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Revision 0

Thermal Extraction Modeling within HYBRID: Nominal and Extraction Conditions in Advanced Reactor Systems

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IES
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ABSTRACT

This document details continuing development of thermal extraction modeling within the HYBRID repository, the modeling repository of the Integrated Energy Systems (IES) program at Idaho National Laboratory. The focus of the thermal extraction work is setting up template energy conversion systems for advanced reactor systems. Based on these nominal conditions, the IES team is developing extraction capability maps that present the system thermal-to-electric efficiency of the remaining non-extracted flow and the mass extraction fraction capability of these systems. The results sweep across conditions extracting steam at various pressures to send steam to applications at a lower given pressure, with curves representing multiple of these lower pressures. These curves are mapped on what has been termed a "whale chart" due to the appearance of the results. Multiple advanced reactor systems are complete, and it is anticipated that all four of the main advanced reactor types—advanced light-water reactors, high-temperature gas-cooled reactors, liquid metal fast reactors, and molten salt reactors—will be complete by the end of the fiscal year.

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FIGURES

TABLES

LIST OF ACRONYMS

A-LWR	advanced light-water reactor
BOP	balance of plant
CFWH	closed feed water heating
CHP	combined heat and power
HPT	high pressure turbine
HTGR	high-temperature gas-cooled reactor
IES	integrated energy systems
LPT	low-pressure turbine
LWR	light-water reactor
MSR	molten salt reactor
OFWH	open feed water heating
PHX	primary heat exchanger
SFR	sodium-cooled fast reactor
SHX	secondary heat exchanger

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1. INTRODUCTION

There is growing interest in how nuclear reactors can be used primarily as heat generators and integrated into thermal demand processes [1]. As relatively low-quality heat generators (producing lower temperatures available to thermal-to-electric conversion equipment) relative to carbon sources, nuclear reactors have lower thermal-to-electric efficiencies than carbon-burning systems like coal and natural gas plants. Because of this, the overall energy utilization is lower from nuclear reactor systems than from carbon-burning systems. With the ongoing push to decarbonize energy use across all sectors, there is a renewed interest in how nuclear reactors can be designed to operate in ways that generate more than just baseload electricity. This includes load-following and combined heat and power (CHP) operations. These new dynamic operating capabilities should allow for the nuclear core to operate at nominal full neutron power while dispatching thermal power dynamically to one or more energy consumers.

Understanding how thermal energy can be extracted from the electricity-generating balance of plant (BOP) system of advanced reactors is key to proposing new opportunities for nuclear generators. The nominal BOP system within a power plant is to produce steam and run that steam through a turbine to produce electricity. Nominally, electricity production is expected to continue for many of these systems. As such, this is the general design focus within advanced reactor vendor companies and is thus a focus for the Integrated Energy Systems (IES) program. Within this report, a new model is demonstrated that can calculate nominal and atypical conditions within a turbo-generator system. Additionally, solution maps show how thermal-to-electric efficiency changes when varying amounts of steam are withdrawn from the system. This map also shows the relationship between design turbine extraction pressure and application pressure, illustrating how much mass is accessible to a given thermal application case when paired with a specific reactor type.

This status update is a follow-up to INL/RPT-23-03062 [2], which detailed the legacy BOP modeling techniques used within the HYBRID repository [3].

2. BALANCE OF PLANT MODELING

BOP models of simplified plant configurations have been created that can operate in multiple operating modes. BOP models, often mentioned as secondary circuit of system, contain several power machineries where a series of equipment such as feedwater system and steam discharge system, various control valves, safety valves participate in the heat discharge. The steam that is extracted from extraction points of a turbine can go directly to industrial process.

A typical on-design BOP design would be operating at 100% nominal thermal and electrical power. If heat is extracted, either via an extraction stage or from piping between turbines, within the BOP at a different than nominal rate, then operation will shift from on-design to off-design. The standard BOP models developed for the HYBRID repository allow for on-design and off-design operation calculations with different configurations. The term standard here is used to describe the BOP models because the intent is to have these BOP models used to describe the thermal-to-electric conversion within systems powered by various advanced nuclear reactors. These models are not intended to define the entire suite of possible BOP configurations, which would exceed the analysis goals of the project. The main difference between the two standard BOP models is the method of feedwater heating: closed versus open. Closed feedwater heating uses a heat exchanger to pass heat from a hot stream, nominally a turbine bypass stream, to heat feedwater. Open feedwater heating mixes turbine bypass streams into the feedwater stream. There are design advantages to both systems. Closed systems allow for much more dynamic and for mismatched pressures within the turbine bypass streams and the feedwater system. Open feedwater systems are thermodynamically advantageous, as mixing the streams is effectively a perfect heat exchanger. Real systems use single open feedwater heater acting also as deaerator and about 4 to 8 closed feedwater heaters.

