.1	21.11 *
Pressure (kPa)	148.3 *	144.6	135.8	389.6	381.8
Mass Flow (kg/s)	0.92378063	0.92378063	0.92378063	0.92378063	0.92378063
Mass Density (kg/m3)	0.90642639	0.88463860	1.5559534	3.0485368	4.3799524
Mass Enthalpy (kJ/kg)	268.7	268.4	-4.426	138.7	-5.114
Mass Entropy (kJ/kg-C)	5.825	5.831	5.185	5.271	4.876

Name	9	10	11	12	13
Temperature (C)	157.2	252.2	251.8	574.0	157.0
Pressure (kPa)	1096 *	1073	1073	1051	1095
Mass Flow (kg/s)	0.92378063	0.92378063	0.92378063	0.92378063	0.92378063
Mass Density (kg/m3)	8.5567835	6.8598616	6.8609849	4.1674578	8.5576377
Mass Enthalpy (kJ/kg)	138.0	240.7	240.3	599.2	137.8
Mass Entropy (kJ/kg-C)	4.962	5.184	5.183	5.722	4.962

Name	14				
Temperature (C)	181.8				
Pressure (kPa)	138.6				
Mass Flow (kg/s)	0.92378063				
Mass Density (kg/m3)	1.0259935				
Mass Enthalpy (kJ/kg)	165.2				
Mass Entropy (kJ/kg-C)	5.638				

Compositions

Fluid Pkg: All

Name	Into PCU Simulator	6	4	1	2
Comp Mole Frac (Nitrogen)	1.0000 *	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (CO2)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000 *	0.0000	0.0000	0.0000	0.0000

Name	3	Out PCU Simulator	5	7	8
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	0.0000

Name	9	10	11	12	13
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	0.0000

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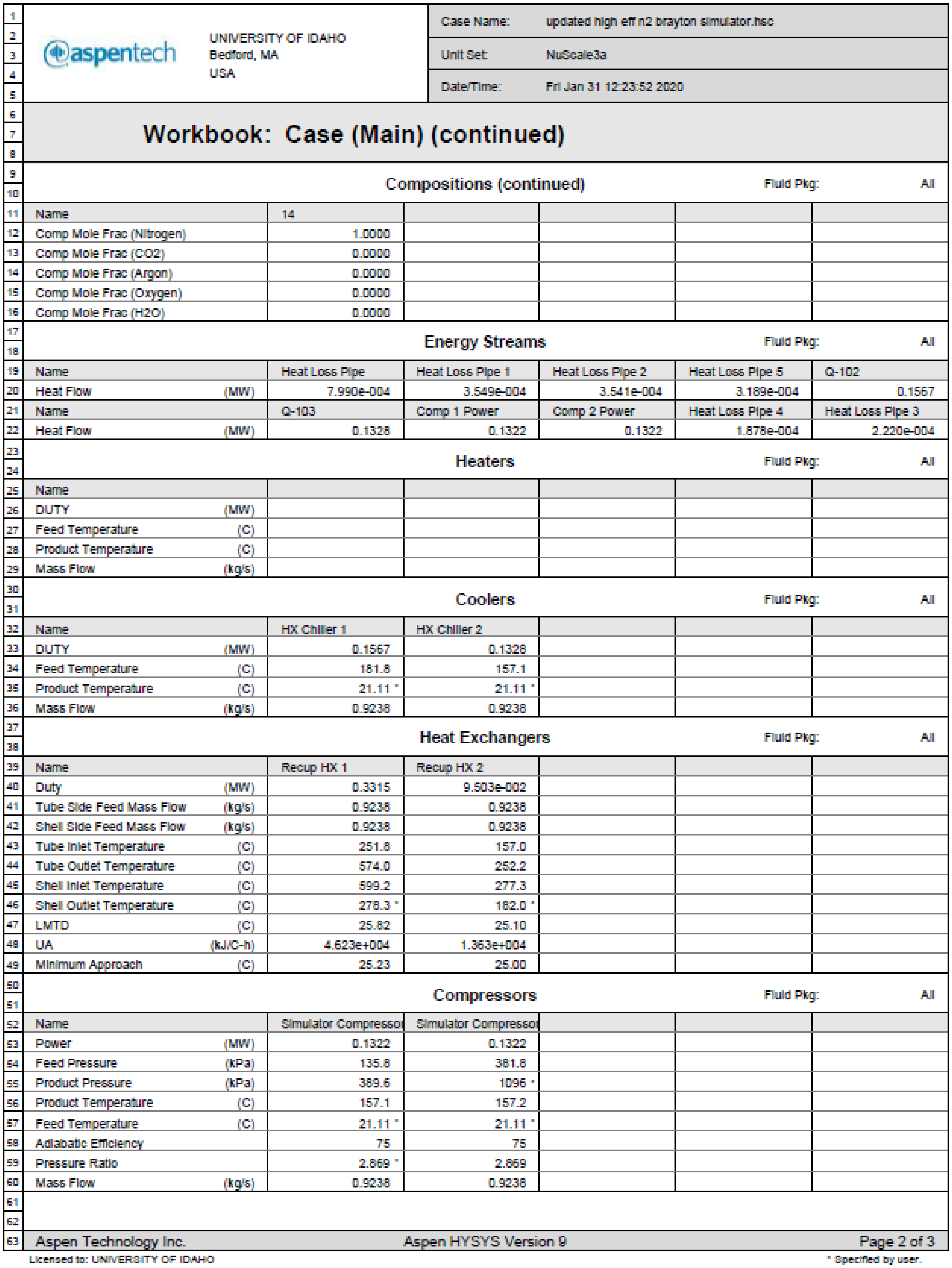

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Bedford, MA
USA

Case Name:	updated high eff n2 brayton simulator.hsc
Unit Set:	NuScale3a
Date/Time:	Fri Jan 31 12:23:52 2020

Workbook: Case (Main) (continued)

Compositions (continued)

Fluid Pkg: All

Name	14				
Comp Mole Frac (Nitrogen)	1.0000				
Comp Mole Frac (CO2)	0.0000				
Comp Mole Frac (Argon)	0.0000				
Comp Mole Frac (Oxygen)	0.0000				
Comp Mole Frac (H2O)	0.0000				

Energy Streams

Fluid Pkg: All

Name	Heat Loss Pipe	Heat Loss Pipe 1	Heat Loss Pipe 2	Heat Loss Pipe 5	Q-102
Heat Flow (MW)	7.990e-004	3.549e-004	3.541e-004	3.189e-004	0.1567
Name	Q-103	Comp 1 Power	Comp 2 Power	Heat Loss Pipe 4	Heat Loss Pipe 3
Heat Flow (MW)	0.1328	0.1322	0.1322	1.878e-004	2.220e-004

Heaters

Fluid Pkg: All

Name					
DUTY (MW)					
Feed Temperature (C)					
Product Temperature (C)					
Mass Flow (kg/s)					

Coolers

Fluid Pkg: All

Name	HX Chiller 1	HX Chiller 2			
DUTY (MW)	0.1567	0.1328			
Feed Temperature (C)	181.8	157.1			
Product Temperature (C)	21.11 *	21.11 *			
Mass Flow (kg/s)	0.9238	0.9238			

Heat Exchangers

Fluid Pkg: All

Name	Recup HX 1	Recup HX 2			
Duty (MW)	0.3315	9.503e-002			
Tube Side Feed Mass Flow (kg/s)	0.9238	0.9238			
Shell Side Feed Mass Flow (kg/s)	0.9238	0.9238			
Tube Inlet Temperature (C)	251.8	157.0			
Tube Outlet Temperature (C)	574.0	252.2			
Shell Inlet Temperature (C)	599.2	277.3			
Shell Outlet Temperature (C)	278.3 *	182.0 *			
LMTD (C)	25.82	25.10			
UA (kJ/C-h)	4.623e+004	1.363e+004			
Minimum Approach (C)	25.23	25.00			

Compressors

Fluid Pkg: All

Name	Simulator Compressor	Simulator Compressor			
Power (MW)	0.1322	0.1322			
Feed Pressure (kPa)	135.8	381.8			
Product Pressure (kPa)	389.6	1096 *			
Product Temperature (C)	157.1	157.2			
Feed Temperature (C)	21.11 *	21.11 *			
Adiabatic Efficiency	75	75			
Pressure Ratio	2.869 *	2.869			
Mass Flow (kg/s)	0.9238	0.9238			

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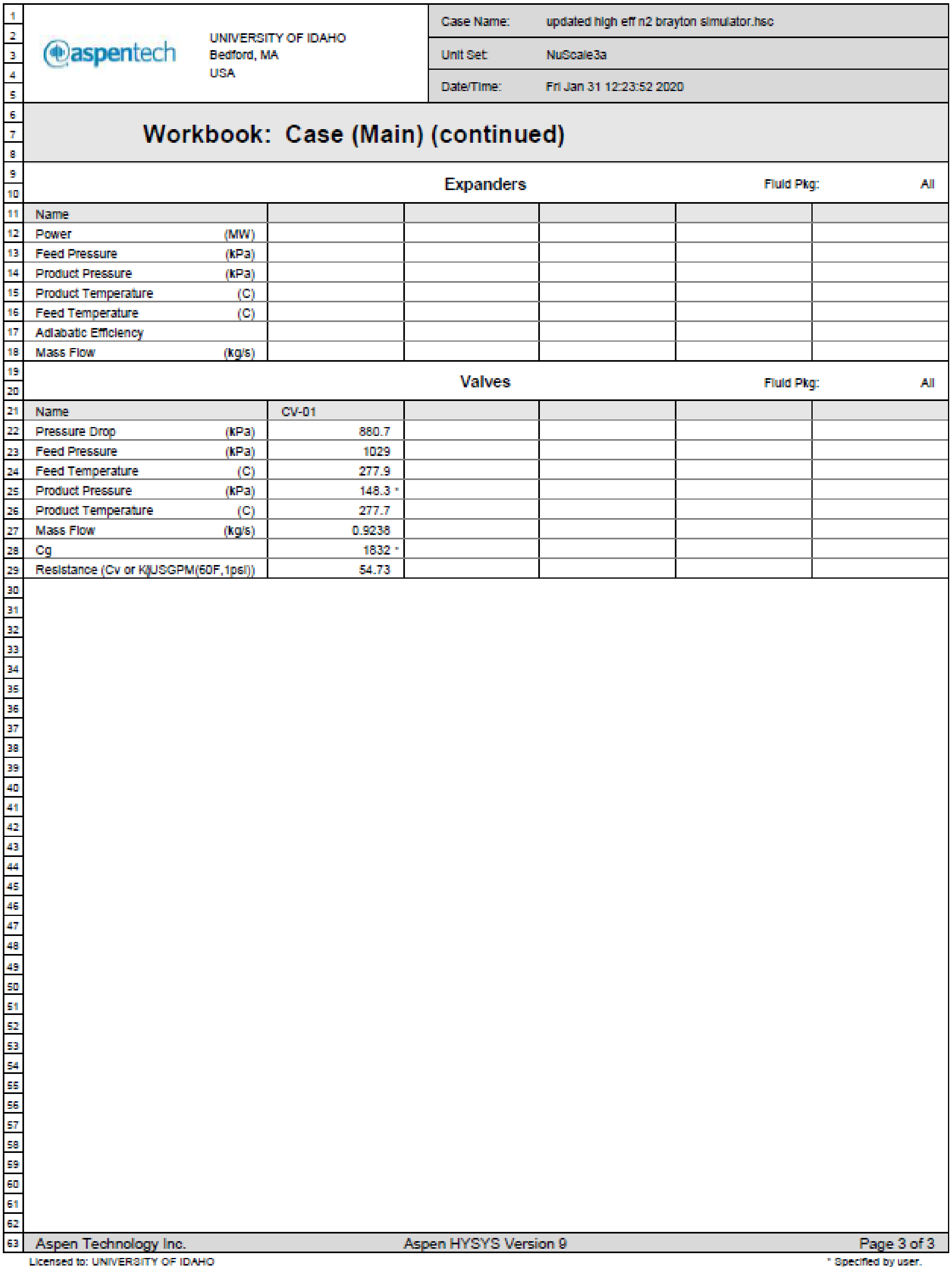

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Bedford, MA
USA

Case Name:	updated high eff n2 brayton simulator.hsc
Unit Set:	NuScale3a
Date/Time:	Fri Jan 31 12:23:52 2020

Workbook: Case (Main) (continued)

Expanders

Fluid Pkg: All

Name					
Power (MW)					
Feed Pressure (kPa)					
Product Pressure (kPa)					
Product Temperature (C)					
Feed Temperature (C)					
Adiabatic Efficiency					
Mass Flow (kg/s)					

Valves

Fluid Pkg: All

Name	CV-01				
Pressure Drop (kPa)	880.7				
Feed Pressure (kPa)	1029				
Feed Temperature (C)	277.9				
Product Pressure (kPa)	148.3 *				
Product Temperature (C)	277.7				
Mass Flow (kg/s)	0.9238				
Cg	1832 *				
Resistance (Cv or K)(USGPM(60F,1psi))	54.73				

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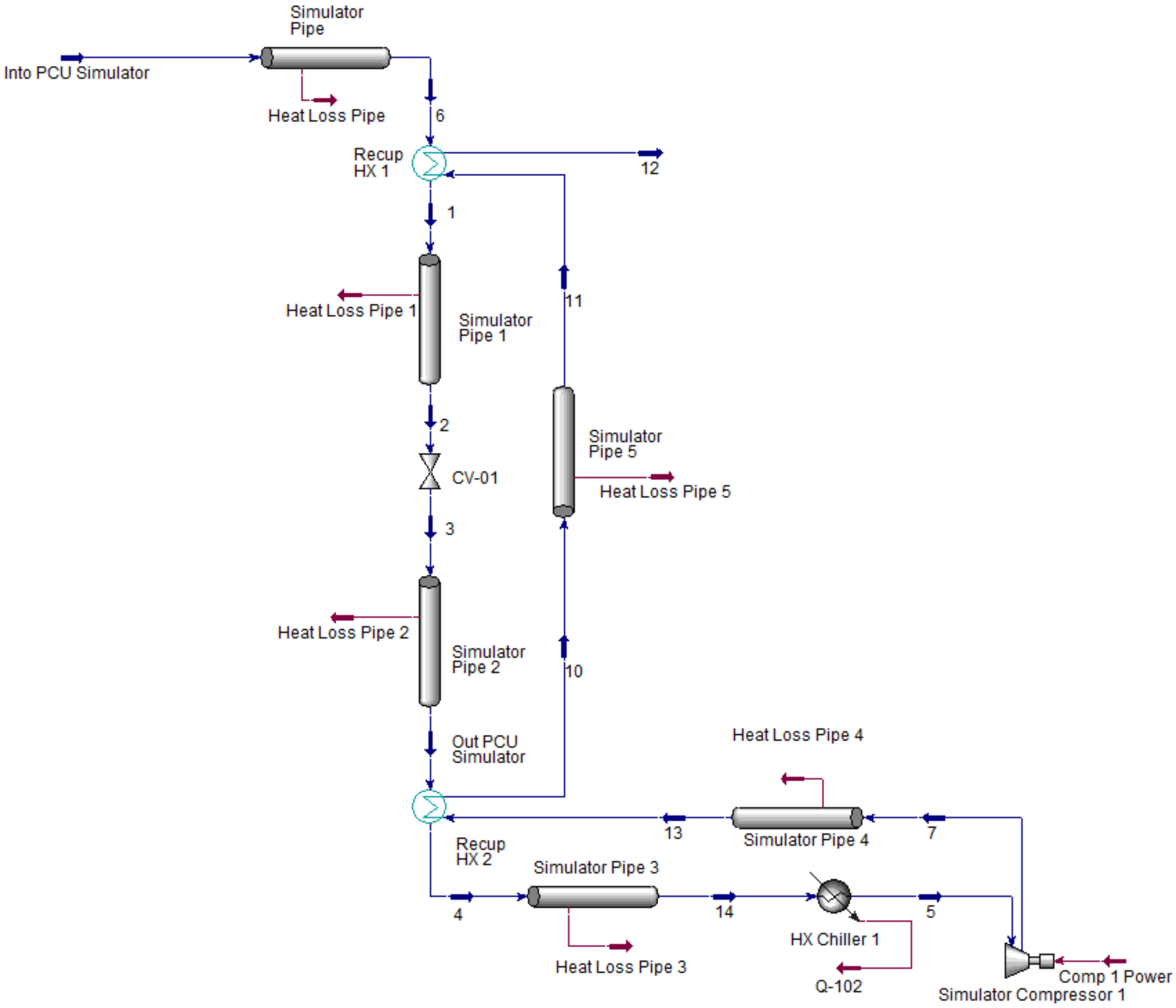
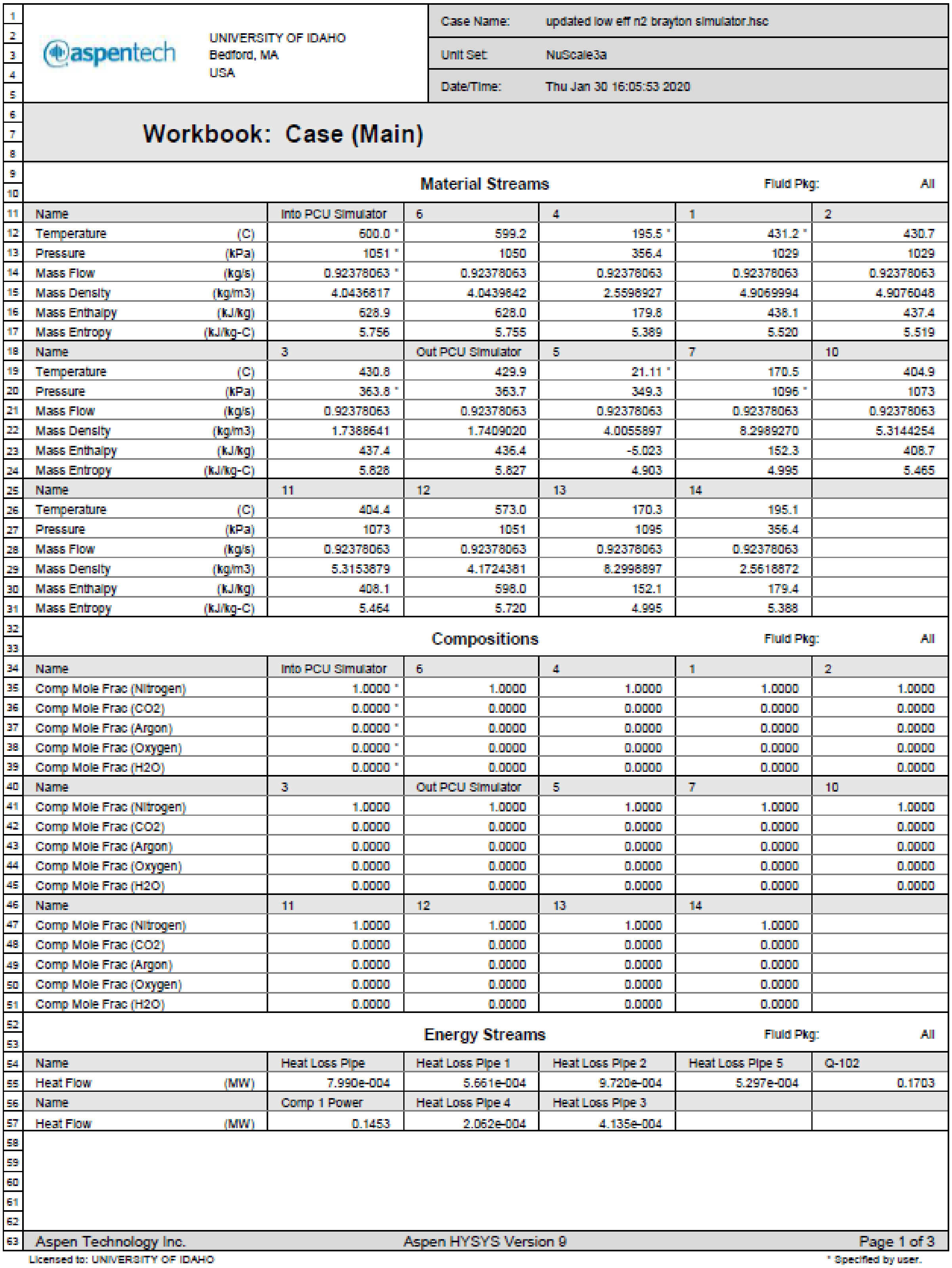
Modified Simple Nitrogen Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 70% and 80%





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USA

Case Name:	updated low eff n2 brayton simulator.hsc
Unit Set:	NuScale3a
Date/Time:	Thu Jan 30 16:05:53 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name	Into PCU Simulator	6	4	1	2
Temperature (C)	600.0 *	599.2	195.5 *	431.2 *	430.7
Pressure (kPa)	1051 *	1050	356.4	1029	1029
Mass Flow (kg/s)	0.92378063 *	0.92378063	0.92378063	0.92378063	0.92378063
Mass Density (kg/m3)	4.0436817	4.0439842	2.5598927	4.9069994	4.9076048
Mass Enthalpy (kJ/kg)	628.9	628.0	179.8	438.1	437.4
Mass Entropy (kJ/kg-C)	5.756	5.755	5.389	5.520	5.519

Name	3	Out PCU Simulator	5	7	10
Temperature (C)	430.8	429.9	21.11 *	170.5	404.9
Pressure (kPa)	363.8 *	363.7	349.3	1096 *	1073
Mass Flow (kg/s)	0.92378063	0.92378063	0.92378063	0.92378063	0.92378063
Mass Density (kg/m3)	1.7388641	1.7409020	4.0055897	8.2989270	5.3144254
Mass Enthalpy (kJ/kg)	437.4	436.4	-5.023	152.3	408.7
Mass Entropy (kJ/kg-C)	5.828	5.827	4.903	4.995	5.465

Name	11	12	13	14	
Temperature (C)	404.4	573.0	170.3	195.1	
Pressure (kPa)	1073	1051	1095	356.4	
Mass Flow (kg/s)	0.92378063	0.92378063	0.92378063	0.92378063	
Mass Density (kg/m3)	5.3153879	4.1724381	8.2998897	2.5618872	
Mass Enthalpy (kJ/kg)	408.1	598.0	152.1	179.4	
Mass Entropy (kJ/kg-C)	5.464	5.720	4.995	5.388	

Compositions

Fluid Pkg: All

Name	Into PCU Simulator	6	4	1	2
Comp Mole Frac (Nitrogen)	1.0000 *	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (CO_2)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H_2O)	0.0000 *	0.0000	0.0000	0.0000	0.0000

Name	3	Out PCU Simulator	5	7	10
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (CO_2)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H_2O)	0.0000	0.0000	0.0000	0.0000	0.0000

Name	11	12	13	14	
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000	
Comp Mole Frac (CO_2)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (H_2O)	0.0000	0.0000	0.0000	0.0000	

Energy Streams

Fluid Pkg: All

Name	Heat Loss Pipe	Heat Loss Pipe 1	Heat Loss Pipe 2	Heat Loss Pipe 5	Q-102
Heat Flow (MW)	7.990e-004	5.661e-004	9.720e-004	5.297e-004	0.1703
Name	**Comp 1 Power**	**Heat Loss Pipe 4**	**Heat Loss Pipe 3**		
Heat Flow (MW)	0.1453	2.062e-004	4.135e-004		

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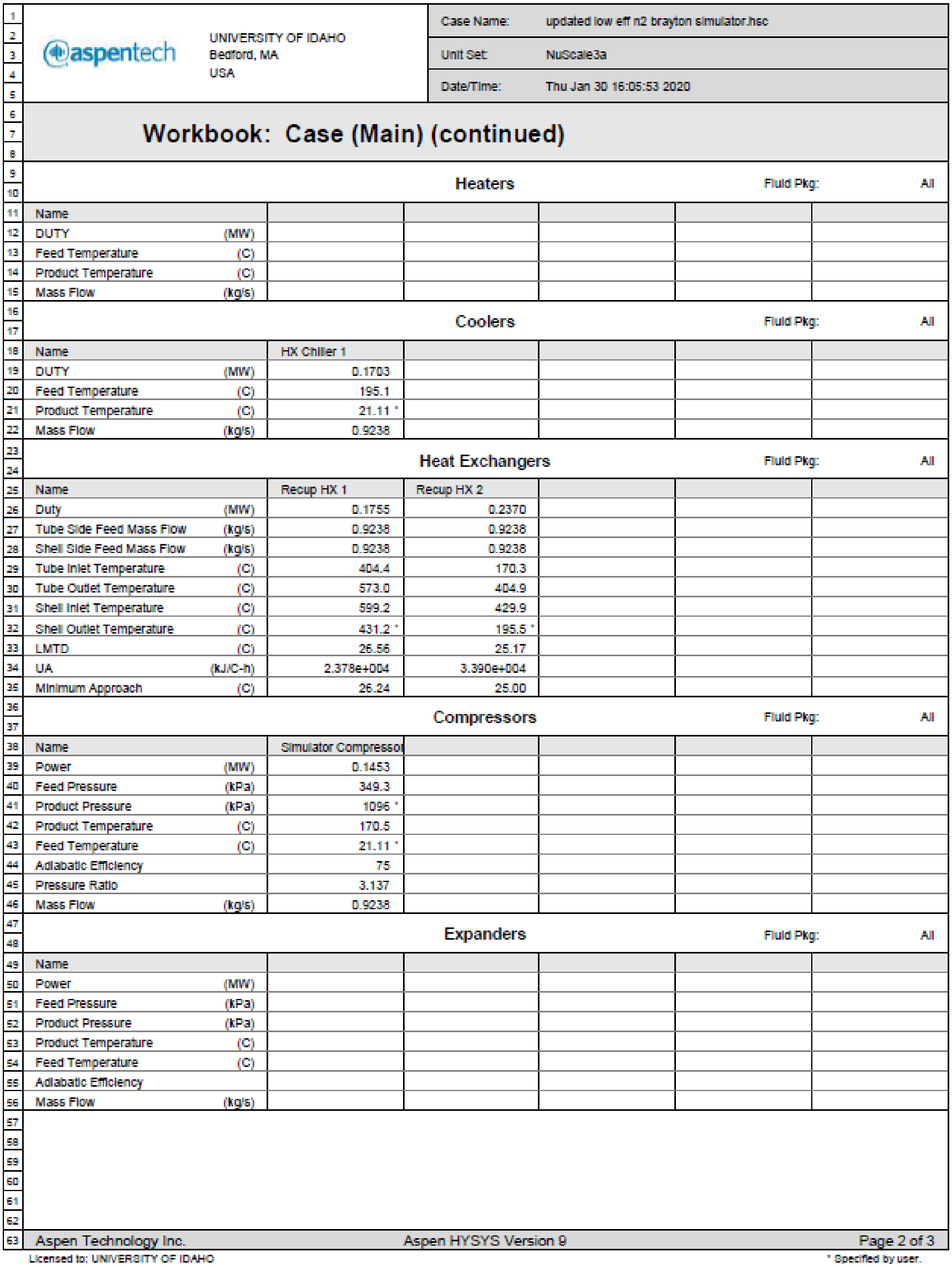

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	updated low eff n2 brayton simulator.hsc
Unit Set:	NuScale3a
Date/Time:	Thu Jan 30 16:05:53 2020

Workbook: Case (Main) (continued)

Heaters

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

Coolers

Fluid Pkg: All

Name		HX Chiller 1				
DUTY	(MW)	0.1703				
Feed Temperature	(C)	195.1				
Product Temperature	(C)	21.11 *				
Mass Flow	(kg/s)	0.9238				

Heat Exchangers

Fluid Pkg: All

Name		Recup HX 1	Recup HX 2			
Duty	(MW)	0.1755	0.2370			
Tube Side Feed Mass Flow	(kg/s)	0.9238	0.9238			
Shell Side Feed Mass Flow	(kg/s)	0.9238	0.9238			
Tube Inlet Temperature	(C)	404.4	170.3			
Tube Outlet Temperature	(C)	573.0	404.9			
Shell Inlet Temperature	(C)	599.2	429.9			
Shell Outlet Temperature	(C)	431.2 *	195.5 *			
LMTD	(C)	26.56	25.17			
UA	(kJ/C-h)	2.378e+004	3.390e+004			
Minimum Approach	(C)	26.24	25.00			

Compressors

Fluid Pkg: All

Name		Simulator Compressor				
Power	(MW)	0.1453				
Feed Pressure	(kPa)	349.3				
Product Pressure	(kPa)	1096 *				
Product Temperature	(C)	170.5				
Feed Temperature	(C)	21.11 *				
Adiabatic Efficiency		75				
Pressure Ratio		3.137				
Mass Flow	(kg/s)	0.9238				

Expanders

Fluid Pkg: All

Name						
Power	(MW)					
Feed Pressure	(kPa)					
Product Pressure	(kPa)					
Product Temperature	(C)					
Feed Temperature	(C)					
Adiabatic Efficiency						
Mass Flow	(kg/s)					

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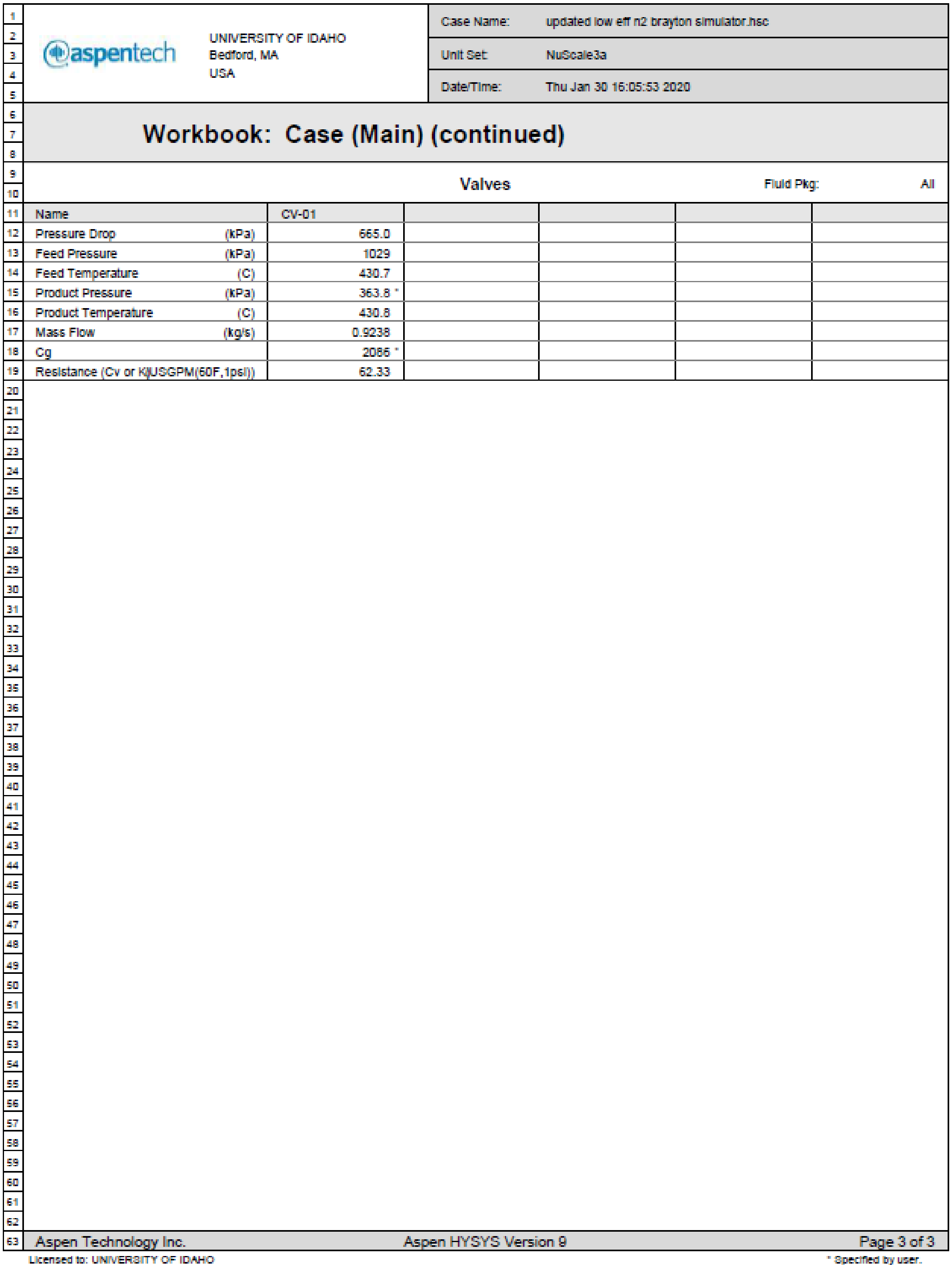

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Bedford, MA
USA

Case Name: updated low eff n2 brayton simulator.hsc
Unit Set: NuScale3a
Date/Time: Thu Jan 30 16:05:53 2020

Workbook: Case (Main) (continued)

Valves

Fluid Pkg: All

Name	CV-01				
Pressure Drop (kPa)	665.0				
Feed Pressure (kPa)	1029				
Feed Temperature (C)	430.7				
Product Pressure (kPa)	363.8 *				
Product Temperature (C)	430.8				
Mass Flow (kg/s)	0.9238				
Cg	2086 *				
Resistance (Cv or K)(USGPM(60F,1psi))	62.33				

Aspen Technology Inc. Aspen HYSYS Version 9 Page 3 of 3

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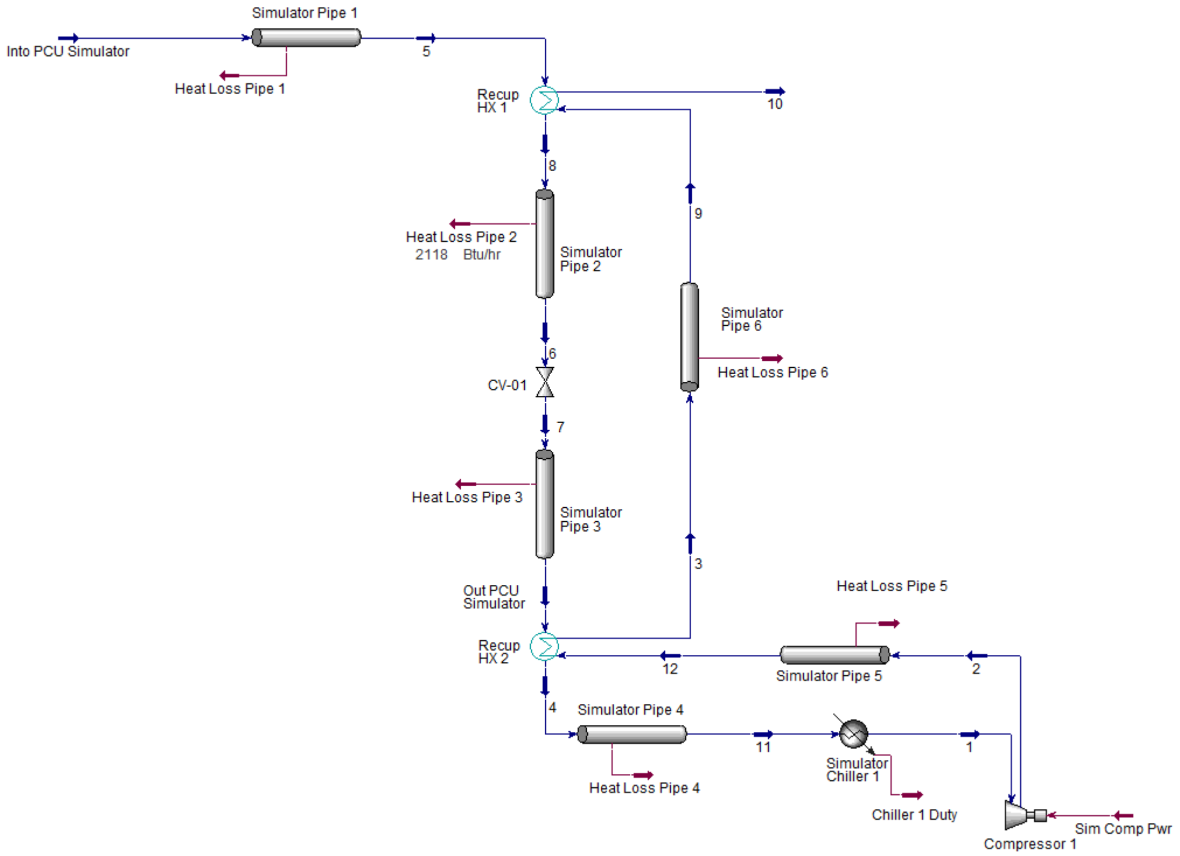
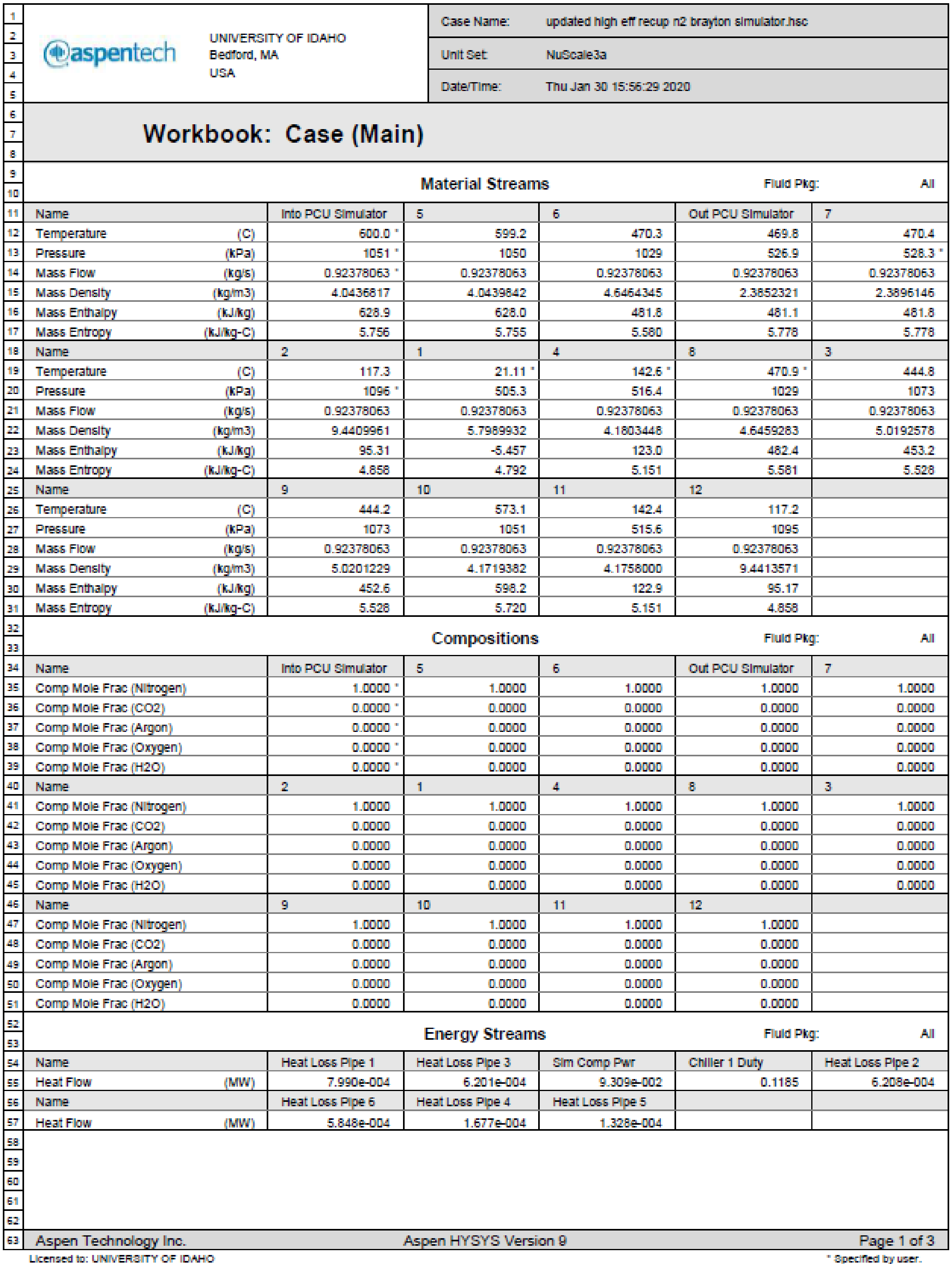
Modified Nitrogen Recuperated Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 85% and 90%





aspentech

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	updated high eff recup n2 brayton simulator.hsc
Unit Set:	NuScale3a
Date/Time:	Thu Jan 30 15:56:29 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name	Into PCU Simulator	5	6	Out PCU Simulator	7
Temperature (C)	600.0 *	599.2	470.3	469.8	470.4
Pressure (kPa)	1051 *	1050	1029	526.9	528.3 *
Mass Flow (kg/s)	0.92378063 *	0.92378063	0.92378063	0.92378063	0.92378063
Mass Density (kg/m3)	4.0436817	4.0439842	4.6464345	2.3852321	2.3896146
Mass Enthalpy (kJ/kg)	628.9	628.0	481.8	481.1	481.8
Mass Entropy (kJ/kg-C)	5.756	5.755	5.580	5.778	5.778
Name	**2**	**1**	**4**	**8**	**3**
Temperature (C)	117.3	21.11 *	142.6 *	470.9 *	444.8
Pressure (kPa)	1096 *	505.3	516.4	1029	1073
Mass Flow (kg/s)	0.92378063	0.92378063	0.92378063	0.92378063	0.92378063
Mass Density (kg/m3)	9.4409961	5.7989932	4.1803448	4.6459283	5.0192578
Mass Enthalpy (kJ/kg)	95.31	-5.457	123.0	482.4	453.2
Mass Entropy (kJ/kg-C)	4.858	4.792	5.151	5.581	5.528
Name	**9**	**10**	**11**	**12**	
Temperature (C)	444.2	573.1	142.4	117.2	
Pressure (kPa)	1073	1051	515.6	1095	
Mass Flow (kg/s)	0.92378063	0.92378063	0.92378063	0.92378063	
Mass Density (kg/m3)	5.0201229	4.1719382	4.1758000	9.4413571	
Mass Enthalpy (kJ/kg)	452.6	598.2	122.9	95.17	
Mass Entropy (kJ/kg-C)	5.528	5.720	5.151	4.858	

Compositions

Fluid Pkg: All

Name	Into PCU Simulator	5	6	Out PCU Simulator	7
Comp Mole Frac (Nitrogen)	1.0000 *	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (CO2)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Name	**2**	**1**	**4**	**8**	**3**
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	0.0000
Name	**9**	**10**	**11**	**12**	
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000	
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	

Energy Streams

Fluid Pkg: All

Name	Heat Loss Pipe 1	Heat Loss Pipe 3	Sim Comp Pwr	Chiller 1 Duty	Heat Loss Pipe 2
Heat Flow (MW)	7.990e-004	6.201e-004	9.309e-002	0.1185	6.208e-004
Name	**Heat Loss Pipe 6**	**Heat Loss Pipe 4**	**Heat Loss Pipe 5**		
Heat Flow (MW)	5.848e-004	1.677e-004	1.328e-004		

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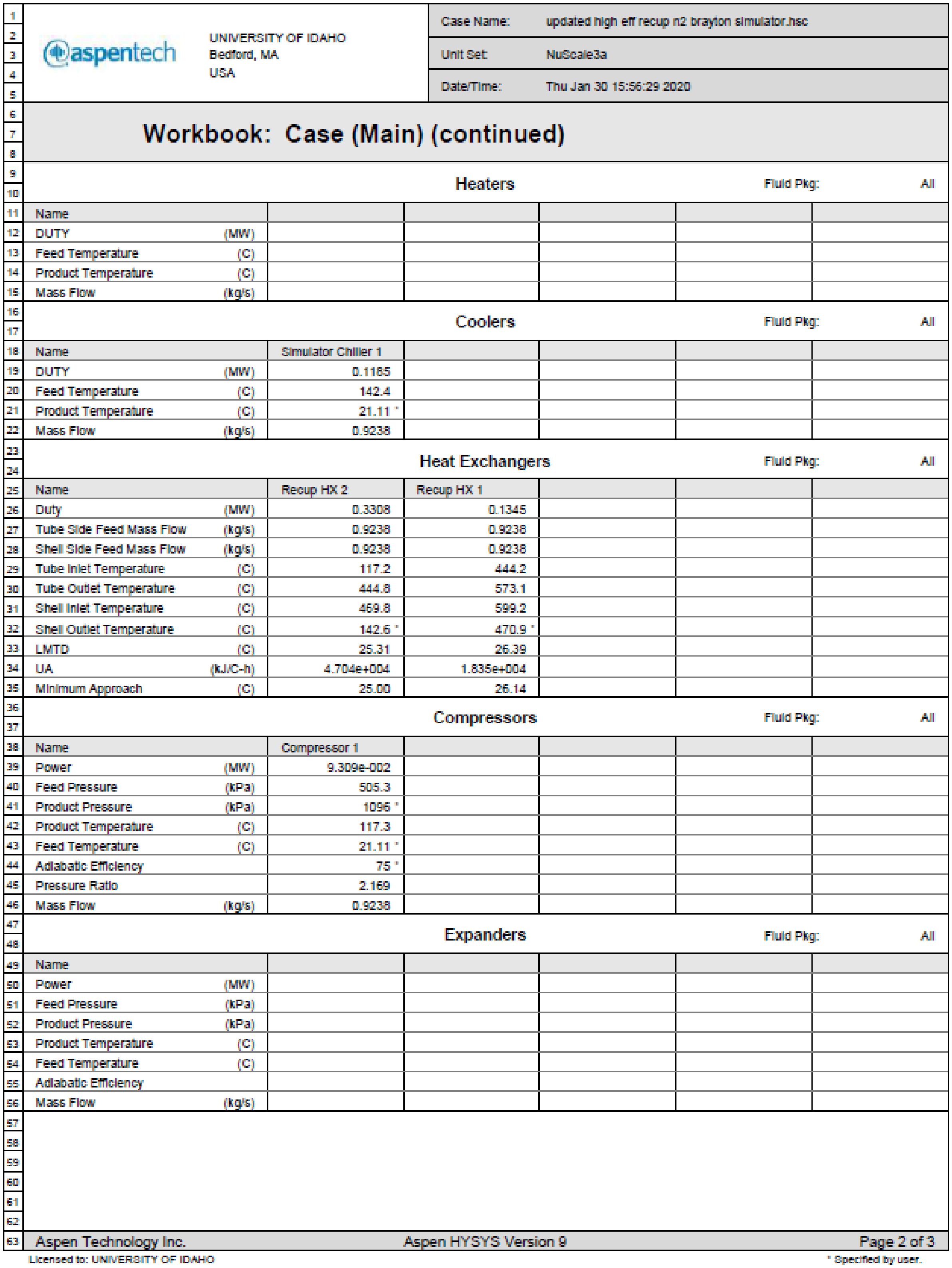

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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: updated high eff recup n2 brayton simulator.hsc

Unit Set: NuScale3a

Date/Time: Thu Jan 30 15:56:29 2020

Workbook: Case (Main) (continued)

Heaters

Fluid Pkg: All

Name					
DUTY (MW)					
Feed Temperature (C)					
Product Temperature (C)					
Mass Flow (kg/s)					

Coolers

Fluid Pkg: All

Name	Simulator Chiller 1				
DUTY (MW)	0.1185				
Feed Temperature (C)	142.4				
Product Temperature (C)	21.11 *				
Mass Flow (kg/s)	0.9238				

Heat Exchangers

Fluid Pkg: All

Name	Recup HX 2	Recup HX 1			
Duty (MW)	0.3308	0.1345			
Tube Side Feed Mass Flow (kg/s)	0.9238	0.9238			
Shell Side Feed Mass Flow (kg/s)	0.9238	0.9238			
Tube Inlet Temperature (C)	117.2	444.2			
Tube Outlet Temperature (C)	444.8	573.1			
Shell Inlet Temperature (C)	469.8	599.2			
Shell Outlet Temperature (C)	142.6 *	470.9 *			
LMTD (C)	25.31	26.39			
UA (kJ/C-h)	4.704e+004	1.835e+004			
Minimum Approach (C)	25.00	26.14			

Compressors

Fluid Pkg: All

Name	Compressor 1				
Power (MW)	9.309e-002				
Feed Pressure (kPa)	505.3				
Product Pressure (kPa)	1096 *				
Product Temperature (C)	117.3				
Feed Temperature (C)	21.11 *				
Adiabatic Efficiency	75 *				
Pressure Ratio	2.169				
Mass Flow (kg/s)	0.9238				

Expanders

Fluid Pkg: All

Name					
Power (MW)					
Feed Pressure (kPa)					
Product Pressure (kPa)					
Product Temperature (C)					
Feed Temperature (C)					
Adiabatic Efficiency					
Mass Flow (kg/s)					

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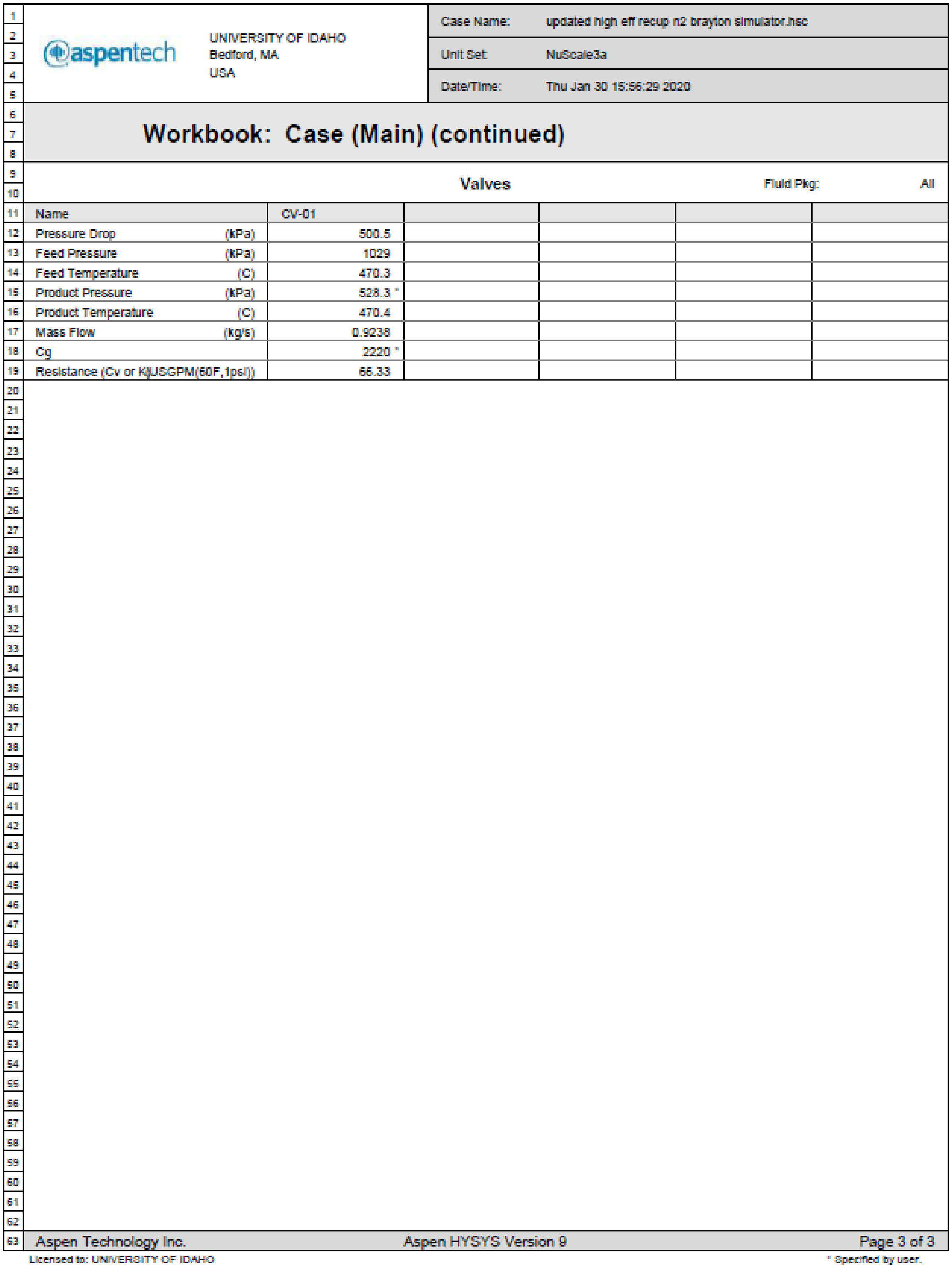

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Bedford, MA
USA

Case Name: updated high eff recup n2 brayton simulator.hsc
Unit Set: NuScale3a
Date/Time: Thu Jan 30 15:56:29 2020

Workbook: Case (Main) (continued)

Valves

Fluid Pkg: All

Name	CV-01				
Pressure Drop (kPa)	500.5				
Feed Pressure (kPa)	1029				
Feed Temperature (C)	470.3				
Product Pressure (kPa)	528.3 *				
Product Temperature (C)	470.4				
Mass Flow (kg/s)	0.9238				
Cg	2220 *				
Resistance (Cv or K)(USGPM(60F,1psi))	66.33				

Aspen Technology Inc. Aspen HYSYS Version 9 Page 3 of 3

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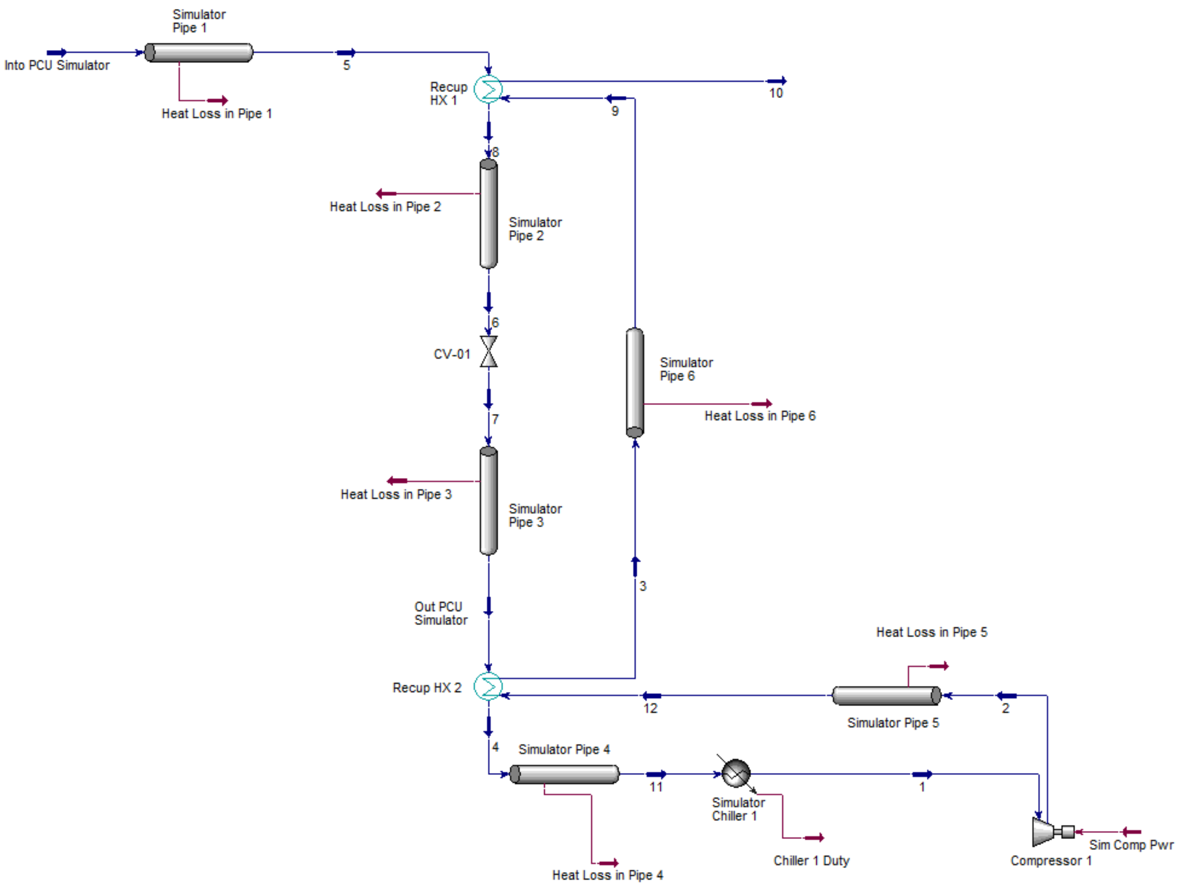
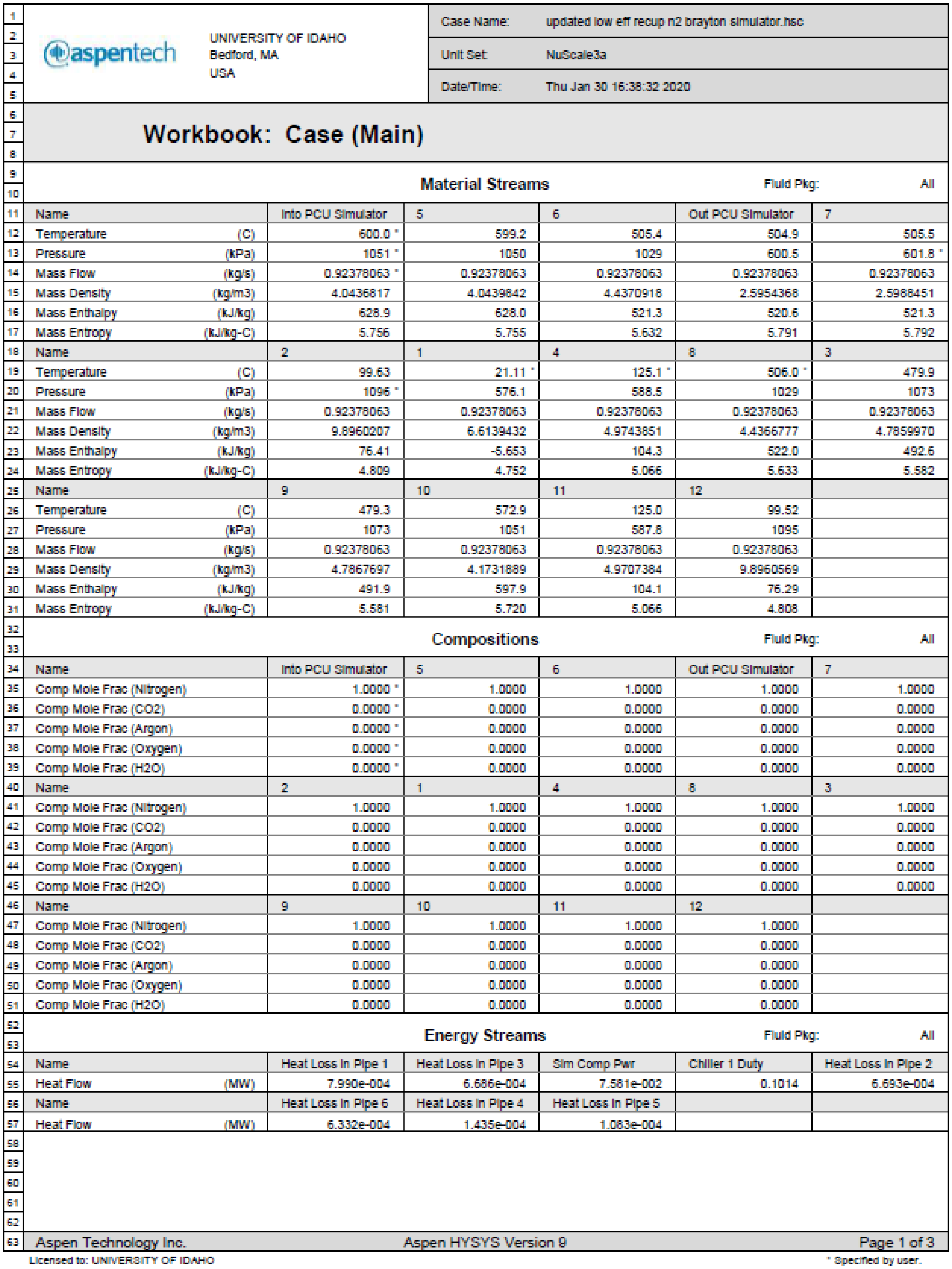
Modified Nitrogen Recuperated Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 70% and 80%





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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: updated low eff recup n2 brayton simulator.hsc

Unit Set: NuScale3a

Date/Time: Thu Jan 30 16:38:32 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Into PCU Simulator	5	6	Out PCU Simulator	7
Temperature	(C)	600.0 *	599.2	505.4	504.9	505.5
Pressure	(kPa)	1051 *	1050	1029	600.5	601.8 *
Mass Flow	(kg/s)	0.92378063 *	0.92378063	0.92378063	0.92378063	0.92378063
Mass Density	(kg/m3)	4.0436817	4.0439842	4.4370918	2.5954368	2.5988451
Mass Enthalpy	(kJ/kg)	628.9	628.0	521.3	520.6	521.3
Mass Entropy	(kJ/kg-C)	5.756	5.755	5.632	5.791	5.792

Name		2	1	4	8	3
Temperature	(C)	99.63	21.11 *	125.1 *	506.0 *	479.9
Pressure	(kPa)	1096 *	576.1	588.5	1029	1073
Mass Flow	(kg/s)	0.92378063	0.92378063	0.92378063	0.92378063	0.92378063
Mass Density	(kg/m3)	9.8960207	6.6139432	4.9743851	4.4366777	4.7859970
Mass Enthalpy	(kJ/kg)	76.41	-5.653	104.3	522.0	492.6
Mass Entropy	(kJ/kg-C)	4.809	4.752	5.066	5.633	5.582

Name		9	10	11	12	
Temperature	(C)	479.3	572.9	125.0	99.52	
Pressure	(kPa)	1073	1051	587.8	1095	
Mass Flow	(kg/s)	0.92378063	0.92378063	0.92378063	0.92378063	
Mass Density	(kg/m3)	4.7867697	4.1731889	4.9707384	9.8960569	
Mass Enthalpy	(kJ/kg)	491.9	597.9	104.1	76.29	
Mass Entropy	(kJ/kg-C)	5.581	5.720	5.066	4.808	

Compositions

Fluid Pkg: All

Name	Into PCU Simulator	5	6	Out PCU Simulator	7
Comp Mole Frac (Nitrogen)	1.0000 *	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (CO2)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000 *	0.0000	0.0000	0.0000	0.0000

Name	2	1	4	8	3
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	0.0000

Name	9	10	11	12	
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000	
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	

Energy Streams

Fluid Pkg: All

Name		Heat Loss In Pipe 1	Heat Loss In Pipe 3	Sim Comp Pwr	Chiller 1 Duty	Heat Loss In Pipe 2
Heat Flow	(MW)	7.990e-004	6.686e-004	7.581e-002	0.1014	6.693e-004

Name		Heat Loss In Pipe 6	Heat Loss In Pipe 4	Heat Loss In Pipe 5		
Heat Flow	(MW)	6.332e-004	1.435e-004	1.083e-004		

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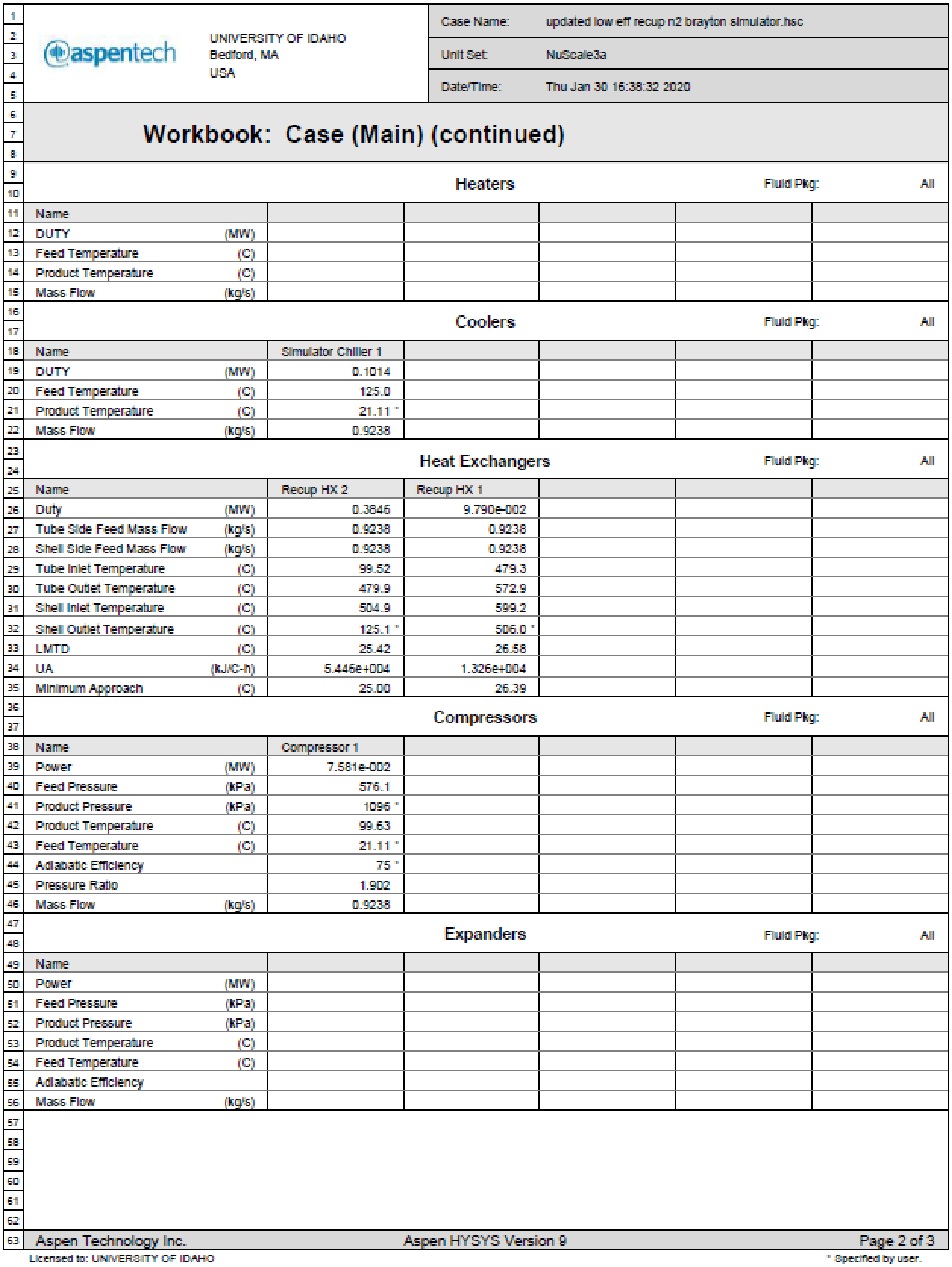

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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: updated low eff recup n2 brayton simulator.hsc
Unit Set: NuScale3a
Date/Time: Thu Jan 30 16:38:32 2020

Workbook: Case (Main) (continued)

Heaters

Fluid Pkg: All

Name					
DUTY (MW)					
Feed Temperature (C)					
Product Temperature (C)					
Mass Flow (kg/s)					

Coolers

Fluid Pkg: All

Name	Simulator Chiller 1				
DUTY (MW)	0.1014				
Feed Temperature (C)	125.0				
Product Temperature (C)	21.11 *				
Mass Flow (kg/s)	0.9238				

Heat Exchangers

Fluid Pkg: All

Name	Recup HX 2	Recup HX 1			
Duty (MW)	0.3846	9.790e-002			
Tube Side Feed Mass Flow (kg/s)	0.9238	0.9238			
Shell Side Feed Mass Flow (kg/s)	0.9238	0.9238			
Tube Inlet Temperature (C)	99.52	479.3			
Tube Outlet Temperature (C)	479.9	572.9			
Shell Inlet Temperature (C)	504.9	599.2			
Shell Outlet Temperature (C)	125.1 *	506.0 *			
LMTD (C)	25.42	26.58			
UA (kJ/C-h)	5.446e+004	1.326e+004			
Minimum Approach (C)	25.00	26.39			

Compressors

Fluid Pkg: All

Name	Compressor 1				
Power (MW)	7.581e-002				
Feed Pressure (kPa)	576.1				
Product Pressure (kPa)	1096 *				
Product Temperature (C)	99.63				
Feed Temperature (C)	21.11 *				
Adiabatic Efficiency	75 *				
Pressure Ratio	1.902				
Mass Flow (kg/s)	0.9238				

Expanders

Fluid Pkg: All

Name					
Power (MW)					
Feed Pressure (kPa)					
Product Pressure (kPa)					
Product Temperature (C)					
Feed Temperature (C)					
Adiabatic Efficiency					
Mass Flow (kg/s)					

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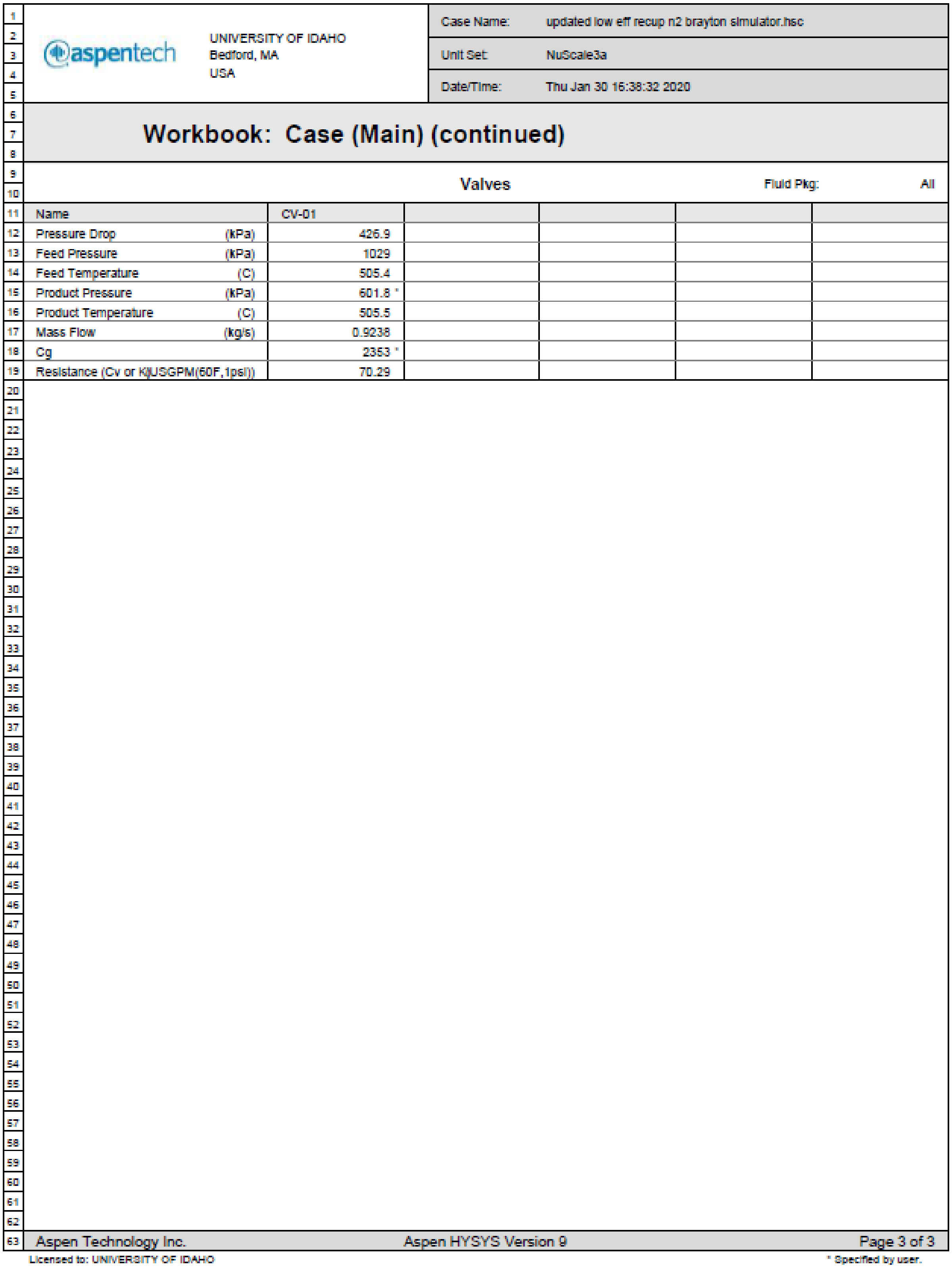

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: updated low eff recup n2 brayton simulator.hsc

Unit Set: NuScale3a

Date/Time: Thu Jan 30 16:38:32 2020

Workbook: Case (Main) (continued)

Valves

Fluid Pkg: All

Name		CV-01				
Pressure Drop	(kPa)	426.9				
Feed Pressure	(kPa)	1029				
Feed Temperature	(C)	505.4				
Product Pressure	(kPa)	601.8 *				
Product Temperature	(C)	505.5				
Mass Flow	(kg/s)	0.9238				
Cg		2353 *				
Resistance (Cv or K)(USGPM(60F,1psi))		70.29				