2.1 Three-Section Turbine – Open Feed Water Heating

An updated three-sections turbine model was created using the previous three-sections model described in [2]. The input data block was simplified to make parameterization, nominal physical characterization of the system, easier. A second open feed water heater (OFWH) was added to more accurately reflect a real Rankine cycle, and one feedwater heater was moved to use steam offtake bypassed from before the high pressure turbine, to be able to reach higher feed water temperatures, even though this configuration brings no thermodynamic benefit. A block diagram of this model is shown in Figure 1.

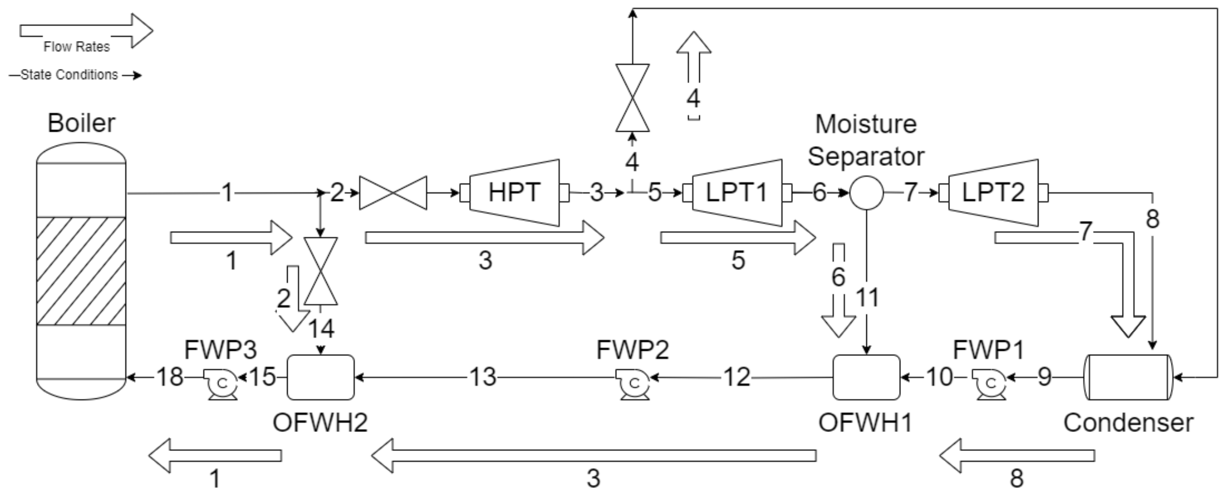
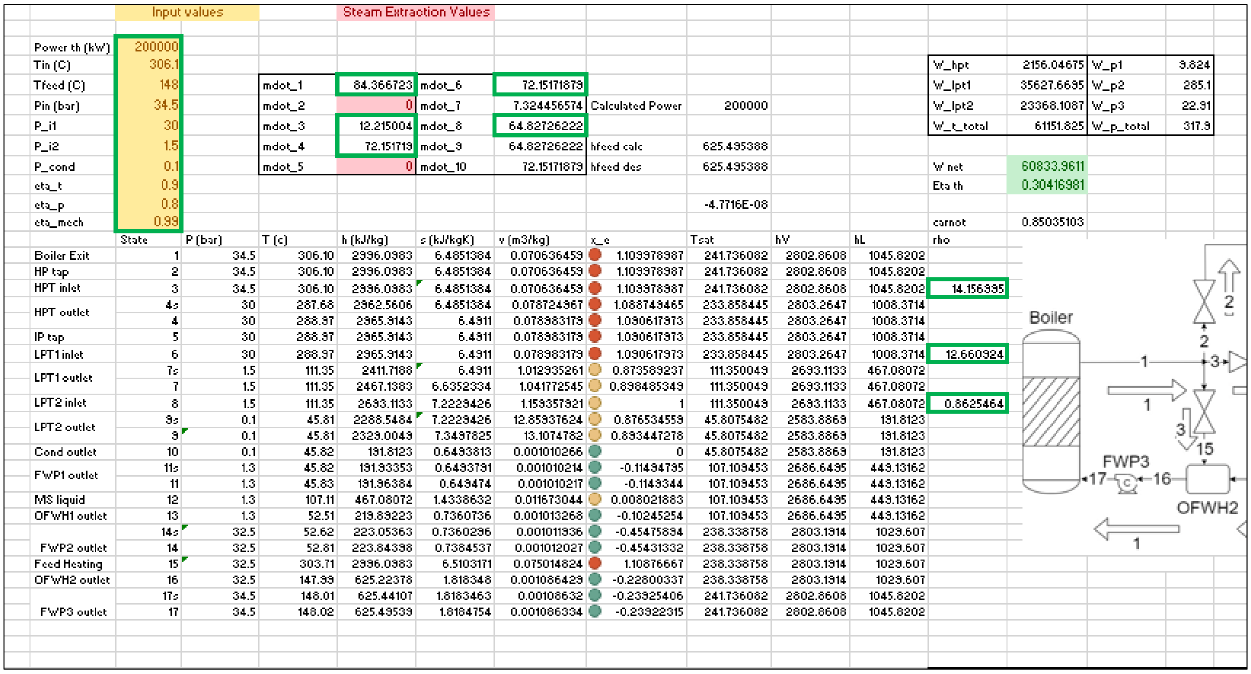


Figure 1. Block diagram of balance of plant with open feed water heating three-section turbine.