Aspen Technology Inc. Aspen HYSYS Version 9 Page 3 of 3

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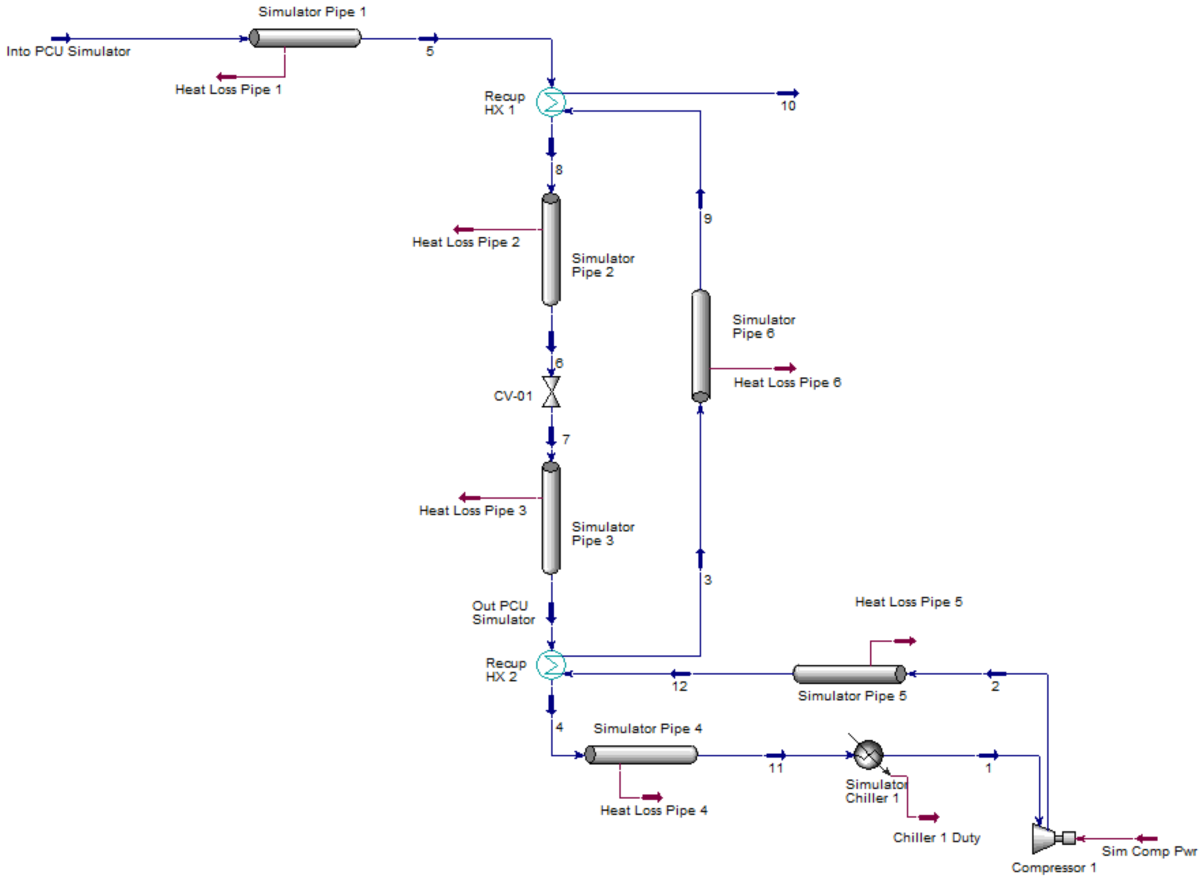
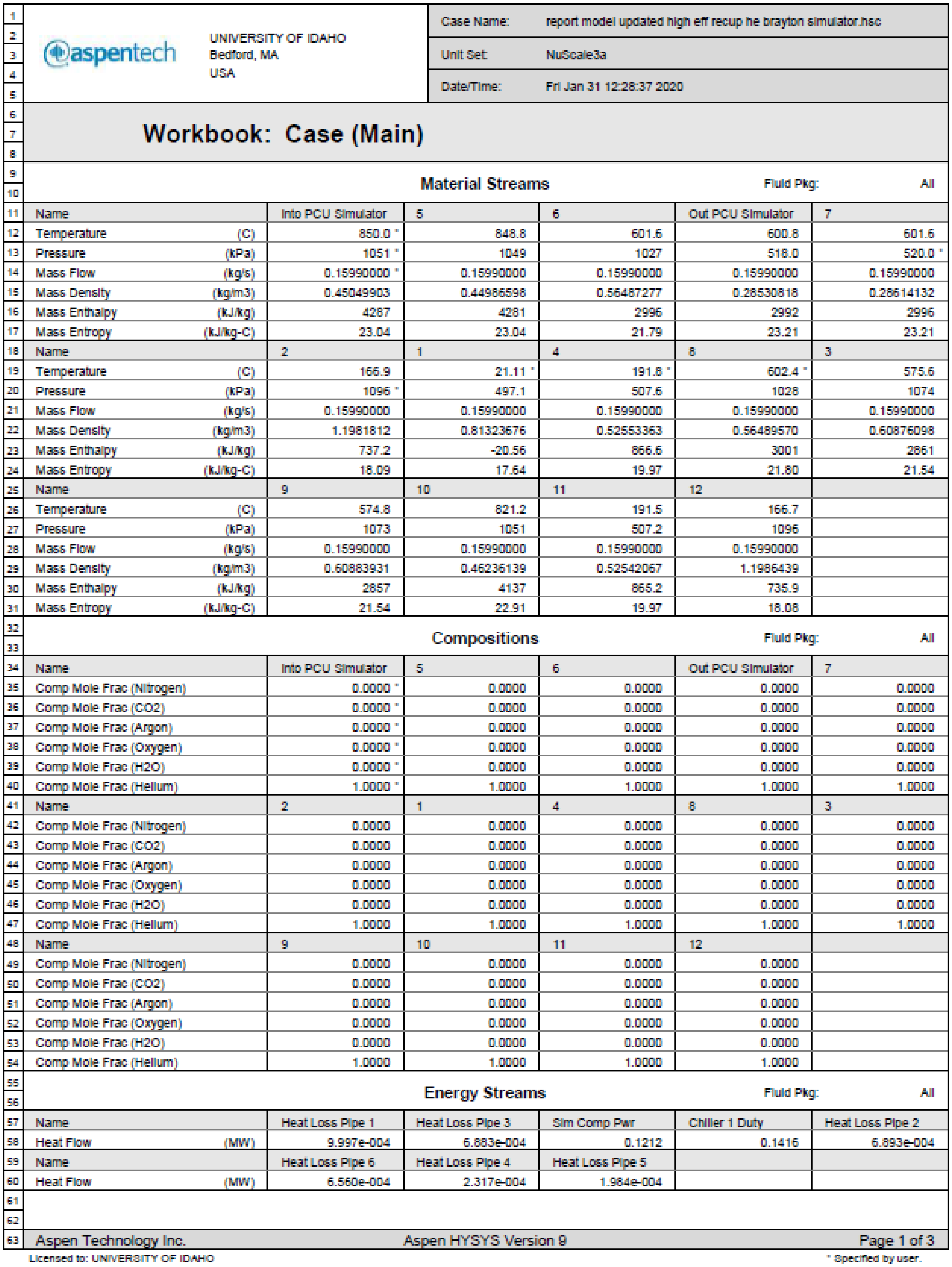
Modified Helium Recuperated Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 85% and 90%





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Bedford, MA
USA

Case Name: report model updated high eff recup he brayton simulator.hsc
Unit Set: NuScale3a
Date/Time: Fri Jan 31 12:28:37 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Into PCU Simulator	5	6	Out PCU Simulator	7
Temperature	(C)	850.0 *	848.8	601.6	600.8	601.6
Pressure	(kPa)	1051 *	1049	1027	518.0	520.0 *
Mass Flow	(kg/s)	0.15990000 *	0.15990000	0.15990000	0.15990000	0.15990000
Mass Density	(kg/m3)	0.45049903	0.44986598	0.56487277	0.28530818	0.28614132
Mass Enthalpy	(kJ/kg)	4287	4281	2996	2992	2996
Mass Entropy	(kJ/kg-C)	23.04	23.04	21.79	23.21	23.21
Name		2	1	4	8	3
Temperature	(C)	166.9	21.11 *	191.8 *	602.4 *	575.6
Pressure	(kPa)	1096 *	497.1	507.6	1028	1074
Mass Flow	(kg/s)	0.15990000	0.15990000	0.15990000	0.15990000	0.15990000
Mass Density	(kg/m3)	1.1981812	0.81323676	0.52553363	0.56489570	0.60876098
Mass Enthalpy	(kJ/kg)	737.2	-20.56	866.6	3001	2861
Mass Entropy	(kJ/kg-C)	18.09	17.64	19.97	21.80	21.54
Name		9	10	11	12	
Temperature	(C)	574.8	821.2	191.5	166.7	
Pressure	(kPa)	1073	1051	507.2	1096	
Mass Flow	(kg/s)	0.15990000	0.15990000	0.15990000	0.15990000	
Mass Density	(kg/m3)	0.60883931	0.46236139	0.52542067	1.1986439	
Mass Enthalpy	(kJ/kg)	2857	4137	865.2	735.9	
Mass Entropy	(kJ/kg-C)	21.54	22.91	19.97	18.08	

Compositions

Fluid Pkg: All

Name	Into PCU Simulator	5	6	Out PCU Simulator	7
Comp Mole Frac (Nitrogen)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (CO2)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Helium)	1.0000 *	1.0000	1.0000	1.0000	1.0000
Name	2	1	4	8	3
Comp Mole Frac (Nitrogen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Helium)	1.0000	1.0000	1.0000	1.0000	1.0000
Name	9	10	11	12	
Comp Mole Frac (Nitrogen)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Helium)	1.0000	1.0000	1.0000	1.0000	

Energy Streams

Fluid Pkg: All

Name		Heat Loss Pipe 1	Heat Loss Pipe 3	Sim Comp Pwr	Chiller 1 Duty	Heat Loss Pipe 2
Heat Flow	(MW)	9.997e-004	6.883e-004	0.1212	0.1416	6.893e-004
Name		Heat Loss Pipe 6	Heat Loss Pipe 4	Heat Loss Pipe 5		
Heat Flow	(MW)	6.560e-004	2.317e-004	1.984e-004		

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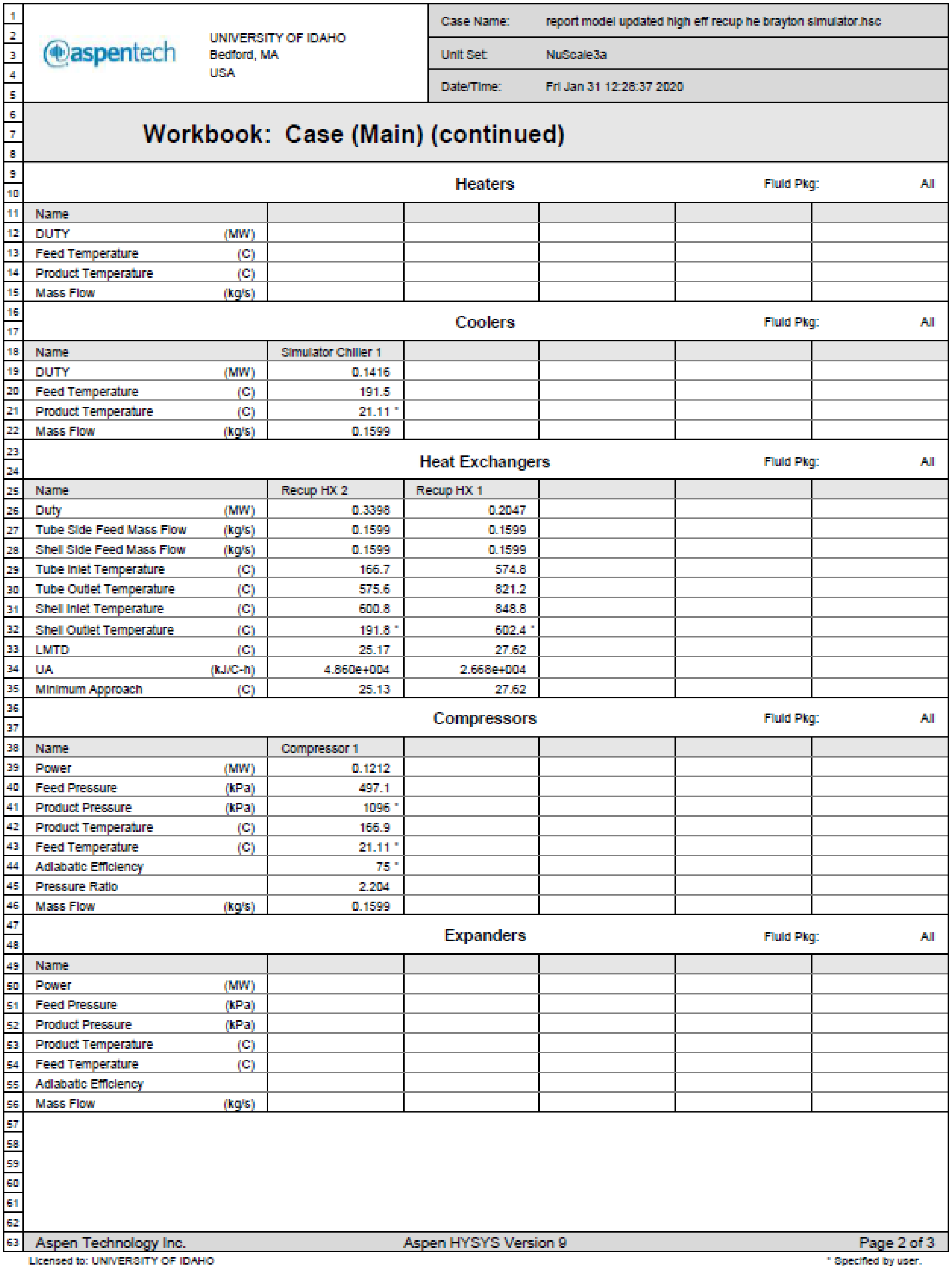

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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	report model updated high eff recup he brayton simulator.hsc
Unit Set:	NuScale3a
Date/Time:	Fri Jan 31 12:28:37 2020

Workbook: Case (Main) (continued)

Heaters

Fluid Pkg: All

Name					
DUTY (MW)					
Feed Temperature (C)					
Product Temperature (C)					
Mass Flow (kg/s)					

Coolers

Fluid Pkg: All

Name	Simulator Chiller 1				
DUTY (MW)	0.1416				
Feed Temperature (C)	191.5				
Product Temperature (C)	21.11 *				
Mass Flow (kg/s)	0.1599				

Heat Exchangers

Fluid Pkg: All

Name	Recup HX 2	Recup HX 1			
Duty (MW)	0.3398	0.2047			
Tube Side Feed Mass Flow (kg/s)	0.1599	0.1599			
Shell Side Feed Mass Flow (kg/s)	0.1599	0.1599			
Tube Inlet Temperature (C)	166.7	574.8			
Tube Outlet Temperature (C)	575.6	821.2			
Shell Inlet Temperature (C)	600.8	848.8			
Shell Outlet Temperature (C)	191.8 *	602.4 *			
LMTD (C)	25.17	27.62			
UA (kJ/C-h)	4.860e+004	2.668e+004			
Minimum Approach (C)	25.13	27.62			

Compressors

Fluid Pkg: All

Name	Compressor 1				
Power (MW)	0.1212				
Feed Pressure (kPa)	497.1				
Product Pressure (kPa)	1096 *				
Product Temperature (C)	166.9				
Feed Temperature (C)	21.11 *				
Adiabatic Efficiency	75 *				
Pressure Ratio	2.204				
Mass Flow (kg/s)	0.1599				

Expanders

Fluid Pkg: All

Name					
Power (MW)					
Feed Pressure (kPa)					
Product Pressure (kPa)					
Product Temperature (C)					
Feed Temperature (C)					
Adiabatic Efficiency					
Mass Flow (kg/s)					

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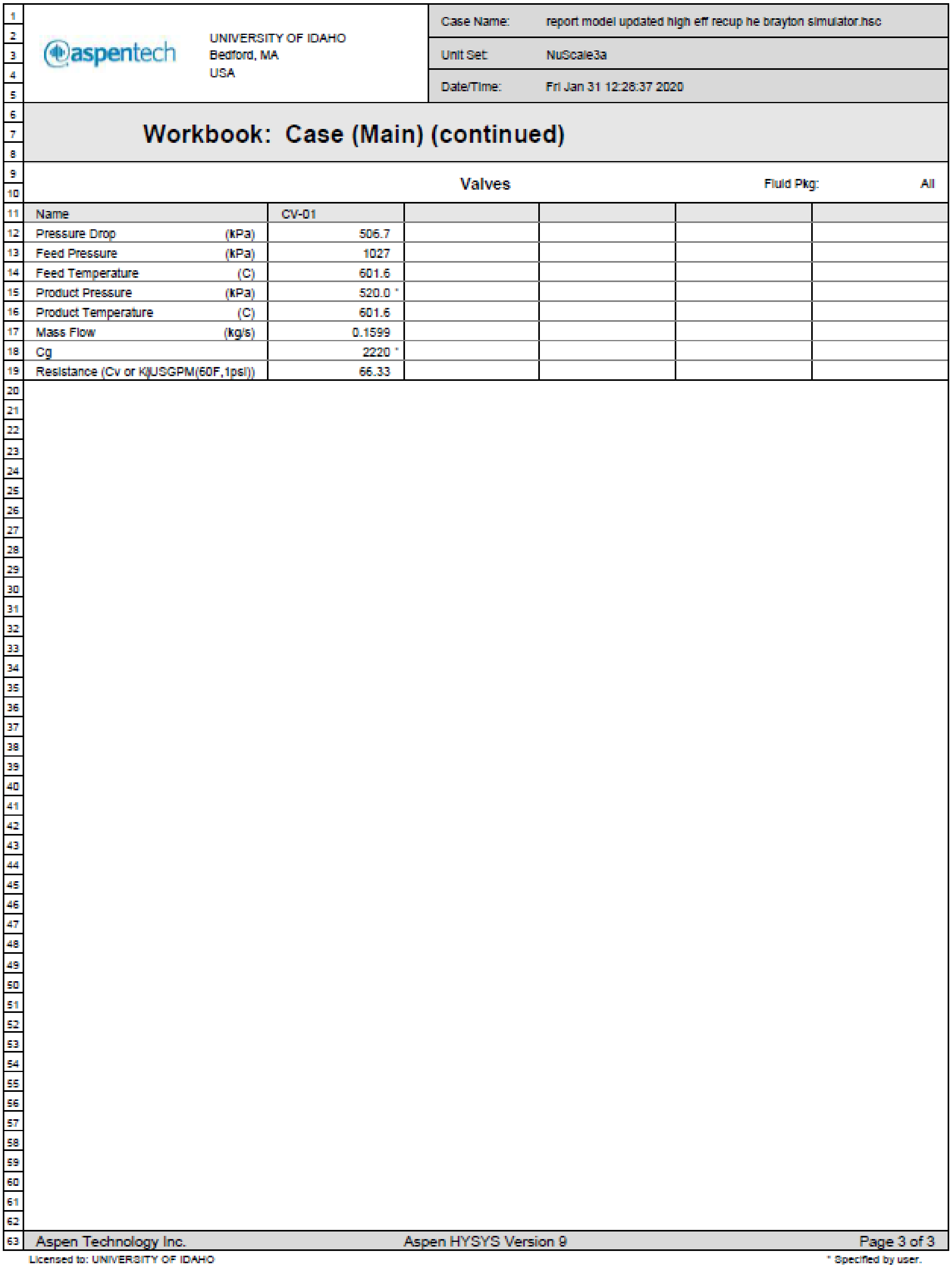

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USA

Case Name: report model updated high eff recup he brayton simulator.hsc

Unit Set: NuScale3a

Date/Time: Fri Jan 31 12:28:37 2020

Workbook: Case (Main) (continued)

Valves

Fluid Pkg: All

Name	CV-01				
Pressure Drop (kPa)	506.7				
Feed Pressure (kPa)	1027				
Feed Temperature (C)	601.6				
Product Pressure (kPa)	520.0 *				
Product Temperature (C)	601.6				
Mass Flow (kg/s)	0.1599				
Cg	2220 *				
Resistance (Cv or K)(USGPM(60F,1psi))	66.33				

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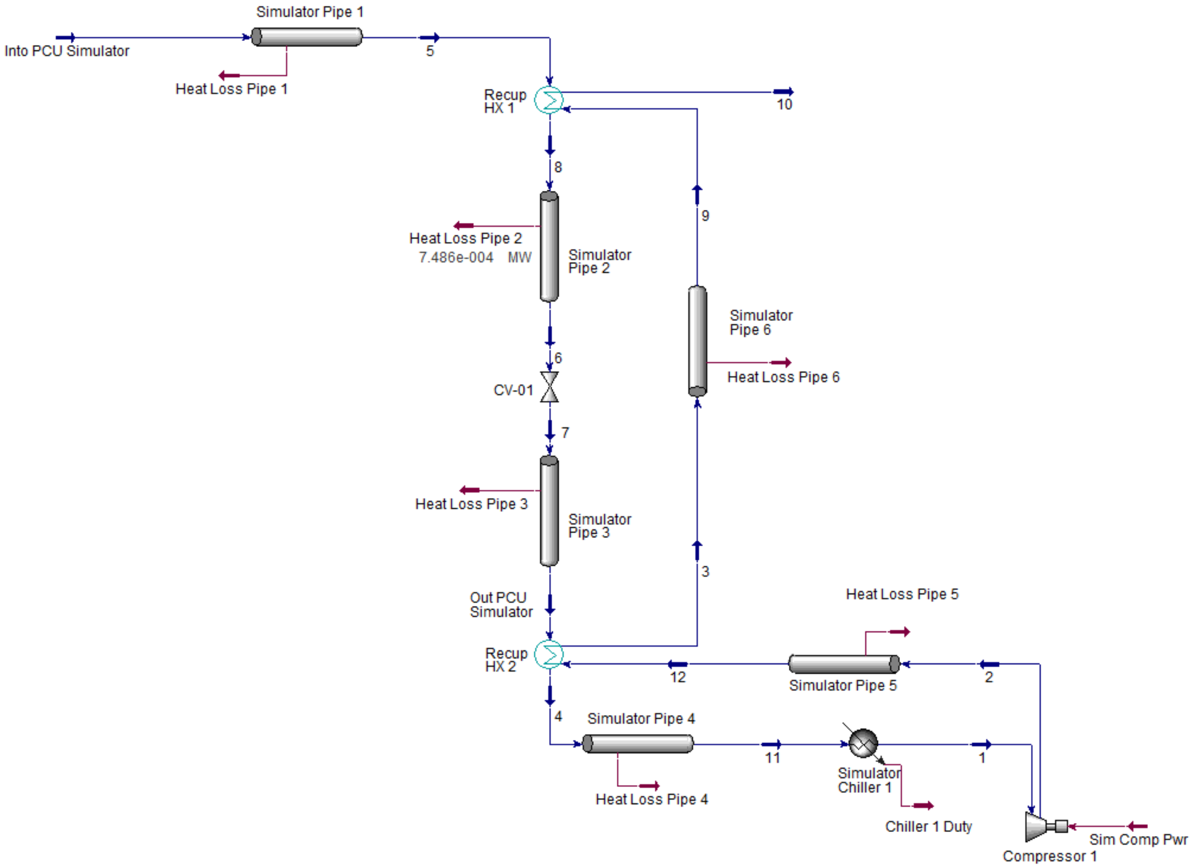
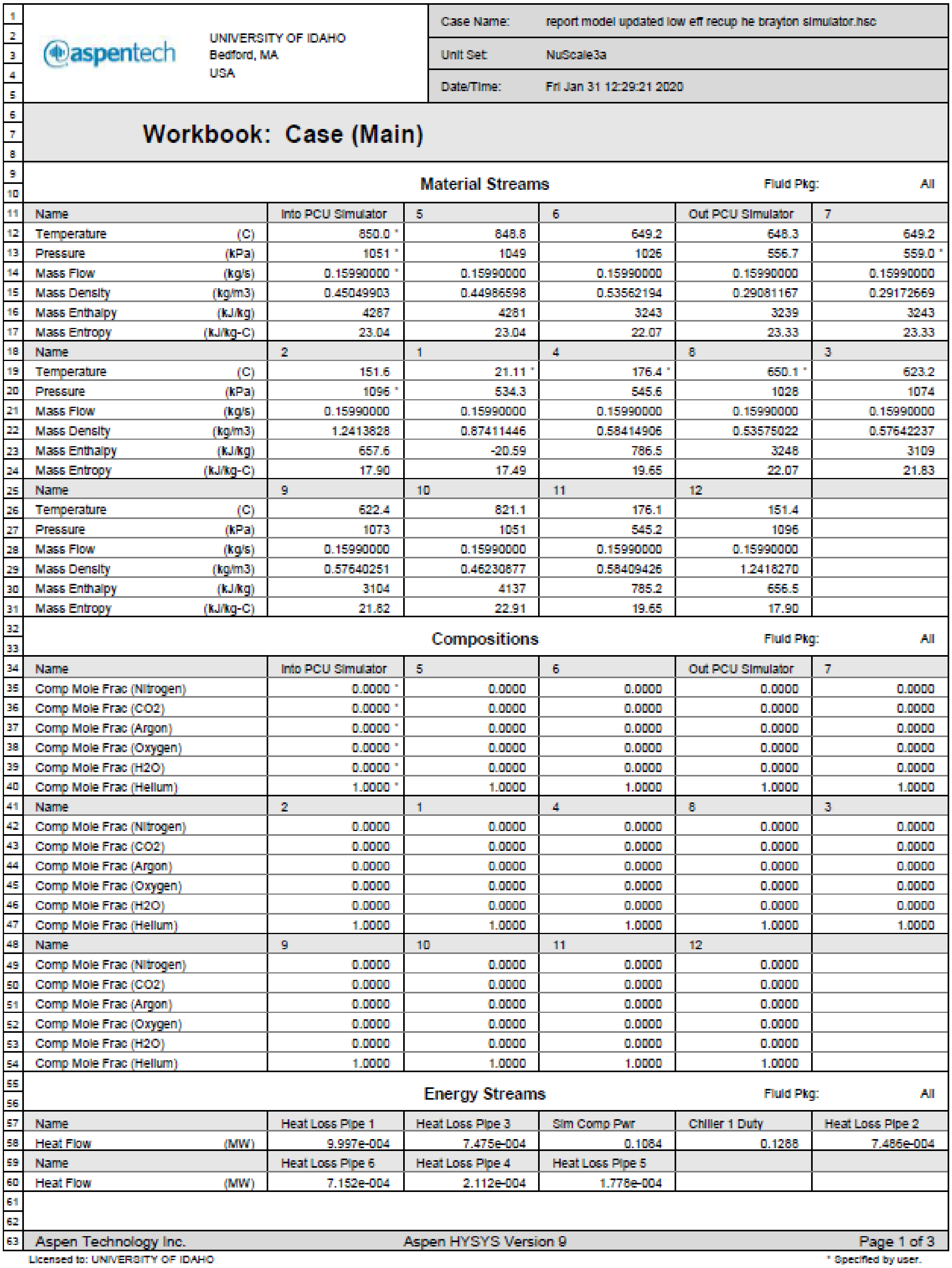
Modified Helium Recuperated Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 70% and 80%





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Case Name:	report model updated low eff recup he brayton simulator.hsc
Unit Set:	NuScale3a
Date/Time:	Fri Jan 31 12:29:21 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name	Into PCU Simulator	5	6	Out PCU Simulator	7
Temperature (C)	850.0 *	848.8	649.2	648.3	649.2
Pressure (kPa)	1051 *	1049	1026	556.7	559.0 *
Mass Flow (kg/s)	0.15990000 *	0.15990000	0.15990000	0.15990000	0.15990000
Mass Density (kg/m3)	0.45049903	0.44986598	0.53562194	0.29081167	0.29172669
Mass Enthalpy (kJ/kg)	4287	4281	3243	3239	3243
Mass Entropy (kJ/kg-C)	23.04	23.04	22.07	23.33	23.33
Name	**2**	**1**	**4**	**8**	**3**
Temperature (C)	151.6	21.11 *	176.4 *	650.1 *	623.2
Pressure (kPa)	1096 *	534.3	545.6	1028	1074
Mass Flow (kg/s)	0.15990000	0.15990000	0.15990000	0.15990000	0.15990000
Mass Density (kg/m3)	1.2413828	0.87411446	0.58414906	0.53575022	0.57642237
Mass Enthalpy (kJ/kg)	657.6	-20.59	786.5	3248	3109
Mass Entropy (kJ/kg-C)	17.90	17.49	19.65	22.07	21.83
Name	**9**	**10**	**11**	**12**	
Temperature (C)	622.4	821.1	176.1	151.4	
Pressure (kPa)	1073	1051	545.2	1096	
Mass Flow (kg/s)	0.15990000	0.15990000	0.15990000	0.15990000	
Mass Density (kg/m3)	0.57640251	0.46230677	0.58409426	1.2418270	
Mass Enthalpy (kJ/kg)	3104	4137	785.2	656.5	
Mass Entropy (kJ/kg-C)	21.82	22.91	19.65	17.90	

Compositions

Fluid Pkg: All

Name	Into PCU Simulator	5	6	Out PCU Simulator	7
Comp Mole Frac (Nitrogen)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (CO2)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Helium)	1.0000 *	1.0000	1.0000	1.0000	1.0000
Name	**2**	**1**	**4**	**8**	**3**
Comp Mole Frac (Nitrogen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Helium)	1.0000	1.0000	1.0000	1.0000	1.0000
Name	**9**	**10**	**11**	**12**	
Comp Mole Frac (Nitrogen)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Helium)	1.0000	1.0000	1.0000	1.0000	

Energy Streams

Fluid Pkg: All

Name	Heat Loss Pipe 1	Heat Loss Pipe 3	Sim Comp Pwr	Chiller 1 Duty	Heat Loss Pipe 2
Heat Flow (MW)	9.997e-004	7.475e-004	0.1084	0.1288	7.486e-004
Name	**Heat Loss Pipe 6**	**Heat Loss Pipe 4**	**Heat Loss Pipe 5**		
Heat Flow (MW)	7.152e-004	2.112e-004	1.778e-004		

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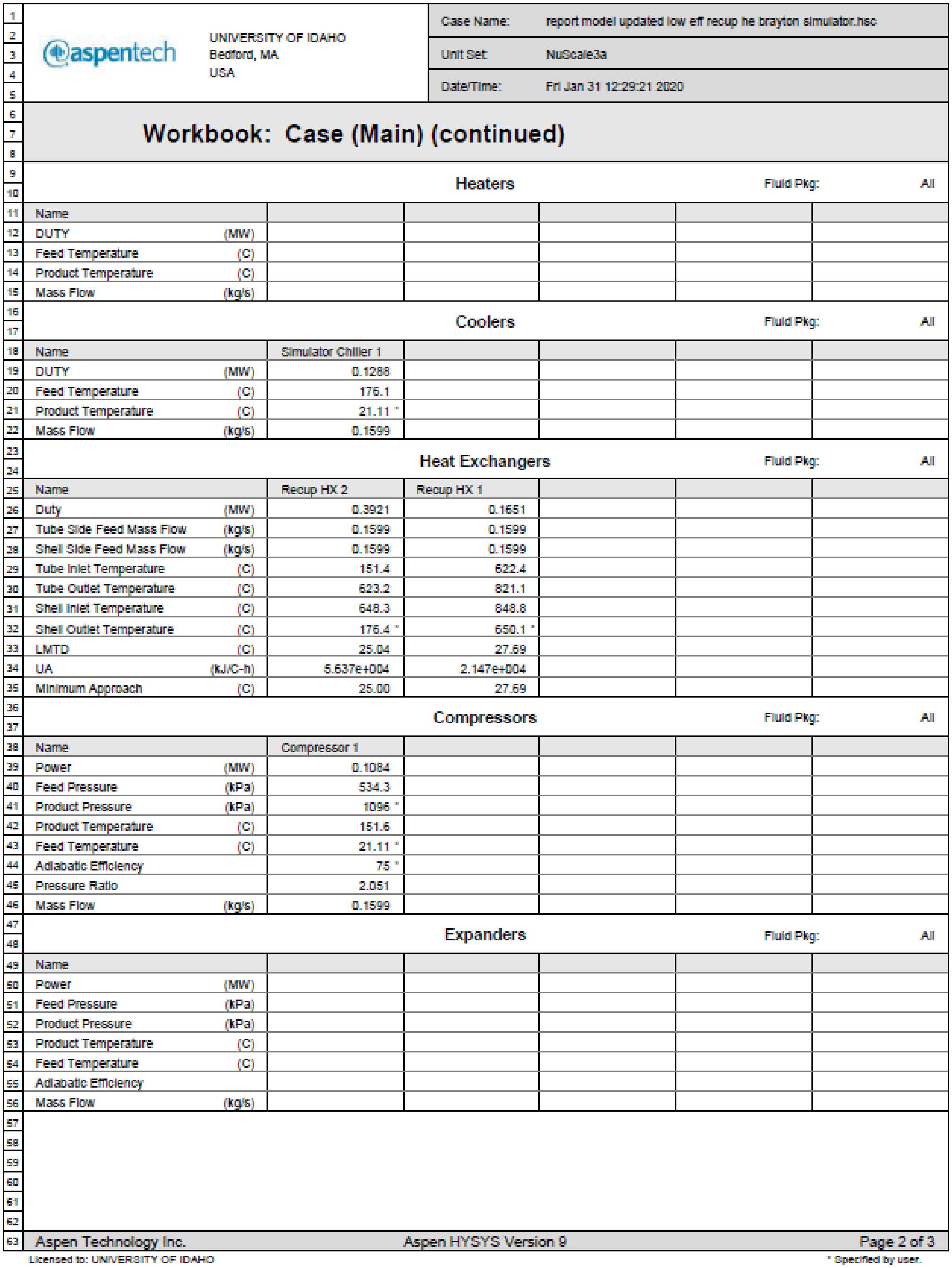

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Case Name: report model updated low eff recup he brayton simulator.hsc
Unit Set: NuScale3a
Date/Time: Fri Jan 31 12:29:21 2020

Workbook: Case (Main) (continued)

Heaters

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

Coolers

Fluid Pkg: All

Name		Simulator Chiller 1				
DUTY	(MW)	0.1288				
Feed Temperature	(C)	176.1				
Product Temperature	(C)	21.11 *				
Mass Flow	(kg/s)	0.1599				

Heat Exchangers

Fluid Pkg: All

Name		Recup HX 2	Recup HX 1			
Duty	(MW)	0.3921	0.1651			
Tube Side Feed Mass Flow	(kg/s)	0.1599	0.1599			
Shell Side Feed Mass Flow	(kg/s)	0.1599	0.1599			
Tube Inlet Temperature	(C)	151.4	622.4			
Tube Outlet Temperature	(C)	623.2	821.1			
Shell Inlet Temperature	(C)	648.3	848.8			
Shell Outlet Temperature	(C)	176.4 *	650.1 *			
LMTD	(C)	25.04	27.69			
UA	(kJ/C-h)	5.637e+004	2.147e+004			
Minimum Approach	(C)	25.00	27.69			

Compressors

Fluid Pkg: All

Name		Compressor 1				
Power	(MW)	0.1084				
Feed Pressure	(kPa)	534.3				
Product Pressure	(kPa)	1096 *				
Product Temperature	(C)	151.6				
Feed Temperature	(C)	21.11 *				
Adiabatic Efficiency		75 *				
Pressure Ratio		2.051				
Mass Flow	(kg/s)	0.1599				

Expanders

Fluid Pkg: All

Name						
Power	(MW)					
Feed Pressure	(kPa)					
Product Pressure	(kPa)					
Product Temperature	(C)					
Feed Temperature	(C)					
Adiabatic Efficiency						
Mass Flow	(kg/s)					

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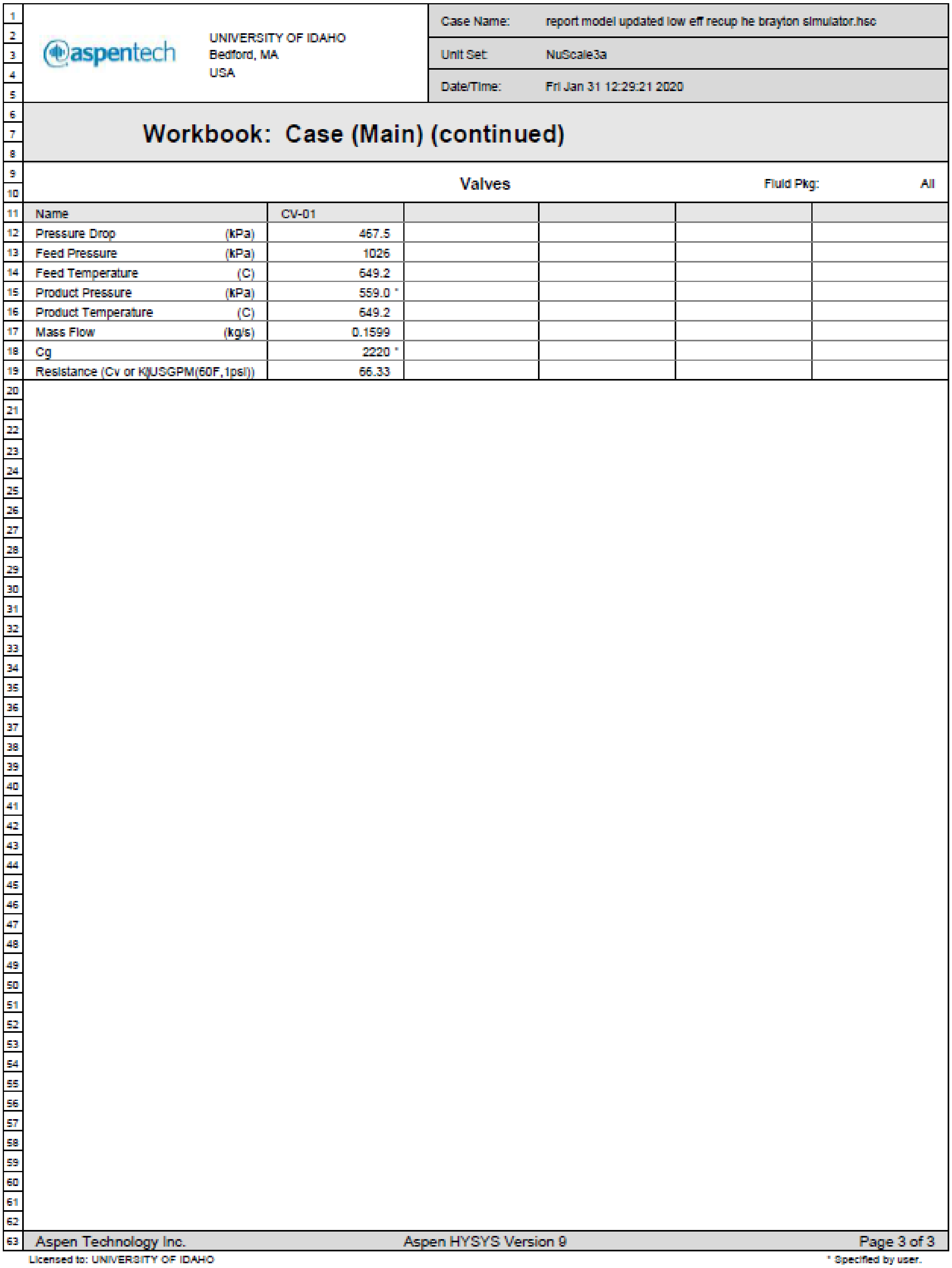

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Case Name: report model updated low eff recup he brayton simulator.hsc

Unit Set: NuScale3a

Date/Time: Fri Jan 31 12:29:21 2020

Workbook: Case (Main) (continued)

Valves

Fluid Pkg: All

Name		CV-01				
Pressure Drop	(kPa)	467.5				
Feed Pressure	(kPa)	1026				
Feed Temperature	(C)	649.2				
Product Pressure	(kPa)	559.0 *				
Product Temperature	(C)	649.2				
Mass Flow	(kg/s)	0.1599				
Cg		2220 *				
Resistance (Cv or K)(USGPM(60F,1psi))		66.33				

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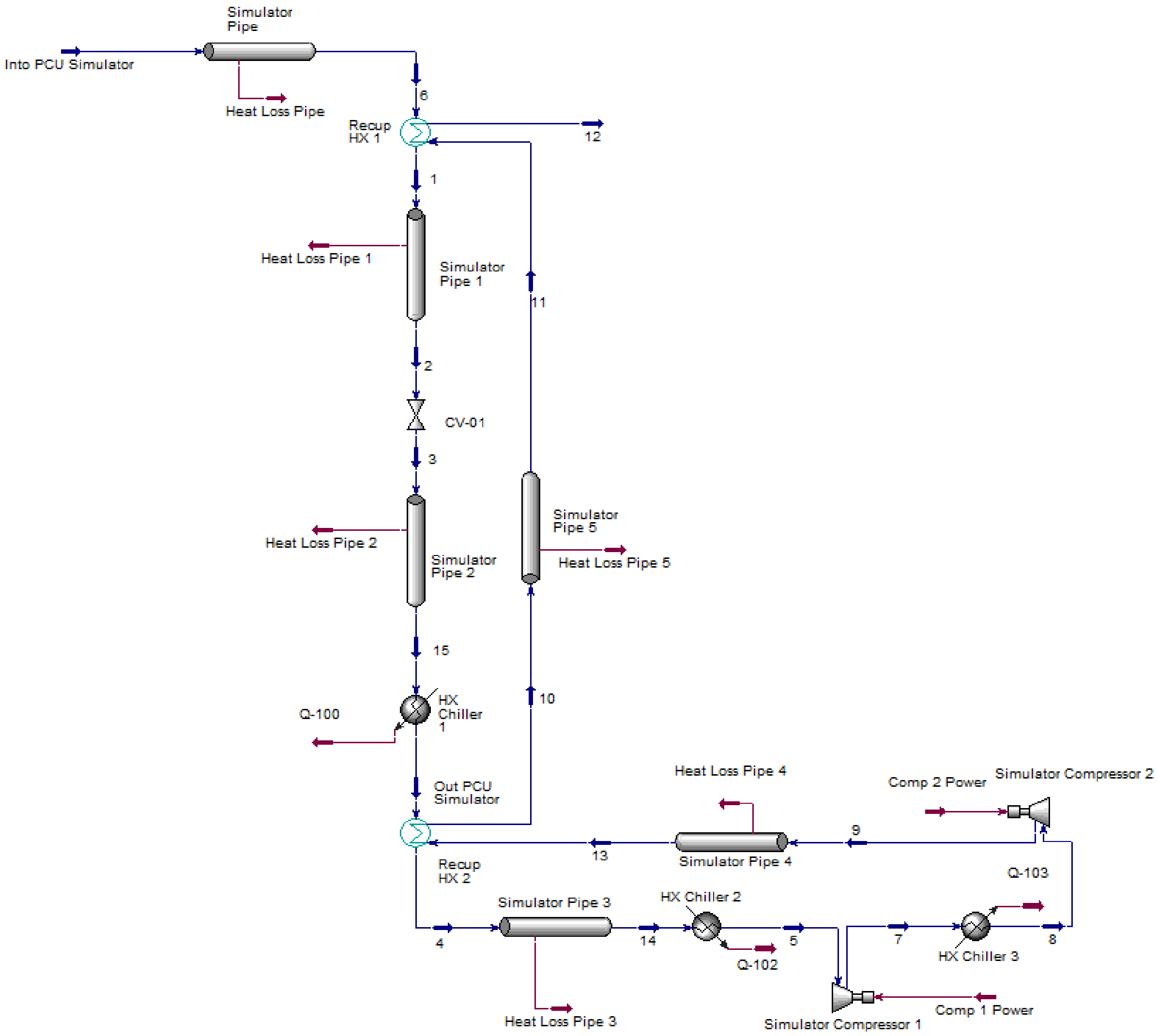
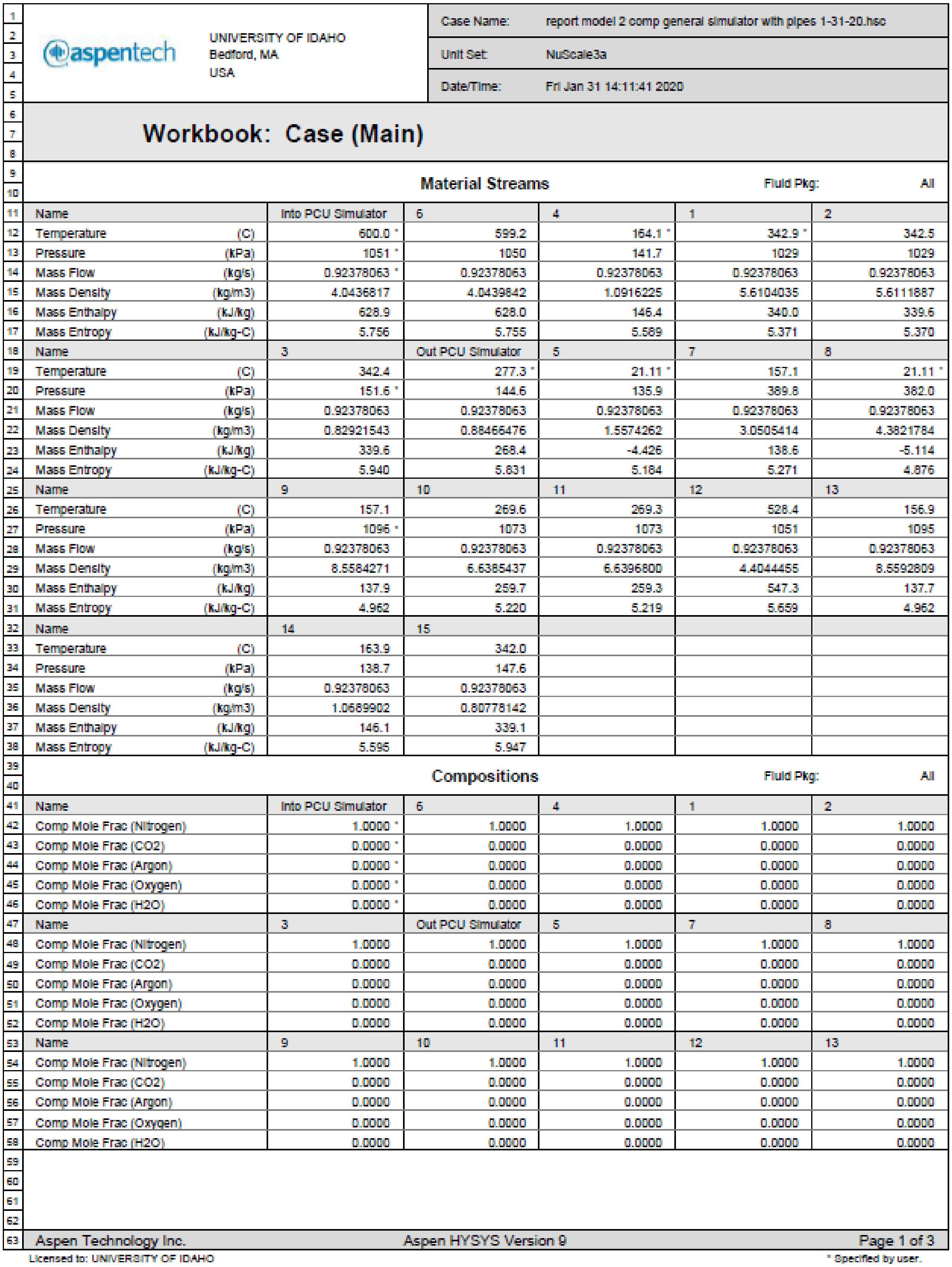
Appendix I: Aspen HYSYS PCU Simulator Models

PCU Simulator Loop for Nitrogen Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 85% and 90%





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Case Name: report model 2 comp general simulator with pipes 1-31-20.hsc

Unit Set: NuScale3a

Date/Time: Fri Jan 31 14:11:41 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Into PCU Simulator	6	4	1	2
Temperature	(C)	600.0 *	599.2	164.1 *	342.9 *	342.5
Pressure	(kPa)	1051 *	1050	141.7	1029	1029
Mass Flow	(kg/s)	0.92378063 *	0.92378063	0.92378063	0.92378063	0.92378063
Mass Density	(kg/m3)	4.0436817	4.0439842	1.0916225	5.6104035	5.6111887
Mass Enthalpy	(kJ/kg)	628.9	628.0	146.4	340.0	339.6
Mass Entropy	(kJ/kg-C)	5.756	5.755	5.589	5.371	5.370
Name		3	Out PCU Simulator	5	7	8
Temperature	(C)	342.4	277.3 *	21.11 *	157.1	21.11 *
Pressure	(kPa)	151.6 *	144.6	135.9	389.8	382.0
Mass Flow	(kg/s)	0.92378063	0.92378063	0.92378063	0.92378063	0.92378063
Mass Density	(kg/m3)	0.82921543	0.88466476	1.5574262	3.0505414	4.3821784
Mass Enthalpy	(kJ/kg)	339.6	268.4	-4.426	138.6	-5.114
Mass Entropy	(kJ/kg-C)	5.940	5.831	5.184	5.271	4.876
Name		9	10	11	12	13
Temperature	(C)	157.1	269.6	269.3	528.4	156.9
Pressure	(kPa)	1096 *	1073	1073	1051	1095
Mass Flow	(kg/s)	0.92378063	0.92378063	0.92378063	0.92378063	0.92378063
Mass Density	(kg/m3)	8.5584271	6.6385437	6.6396800	4.4044455	8.5592809
Mass Enthalpy	(kJ/kg)	137.9	259.7	259.3	547.3	137.7
Mass Entropy	(kJ/kg-C)	4.962	5.220	5.219	5.659	4.962
Name		14	15			
Temperature	(C)	163.9	342.0			
Pressure	(kPa)	138.7	147.6			
Mass Flow	(kg/s)	0.92378063	0.92378063			
Mass Density	(kg/m3)	1.0689902	0.80778142			
Mass Enthalpy	(kJ/kg)	146.1	339.1			
Mass Entropy	(kJ/kg-C)	5.595	5.947			

Compositions

Fluid Pkg: All

Name	Into PCU Simulator	6	4	1	2
Comp Mole Frac (Nitrogen)	1.0000 *	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (CO2)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Name	3	Out PCU Simulator	5	7	8
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	0.0000
Name	9	10	11	12	13
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	0.0000

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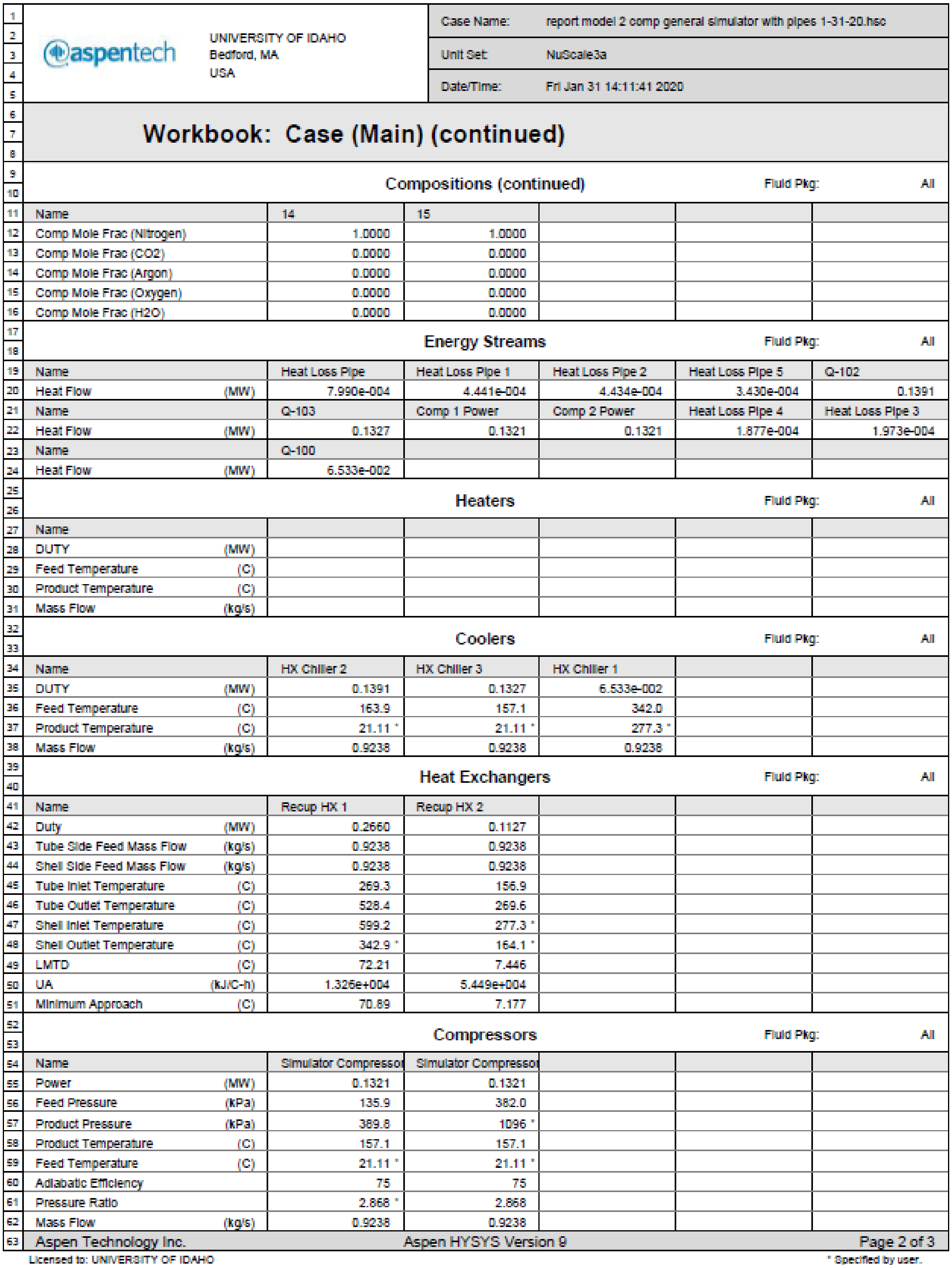

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Case Name: report model 2 comp general simulator with pipes 1-31-20.hsc

Unit Set: NuScale3a

Date/Time: Fri Jan 31 14:11:41 2020

Workbook: Case (Main) (continued)

Compositions (continued)

Fluid Pkg: All

Name	14	15			
Comp Mole Frac (Nitrogen)	1.0000	1.0000			
Comp Mole Frac (CO2)	0.0000	0.0000			
Comp Mole Frac (Argon)	0.0000	0.0000			
Comp Mole Frac (Oxygen)	0.0000	0.0000			
Comp Mole Frac (H2O)	0.0000	0.0000			

Energy Streams

Fluid Pkg: All

Name	Heat Loss Pipe	Heat Loss Pipe 1	Heat Loss Pipe 2	Heat Loss Pipe 5	Q-102
Heat Flow (MW)	7.990e-004	4.441e-004	4.434e-004	3.430e-004	0.1391
Name	Q-103	Comp 1 Power	Comp 2 Power	Heat Loss Pipe 4	Heat Loss Pipe 3
Heat Flow (MW)	0.1327	0.1321	0.1321	1.877e-004	1.973e-004
Name	Q-100				
Heat Flow (MW)	6.533e-002				

Heaters

Fluid Pkg: All

Name					
DUTY (MW)					
Feed Temperature (C)					
Product Temperature (C)					
Mass Flow (kg/s)					

Coolers

Fluid Pkg: All

Name	HX Chiller 2	HX Chiller 3	HX Chiller 1		
DUTY (MW)	0.1391	0.1327	6.533e-002		
Feed Temperature (C)	163.9	157.1	342.0		
Product Temperature (C)	21.11 *	21.11 *	277.3 *		
Mass Flow (kg/s)	0.9238	0.9238	0.9238		

Heat Exchangers

Fluid Pkg: All

Name	Recup HX 1	Recup HX 2			
Duty (MW)	0.2660	0.1127			
Tube Side Feed Mass Flow (kg/s)	0.9238	0.9238			
Shell Side Feed Mass Flow (kg/s)	0.9238	0.9238			
Tube Inlet Temperature (C)	269.3	156.9			
Tube Outlet Temperature (C)	528.4	269.6			
Shell Inlet Temperature (C)	599.2	277.3 *			
Shell Outlet Temperature (C)	342.9 *	164.1 *			
LMTD (C)	72.21	7.446			
UA (kJ/C-h)	1.326e+004	5.449e+004			
Minimum Approach (C)	70.89	7.177			

Compressors

Fluid Pkg: All

Name	Simulator Compressor	Simulator Compressor			
Power (MW)	0.1321	0.1321			
Feed Pressure (kPa)	135.9	382.0			
Product Pressure (kPa)	389.8	1096 *			
Product Temperature (C)	157.1	157.1			
Feed Temperature (C)	21.11 *	21.11 *			
Adiabatic Efficiency	75	75			
Pressure Ratio	2.868 *	2.868			
Mass Flow (kg/s)	0.9238	0.9238			

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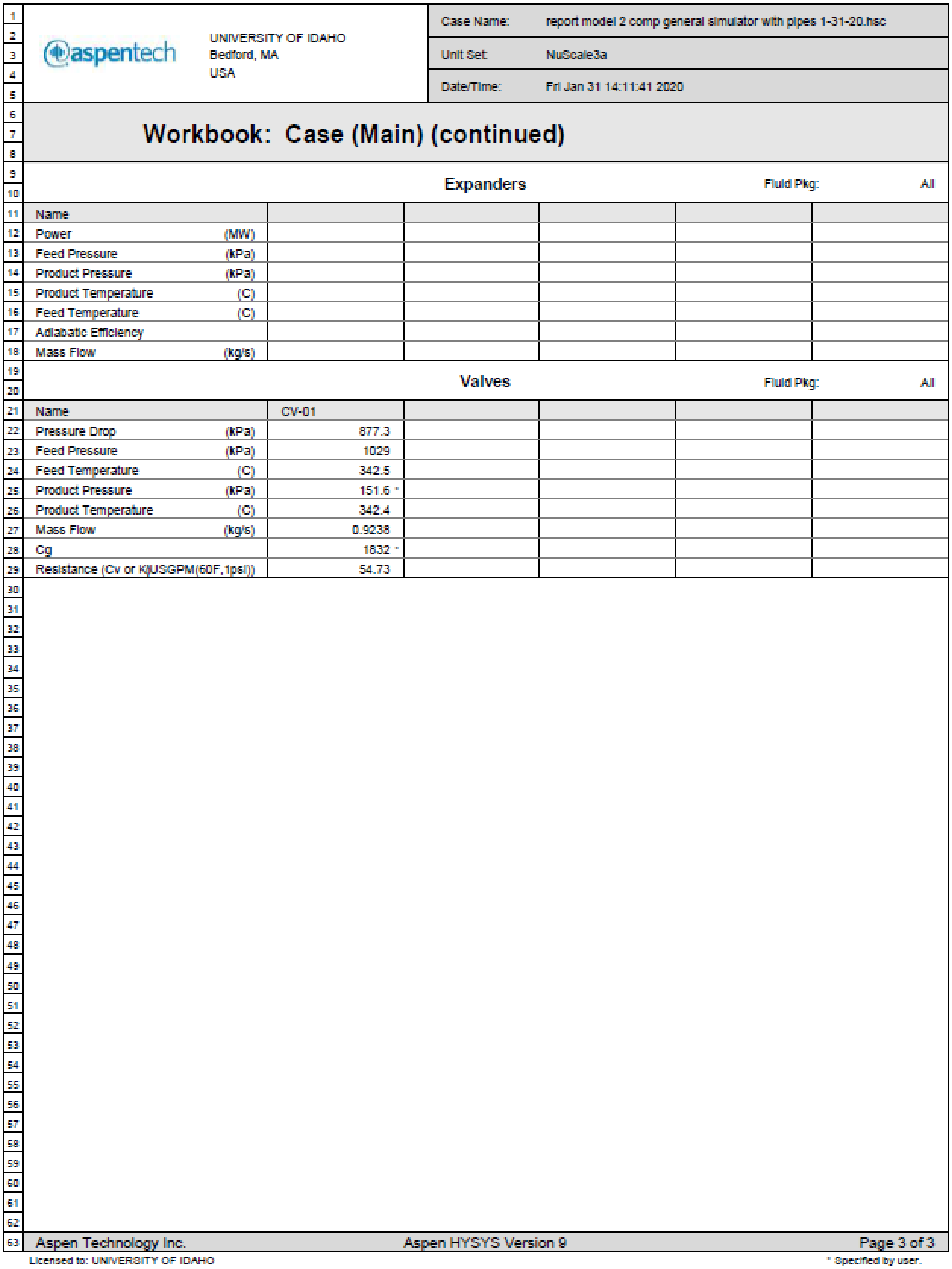

Case Name:	report model 2 comp general simulator with pipes 1-31-20.hsc
Unit Set:	NuScale3a
Date/Time:	Fri Jan 31 14:11:41 2020

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USA

Workbook: Case (Main) (continued)

Expanders

Fluid Pkg: All

Name					
Power (MW)					
Feed Pressure (kPa)					
Product Pressure (kPa)					
Product Temperature (C)					
Feed Temperature (C)					
Adiabatic Efficiency					
Mass Flow (kg/s)					

Valves

Fluid Pkg: All

Name	CV-01				
Pressure Drop (kPa)	877.3				
Feed Pressure (kPa)	1029				
Feed Temperature (C)	342.5				
Product Pressure (kPa)	151.6 *				
Product Temperature (C)	342.4				
Mass Flow (kg/s)	0.9238				
Cg	1832 *				
Resistance (Cv or K)USGPM(60F,1psi))	54.73				

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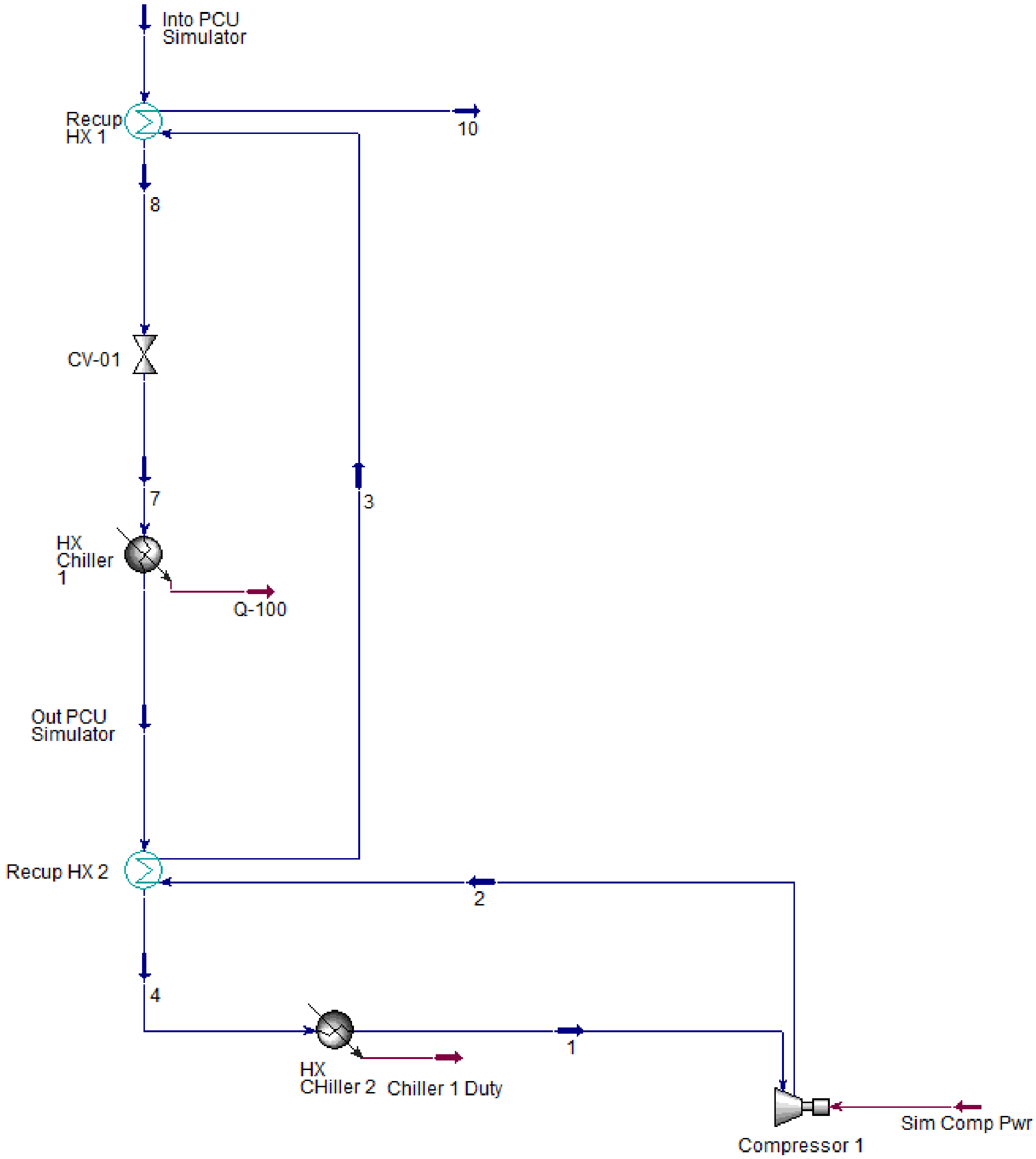
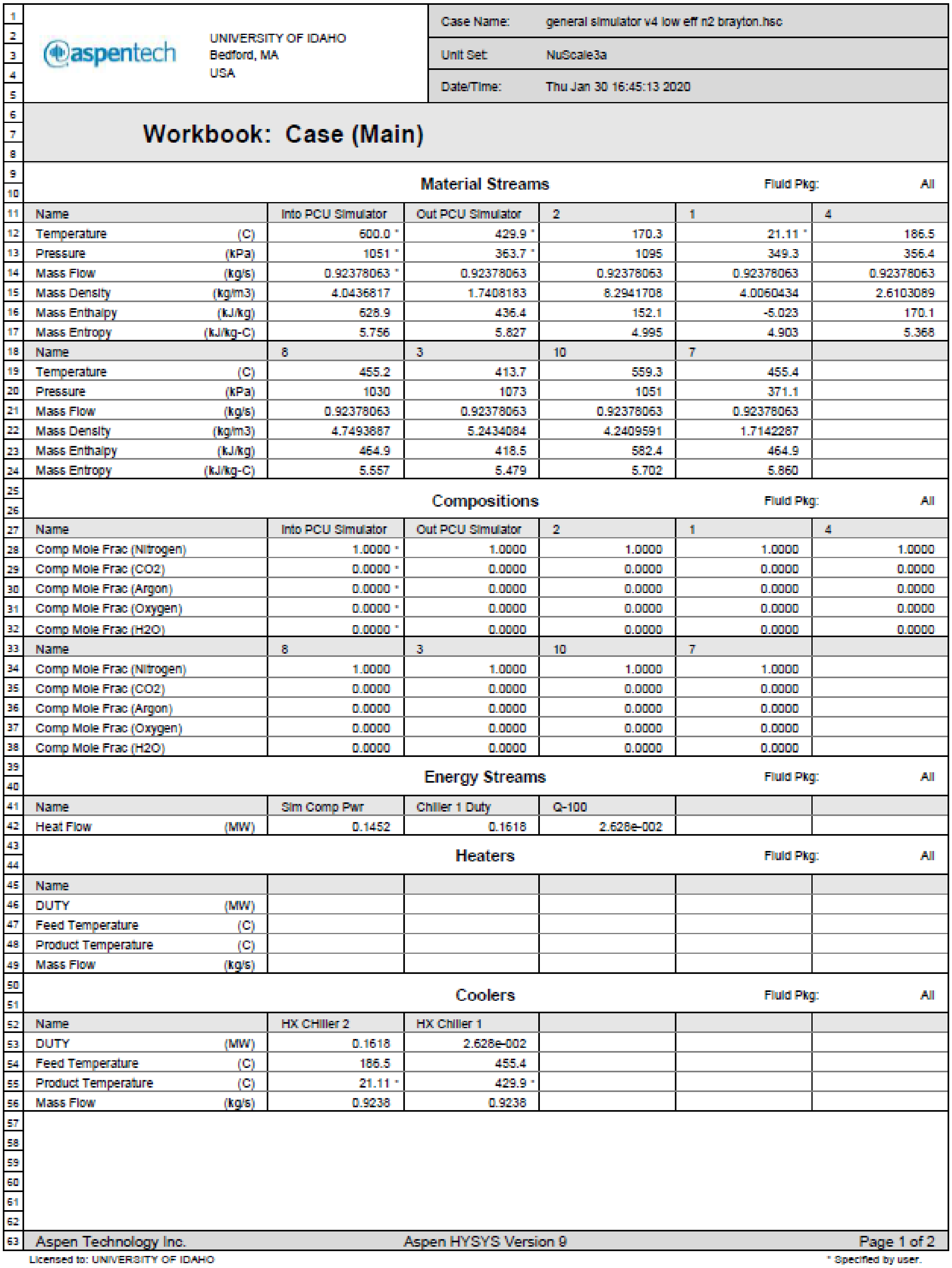
PCU Simulator Loop for Nitrogen Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 70% and 80%





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Case Name:	general simulator v4 low eff n2 brayton.hsc
Unit Set:	NuScale3a
Date/Time:	Thu Jan 30 16:45:13 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name	Into PCU Simulator	Out PCU Simulator	2	1	4
Temperature (C)	600.0 *	429.9 *	170.3	21.11 *	186.5
Pressure (kPa)	1051 *	363.7 *	1095	349.3	356.4
Mass Flow (kg/s)	0.92378063 *	0.92378063	0.92378063	0.92378063	0.92378063
Mass Density (kg/m3)	4.0436817	1.7408183	8.2941708	4.0060434	2.6103089
Mass Enthalpy (kJ/kg)	628.9	436.4	152.1	-5.023	170.1
Mass Entropy (kJ/kg-C)	5.756	5.827	4.995	4.903	5.368
Name	8	3	10	7	
Temperature (C)	455.2	413.7	559.3	455.4	
Pressure (kPa)	1030	1073	1051	371.1	
Mass Flow (kg/s)	0.92378063	0.92378063	0.92378063	0.92378063	
Mass Density (kg/m3)	4.7493887	5.2434084	4.2409591	1.7142287	
Mass Enthalpy (kJ/kg)	464.9	418.5	582.4	464.9	
Mass Entropy (kJ/kg-C)	5.557	5.479	5.702	5.860	

Compositions

Fluid Pkg: All

Name	Into PCU Simulator	Out PCU Simulator	2	1	4
Comp Mole Frac (Nitrogen)	1.0000 *	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (CO2)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Name	8	3	10	7	
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000	
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	

Energy Streams

Fluid Pkg: All

Name	Sim Comp Pwr	Chiller 1 Duty	Q-100		
Heat Flow (MW)	0.1452	0.1618	2.626e-002		

Heaters

Fluid Pkg: All

Name					
DUTY (MW)					
Feed Temperature (C)					
Product Temperature (C)					
Mass Flow (kg/s)					

Coolers

Fluid Pkg: All

Name	HX Chiller 2	HX Chiller 1			
DUTY (MW)	0.1618	2.626e-002			
Feed Temperature (C)	186.5	455.4			
Product Temperature (C)	21.11 *	429.9 *			
Mass Flow (kg/s)	0.9238	0.9238			

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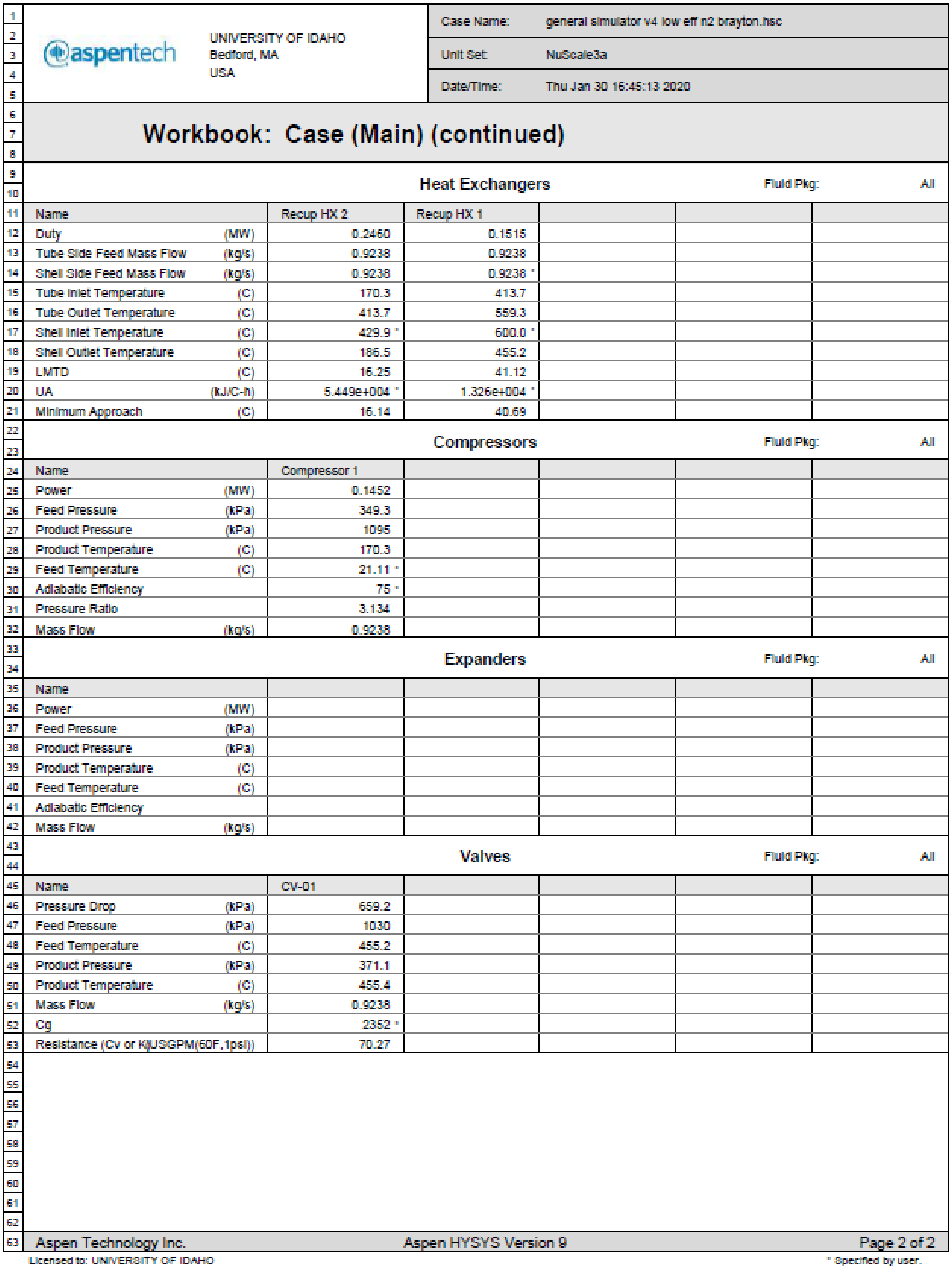

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Bedford, MA
USA

Case Name:	general simulator v4 low eff n2 brayton.hsc
Unit Set:	NuScale3a
Date/Time:	Thu Jan 30 16:45:13 2020

Workbook: Case (Main) (continued)

Heat Exchangers

Fluid Pkg: All

Name		Recup HX 2	Recup HX 1			
Duty	(MW)	0.2460	0.1515			
Tube Side Feed Mass Flow	(kg/s)	0.9238	0.9238			
Shell Side Feed Mass Flow	(kg/s)	0.9238	0.9238 *			
Tube Inlet Temperature	(C)	170.3	413.7			
Tube Outlet Temperature	(C)	413.7	559.3			
Shell Inlet Temperature	(C)	429.9 *	600.0 *			
Shell Outlet Temperature	(C)	186.5	455.2			
LMTD	(C)	16.25	41.12			
UA	(kJ/C-h)	5.449e+004 *	1.326e+004 *			
Minimum Approach	(C)	16.14	40.69			

Compressors

Fluid Pkg: All

Name		Compressor 1				
Power	(MW)	0.1452				
Feed Pressure	(kPa)	349.3				
Product Pressure	(kPa)	1095				
Product Temperature	(C)	170.3				
Feed Temperature	(C)	21.11 *				
Adiabatic Efficiency		75 *				
Pressure Ratio		3.134				
Mass Flow	(kg/s)	0.9238				

Expanders

Fluid Pkg: All

Name						
Power	(MW)					
Feed Pressure	(kPa)					
Product Pressure	(kPa)					
Product Temperature	(C)					
Feed Temperature	(C)					
Adiabatic Efficiency						
Mass Flow	(kg/s)					

Valves

Fluid Pkg: All

Name		CV-01				
Pressure Drop	(kPa)	659.2				
Feed Pressure	(kPa)	1030				
Feed Temperature	(C)	455.2				
Product Pressure	(kPa)	371.1				
Product Temperature	(C)	455.4				
Mass Flow	(kg/s)	0.9238				
Cg		2352 *				
Resistance (Cv or K)USGPM(60F,1psi))		70.27				