Table 1. The steady-state thermodynamic model inputs.

Parameter	Description	Unit
Power_th	Core Thermal Power	MW
T_in	Inlet Steam Temperature	°C
T_feed	Feed Water Temperature	°C
P_in	High Pressure Turbine Impulse Pressure	Bar
P_i1	Low Pressure Turbine 1 Impulse Pressure	Bar
P_i2	Low Pressure Turbine 2 Impulse Pressure	Bar
P_cond	Condenser Pressure	Bar
Eta_t	Turbine Isentropic Efficiency	%
Eta_p	Pump Isentropic Efficiency	%
Eta_mech	Turbine Mechanical Efficiency	%

The steady-state (design) thermodynamic model of the Rankine cycle was created alongside the BOP models to allow for easy parameterization. The Excel sheet shown in Figure 2 uses a set of inputs shown in Table 1 and gives the state conditions for each component in the cycle. These values are used to find the nominal condition for the system. These nominal conditions allow off-design performance of the turbines to be modeled. The needed parameters are shown in Table 1. The design thermodynamic model assumes steady-state conditions with no pressure drop across valves or the reactor, and ideal moisture separation. The thermodynamic state for each component is calculated and the mass flow rates through each component is listed. These values and all of the other ones outlined in thick green-colored boxes are used as nominal conditions within the parameterization data block in the Modelica model.



Power th (kW)	200000
Tin (C)	306.1
Tfeed (C)	148
Pin (bar)	34.5
P_i1	30
P_i2	1.5
P_cond	0.1
eta_t	0.9
eta_p	0.8
eta_mech	0.99

mdot_1	84.366723	mdot_6	72.15171879
mdot_2	0	mdot_7	7.324456574
mdot_3	12.215004	mdot_8	64.82726222
mdot_4	72.151719	mdot_9	64.82726222
mdot_5	0	mdot_10	72.15171879

Calculated Power	200000
hfeed calc	625.495388
hfeed des	625.495388
	-4.7716E-08

W_hpt	2156.04675	W_p1	9.824
W_lpt1	35627.6695	W_p2	285.1
W_lpt2	23368.1087	W_p3	22.91
W_t_total	61151.825	W_p_total	317.9

W net	60833.9611
Eta th	0.30416981
carnot	0.85035103

	State	P (bar)	T (c)	h (kJ/kg)	s (kJ/kgK)	v (m3/kg)	x_e	Tsat	hV	hL	rho
Boiler Exit	1	34.5	306.10	2996.0983	6.4851384	0.070636459	1.109978987	241.736082	2802.8608	1045.8202	
HP tap	2	34.5	306.10	2996.0983	6.4851384	0.070636459	1.109978987	241.736082	2802.8608	1045.8202	
HPT inlet	3	34.5	306.10	2996.0983	6.4851384	0.070636459	1.109978987	241.736082	2802.8608	1045.8202	14.156995
HPT outlet	4s	30	287.68	2962.5606	6.4851384	0.078724967	1.088749465	233.858445	2803.2647	1008.3714	
	4	30	288.97	2965.9143	6.4911	0.078983179	1.090617973	233.858445	2803.2647	1008.3714	
IP tap	5	30	288.97	2965.9143	6.4911	0.078983179	1.090617973	233.858445	2803.2647	1008.3714	
LPT1 inlet	6	30	288.97	2965.9143	6.4911	0.078983179	1.090617973	233.858445	2803.2647	1008.3714	12.660924
LPT1 outlet	7s	1.5	111.35	2411.7188	6.4911	1.012935261	0.873589237	111.350049	2693.1133	467.08072	
	7	1.5	111.35	2467.1383	6.6352334	1.041772545	0.898485349	111.350049	2693.1133	467.08072	
LPT2 inlet	8	1.5	111.35	2693.1133	7.2229426	1.159357921	1	111.350049	2693.1133	467.08072	0.8625464
LPT2 outlet	9s	0.1	45.81	2288.5484	7.2229426	12.85937624	0.876534559	45.8075482	2583.8869	191.8123	
	9	0.1	45.81	2329.0049	7.3497825	13.1074782	0.893447278	45.8075482	2583.8869	191.8123	
Cond outlet	10	0.1	45.82	191.8123	0.6493813	0.001010266	0	45.8075482	2583.8869	191.8123	
FWP1 outlet	11s	1.3	45.82	191.93353	0.6493791	0.001010214	-0.11494795	107.109453	2686.6495	449.13162	
	11	1.3	45.83	191.96384	0.649474	0.001010217	-0.1149344	107.109453	2686.6495	449.13162	
MS liquid	12	1.3	107.11	467.08072	1.4338632	0.011673044	0.008021883	107.109453	2686.6495	449.13162	
OFWH1 outlet	13	1.3	52.51	219.89223	0.7360736	0.001013268	-0.10245254	107.109453	2686.6495	449.13162	
	14s	32.5	52.62	223.05363	0.7360296	0.001011936	-0.45475894	238.338758	2803.1914	1029.607	
FWP2 outlet	14	32.5	52.81	223.84398	0.7384537	0.001012027	-0.45431332	238.338758	2803.1914	1029.607	
Feed Heating	15	32.5	303.71	2996.0983	6.5103171	0.075014824	1.10876667	238.338758	2803.1914	1029.607	
OFWH2 outlet	16	32.5	147.99	625.22378	1.818348	0.001086429	-0.22800337	238.338758	2803.1914	1029.607	
	17s	34.5	148.01	625.44107	1.8183463	0.00108632	-0.23925406	241.736082	2802.8608	1045.8202	
FWP3 outlet	17	34.5	148.02	625.49539	1.8184754	0.001086334	-0.23922315	241.736082	2802.8608	1045.8202	