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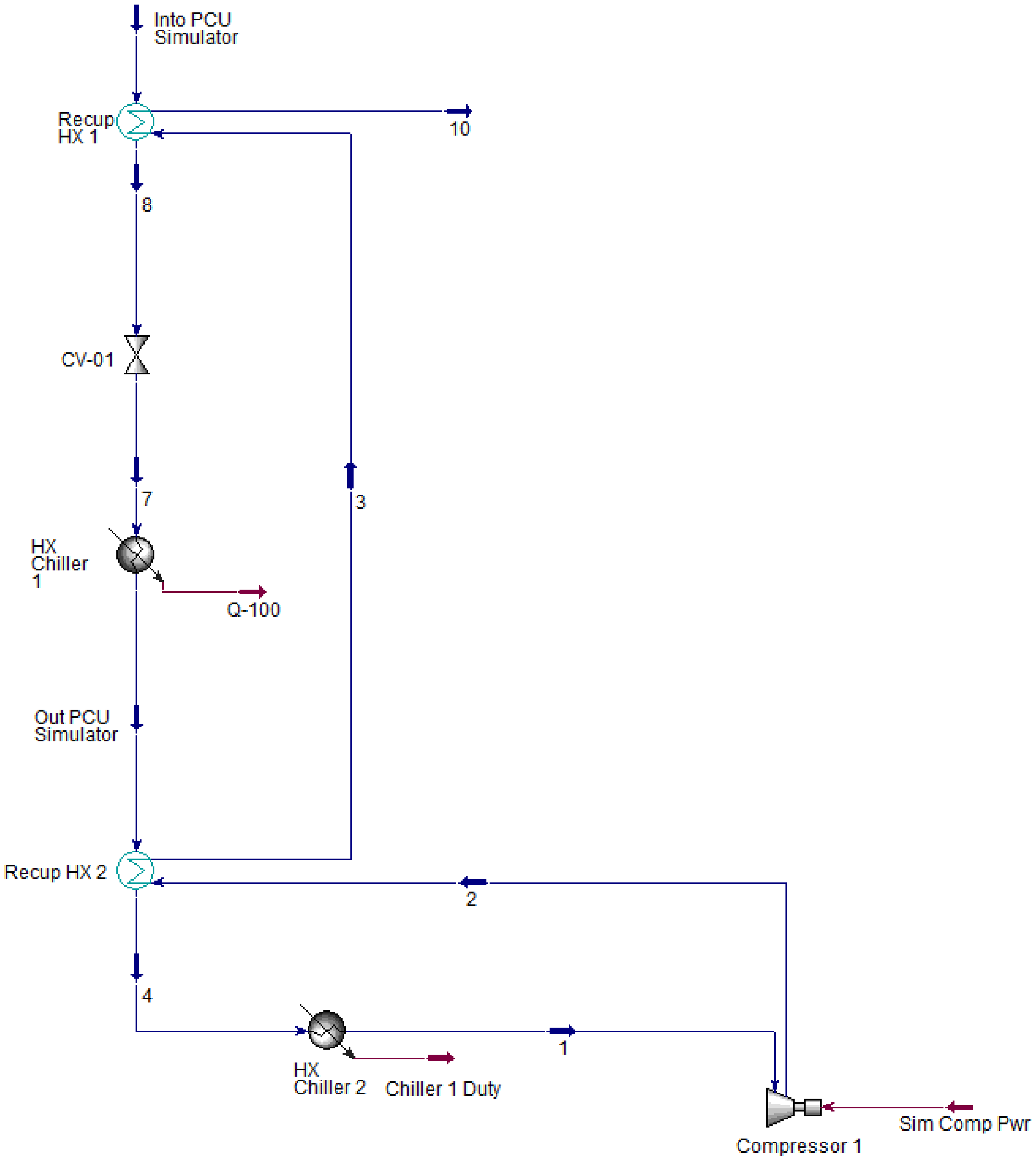
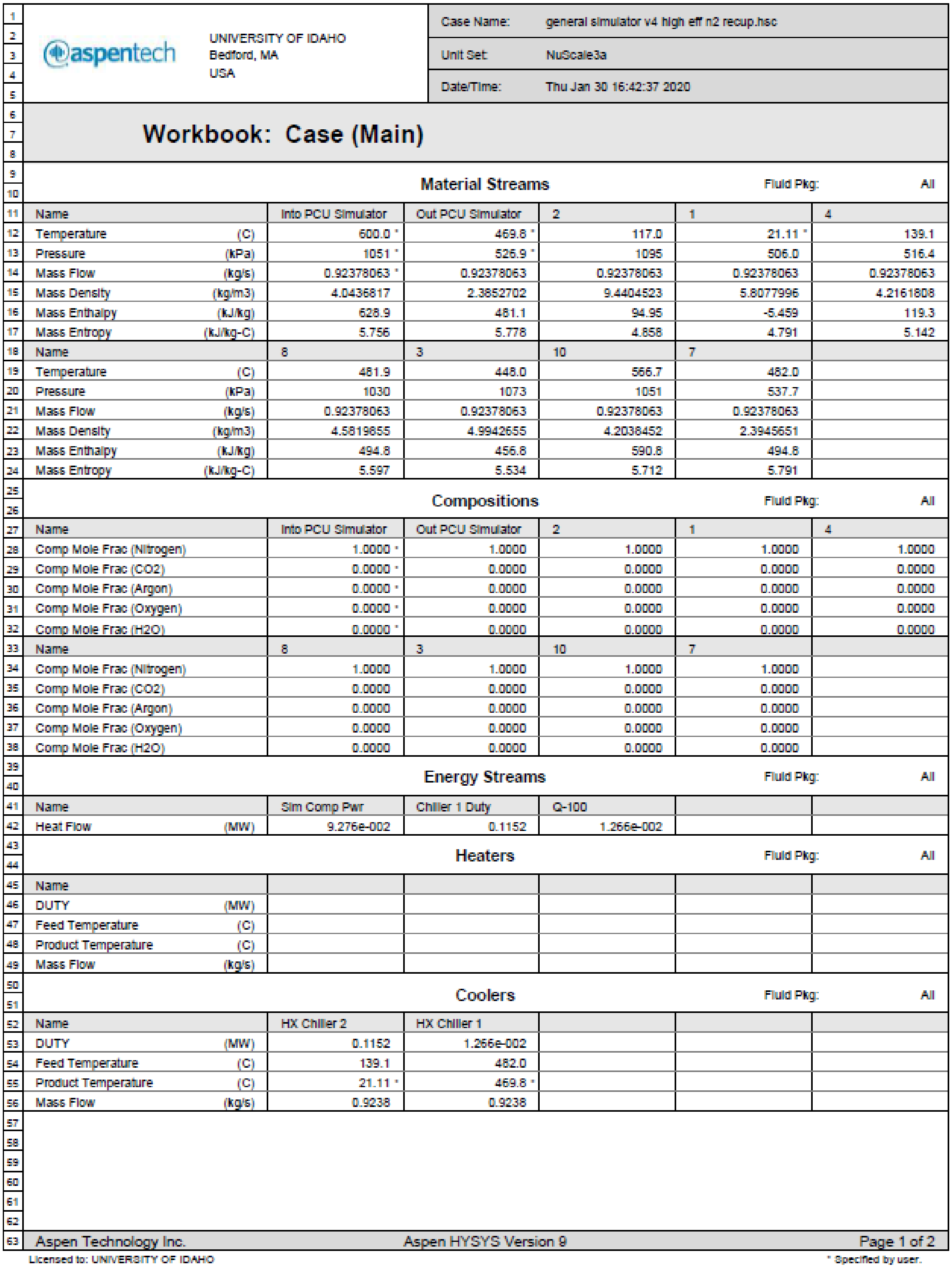
* Specified by user.

PCU Simulator Loop for Nitrogen Recuperated Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 85% and 90%





UNIVERSITY OF IDAHO Bedford, MA USA	Case Name: general simulator v4 high eff n2 recup.hsc Unit Set: NuScale3a Date/Time: Thu Jan 30 16:42:37 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Into PCU Simulator	Out PCU Simulator	2	1	4
Temperature	(C)	600.0 *	469.8 *	117.0	21.11 *	139.1
Pressure	(kPa)	1051 *	526.9 *	1095	506.0	516.4
Mass Flow	(kg/s)	0.92378063 *	0.92378063	0.92378063	0.92378063	0.92378063
Mass Density	(kg/m3)	4.0436817	2.3852702	9.4404523	5.8077996	4.2161808
Mass Enthalpy	(kJ/kg)	628.9	481.1	94.95	-5.459	119.3
Mass Entropy	(kJ/kg-C)	5.756	5.778	4.858	4.791	5.142

Name		8	3	10	7	
Temperature	(C)	481.9	448.0	566.7	482.0	
Pressure	(kPa)	1030	1073	1051	537.7	
Mass Flow	(kg/s)	0.92378063	0.92378063	0.92378063	0.92378063	
Mass Density	(kg/m3)	4.5819855	4.9942655	4.2038452	2.3945651	
Mass Enthalpy	(kJ/kg)	494.8	456.8	590.8	494.8	
Mass Entropy	(kJ/kg-C)	5.597	5.534	5.712	5.791	

Compositions

Fluid Pkg: All

Name	Into PCU Simulator	Out PCU Simulator	2	1	4
Comp Mole Frac (Nitrogen)	1.0000 *	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (CO2)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000 *	0.0000	0.0000	0.0000	0.0000

Name	8	3	10	7	
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000	
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	

Energy Streams

Fluid Pkg: All

Name		Sim Comp Pwr	Chiller 1 Duty	Q-100		
Heat Flow	(MW)	9.276e-002	0.1152	1.266e-002		

Heaters

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

Coolers

Fluid Pkg: All

Name		HX Chiller 2	HX Chiller 1			
DUTY	(MW)	0.1152	1.266e-002			
Feed Temperature	(C)	139.1	482.0			
Product Temperature	(C)	21.11 *	469.8 *			
Mass Flow	(kg/s)	0.9238	0.9238			

Aspen Technology Inc. Aspen HYSYS Version 9 Page 1 of 2

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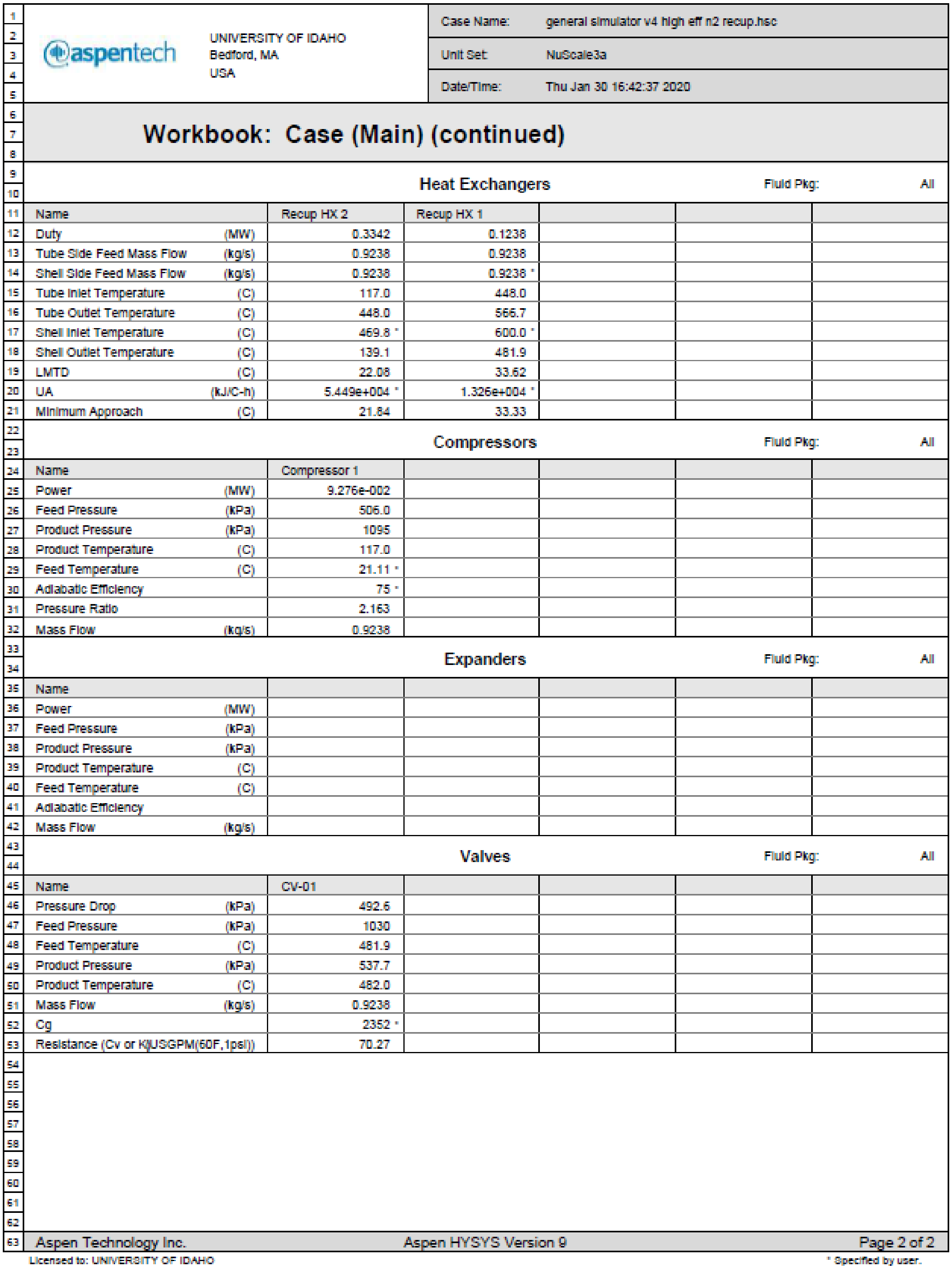
* Specified by user.



UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	general simulator v4 high eff n2 recup.hsc
Unit Set:	NuScale3a
Date/Time:	Thu Jan 30 16:42:37 2020

Workbook: Case (Main) (continued)

Heat Exchangers

Fluid Pkg: All

Name		Recup HX 2	Recup HX 1			
Duty	(MW)	0.3342	0.1236			
Tube Side Feed Mass Flow	(kg/s)	0.9238	0.9238			
Shell Side Feed Mass Flow	(kg/s)	0.9238	0.9238 *			
Tube Inlet Temperature	(C)	117.0	448.0			
Tube Outlet Temperature	(C)	448.0	566.7			
Shell Inlet Temperature	(C)	469.8 *	600.0 *			
Shell Outlet Temperature	(C)	139.1	481.9			
LMTD	(C)	22.08	33.62			
UA	(kJ/C-h)	5.449e+004 *	1.326e+004 *			
Minimum Approach	(C)	21.84	33.33			

Compressors

Fluid Pkg: All

Name		Compressor 1				
Power	(MW)	9.276e-002				
Feed Pressure	(kPa)	506.0				
Product Pressure	(kPa)	1095				
Product Temperature	(C)	117.0				
Feed Temperature	(C)	21.11 *				
Adiabatic Efficiency		75 *				
Pressure Ratio		2.163				
Mass Flow	(kg/s)	0.9238				

Expanders

Fluid Pkg: All

Name						
Power	(MW)					
Feed Pressure	(kPa)					
Product Pressure	(kPa)					
Product Temperature	(C)					
Feed Temperature	(C)					
Adiabatic Efficiency						
Mass Flow	(kg/s)					

Valves

Fluid Pkg: All

Name		CV-01				
Pressure Drop	(kPa)	492.6				
Feed Pressure	(kPa)	1030				
Feed Temperature	(C)	481.9				
Product Pressure	(kPa)	537.7				
Product Temperature	(C)	482.0				
Mass Flow	(kg/s)	0.9238				
Cg		2352 *				
Resistance (Cv or K)USGPM(60F,1psi))		70.27				

Aspen Technology Inc. Aspen HYSYS Version 9 Page 2 of 2

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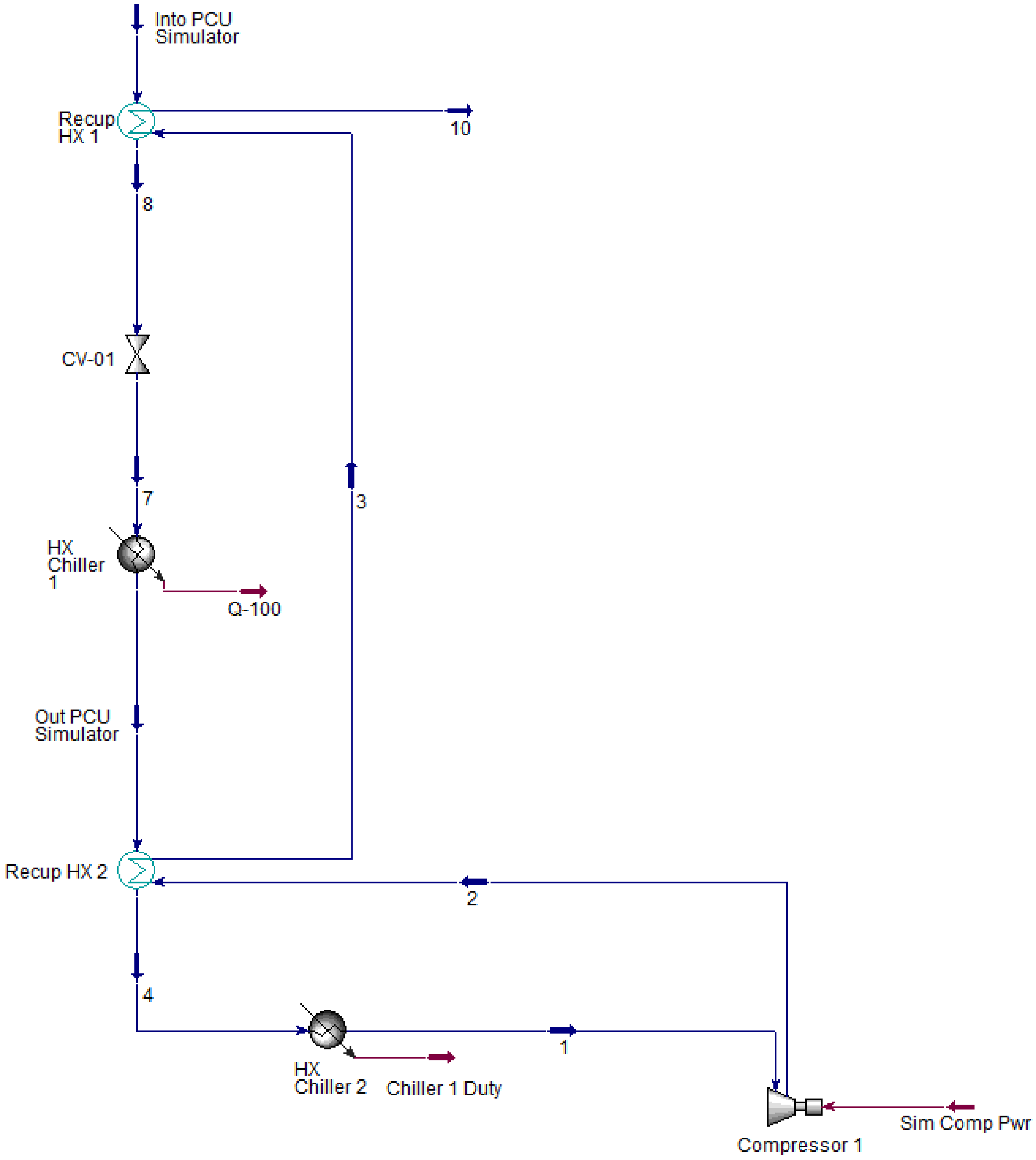
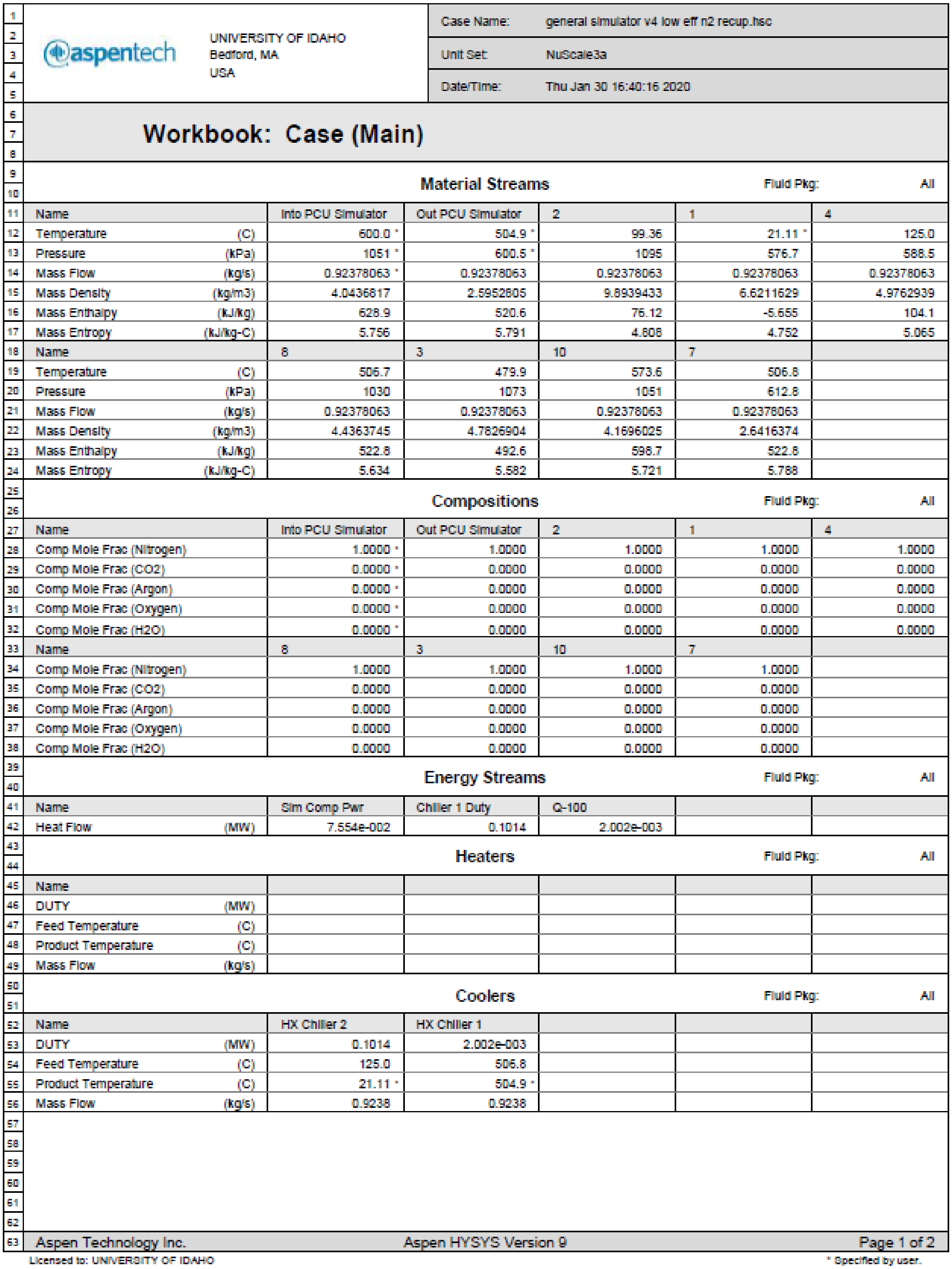
* Specified by user.

PCU Simulator Loop for Nitrogen Recuperated Brayton Cycle with Compressor and Turbine Adiabatic Efficiencies of 70% and 80%





aspentech

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: general simulator v4 low eff n2 recup.hsc

Unit Set: NuScale3a

Date/Time: Thu Jan 30 16:40:16 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Into PCU Simulator	Out PCU Simulator	2	1	4
Temperature	(C)	600.0 *	504.9 *	99.36	21.11 *	125.0
Pressure	(kPa)	1051 *	600.5 *	1095	576.7	588.5
Mass Flow	(kg/s)	0.92378063 *	0.92378063	0.92378063	0.92378063	0.92378063
Mass Density	(kg/m3)	4.0436817	2.5952805	9.8939433	6.6211629	4.9762939
Mass Enthalpy	(kJ/kg)	628.9	520.6	76.12	-5.655	104.1
Mass Entropy	(kJ/kg-C)	5.756	5.791	4.808	4.752	5.065
Name		**8**	**3**	**10**	**7**	
Temperature	(C)	506.7	479.9	573.6	506.8	
Pressure	(kPa)	1030	1073	1051	612.8	
Mass Flow	(kg/s)	0.92378063	0.92378063	0.92378063	0.92378063	
Mass Density	(kg/m3)	4.4363745	4.7826904	4.1696025	2.6416374	
Mass Enthalpy	(kJ/kg)	522.8	492.6	598.7	522.8	
Mass Entropy	(kJ/kg-C)	5.634	5.582	5.721	5.788	

Compositions

Fluid Pkg: All

Name	Into PCU Simulator	Out PCU Simulator	2	1	4
Comp Mole Frac (Nitrogen)	1.0000 *	1.0000	1.0000	1.0000	1.0000
Comp Mole Frac (CO2)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Argon)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (Oxygen)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (H2O)	0.0000 *	0.0000	0.0000	0.0000	0.0000
Name	**8**	**3**	**10**	**7**	
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000	
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000	
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000	

Energy Streams

Fluid Pkg: All

Name		Sim Comp Pwr	Chiller 1 Duty	Q-100		
Heat Flow	(MW)	7.554e-002	0.1014	2.002e-003		

Heaters

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

Coolers

Fluid Pkg: All

Name		HX Chiller 2	HX Chiller 1			
DUTY	(MW)	0.1014	2.002e-003			
Feed Temperature	(C)	125.0	506.8			
Product Temperature	(C)	21.11 *	504.9 *			
Mass Flow	(kg/s)	0.9238	0.9238			

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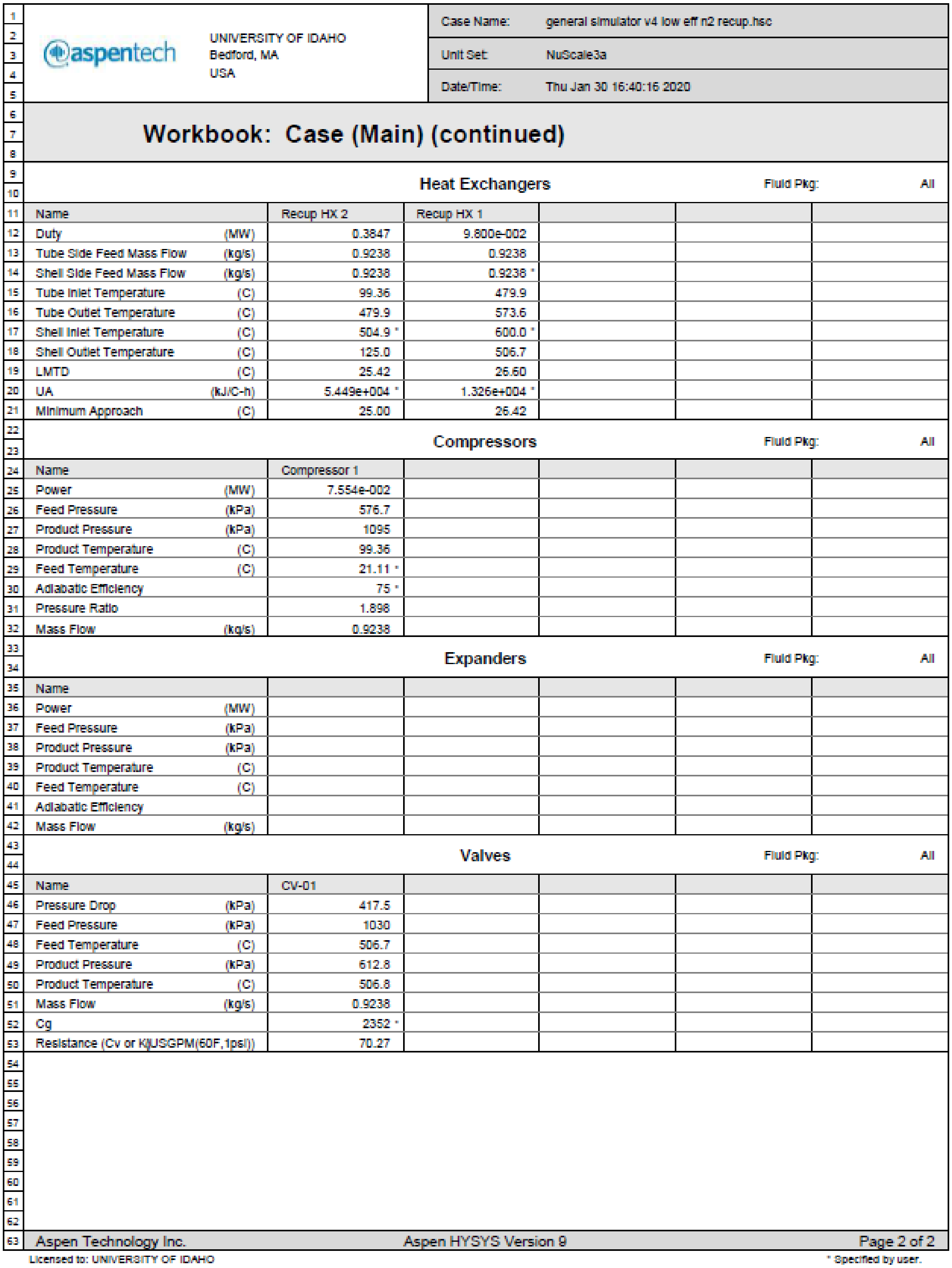
* Specified by user.



aspentech

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: general simulator v4 low eff n2 recup.hsc
Unit Set: NuScale3a
Date/Time: Thu Jan 30 16:40:16 2020

Workbook: Case (Main) (continued)

Heat Exchangers

Fluid Pkg: All

Name	Recup HX 2	Recup HX 1			
Duty (MW)	0.3847	9.800e-002			
Tube Side Feed Mass Flow (kg/s)	0.9238	0.9238			
Shell Side Feed Mass Flow (kg/s)	0.9238	0.9238 *			
Tube Inlet Temperature (C)	99.36	479.9			
Tube Outlet Temperature (C)	479.9	573.6			
Shell Inlet Temperature (C)	504.9 *	600.0 *			
Shell Outlet Temperature (C)	125.0	506.7			
LMTD (C)	25.42	26.60			
UA (kJ/C-h)	5.449e+004 *	1.326e+004 *			
Minimum Approach (C)	25.00	26.42			

Compressors

Fluid Pkg: All

Name	Compressor 1				
Power (MW)	7.554e-002				
Feed Pressure (kPa)	576.7				
Product Pressure (kPa)	1095				
Product Temperature (C)	99.36				
Feed Temperature (C)	21.11 *				
Adiabatic Efficiency	75 *				
Pressure Ratio	1.898				
Mass Flow (kg/s)	0.9238				

Expanders

Fluid Pkg: All

Name					
Power (MW)					
Feed Pressure (kPa)					
Product Pressure (kPa)					
Product Temperature (C)					
Feed Temperature (C)					
Adiabatic Efficiency					
Mass Flow (kg/s)					

Valves

Fluid Pkg: All

Name	CV-01				
Pressure Drop (kPa)	417.5				
Feed Pressure (kPa)	1030				
Feed Temperature (C)	506.7				
Product Pressure (kPa)	612.8				
Product Temperature (C)	506.8				
Mass Flow (kg/s)	0.9238				
Cg	2352 *				
Resistance (Cv or K)USGPM(60F,1psi))	70.27				

Aspen Technology Inc. Aspen HYSYS Version 9 Page 2 of 2

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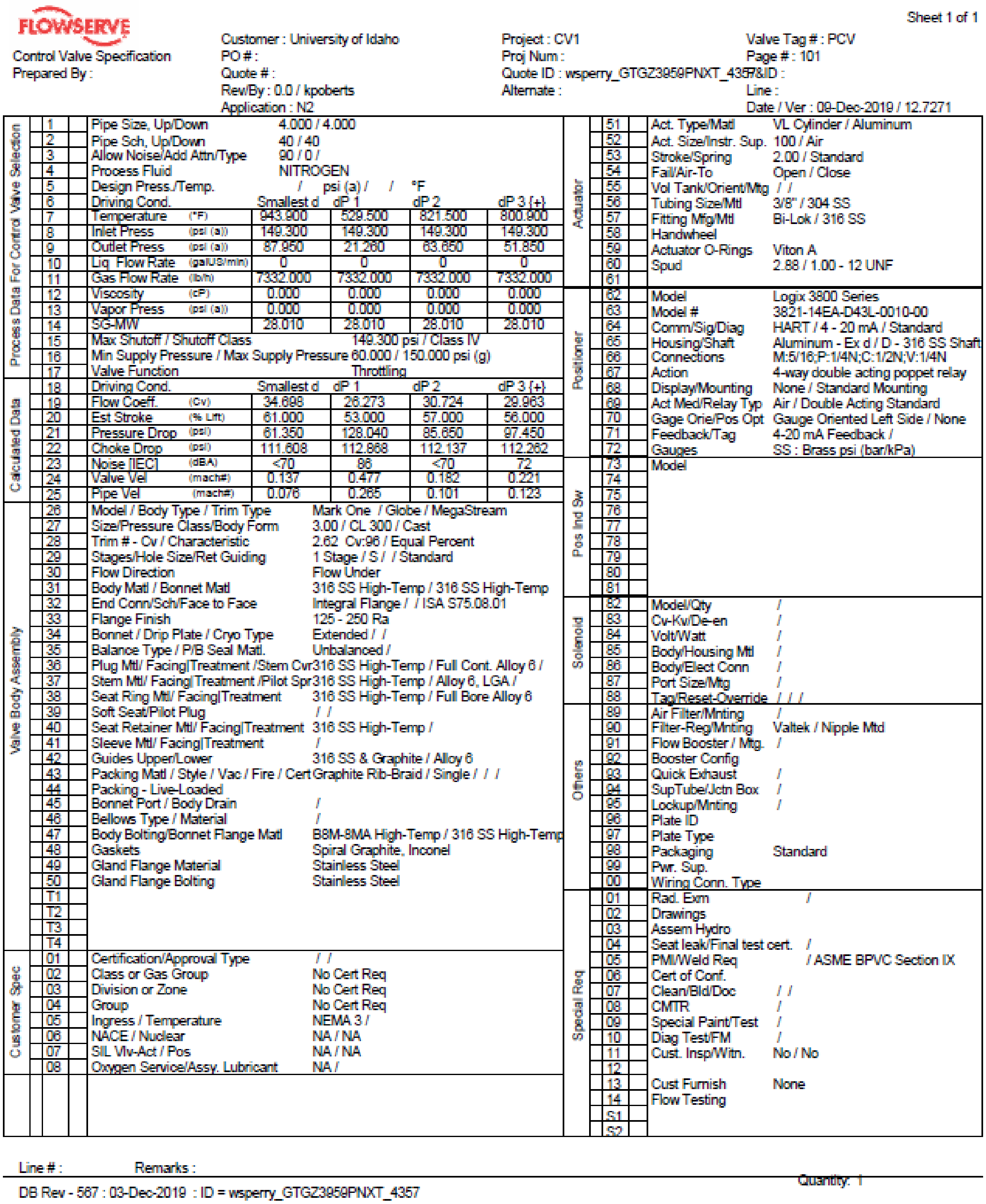
* Specified by user.