Figure 2. Results of the design thermodynamic model of the open feedwater heating three-section turbine balance of plant model.

All of the parameters needed for the Modelica model can be determined from the design thermodynamic model. The list of parameters needed is shown in Table 2. With these inputs, the Modelica model shown in Figure 3 can be parameterized. The values for these parameters vary greatly depending on the reactor type and corresponding steam and feed water conditions.

Table 2. Modelica three-section turbine model inputs (Open Feedwater Heating).

Parameter	Description	Unit
Power_nom	Nominal Electric Power	MW
T_in	Inlet Steam Temperature	°C
T_feed	Feed Water Temperature	°C
P_in	High Pressure Turbine Impulse Pressure	Bar
P_i1	Low Pressure Turbine 1 Impulse Pressure	Bar
P_i2	Low Pressure Turbine 2 Impulse Pressure	Bar
P_cond	Condenser Pressure	Bar
P_dump	Turbine Bypass Relief Valve Set Pressure	Bar
P_use	Application Demand Pressure	Bar
d_HPT_in	High Pressure Turbine Inlet Density	kg/m^3
d_LPT1_in	Low Pressure Turbine 1 Inlet Density	kg/m^3
d_LPT2_in	Low Pressure Turbine 2 Inlet Density	kg/m^3
Mdot_total	Nominal Total Mass Flow Rate	kg/s
Mdot_fd	Nominal Feed Heating Mass Flow Rate	kg/s
Mdot_HPT	Nominal HPT Mass Flow Rate	kg/s
Mdot_LPT1	Nominal LPT1 Mass Flow Rate	kg/s
Mdot_LPT2	Nominal LPT2 Mass Flow Rate	kg/s

Parameter	Description	Unit
Mdot_ext	Extraction Mass Flow Rate	kg/s
Eta_t	Turbine Isentropic Efficiency	%
Eta_p	Pump Isentropic Efficiency	%
Eta_mech	Turbine Mechanical Efficiency	%