Appendix J: Control Valve CV-01 Specification Data Sheet and Quote

Flow Serve Quote for CV-01 Control Valve (Flowserve, 2020)



FLOWSERVE

Sheet 1 of 1

Control Valve Specification
Prepared By :

Customer : University of Idaho
PO # :
Quote # :
Rev/By : 0.0 / kpoberts
Application : N2

Project : CV1
Proj Num :
Quote ID : wsperry_GTGZ3959PNXT_4357
Alternate :

Valve Tag # : PCV
Page # : 101
P&ID :
Line :
Date / Ver : 09-Dec-2019 / 12.7271

Process Data For Control Valve Selection	1	Pipe Size, Up/Down		4.000 / 4.000			
	2	Pipe Sch, Up/Down		40 / 40			
	3	Allow Noise/Add Attn/Type		90 / 0 /			
	4	Process Fluid		NITROGEN			
	5	Design Press./Temp.		/ psi (a) / / °F			
	6	Driving Cond.		Smallest d	dP 1	dP 2	dP 3 {+}
	7	Temperature	(°F)	943.900	529.500	821.500	800.900
	8	Inlet Press	(psi (a))	149.300	149.300	149.300	149.300
	9	Outlet Press	(psi (a))	87.950	21.260	63.650	51.850
	10	Liq Flow Rate	(galUS/min)	0	0	0	0
	11	Gas Flow Rate	(lb/h)	7332.000	7332.000	7332.000	7332.000
	12	Viscosity	(cP)	0.000	0.000	0.000	0.000
	13	Vapor Press	(psi (a))	0.000	0.000	0.000	0.000
	14	SG-MW		28.010	28.010	28.010	28.010
	15	Max Shutoff / Shutoff Class		149.300 psi / Class IV			
	16	Min Supply Pressure / Max Supply Pressure		60.000 / 150.000 psi (g)			
	17	Valve Function		Throttling			
Calculated Data	18	Driving Cond.		Smallest d	dP 1	dP 2	dP 3 {+}
	19	Flow Coeff.	(Cv)	34.698	26.273	30.724	29.963
	20	Est Stroke	(% Lift)	61.000	53.000	57.000	56.000
	21	Pressure Drop	(psi)	61.350	128.040	85.650	97.450
	22	Choke Drop	(psi)	111.608	112.868	112.137	112.262
	23	Noise [IEC]	(dBA)	<70	86	<70	72
	24	Valve Vel	(mach#)	0.137	0.477	0.182	0.221
	25	Pipe Vel	(mach#)	0.076	0.265	0.101	0.123

Valve Body Assembly	26	Model / Body Type / Trim Type	Mark One / Globe / MegaStream
	27	Size/Pressure Class/Body Form	3.00 / CL 300 / Cast
	28	Trim # - Cv / Characteristic	2.62 Cv:96 / Equal Percent
	29	Stages/Hole Size/Ret Guiding	1 Stage / S / / Standard
	30	Flow Direction	Flow Under
	31	Body Matl / Bonnet Matl	316 SS High-Temp / 316 SS High-Temp
	32	End Conn/Sch/Face to Face	Integral Flange / / ISA S75.08.01
	33	Flange Finish	125 - 250 Ra
	34	Bonnet / Drip Plate / Cryo Type	Extended / /
	35	Balance Type / P/B Seal Matl.	Unbalanced /
	36	Plug Mtl/ Facing|Treatment /Stem Cvr	316 SS High-Temp / Full Cont. Alloy 6 /
	37	Stem Mtl/ Facing|Treatment /Pilot Spr	316 SS High-Temp / Alloy 6, LGA /
	38	Seat Ring Mtl/ Facing|Treatment	316 SS High-Temp / Full Bore Alloy 6
	39	Soft Seat/Pilot Plug	/ /
	40	Seat Retainer Mtl/ Facing|Treatment	316 SS High-Temp /
	41	Sleeve Mtl/ Facing|Treatment	/
	42	Guides Upper/Lower	316 SS & Graphite / Alloy 6
	43	Packing Matl / Style / Vac / Fire / Cert	Graphite Rib-Braid / Single / / /
	44	Packing - Live-Loaded	
	45	Bonnet Port / Body Drain	/
	46	Bellows Type / Material	/
	47	Body Bolting/Bonnet Flange Matl	B8M-8MA High-Temp / 316 SS High-Temp
	48	Gaskets	Spiral Graphite, Inconel
	49	Gland Flange Material	Stainless Steel
	50	Gland Flange Bolting	Stainless Steel
	T1		
	T2		
	T3		
	T4		
Customer Spec	01	Certification/Approval Type	/ /
	02	Class or Gas Group	No Cert Req
	03	Division or Zone	No Cert Req
	04	Group	No Cert Req
	05	Ingress / Temperature	NEMA 3 /
	06	NACE / Nuclear	NA / NA
	07	SIL Vlv-Act / Pos	NA / NA
	08	Oxygen Service/Assy. Lubricant	NA /

Actuator	51	Act. Type/Matl	VL Cylinder / Aluminum
	52	Act. Size/Instr. Sup.	100 / Air
	53	Stroke/Spring	2.00 / Standard
	54	Fail/Air-To	Open / Close
	55	Vol Tank/Orient/Mtg	/ /
	56	Tubing Size/Mtl	3/8" / 304 SS
	57	Fitting Mfg/Mtl	Bi-Lok / 316 SS
	58	Handwheel	
	59	Actuator O-Rings	Viton A
	60	Spud	2.88 / 1.00 - 12 UNF
	61		
Positioner	62	Model	Logix 3800 Series
	63	Model #	3821-14EA-D43L-0010-00
	64	Comm/Sig/Diag	HART / 4 - 20 mA / Standard
	65	Housing/Shaft	Aluminum - Ex d / D - 316 SS Shaft
	66	Connections	M:5/16;P:1/4N;C:1/2N;V:1/4N
	67	Action	4-way double acting poppet relay
	68	Display/Mounting	None / Standard Mounting
	69	Act Med/Relay Typ	Air / Double Acting Standard
	70	Gage Orie/Pos Opt	Gauge Oriented Left Side / None
	71	Feedback/Tag	4-20 mA Feedback /
	72	Gauges	SS : Brass psi (bar/kPa)
Pos Ind Sw	73	Model	
	74		
	75		
	76		
	77		
	78		
	79		
	80		
	81		
Solenoid	82	Model/Qty	/
	83	Cv-Kv/De-en	/
	84	Volt/Watt	/
	85	Body/Housing Mtl	/
	86	Body/Elect Conn	/
	87	Port Size/Mtg	/
	88	Tag/Reset-Override	/ / /
Others	89	Air Filter/Mnting	/
	90	Filter-Reg/Mnting	Valtek / Nipple Mtd
	91	Flow Booster / Mtg.	/
	92	Booster Config	
	93	Quick Exhaust	/
	94	SupTube/Jctn Box	/
	95	Lockup/Mnting	/
	96	Plate ID	
	97	Plate Type	
	98	Packaging	Standard
	99	Pwr. Sup.	
	00	Wiring Conn. Type	
Special Req	01	Rad. Exm	/
	02	Drawings	
	03	Assem Hydro	
	04	Seat leak/Final test cert.	/
	05	PMI/Weld Req	/ ASME BPVC Section IX
	06	Cert of Conf.	
	07	Clean/Bld/Doc	/ /
	08	CMTR	/
	09	Special Paint/Test	/
	10	Diag Test/FM	/
	11	Cust. Insp/Witn.	No / No
	12		
	13	Cust Furnish	None
	14	Flow Testing	
	S1		
	S2		

Line # : Remarks :

Quantity: 1

DB Rev - 567 : 03-Dec-2019 : ID = wsperry_GTGZ3959PNXT_4357

Detail Information
Prepared By :

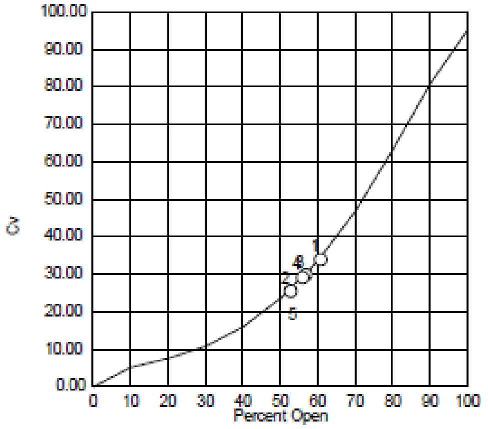
Customer : University of Idaho
PO # :
Quote # :
Rev/By : 0.0 / kpoberts
Application : N2

Project : CV1
Proj Num :
Quote ID : wsperry_GTGZ3959PNXT_435
Alternate :

Valve Tag # : PCV
Page # : 101
P&ID :
Line :
Date / Ver : 09-Dec-2019 / 12.7271

3.00 in (Trim: 2.62 Cv:96) CL 300 Mark One MegaStream Globe

		Smallest dP	dP 1	dP 2	dP 3	Largest dP					
Process Data											
Temp	(°F)	943.900	529.500	821.500	800.900	529.500	---	---	---	---	---
P1	(psi (a))	149.300	149.300	149.300	149.300	149.300	---	---	---	---	---
P2	(psi (a))	87.950	21.260	63.650	51.850	21.200	---	---	---	---	---
Liq Flow	(galUS/min)	- - -	- - -	- - -	- - -	- - -	---	---	---	---	---
Gas Flow	(lb/h)	7332.000	7332.000	7332.000	7332.000	7332.000	---	---	---	---	---
Visc	(cP)	0.000	0.000	0.000	0.000	0.000	---	---	---	---	---
VP	(psi (a))	0.000	0.000	0.000	0.000	0.000	---	---	---	---	---
DP	(psi)	61.350	128.040	85.650	97.450	128.100	---	---	---	---	---
DpC	(psi)	111.608	112.868	112.137	112.262	112.868	---	---	---	---	---
Vel	(mach#)	0.137	0.477	0.182	0.221	0.479	---	---	---	---	---
Pipe Vel	(mach#)	0.076	0.265	0.101	0.123	0.266	---	---	---	---	---
Noise	(dBA)	< 70.0	86.000	< 70.0	72.000	86.000	---	---	---	---	---
Flow Cap	(Cv)	34.698	26.273	30.724	29.963	26.273	---	---	---	---	---
Stroke	(% Lift)	61	53	57	56	53	---	---	---	---	---
Info	()						---	---	---	---	---
Detailed Miscellaneous Information											
FP		0.997	0.998	0.997	0.998	0.998	---	---	---	---	---
FL		- - -	- - -	- - -	- - -	- - -	---	---	---	---	---
FR		1.000	1.000	1.000	1.000	1.000	---	---	---	---	---
Sg		- - -	- - -	- - -	- - -	- - -	---	---	---	---	---
K		1.400	1.400	1.400	1.400	1.400	---	---	---	---	---
Xt		0.750	0.757	0.753	0.754	0.757	---	---	---	---	---
Z		1.015	1.015	1.015	1.015	1.015	---	---	---	---	---
FD		0.070	0.070	0.070	0.070	0.070	---	---	---	---	---
MWT		28.010	28.010	28.010	28.010	28.010	---	---	---	---	---
Detailed Cavitation (Sigma) Information											
Sigma		- - -	- - -	- - -	- - -	- - -	---	---	---	---	---
Sigma MR		- - -	- - -	- - -	- - -	- - -	---	---	---	---	---
PSE		- - -	- - -	- - -	- - -	- - -	---	---	---	---	---
SSE		- - -	- - -	- - -	- - -	- - -	---	---	---	---	---
Sigma V		- - -	- - -	- - -	- - -	- - -	---	---	---	---	---
Sigma P		- - -	- - -	- - -	- - -	- - -	---	---	---	---	---



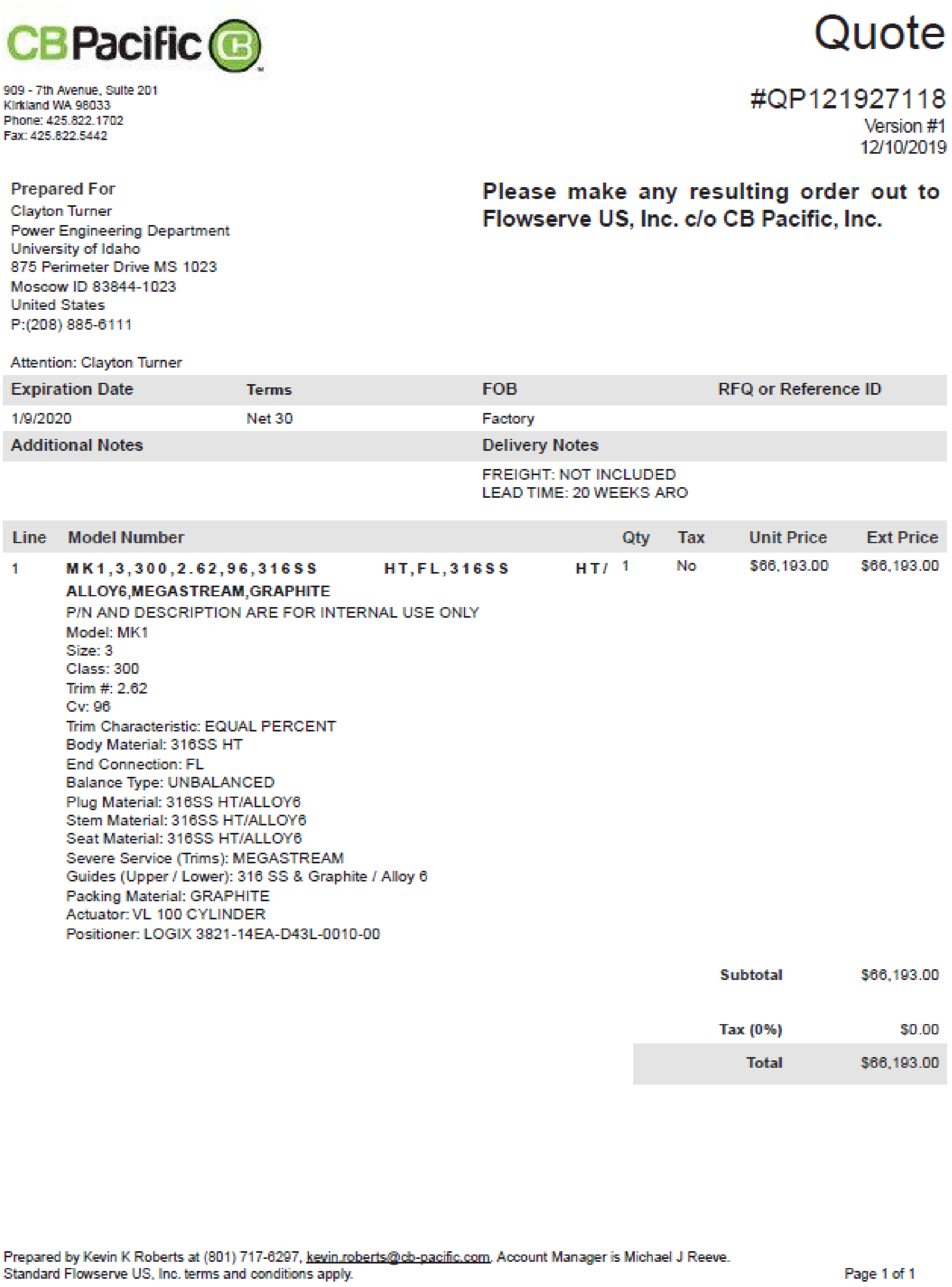
Fluid: NITROGEN
Type: Full
Owner: EVERYONE Fluid List: STANDARD
Vp Equation: Antoine

Critical Pressure (psi (a)/bar (a)) : 492.275 / 33.950
Critical Temperature (°F/°C) : -232.570 / -146.983
Reference Specific Gravity: 0.800
Molecular Weight: 28.010
Specific Heat Ratio: 1.400
Reference Temperature (°F/°C) : -319.070 / -195.039
Vp-A: 11.000 Vp-B: 1059.700
Vp-C: -11.800

Minimum Temperature (°F/°C) : -346.270 / -210.150
Maximum Temperature (°F/°C) : -232.870 / -147.150
Bulk Modulas ((lbf/in²)/(kg/cm²)) : 340000.000 / 4835820.000

Flow Direction : Flow Under
Trim Characteristic : Equal Percent
Balance Type: Unbalanced
Trim Type : MegaStream

DB Rev - 567 : 03-Dec-2019



CB Pacific

909 - 7th Avenue, Suite 201
Kirkland WA 98033
Phone: 425.822.1702
Fax: 425.822.5442

Quote

#QP121927118
Version #1
12/10/2019

Please make any resulting order out to Flowserve US, Inc. c/o CB Pacific, Inc.

Prepared For
Clayton Turner
Power Engineering Department
University of Idaho
875 Perimeter Drive MS 1023
Moscow ID 83844-1023
United States
P:(208) 885-6111

Attention: Clayton Turner

Expiration Date	Terms	FOB	RFQ or Reference ID
1/9/2020	Net 30	Factory	

Additional Notes	Delivery Notes
	FREIGHT: NOT INCLUDED LEAD TIME: 20 WEEKS ARO

Line	Model Number	Qty	Tax	Unit Price	Ext Price
1	**MK1,3,300,2.62,96,316SS HT,FL,316SS HT/ ALLOY6,MEGASTREAM,GRAPHITE** P/N AND DESCRIPTION ARE FOR INTERNAL USE ONLY Model: MK1 Size: 3 Class: 300 Trim #: 2.62 Cv: 96 Trim Characteristic: EQUAL PERCENT Body Material: 316SS HT End Connection: FL Balance Type: UNBALANCED Plug Material: 316SS HT/ALLOY6 Stem Material: 316SS HT/ALLOY6 Seat Material: 316SS HT/ALLOY6 Severe Service (Trims): MEGASTREAM Guides (Upper / Lower): 316 SS & Graphite / Alloy 6 Packing Material: GRAPHITE Actuator: VL 100 CYLINDER Positioner: LOGIX 3821-14EA-D43L-0010-00	1	No	$66,193.00	$66,193.00

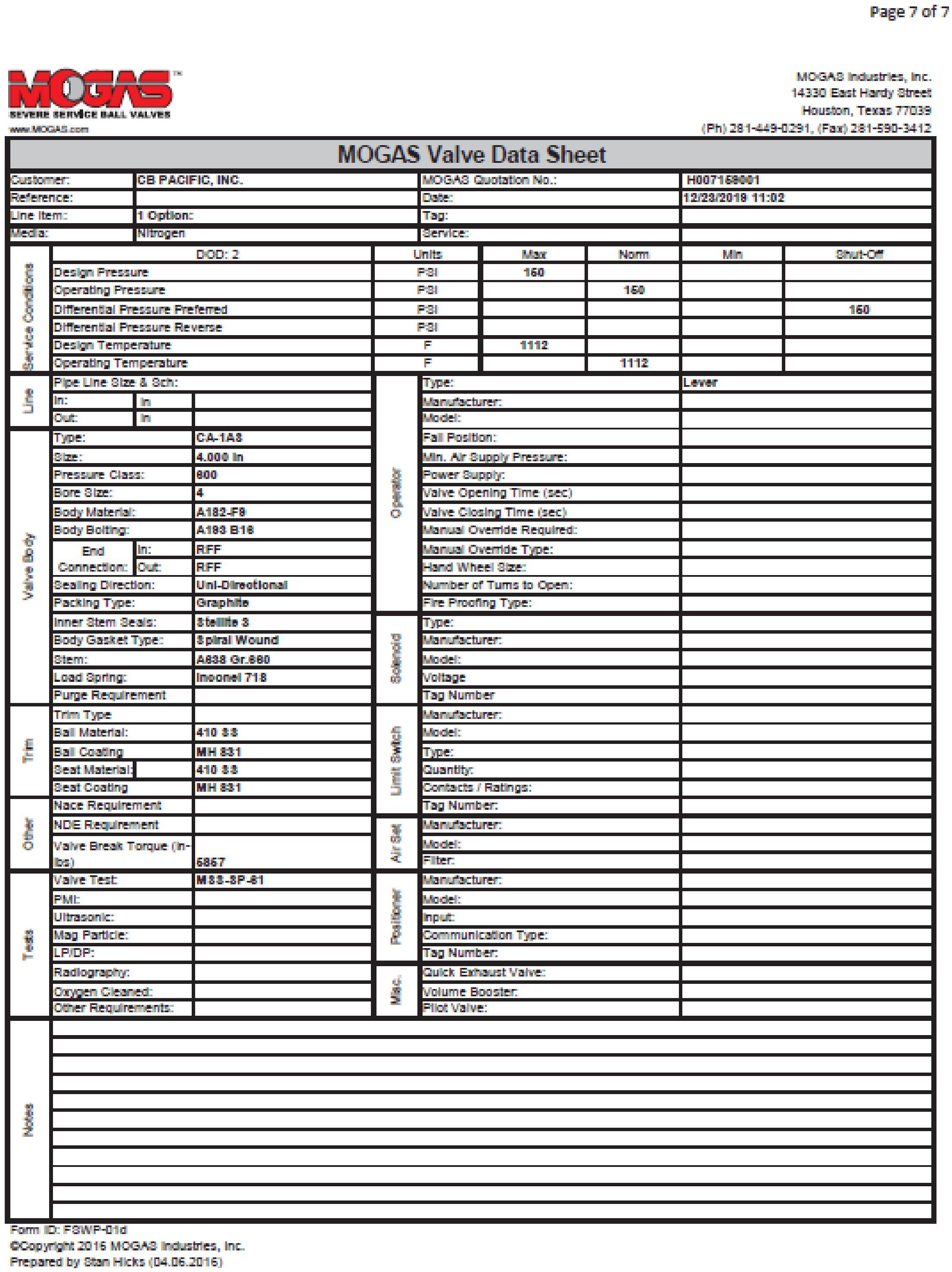
Subtotal	$66,193.00
Tax (0%)	$0.00
Total	$66,193.00

Prepared by Kevin K Roberts at (801) 717-6297, kevin.roberts@cb-pacific.com. Account Manager is Michael J Reeve.
Standard Flowserve US, Inc. terms and conditions apply.

Page 1 of 1

Appendix K: Control Valve BV-01 Specification Data Sheet and Quote

Manual Control Valve BV-01 Data Sheet and Quote (Flowserve, 2020)



Page 7 of 7

SEVERE SERVICE BALL VALVES
www.MOGAS.com

MOGAS Industries, Inc.
14330 East Hardy Street
Houston, Texas 77039
(Ph) 281-449-0291, (Fax) 281-590-3412

MOGAS Valve Data Sheet

Customer:	CB PACIFIC, INC.	MOGAS Quotation No.:	H007158001
Reference:		Date:	12/23/2019 11:02
Line Item:	1 Option:	Tag:	
Media:	Nitrogen	Service:	

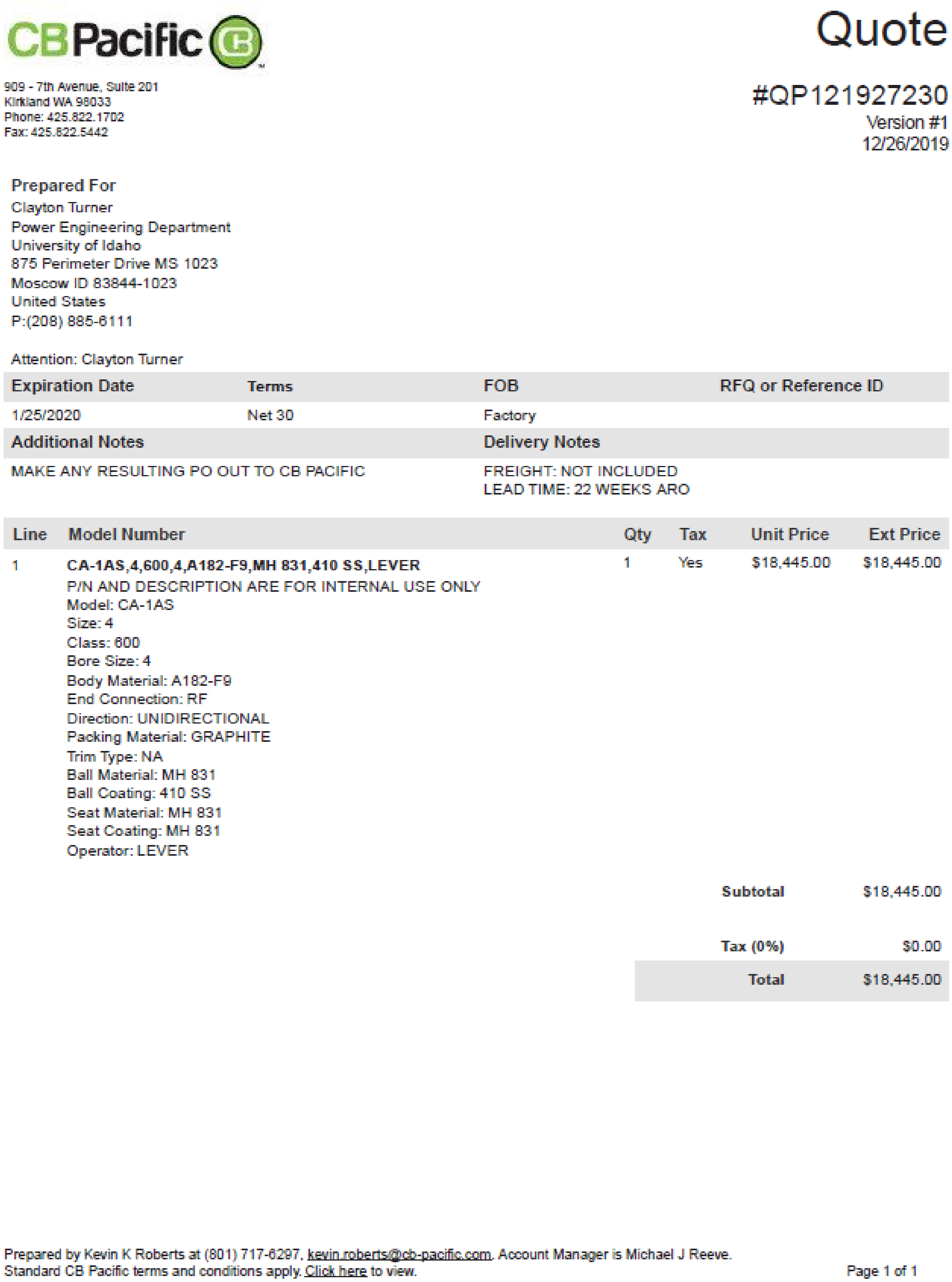
	DOD: 2	Units	Max	Norm	Min	Shut-Off
Service Conditions	Design Pressure	PSI	160			
	Operating Pressure	PSI		160		
	Differential Pressure Preferred	PSI				160
	Differential Pressure Reverse	PSI				
	Design Temperature	F	1112			
	Operating Temperature	F		1112		

Line	Pipe Line Size & Sch:		
	In:	In	
	Out:	In	
Valve Body	Type:		CA-1AS
	Size:		4.000 In
	Pressure Class:		600
	Bore Size:		4
	Body Material:		A182-F9
	Body Bolting:		A193 B16
	End Connection:	In:	RFF
		Out:	RFF
	Sealing Direction:		Uni-Directional
	Packing Type:		Graphite
	Inner Stem Seals:		Stellite 3
	Body Gasket Type:		Spiral Wound
	Stem:		A638 Gr.660
	Load Spring:		Inconel 718
	Purge Requirement		
Trim	Trim Type		
	Ball Material:		410 SS
	Ball Coating		MH 831
	Seat Material:		410 SS
	Seat Coating		MH 831
Other	Nace Requirement		
	NDE Requirement		
	Valve Break Torque (in-lbs)		6867
Tests	Valve Test:		MSS-SP-61
	PMI:		
	Ultrasonic:		
	Mag Particle:		
	LP/DP:		
	Radiography:		
	Oxygen Cleaned:		
	Other Requirements:		

Operator	Type:	Lever
	Manufacturer:	
	Model:	
	Fail Position:	
	Min. Air Supply Pressure:	
	Power Supply:	
	Valve Opening Time (sec)	
	Valve Closing Time (sec)	
	Manual Override Required:	
	Manual Override Type:	
	Hand Wheel Size:	
	Number of Turns to Open:	
	Fire Proofing Type:	
Solenoid	Type:	
	Manufacturer:	
	Model:	
	Voltage	
	Tag Number	
Limit Switch	Manufacturer:	
	Model:	
	Type:	
	Quantity:	
	Contacts / Ratings:	
	Tag Number:	
Air Set	Manufacturer:	
	Model:	
	Filter:	
Positioner	Manufacturer:	
	Model:	
	Input:	
	Communication Type:	
	Tag Number:	
Misc.	Quick Exhaust Valve:	
	Volume Booster:	
	Pilot Valve:	

Notes

Form ID: FSWP-01d
©Copyright 2016 MOGAS Industries, Inc.
Prepared by Stan Hicks (04.06.2016)



CBPacific

909 - 7th Avenue, Suite 201
Kirkland WA 98033
Phone: 425.822.1702
Fax: 425.822.5442

Quote

#QP121927230
Version #1
12/26/2019

Prepared For
Clayton Turner
Power Engineering Department
University of Idaho
875 Perimeter Drive MS 1023
Moscow ID 83844-1023
United States
P:(208) 885-6111

Attention: Clayton Turner

Expiration Date	Terms	FOB	RFQ or Reference ID
1/25/2020	Net 30	Factory	

Additional Notes	Delivery Notes
MAKE ANY RESULTING PO OUT TO CB PACIFIC	FREIGHT: NOT INCLUDED LEAD TIME: 22 WEEKS ARO

Line	Model Number	Qty	Tax	Unit Price	Ext Price
1	**CA-1AS,4,600,4,A182-F9,MH 831,410 SS,LEVER** P/N AND DESCRIPTION ARE FOR INTERNAL USE ONLY Model: CA-1AS Size: 4 Class: 600 Bore Size: 4 Body Material: A182-F9 End Connection: RF Direction: UNIDIRECTIONAL Packing Material: GRAPHITE Trim Type: NA Ball Material: MH 831 Ball Coating: 410 SS Seat Material: MH 831 Seat Coating: MH 831 Operator: LEVER	1	Yes	$18,445.00	$18,445.00

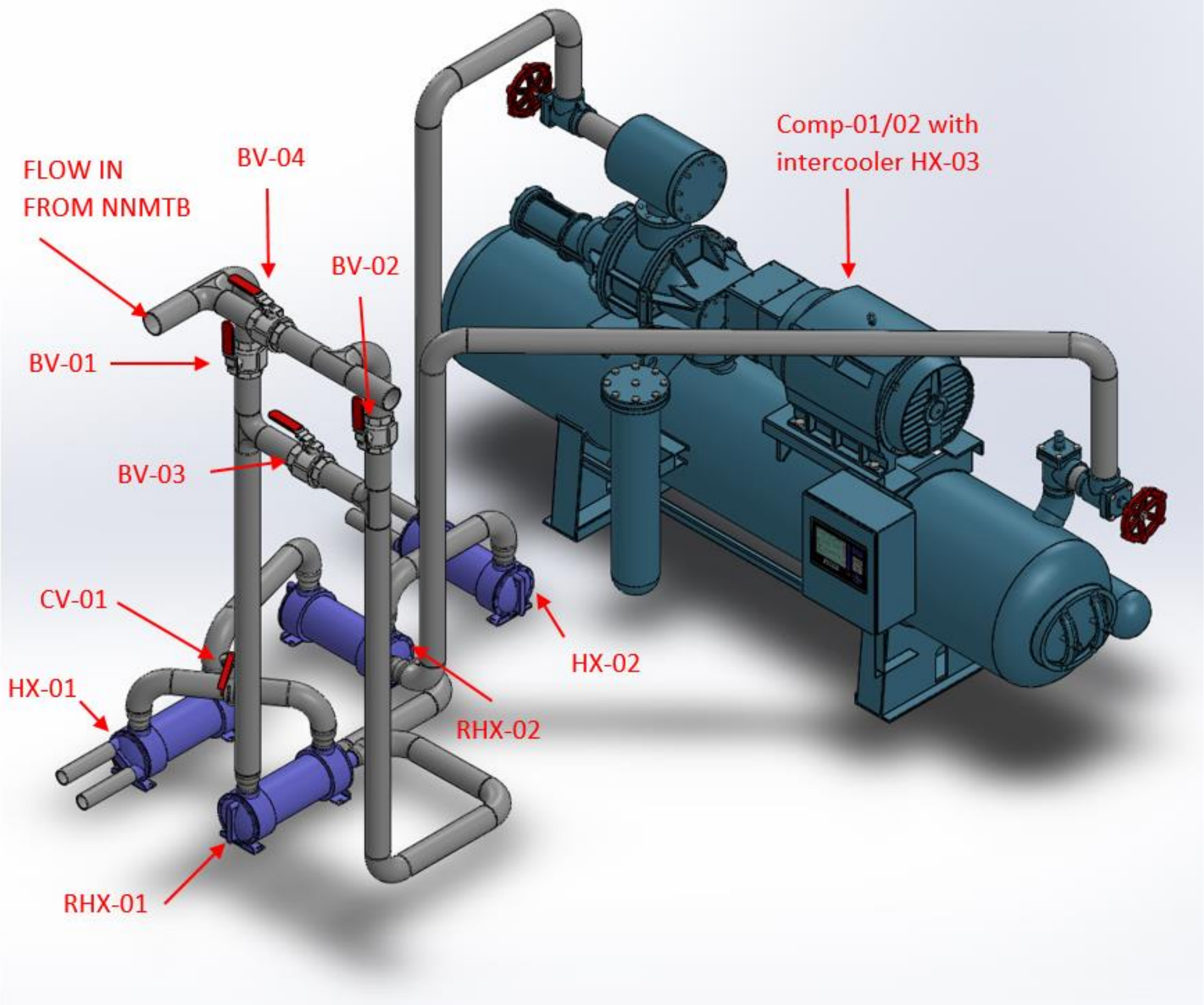
Subtotal	$18,445.00
Tax (0%)	$0.00
Total	$18,445.00

Prepared by Kevin K Roberts at (801) 717-6297, kevin.roberts@cb-pacific.com. Account Manager is Michael J Reeve.
Standard CB Pacific terms and conditions apply. Click here to view.

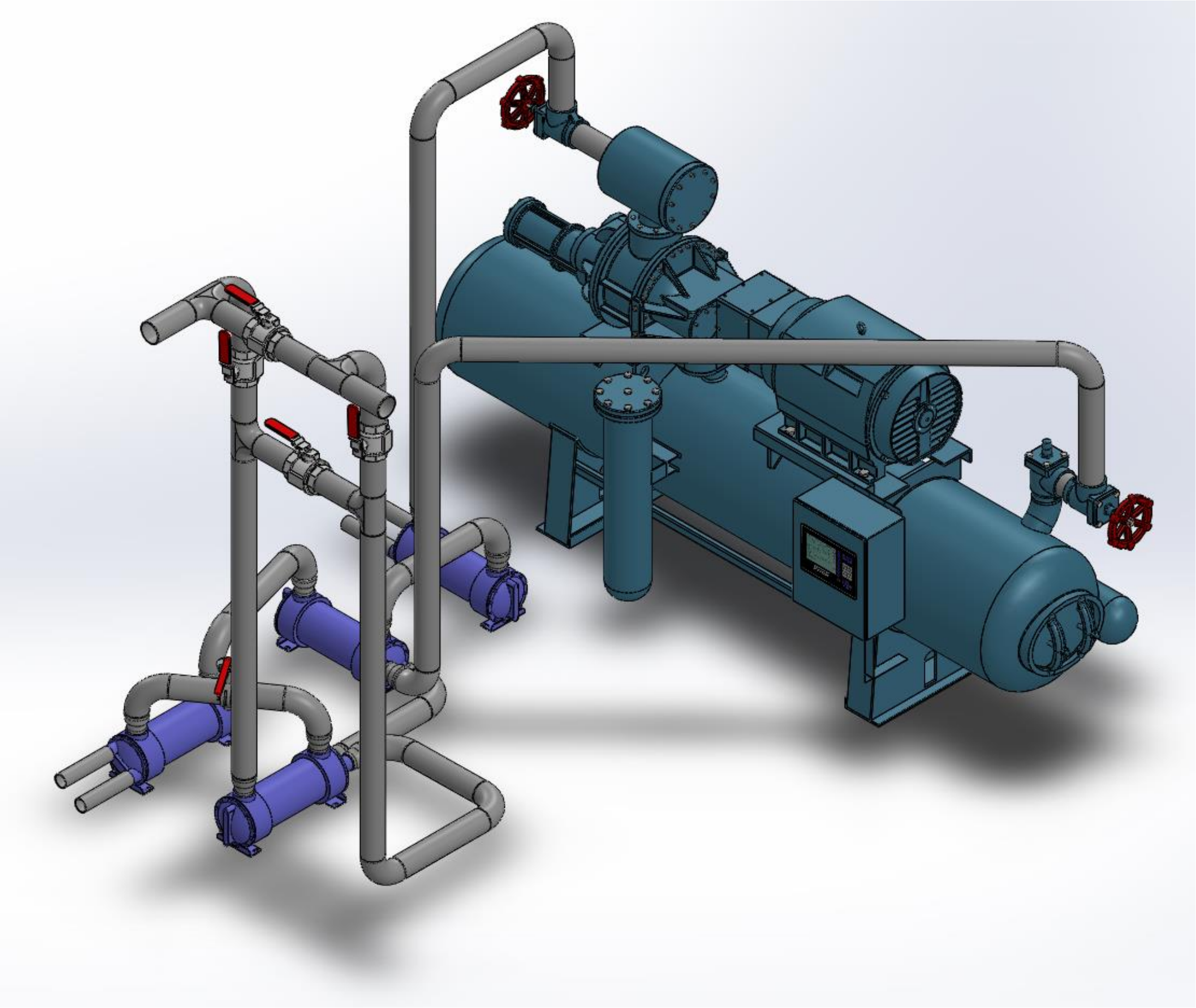
Page 1 of 1

Appendix L: Computer Aided Design Models of Power Conversion Unit Simulator

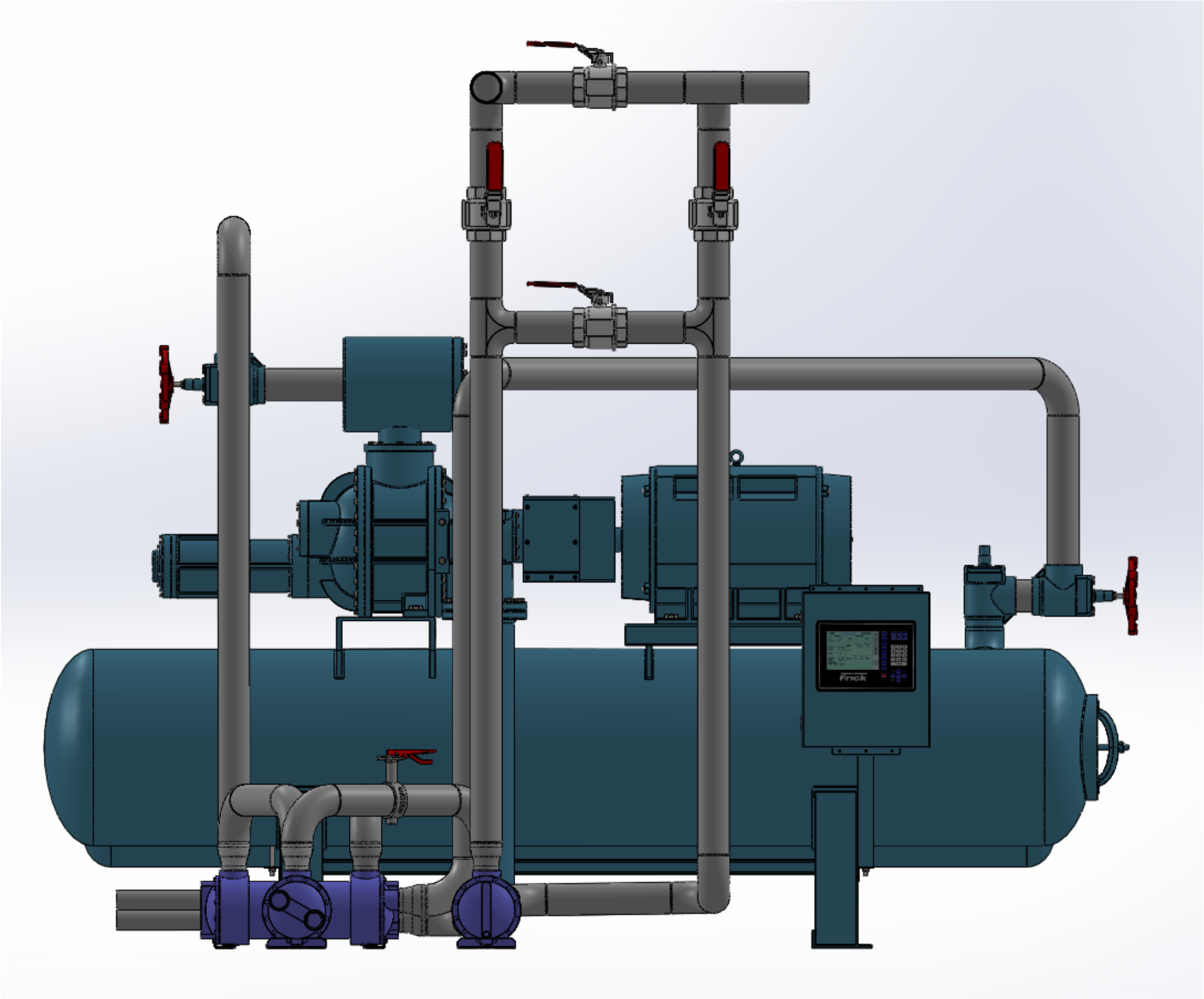
CAD Concepts for the PCU Simulator Listing Parts



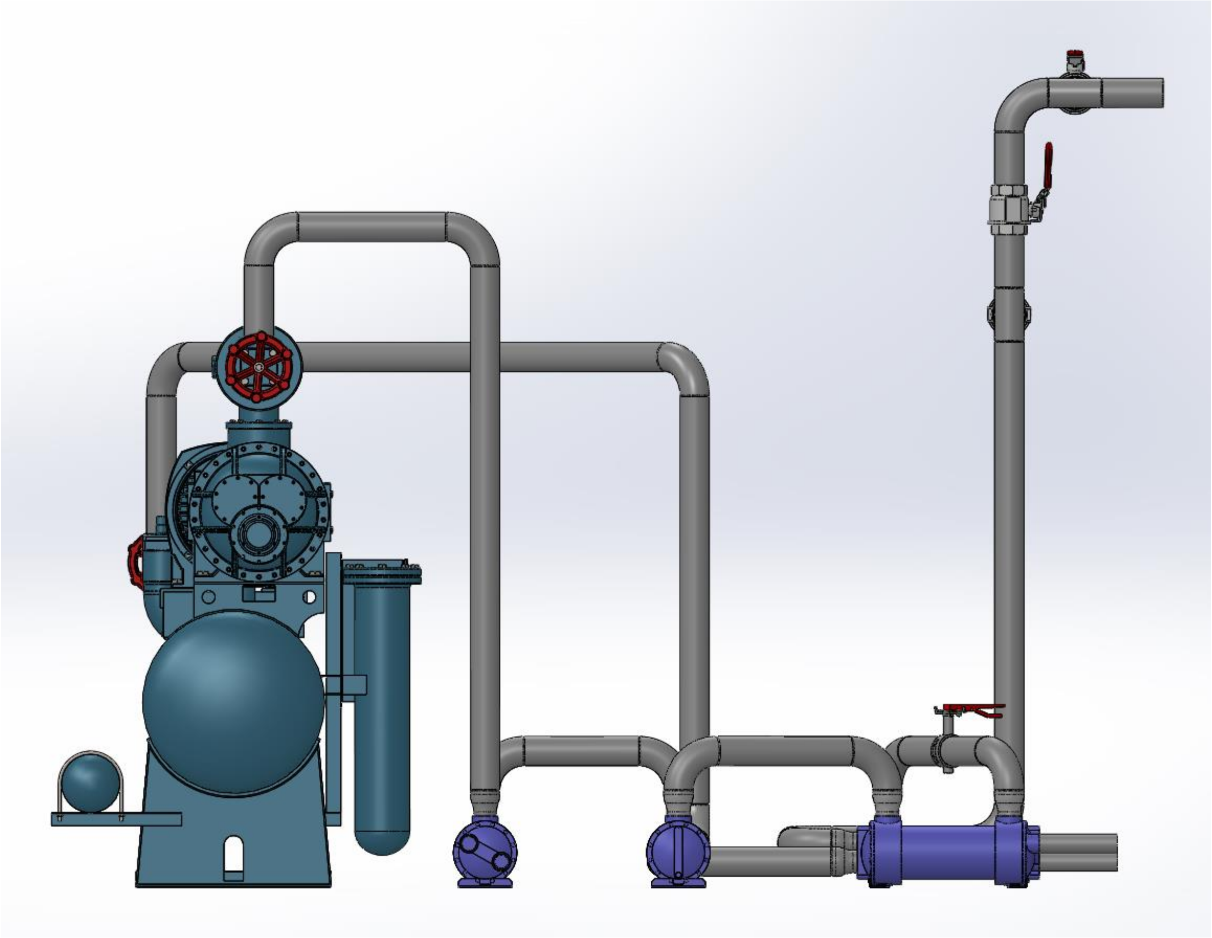
CAD Isometric View



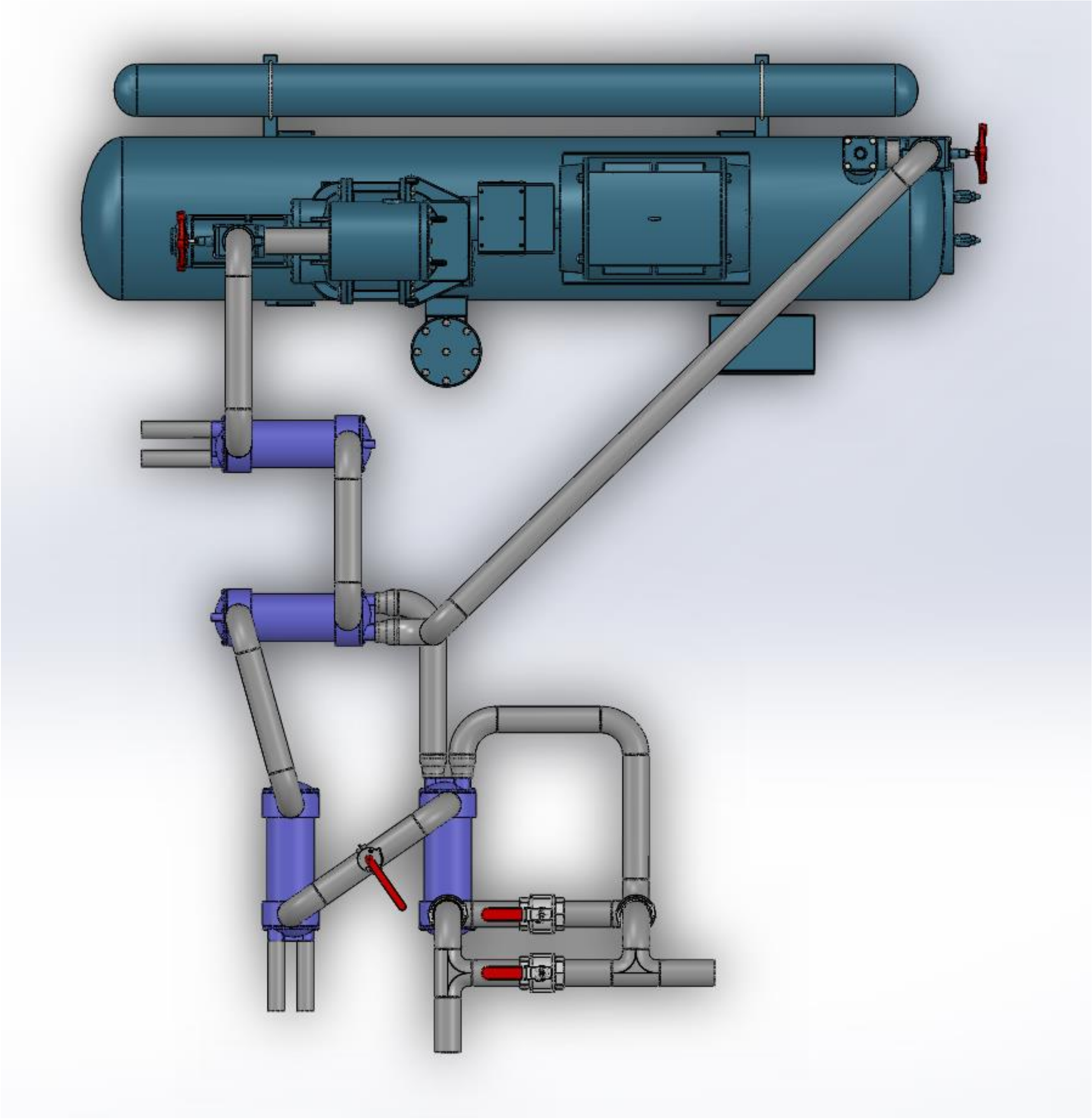
CAD Front View



CAD Side View

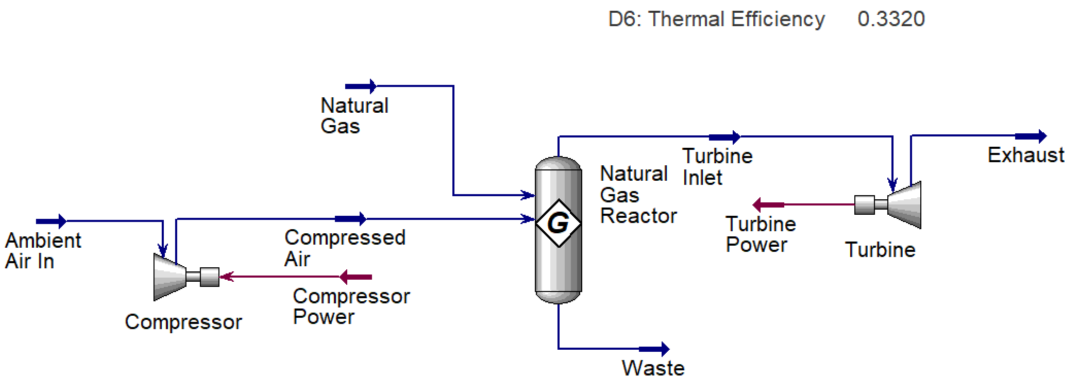


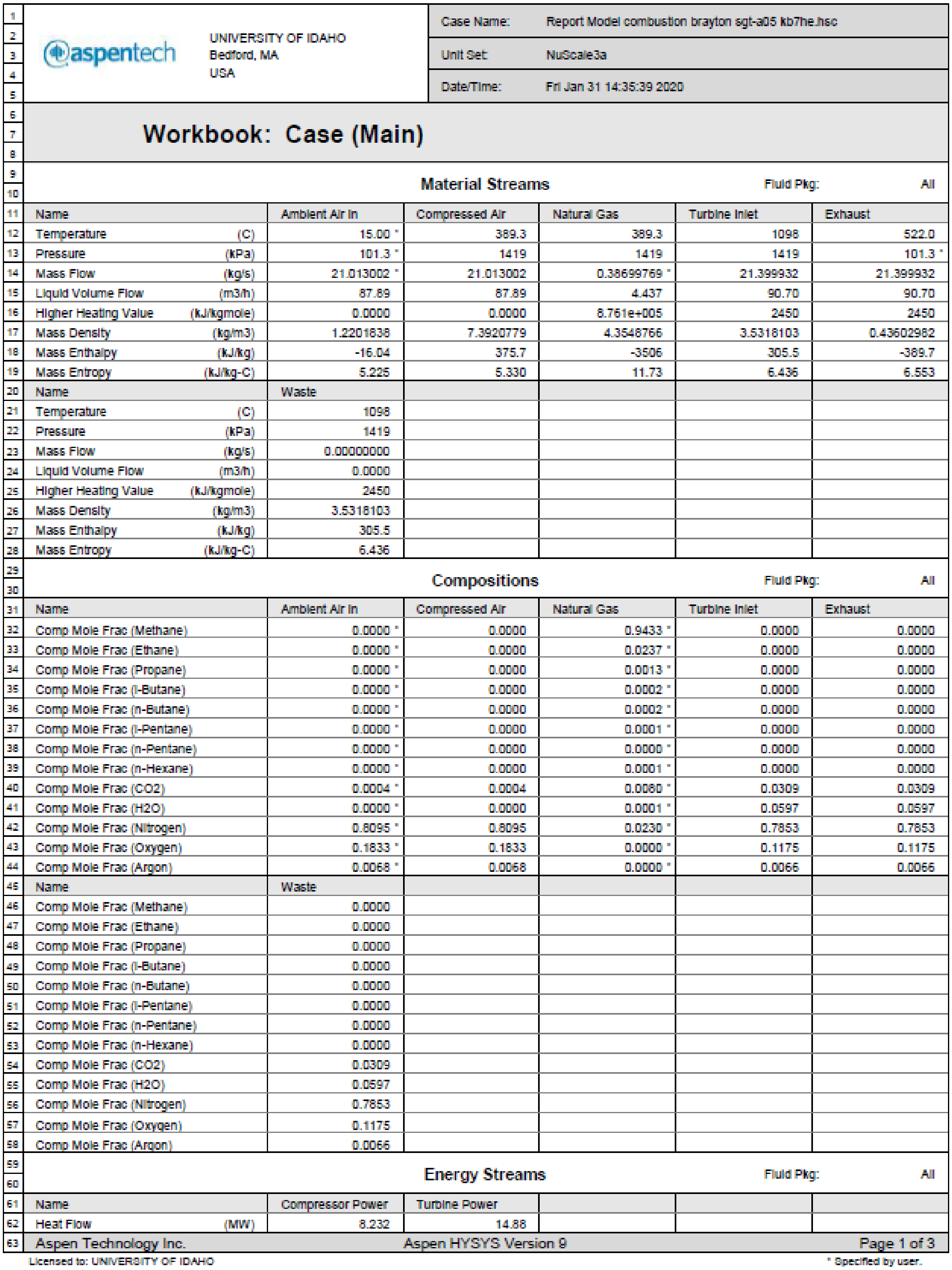
CAD Top View



Appendix M: Aspen HYSYS Models for PCU Start Up

Siemen's SGT-A05 H7KE Natural Gas Open Air Brayton Cycle at 1100°C Turbine Inlet Temperature with Compressor and Turbine Adiabatic Efficiencies of 83.1% and 88.7%





UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	Report Model combustion brayton sgt-a05 kb7he.hsc
Unit Set:	NuScale3a
Date/Time:	Fri Jan 31 14:35:39 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Ambient Air In	Compressed Air	Natural Gas	Turbine Inlet	Exhaust
Temperature	(C)	15.00 *	389.3	389.3	1098	522.0
Pressure	(kPa)	101.3 *	1419	1419	1419	101.3 *
Mass Flow	(kg/s)	21.013002 *	21.013002	0.38699769 *	21.399932	21.399932
Liquid Volume Flow	(m3/h)	87.89	87.89	4.437	90.70	90.70
Higher Heating Value	(kJ/kgmole)	0.0000	0.0000	8.761e+005	2450	2450
Mass Density	(kg/m3)	1.2201838	7.3920779	4.3548766	3.5318103	0.43602982
Mass Enthalpy	(kJ/kg)	-16.04	375.7	-3506	305.5	-389.7
Mass Entropy	(kJ/kg-C)	5.225	5.330	11.73	6.436	6.553
Name		Waste				
Temperature	(C)	1098				
Pressure	(kPa)	1419				
Mass Flow	(kg/s)	0.00000000				
Liquid Volume Flow	(m3/h)	0.0000				
Higher Heating Value	(kJ/kgmole)	2450				
Mass Density	(kg/m3)	3.5318103				
Mass Enthalpy	(kJ/kg)	305.5				
Mass Entropy	(kJ/kg-C)	6.436				

Compositions

Fluid Pkg: All

Name	Ambient Air In	Compressed Air	Natural Gas	Turbine Inlet	Exhaust
Comp Mole Frac (Methane)	0.0000 *	0.0000	0.9433 *	0.0000	0.0000
Comp Mole Frac (Ethane)	0.0000 *	0.0000	0.0237 *	0.0000	0.0000
Comp Mole Frac (Propane)	0.0000 *	0.0000	0.0013 *	0.0000	0.0000
Comp Mole Frac (i-Butane)	0.0000 *	0.0000	0.0002 *	0.0000	0.0000
Comp Mole Frac (n-Butane)	0.0000 *	0.0000	0.0002 *	0.0000	0.0000
Comp Mole Frac (i-Pentane)	0.0000 *	0.0000	0.0001 *	0.0000	0.0000
Comp Mole Frac (n-Pentane)	0.0000 *	0.0000	0.0000 *	0.0000	0.0000
Comp Mole Frac (n-Hexane)	0.0000 *	0.0000	0.0001 *	0.0000	0.0000
Comp Mole Frac (CO2)	0.0004 *	0.0004	0.0080 *	0.0309	0.0309
Comp Mole Frac (H2O)	0.0000 *	0.0000	0.0001 *	0.0597	0.0597
Comp Mole Frac (Nitrogen)	0.8095 *	0.8095	0.0230 *	0.7853	0.7853
Comp Mole Frac (Oxygen)	0.1833 *	0.1833	0.0000 *	0.1175	0.1175
Comp Mole Frac (Argon)	0.0068 *	0.0068	0.0000 *	0.0066	0.0066
Name	Waste				
Comp Mole Frac (Methane)	0.0000				
Comp Mole Frac (Ethane)	0.0000				
Comp Mole Frac (Propane)	0.0000				
Comp Mole Frac (i-Butane)	0.0000				
Comp Mole Frac (n-Butane)	0.0000				
Comp Mole Frac (i-Pentane)	0.0000				
Comp Mole Frac (n-Pentane)	0.0000				
Comp Mole Frac (n-Hexane)	0.0000				
Comp Mole Frac (CO2)	0.0309				
Comp Mole Frac (H2O)	0.0597				
Comp Mole Frac (Nitrogen)	0.7853				
Comp Mole Frac (Oxygen)	0.1175				
Comp Mole Frac (Argon)	0.0066				

Energy Streams

Fluid Pkg: All

Name		Compressor Power	Turbine Power			
Heat Flow	(MW)	8.232	14.88			

Aspen Technology Inc. Aspen HYSYS Version 9 Page 1 of 3

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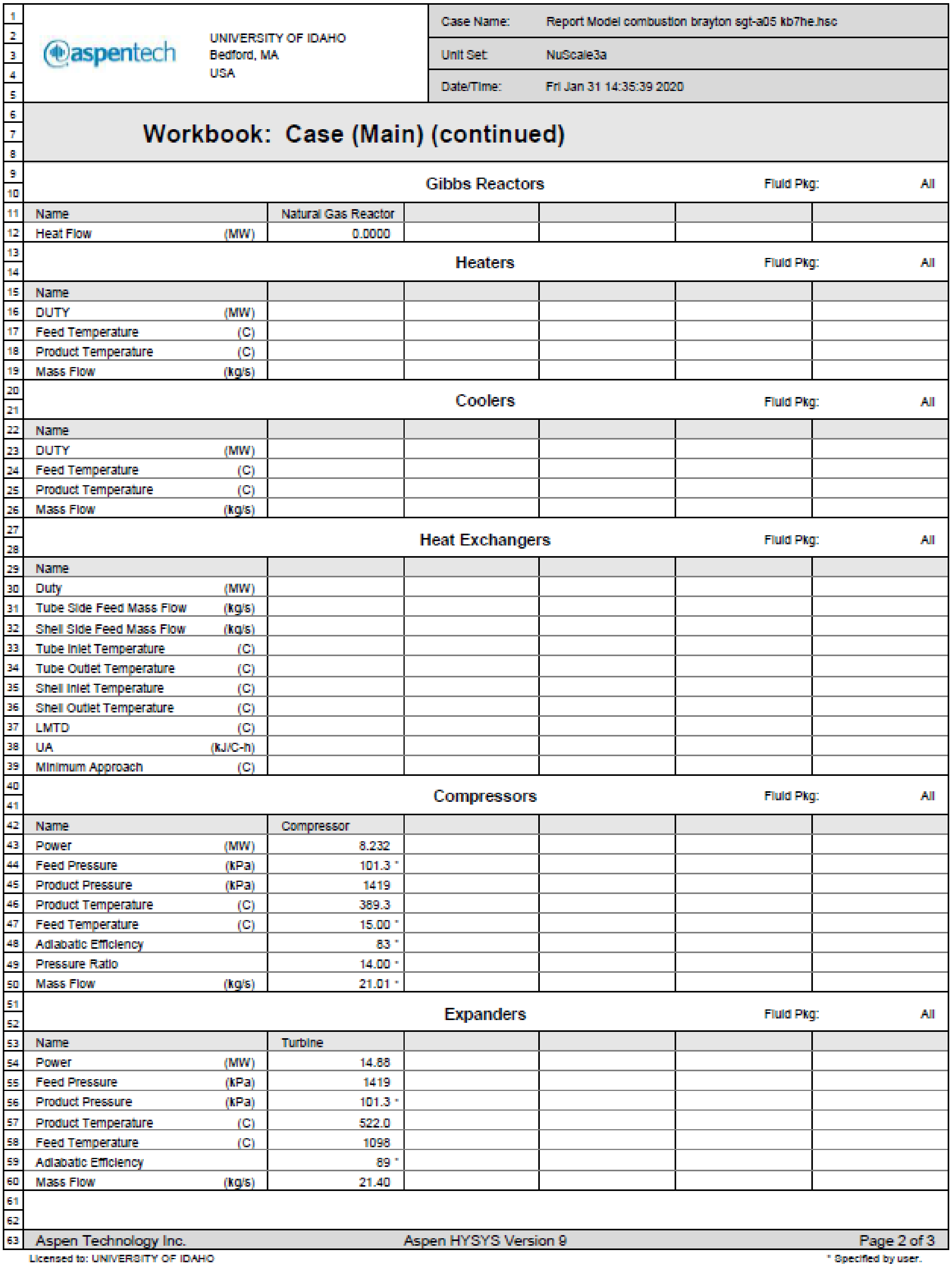
* Specified by user.



UNIVERSITY OF IDAHO Bedford, MA USA	Case Name:	Report Model combustion brayton sgt-a05 kb7he.hsc
	Unit Set:	NuScale3a
	Date/Time:	Fri Jan 31 14:35:39 2020

Workbook: Case (Main) (continued)

Gibbs Reactors

Fluid Pkg: All

Name	Natural Gas Reactor				
Heat Flow (MW)	0.0000				

Heaters

Fluid Pkg: All

Name					
DUTY (MW)					
Feed Temperature (C)					
Product Temperature (C)					
Mass Flow (kg/s)					

Coolers

Fluid Pkg: All

Name					
DUTY (MW)					
Feed Temperature (C)					
Product Temperature (C)					
Mass Flow (kg/s)					

Heat Exchangers

Fluid Pkg: All

Name					
Duty (MW)					
Tube Side Feed Mass Flow (kg/s)					
Shell Side Feed Mass Flow (kg/s)					
Tube Inlet Temperature (C)					
Tube Outlet Temperature (C)					
Shell Inlet Temperature (C)					
Shell Outlet Temperature (C)					
LMTD (C)					
UA (kJ/C-h)					
Minimum Approach (C)					

Compressors

Fluid Pkg: All

Name	Compressor				
Power (MW)	8.232				
Feed Pressure (kPa)	101.3 *				
Product Pressure (kPa)	1419				
Product Temperature (C)	389.3				
Feed Temperature (C)	15.00 *				
Adiabatic Efficiency	83 *				
Pressure Ratio	14.00 *				
Mass Flow (kg/s)	21.01 *				

Expanders

Fluid Pkg: All

Name	Turbine				
Power (MW)	14.88				
Feed Pressure (kPa)	1419				
Product Pressure (kPa)	101.3 *				
Product Temperature (C)	522.0				
Feed Temperature (C)	1098				
Adiabatic Efficiency	89 *				
Mass Flow (kg/s)	21.40				

Aspen Technology Inc. Aspen HYSYS Version 9 Page 2 of 3

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* Specified by user.

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	Report Model combustion brayton sgt-a05 kb7he.hsc
Unit Set:	NuScale3a
Date/Time:	Fri Jan 31 14:35:39 2020

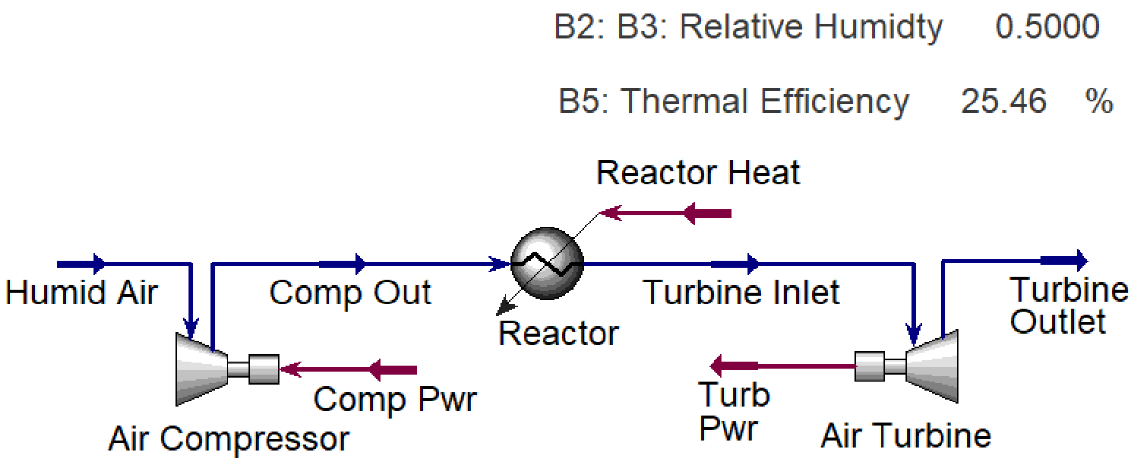
Workbook: Case (Main) (continued)

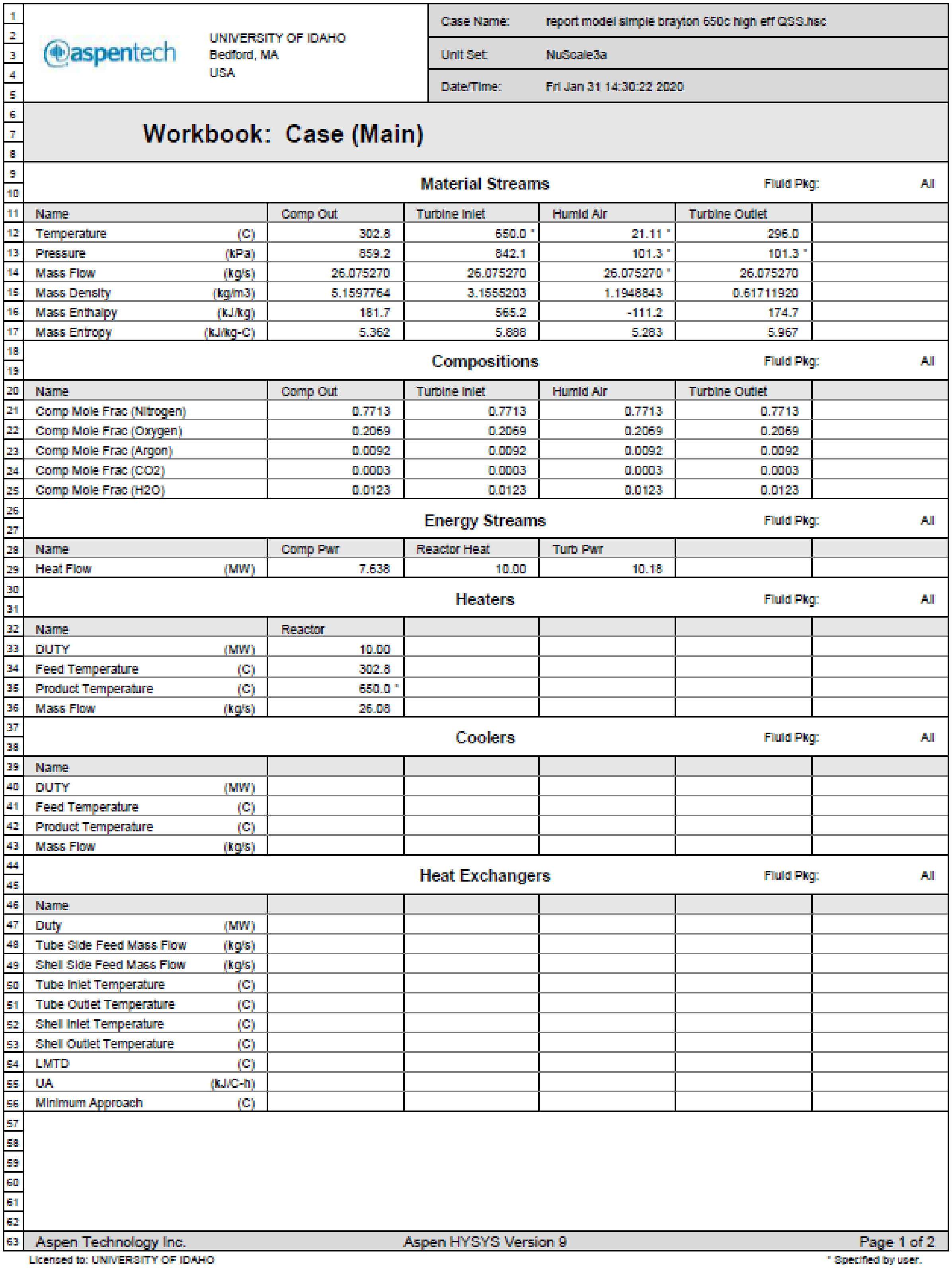
Valves

Fluid Pkg: All

Name							
Pressure Drop	(kPa)						
Feed Pressure	(kPa)						
Feed Temperature	(C)						
Product Pressure	(kPa)						
Product Temperature	(C)						
Mass Flow	(kg/s)						
Cg							
Resistance (Cv or K)							

Open Air Brayton Cycle at 650°C Turbine Inlet Temperature with 10 MW Reactor Power and Compressor and Turbine Adiabatic Efficiencies of 85% and 90%





UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	report model simple brayton 650c high eff QSS.hsc
Unit Set:	NuScale3a
Date/Time:	Fri Jan 31 14:30:22 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Comp Out	Turbine Inlet	Humid Air	Turbine Outlet	
Temperature	(C)	302.8	650.0 *	21.11 *	296.0	
Pressure	(kPa)	859.2	842.1	101.3 *	101.3 *	
Mass Flow	(kg/s)	26.075270	26.075270	26.075270 *	26.075270	
Mass Density	(kg/m3)	5.1597764	3.1555203	1.1948843	0.61711920	
Mass Enthalpy	(kJ/kg)	181.7	565.2	-111.2	174.7	
Mass Entropy	(kJ/kg-C)	5.362	5.888	5.283	5.967	

Compositions

Fluid Pkg: All

Name	Comp Out	Turbine Inlet	Humid Air	Turbine Outlet	
Comp Mole Frac (Nitrogen)	0.7713	0.7713	0.7713	0.7713	
Comp Mole Frac (Oxygen)	0.2069	0.2069	0.2069	0.2069	
Comp Mole Frac (Argon)	0.0092	0.0092	0.0092	0.0092	
Comp Mole Frac (CO2)	0.0003	0.0003	0.0003	0.0003	
Comp Mole Frac (H2O)	0.0123	0.0123	0.0123	0.0123	

Energy Streams

Fluid Pkg: All

Name		Comp Pwr	Reactor Heat	Turb Pwr		
Heat Flow	(MW)	7.638	10.00	10.18		

Heaters

Fluid Pkg: All

Name		Reactor				
DUTY	(MW)	10.00				
Feed Temperature	(C)	302.8				
Product Temperature	(C)	650.0 *				
Mass Flow	(kg/s)	26.08				

Coolers

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

Heat Exchangers

Fluid Pkg: All

Name						
Duty	(MW)					
Tube Side Feed Mass Flow	(kg/s)					
Shell Side Feed Mass Flow	(kg/s)					
Tube Inlet Temperature	(C)					
Tube Outlet Temperature	(C)					
Shell Inlet Temperature	(C)					
Shell Outlet Temperature	(C)					
LMTD	(C)					
UA	(kJ/C-h)					
Minimum Approach	(C)					

Aspen Technology Inc. Aspen HYSYS Version 9 Page 1 of 2

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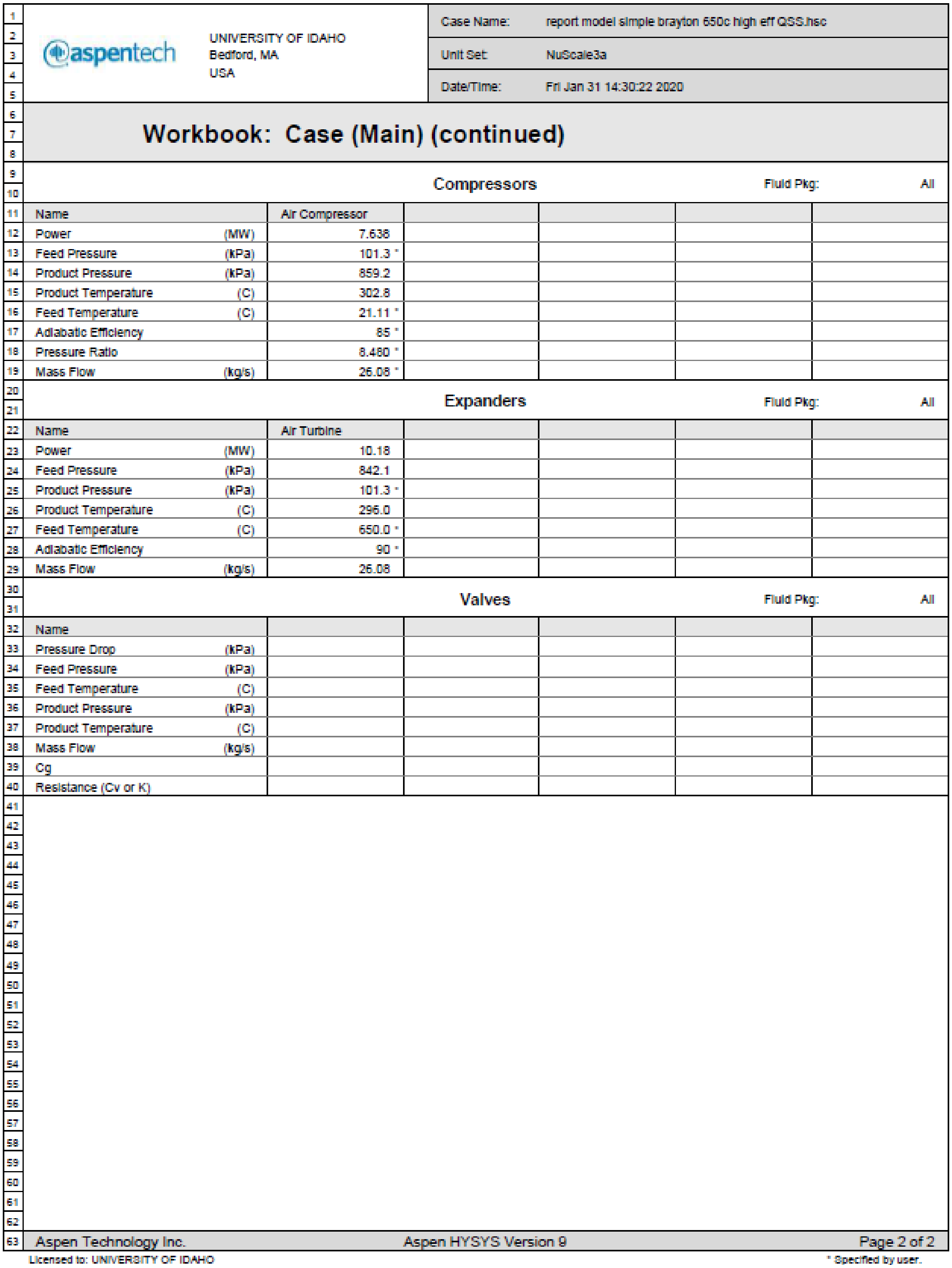
* Specified by user.



aspentech

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: report model simple brayton 650c high eff QSS.hsc

Unit Set: NuScale3a

Date/Time: Fri Jan 31 14:30:22 2020

Workbook: Case (Main) (continued)

Compressors

Fluid Pkg: All

Name	Air Compressor				
Power (MW)	7.636				
Feed Pressure (kPa)	101.3 *				
Product Pressure (kPa)	859.2				
Product Temperature (C)	302.8				
Feed Temperature (C)	21.11 *				
Adiabatic Efficiency	85 *				
Pressure Ratio	8.480 *				
Mass Flow (kg/s)	26.08 *				

Expanders

Fluid Pkg: All

Name	Air Turbine				
Power (MW)	10.18				
Feed Pressure (kPa)	842.1				
Product Pressure (kPa)	101.3 *				
Product Temperature (C)	296.0				
Feed Temperature (C)	650.0 *				
Adiabatic Efficiency	90 *				
Mass Flow (kg/s)	26.08				

Valves

Fluid Pkg: All

Name					
Pressure Drop (kPa)					
Feed Pressure (kPa)					
Feed Temperature (C)					
Product Pressure (kPa)					
Product Temperature (C)					
Mass Flow (kg/s)					
Cg					
Resistance (Cv or K)					