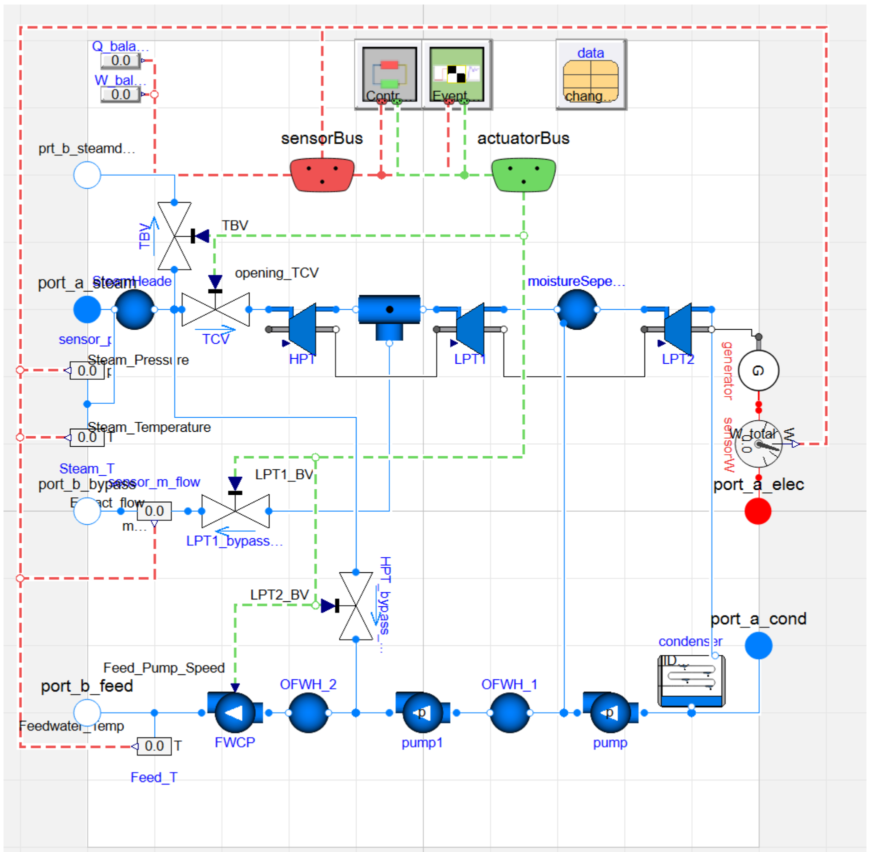


Figure 3. NHES.Systems.BalanceOfPlant.Turbine.SteamTurbine_L3_HPOFWH.

2.2 Three-Section Turbine – Closed Feed Water Heating

A closed feed water heating (CFWH) three-section turbine BOP was also developed. A block diagram of this model can be seen in Figure 4. Like the open feed water cycle, the design thermodynamics model for the CFWH three-section turbine BOP was created to parameterize the system. In addition to the assumptions from the OFWH cycle, it was assumed that there is a 10°C difference between the cold feed water inlet and the feed heating condensate exit temperatures.

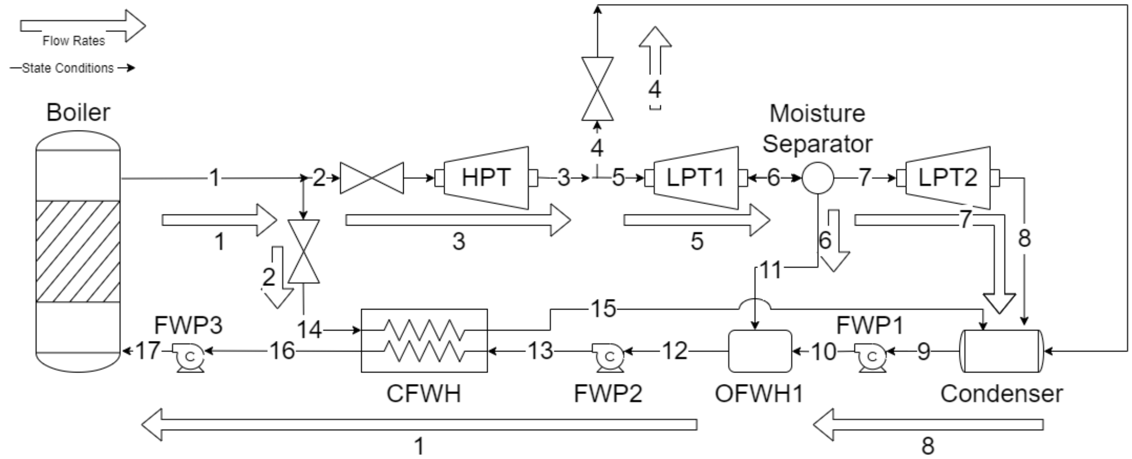
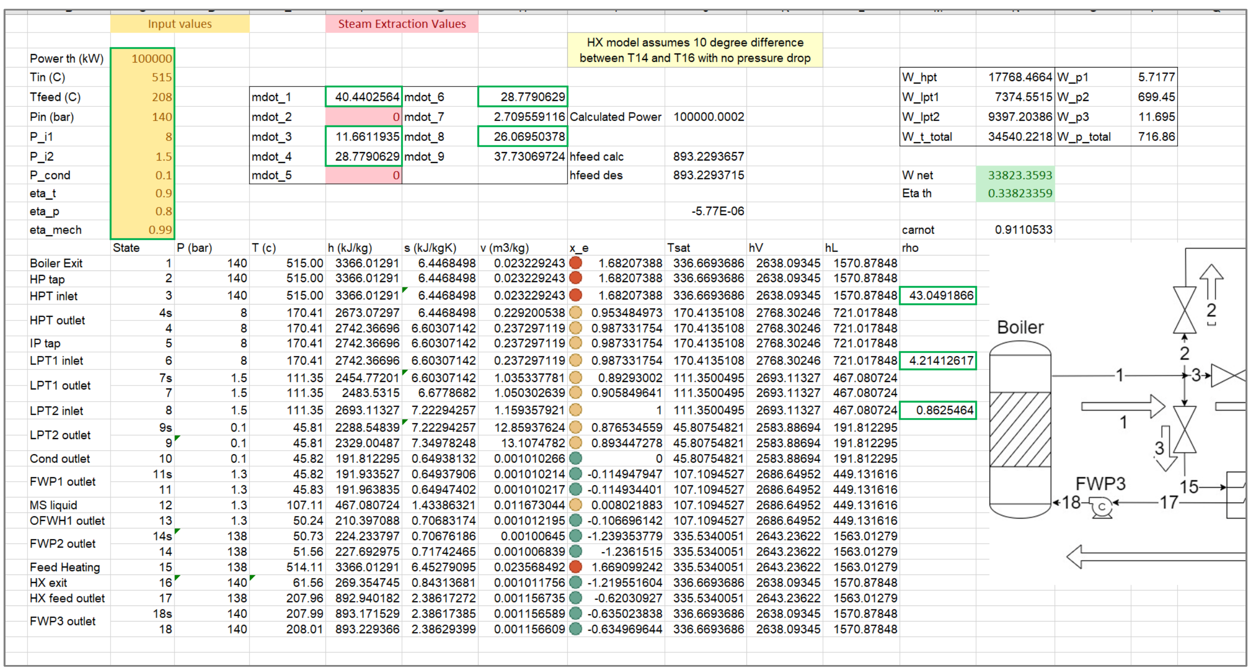


Figure 4. Block diagram of closed feed water heating three-section turbine.

The input parameters for the design thermodynamic model remain the same as the model of the open feed water heating system, seen in Figure 5. Among the Modelica model parameters, provided in Table 3, are few additional inputs compared to the OFWH model. The Modelica model is shown in Figure 6.



Input values			Steam Extraction Values				
Power th (kW)	100000						
Tin (C)	515						
Tfeed (C)	208	mdot_1	40.4402564	mdot_6	28.7790629		
Pin (bar)	140	mdot_2	0	mdot_7	2.709559116	Calculated Power	100000.0002
P_i1	8	mdot_3	11.6611935	mdot_8	26.06950378		
P_i2	1.5	mdot_4	28.7790629	mdot_9	37.73069724	hfeed calc	893.2293657
P_cond	0.1	mdot_5	0			hfeed des	893.2293715
eta_t	0.9						
eta_p	0.8						-5.77E-06
eta_mech	0.99						

HX model assumes 10 degree difference between T14 and T16 with no pressure drop

W_hpt	17768.4664	W_p1	5.7177
W_lpt1	7374.5515	W_p2	699.45
W_lpt2	9397.20386	W_p3	11.695
W_t_total	34540.2218	W_p_total	716.86
W net	33823.3593		
Eta th	0.33823359		
carnot	0.9110533		

	State	P (bar)	T (c)	h (kJ/kg)	s (kJ/kgK)	v (m3/kg)	x_e	Tsat	hV	hL	rho
Boiler Exit	1	140	515.00	3366.01291	6.4468498	0.023229243	1.68207388	336.6693686	2638.09345	1570.87848	
HP tap	2	140	515.00	3366.01291	6.4468498	0.023229243	1.68207388	336.6693686	2638.09345	1570.87848	
HPT inlet	3	140	515.00	3366.01291	6.4468498	0.023229243	1.68207388	336.6693686	2638.09345	1570.87848	43.0491866
HPT outlet	4s	8	170.41	2673.07297	6.4468498	0.229200538	0.953484973	170.4135108	2768.30246	721.017848	
	4	8	170.41	2742.36696	6.60307142	0.237297119	0.987331754	170.4135108	2768.30246	721.017848	
IP tap	5	8	170.41	2742.36696	6.60307142	0.237297119	0.987331754	170.4135108	2768.30246	721.017848	
LPT1 inlet	6	8	170.41	2742.36696	6.60307142	0.237297119	0.987331754	170.4135108	2768.30246	721.017848	4.21412617
LPT1 outlet	7s	1.5	111.35	2454.77201	6.60307142	1.035337781	0.89293002	111.3500495	2693.11327	467.080724	
	7	1.5	111.35	2483.5315	6.6778682	1.050302639	0.905849641	111.3500495	2693.11327	467.080724	
LPT2 inlet	8	1.5	111.35	2693.11327	7.22294257	1.159357921	1	111.3500495	2693.11327	467.080724	0.8625464
LPT2 outlet	9s	0.1	45.81	2288.54839	7.22294257	12.85937624	0.876534559	45.80754821	2583.88694	191.812295	
	9	0.1	45.81	2329.00487	7.34978248	13.1074782	0.893447278	45.80754821	2583.88694	191.812295	
Cond outlet	10	0.1	45.82	191.812295	0.64938132	0.001010266	0	45.80754821	2583.88694	191.812295	
FWP1 outlet	11s	1.3	45.82	191.933527	0.64937906	0.001010214	-0.114947947	107.1094527	2686.64952	449.131616	
	11	1.3	45.83	191.963835	0.64947402	0.001010217	-0.114934401	107.1094527	2686.64952	449.131616	
MS liquid	12	1.3	107.11	467.080724	1.43386321	0.011673044	0.008021883	107.1094527	2686.64952	449.131616	
OFWH1 outlet	13	1.3	50.24	210.397088	0.70683174	0.001012195	-0.106696142	107.1094527	2686.64952	449.131616	
FWP2 outlet	14s	138	50.73	224.233797	0.70676186	0.00100645	-1.239353779	335.5340051	2643.23622	1563.01279	
	14	138	51.56	227.692975	0.71742465	0.001006839	-1.2361515	335.5340051	2643.23622	1563.01279	
Feed Heating	15	138	514.11	3366.01291	6.45279095	0.023568492	1.669099242	335.5340051	2643.23622	1563.01279	
HX exit	16	140	61.56	269.354745	0.84313681	0.001011756	-1.219551604	336.6693686	2638.09345	1570.87848	
HX feed outlet	17	138	207.96	892.940182	2.38617272	0.001156735	-0.62030927	335.5340051	2643.23622	1563.01279	
FWP3 outlet	18s	140	207.99	893.171529	2.38617385	0.001156589	-0.635023838	336.6693686	2638.09345	1570.87848	
	18	140	208.01	893.229366	2.38629399	0.001156609	-0.634969644	336.6693686	2638.09345	1570.87848	