Aspen Technology Inc. Aspen HYSYS Version 9 Page 2 of 2

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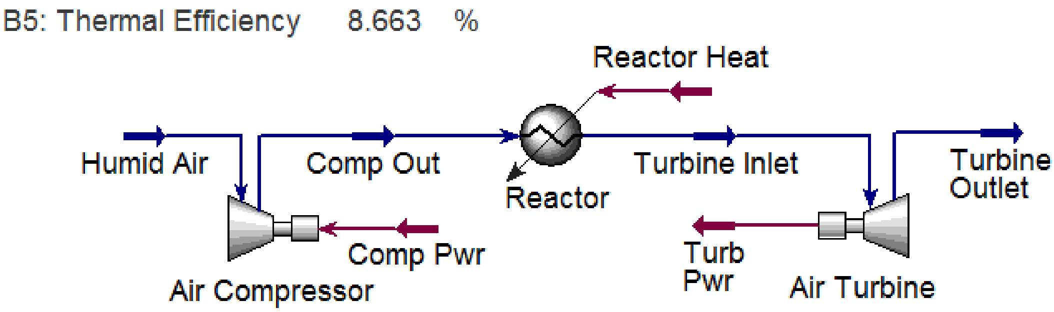
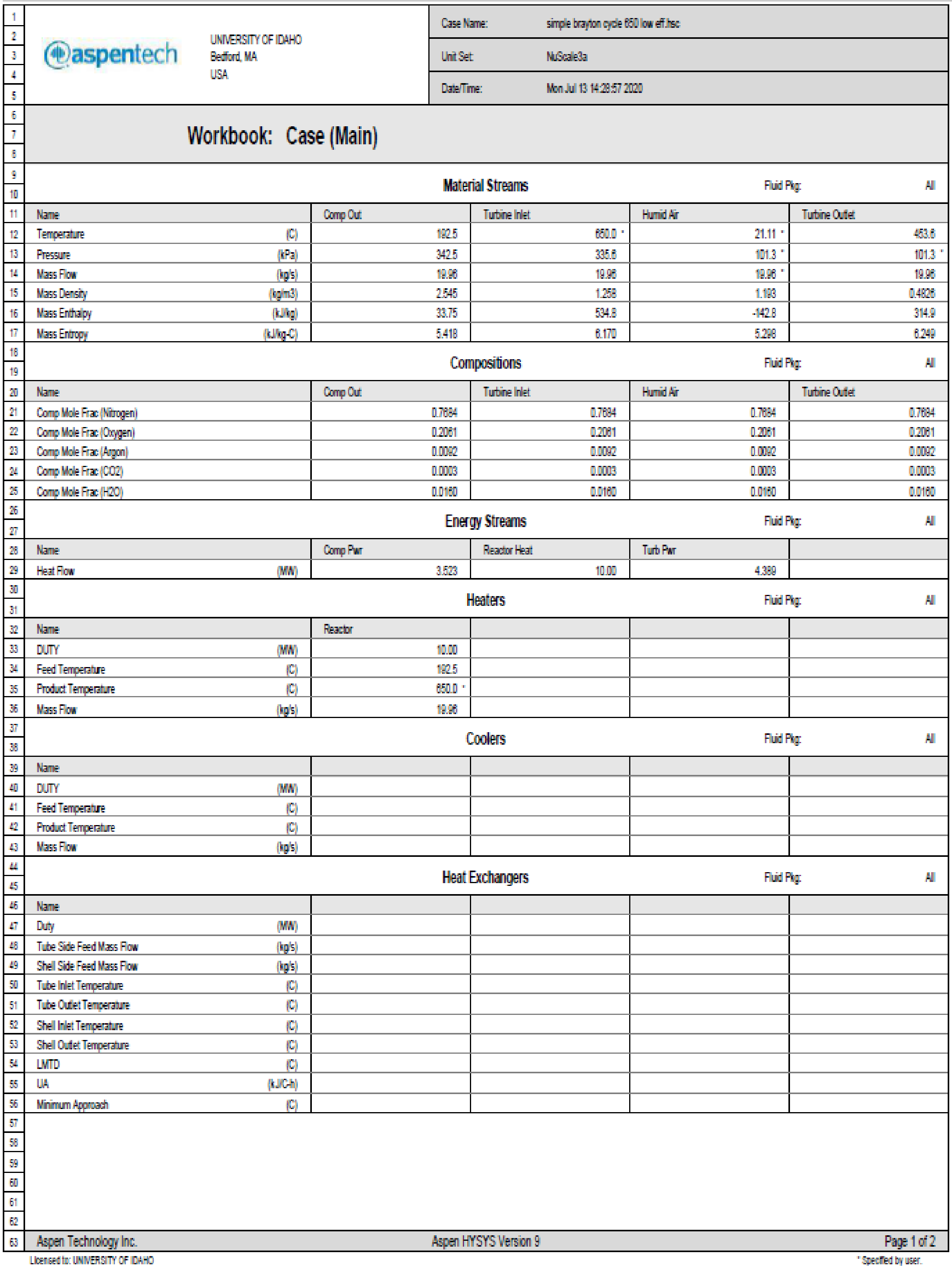
Open Air Brayton cycle at 650° Turbine Inlet Temperature with 10 MW Reactor Power and Compressor and Turbine Adiabatic Efficiencies of 70% and 80%





UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	simple brayton cycle 650 low eff.hsc
Unit Set:	NuScale3a
Date/Time:	Mon Jul 13 14:28:57 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Comp Out	Turbine Inlet	Humid Air	Turbine Outlet
Temperature	(C)	192.5	650.0 *	21.11 *	453.6
Pressure	(kPa)	342.5	335.6	101.3 *	101.3 *
Mass Flow	(kg/s)	19.96	19.96	19.96 *	19.96
Mass Density	(kg/m3)	2.545	1.258	1.193	0.4826
Mass Enthalpy	(kJ/kg)	33.75	534.8	-142.8	314.9
Mass Entropy	(kJ/kg-C)	5.418	6.170	5.298	6.249

Compositions

Fluid Pkg: All

Name	Comp Out	Turbine Inlet	Humid Air	Turbine Outlet
Comp Mole Frac (Nitrogen)	0.7684	0.7684	0.7684	0.7684
Comp Mole Frac (Oxygen)	0.2061	0.2061	0.2061	0.2061
Comp Mole Frac (Argon)	0.0092	0.0092	0.0092	0.0092
Comp Mole Frac (CO2)	0.0003	0.0003	0.0003	0.0003
Comp Mole Frac (H2O)	0.0160	0.0160	0.0160	0.0160

Energy Streams

Fluid Pkg: All

Name		Comp Pwr	Reactor Heat	Turb Pwr	
Heat Flow	(MW)	3.523	10.00	4.389	

Heaters

Fluid Pkg: All

Name		Reactor			
DUTY	(MW)	10.00			
Feed Temperature	(C)	192.5			
Product Temperature	(C)	650.0 *			
Mass Flow	(kg/s)	19.96			

Coolers

Fluid Pkg: All

Name					
DUTY	(MW)				
Feed Temperature	(C)				
Product Temperature	(C)				
Mass Flow	(kg/s)				

Heat Exchangers

Fluid Pkg: All

Name					
Duty	(MW)				
Tube Side Feed Mass Flow	(kg/s)				
Shell Side Feed Mass Flow	(kg/s)				
Tube Inlet Temperature	(C)				
Tube Outlet Temperature	(C)				
Shell Inlet Temperature	(C)				
Shell Outlet Temperature	(C)				
LMTD	(C)				
UA	(kJ/C-h)				
Minimum Approach	(C)				

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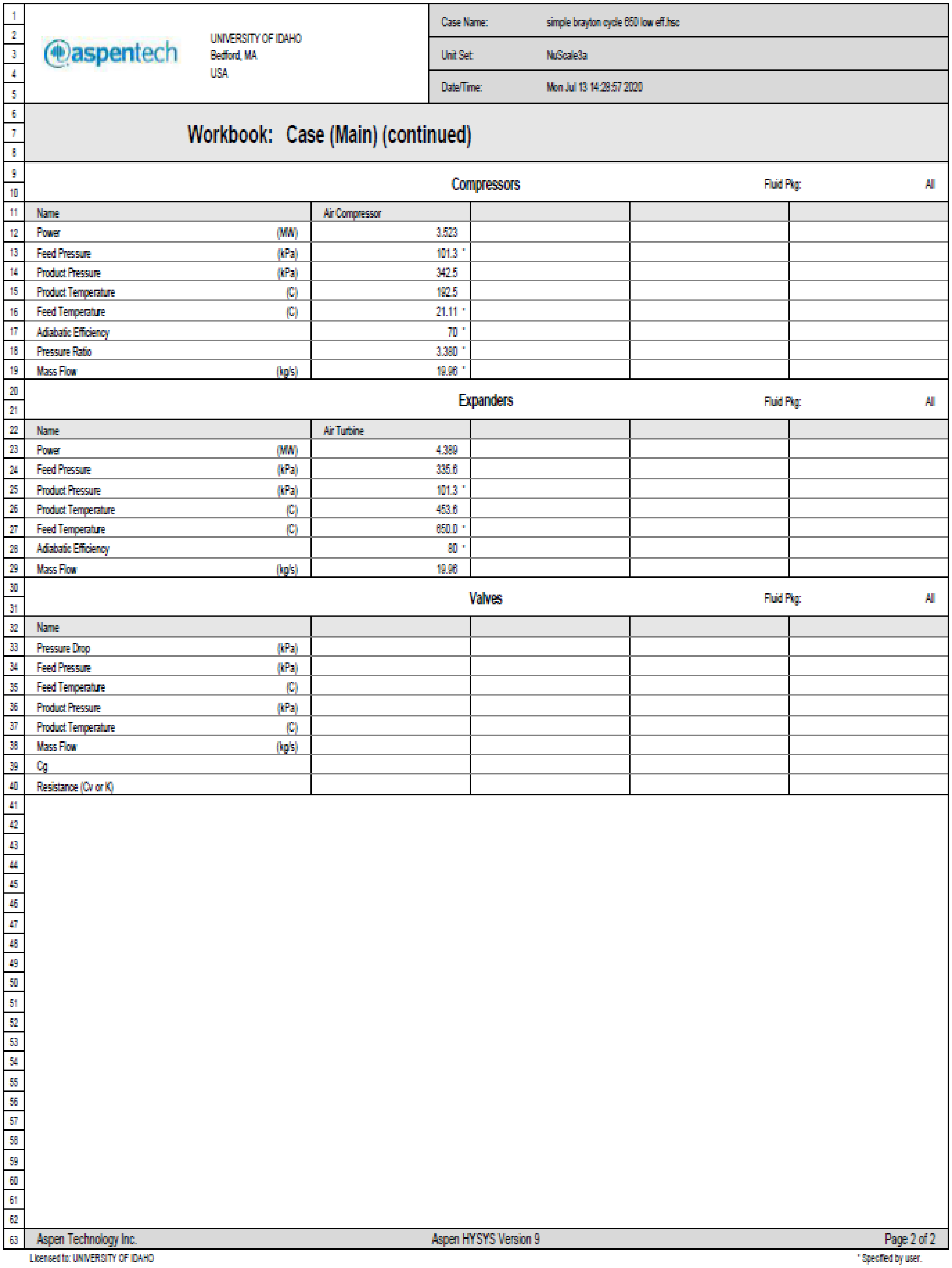

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name: simple brayton cycle 650 low eff.hsc
Unit Set: NuScale3a
Date/Time: Mon Jul 13 14:28:57 2020

Workbook: Case (Main) (continued)

Compressors

Fluid Pkg: All

Name		Air Compressor			
Power	(MW)	3.523			
Feed Pressure	(kPa)	101.3 *			
Product Pressure	(kPa)	342.5			
Product Temperature	(C)	192.5			
Feed Temperature	(C)	21.11 *			
Adiabatic Efficiency		70 *			
Pressure Ratio		3.380 *			
Mass Flow	(kg/s)	19.96 *			

Expanders

Fluid Pkg: All

Name		Air Turbine			
Power	(MW)	4.389			
Feed Pressure	(kPa)	335.6			
Product Pressure	(kPa)	101.3 *			
Product Temperature	(C)	453.6			
Feed Temperature	(C)	650.0 *			
Adiabatic Efficiency		80 *			
Mass Flow	(kg/s)	19.96			

Valves

Fluid Pkg: All

Name					
Pressure Drop	(kPa)				
Feed Pressure	(kPa)				
Feed Temperature	(C)				
Product Pressure	(kPa)				
Product Temperature	(C)				
Mass Flow	(kg/s)				
Cg					
Resistance (Cv or K)					

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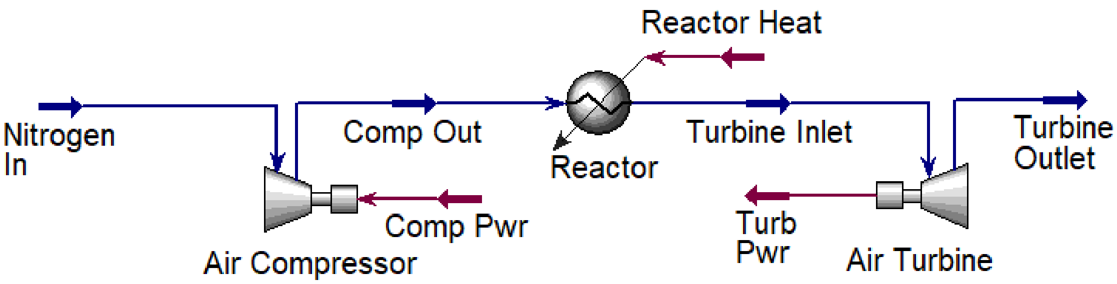
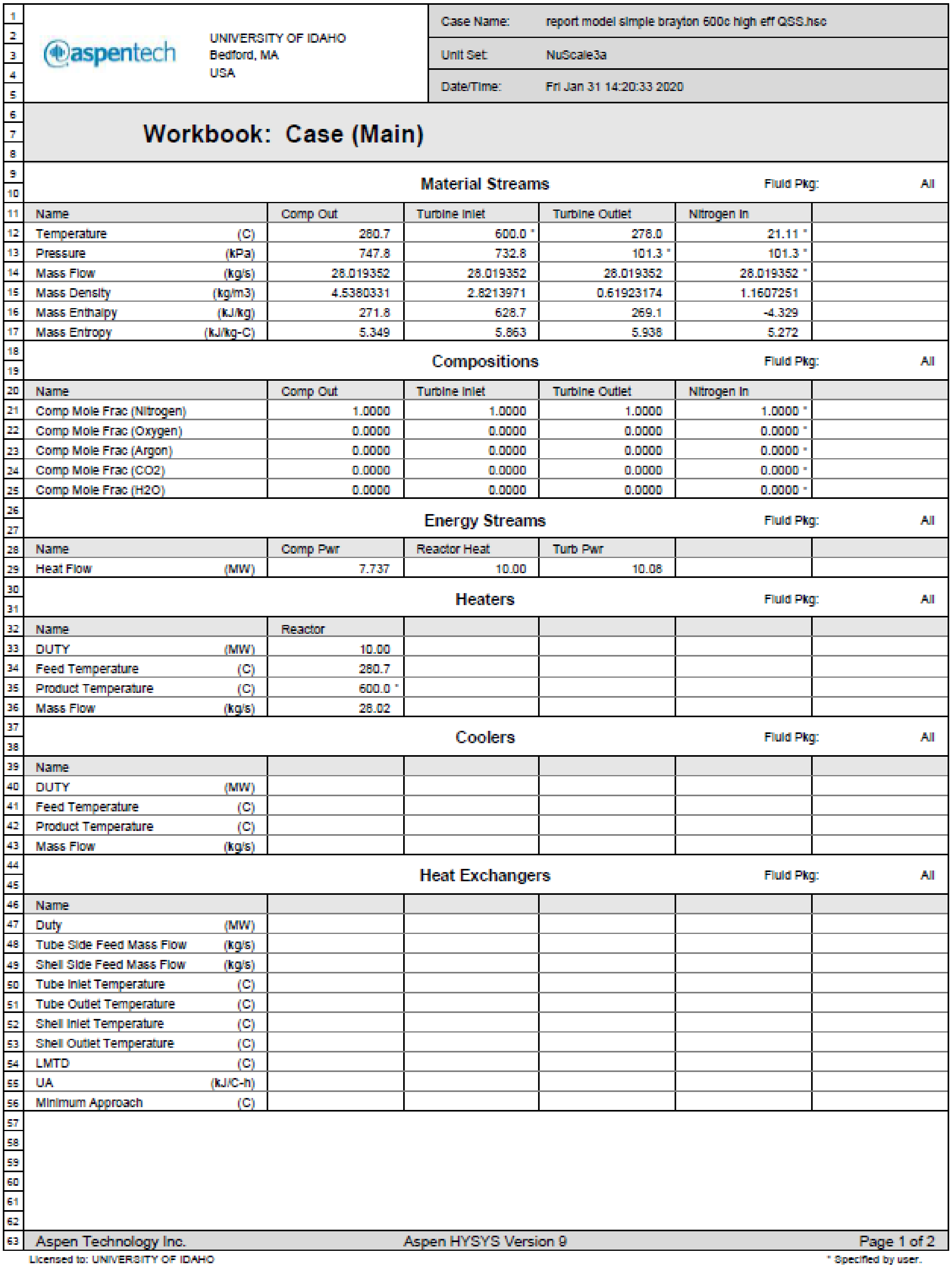
Nitrogen Brayton Cycle at 600°C Turbine Inlet Temperature with 10 MW Reactor Power and Compressor and Turbine Adiabatic Efficiencies of 85% and 90%

B5: Thermal Efficiency 23.39 %





UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	report model simple brayton 600c high eff QSS.hsc
Unit Set:	NuScale3a
Date/Time:	Fri Jan 31 14:20:33 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Comp Out	Turbine Inlet	Turbine Outlet	Nitrogen In	
Temperature	(C)	280.7	600.0 *	276.0	21.11 *	
Pressure	(kPa)	747.8	732.8	101.3 *	101.3 *	
Mass Flow	(kg/s)	28.019352	28.019352	28.019352	28.019352 *	
Mass Density	(kg/m3)	4.5380331	2.8213971	0.61923174	1.1607251	
Mass Enthalpy	(kJ/kg)	271.8	628.7	269.1	-4.329	
Mass Entropy	(kJ/kg-C)	5.349	5.863	5.938	5.272	

Compositions

Fluid Pkg: All

Name	Comp Out	Turbine Inlet	Turbine Outlet	Nitrogen In	
Comp Mole Frac (Nitrogen)	1.0000	1.0000	1.0000	1.0000 *	
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.0000	0.0000 *	
Comp Mole Frac (Argon)	0.0000	0.0000	0.0000	0.0000 *	
Comp Mole Frac (CO2)	0.0000	0.0000	0.0000	0.0000 *	
Comp Mole Frac (H2O)	0.0000	0.0000	0.0000	0.0000 *	

Energy Streams

Fluid Pkg: All

Name		Comp Pwr	Reactor Heat	Turb Pwr		
Heat Flow	(MW)	7.737	10.00	10.08		

Heaters

Fluid Pkg: All

Name		Reactor				
DUTY	(MW)	10.00				
Feed Temperature	(C)	280.7				
Product Temperature	(C)	600.0 *				
Mass Flow	(kg/s)	28.02				

Coolers

Fluid Pkg: All

Name						
DUTY	(MW)					
Feed Temperature	(C)					
Product Temperature	(C)					
Mass Flow	(kg/s)					

Heat Exchangers

Fluid Pkg: All

Name						
Duty	(MW)					
Tube Side Feed Mass Flow	(kg/s)					
Shell Side Feed Mass Flow	(kg/s)					
Tube Inlet Temperature	(C)					
Tube Outlet Temperature	(C)					
Shell Inlet Temperature	(C)					
Shell Outlet Temperature	(C)					
LMTD	(C)					
UA	(kJ/C-h)					
Minimum Approach	(C)					

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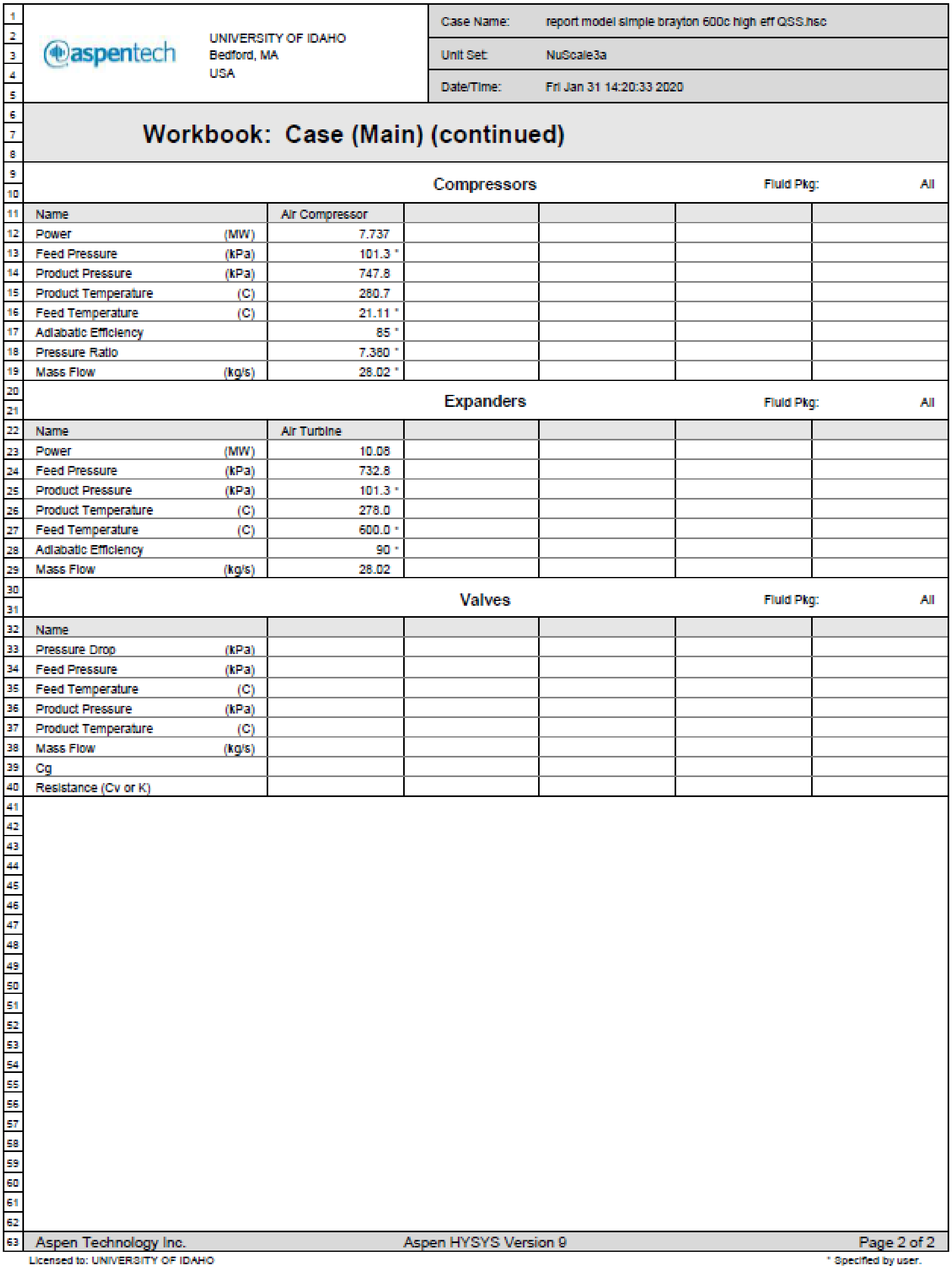

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	report model simple brayton 600c high eff QSS.hsc
Unit Set:	NuScale3a
Date/Time:	Fri Jan 31 14:20:33 2020

Workbook: Case (Main) (continued)

Compressors

Fluid Pkg: All

Name		Air Compressor				
Power	(MW)	7.737				
Feed Pressure	(kPa)	101.3 *				
Product Pressure	(kPa)	747.8				
Product Temperature	(C)	280.7				
Feed Temperature	(C)	21.11 *				
Adiabatic Efficiency		85 *				
Pressure Ratio		7.380 *				
Mass Flow	(kg/s)	28.02 *				

Expanders

Fluid Pkg: All

Name		Air Turbine				
Power	(MW)	10.08				
Feed Pressure	(kPa)	732.8				
Product Pressure	(kPa)	101.3 *				
Product Temperature	(C)	278.0				
Feed Temperature	(C)	600.0 *				
Adiabatic Efficiency		90 *				
Mass Flow	(kg/s)	28.02				

Valves

Fluid Pkg: All

Name						
Pressure Drop	(kPa)					
Feed Pressure	(kPa)					
Feed Temperature	(C)					
Product Pressure	(kPa)					
Product Temperature	(C)					
Mass Flow	(kg/s)					
Cg						
Resistance (Cv or K)						

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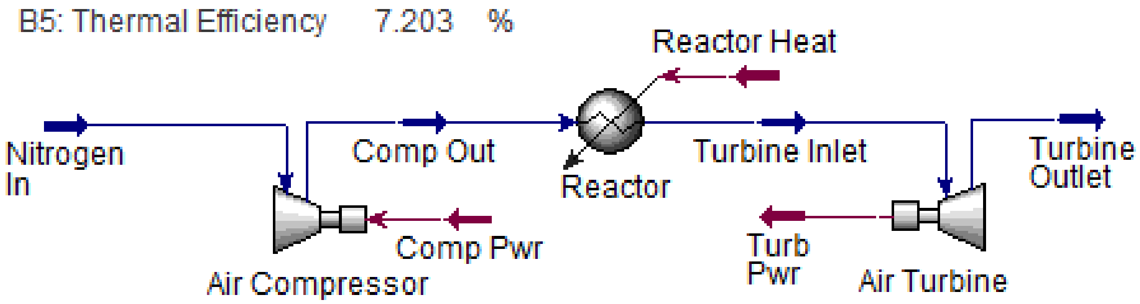
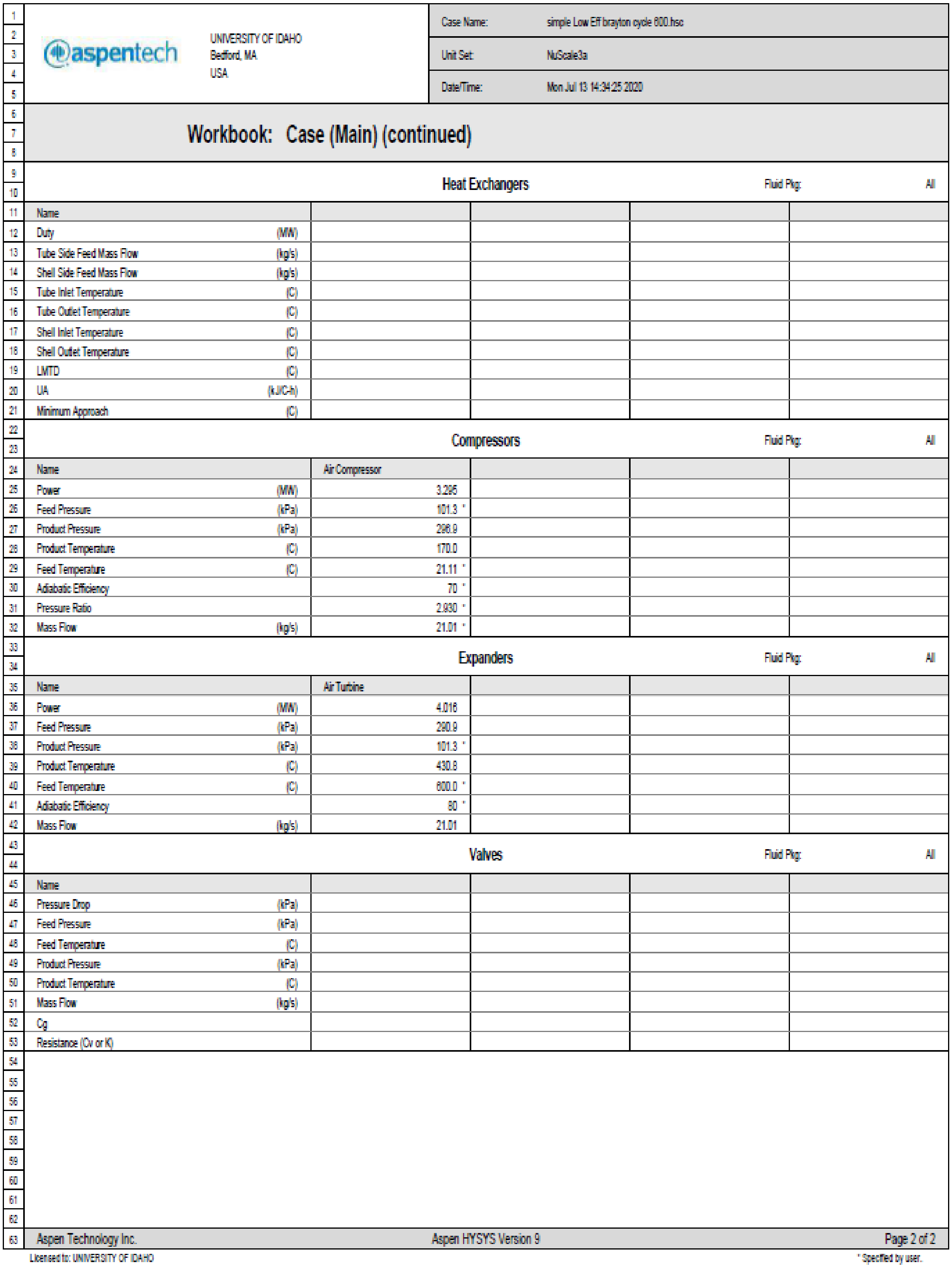
Nitrogen Brayton Cycle at 600°C Turbine Inlet Temperature with 10 MW Reactor Power and Compressor and Turbine Adiabatic Efficiencies of 70% and 80%





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UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	simple Low Eff brayton cycle 600.hsc
Unit Set:	NuScale3a
Date/Time:	Mon Jul 13 14:34:25 2020

Workbook: Case (Main) (continued)

Heat Exchangers

Fluid Pkg: All

Name					
Duty	(MW)				
Tube Side Feed Mass Flow	(kg/s)				
Shell Side Feed Mass Flow	(kg/s)				
Tube Inlet Temperature	(C)				
Tube Outlet Temperature	(C)				
Shell Inlet Temperature	(C)				
Shell Outlet Temperature	(C)				
LMTD	(C)				
UA	(kJ/C-h)				
Minimum Approach	(C)				

Compressors

Fluid Pkg: All

Name		Air Compressor			
Power	(MW)	3.295			
Feed Pressure	(kPa)	101.3 *			
Product Pressure	(kPa)	296.9			
Product Temperature	(C)	170.0			
Feed Temperature	(C)	21.11 *			
Adiabatic Efficiency		70 *			
Pressure Ratio		2.930 *			
Mass Flow	(kg/s)	21.01 *			

Expanders

Fluid Pkg: All

Name		Air Turbine			
Power	(MW)	4.016			
Feed Pressure	(kPa)	290.9			
Product Pressure	(kPa)	101.3 *			
Product Temperature	(C)	430.8			
Feed Temperature	(C)	600.0 *			
Adiabatic Efficiency		80 *			
Mass Flow	(kg/s)	21.01			

Valves

Fluid Pkg: All

Name					
Pressure Drop	(kPa)				
Feed Pressure	(kPa)				
Feed Temperature	(C)				
Product Pressure	(kPa)				
Product Temperature	(C)				
Mass Flow	(kg/s)				
Cg					
Resistance (Cv or K)					

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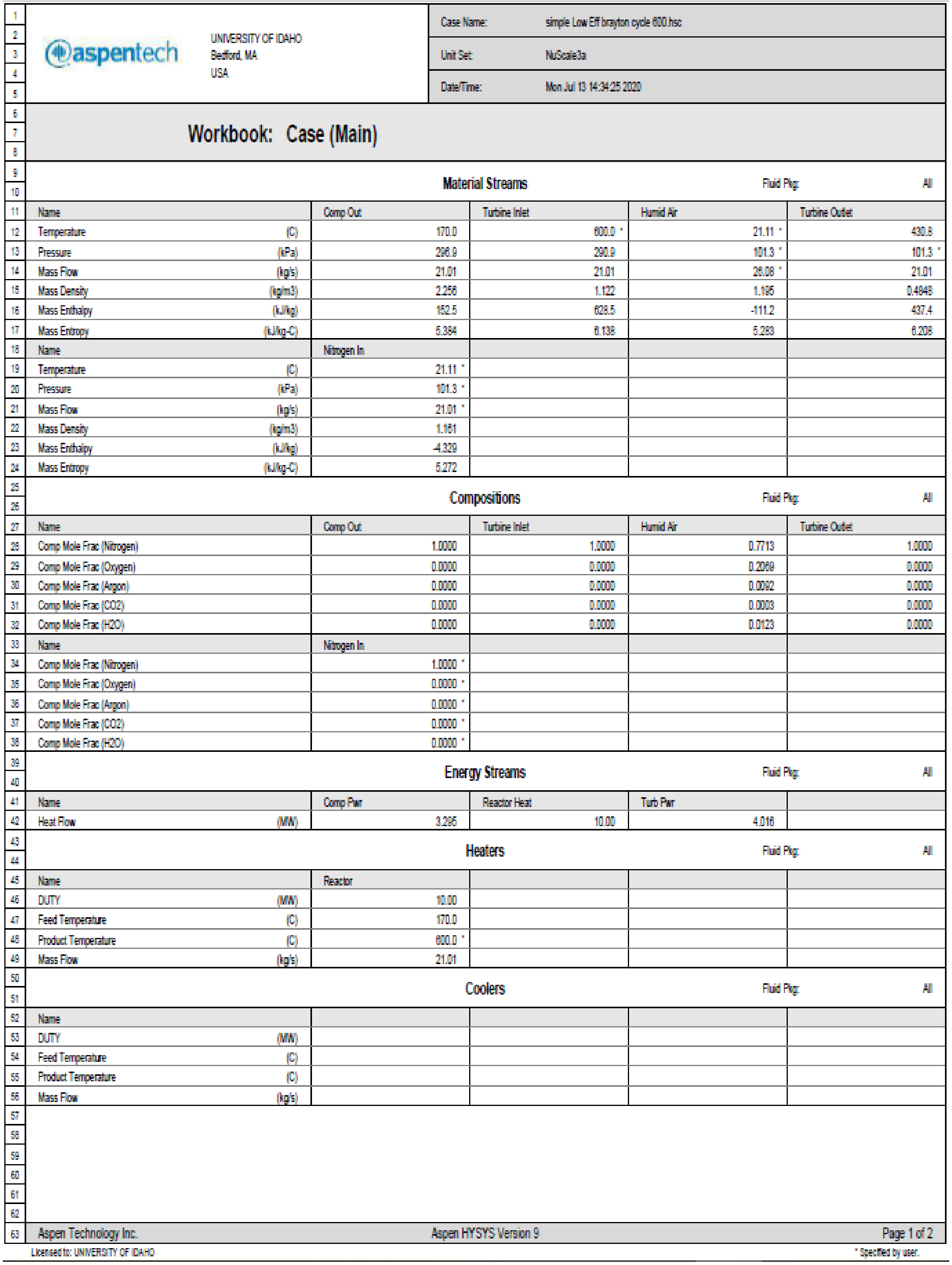

UNIVERSITY OF IDAHO
Bedford, MA
USA

Case Name:	simple Low Eff brayton cycle 600.hsc
Unit Set:	NuScale3a
Date/Time:	Mon Jul 13 14:34:25 2020

Workbook: Case (Main)

Material Streams

Fluid Pkg: All

Name		Comp Out	Turbine Inlet	Humid Air	Turbine Outlet
Temperature	(C)	170.0	600.0 *	21.11 *	430.8
Pressure	(kPa)	296.9	290.9	101.3 *	101.3 *
Mass Flow	(kg/s)	21.01	21.01	26.08 *	21.01
Mass Density	(kg/m3)	2.256	1.122	1.195	0.4848
Mass Enthalpy	(kJ/kg)	152.5	628.5	-111.2	437.4
Mass Entropy	(kJ/kg-C)	5.384	6.138	5.283	6.208
Name		Nitrogen In			
Temperature	(C)	21.11 *			
Pressure	(kPa)	101.3 *			
Mass Flow	(kg/s)	21.01 *			
Mass Density	(kg/m3)	1.161			
Mass Enthalpy	(kJ/kg)	-4.329			
Mass Entropy	(kJ/kg-C)	5.272			

Compositions

Fluid Pkg: All

Name	Comp Out	Turbine Inlet	Humid Air	Turbine Outlet
Comp Mole Frac (Nitrogen)	1.0000	1.0000	0.7713	1.0000
Comp Mole Frac (Oxygen)	0.0000	0.0000	0.2069	0.0000
Comp Mole Frac (Argon)	0.0000	0.0000	0.0092	0.0000
Comp Mole Frac (CO2)	0.0000	0.0000	0.0003	0.0000
Comp Mole Frac (H2O)	0.0000	0.0000	0.0123	0.0000
Name	Nitrogen In			
Comp Mole Frac (Nitrogen)	1.0000 *			
Comp Mole Frac (Oxygen)	0.0000 *			
Comp Mole Frac (Argon)	0.0000 *			
Comp Mole Frac (CO2)	0.0000 *			
Comp Mole Frac (H2O)	0.0000 *			

Energy Streams

Fluid Pkg: All

Name		Comp Pwr	Reactor Heat	Turb Pwr	
Heat Flow	(MW)	3.295	10.00	4.016	

Heaters

Fluid Pkg: All

Name		Reactor			
DUTY	(MW)	10.00			
Feed Temperature	(C)	170.0			
Product Temperature	(C)	600.0 *			
Mass Flow	(kg/s)	21.01			

Coolers

Fluid Pkg: All

Name					
DUTY	(MW)				
Feed Temperature	(C)				
Product Temperature	(C)				
Mass Flow	(kg/s)				

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