Figure 5. Results of the design thermodynamic model of the closed feedwater heating three-section turbine balance of plant model.

Table 3. Modelica three-section turbine model inputs (Closed Feedwater Heating).

Parameter	Description	Unit
Power_nom	Nominal Electric Power	MW
T_in	Inlet Steam Temperature	°C
T_feed	Feed Water Temperature	°C

Table 3. (continued).

Parameter	Description	Unit
P_in	High Pressure Turbine Impulse Pressure	Bar
P_i1	Low Pressure Turbine 1 Impulse Pressure	Bar
P_i2	Low Pressure Turbine 2 Impulse Pressure	Bar
P_cond	Condenser Pressure	Bar
P_dump	Turbine Bypass Relief Valve Set Pressure	Bar
P_use	Application Demand Pressure	Bar
d_HPT_in	High Pressure Turbine Inlet Density	kg/m^3
d_LPT1_in	Low Pressure Turbine 1 Inlet Density	kg/m^3
d_LPT2_in	Low Pressure Turbine 2 Inlet Density	kg/m^3
Mdot_total	Nominal Total Mass Flow Rate	kg/s
Mdot_fd	Nominal Feed Heating Mass Flow Rate	kg/s
Mdot_HPT	Nominal HPT Mass Flow Rate	kg/s
Mdot_LPT1	Nominal LPT1 Mass Flow Rate	kg/s
Mdot_LPT2	Nominal LPT2 Mass Flow Rate	kg/s
Mdot_ext	Extraction Mass Flow Rate	kg/s
Eta_t	Turbine Isentropic Efficiency	%
Eta_p	Pump Isentropic Efficiency	%
Eta_mech	Turbine Mechanical Efficiency	%
Heater_NTU	Number of Transfer Units of the feed water heater	—
Heater_K-tube	K value of tube in the feed water heater	$1/m^4$
Heater_K-shell	K value of shell in the feed water heater	$1/m^4$
Heater_V-tube	Tube side volume of the feed water heater	m^3
Heater_V-shell	Shell side volume of the feed water heater	m^3

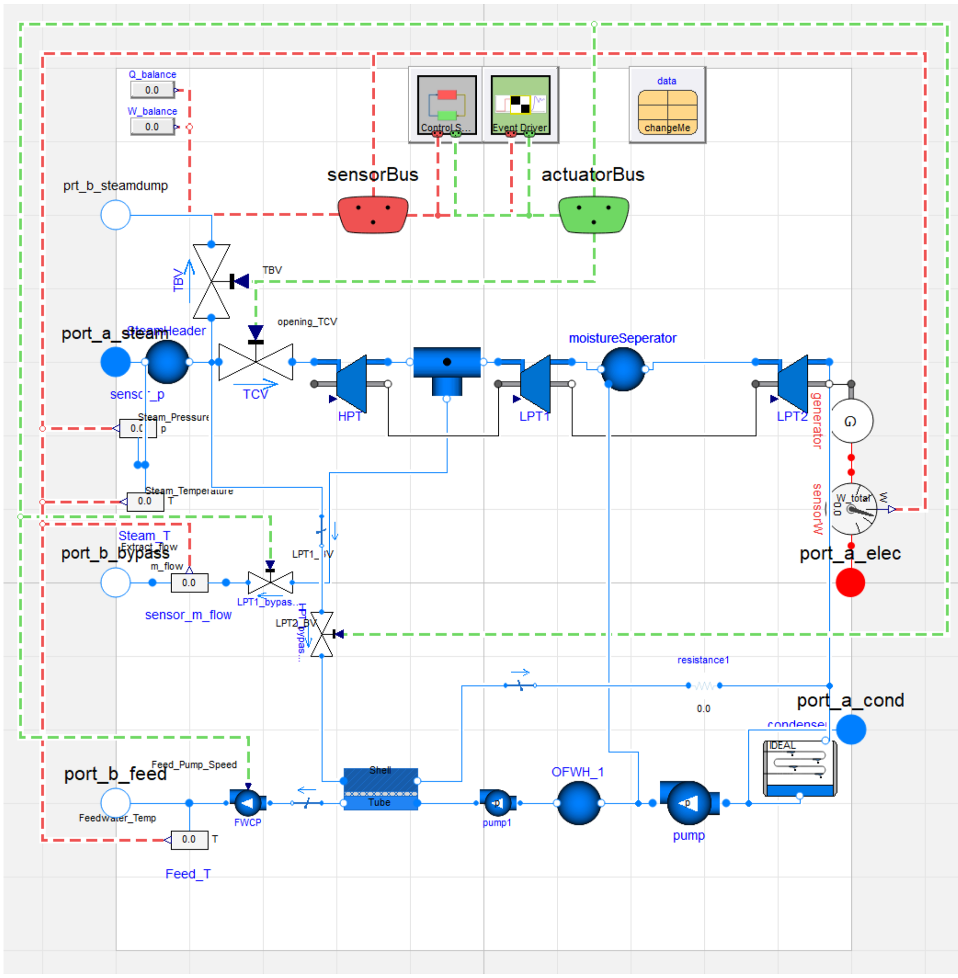


Figure 6. NHES.Systems.BalanceOfPlant.Turbine.SteamTurbine_L3_HPCFWH.

3. TEMPLATE BOP MODELS

Nominal conditions are characterized by reactor type based on the template primary side conditions. Those conditions inform the potential BOP conditions based on each advanced reactor type. Notice that the "template" is simply a set of nominal conditions to produce power from a specified reactor and BOP model. The "template" BOP for a given reactor provides a reference point from which the developed models can calculate the on-design and off-design behavior. The completed models are reported in the following sections.

3.1 A-LWR

Table 4 shows the input conditions for the advanced light-water reactor (A-LWR), which is a natural circulation integral pressurized water reactor. Figure 7 shows the Modelica template of the coupled light-water reactor and BOP models.

Table 4. A-LWR nominal conditions.

Parameter	Value	Unit
Power_th	200	MWt
T_in	306.1	°C
T_feed	148	°C

Parameter	Value	Unit
P_in	34.5	Bar
P_i1	3	Bar
P_i2	1.5	Bar
P_cond	0.1	Bar
Eta_t	0.9	—
Eta_p	0.8	—
Eta_mech	0.99	—

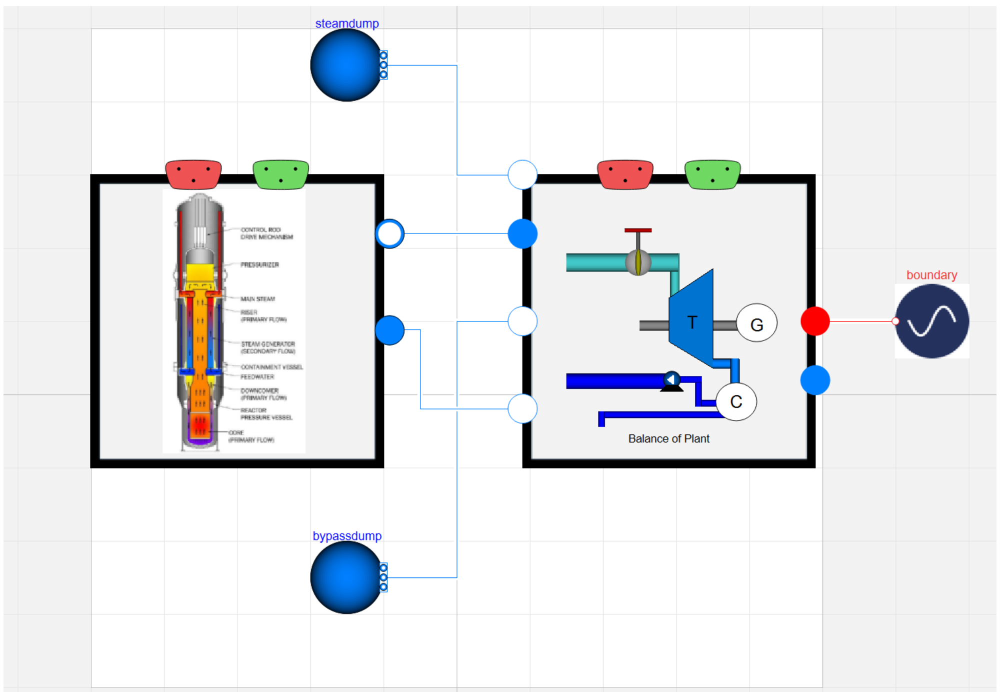


Figure 7. NHES.Systems.PrimaryHeatSystems.SMR_Generic.SMR_Test_3ST.

3.2 High Temperature Gas-Cooled Reactor

Table 5 shows the input conditions for the High Temperature Gas-Cooled Reactor (HTGR), which is a helium-cooled pebble bed style reactor. Figure 8 shows the Modelica models of the coupled HTGR and BOP models.

Table 5. HTGR nominal conditions.

Parameter	Value	Unit
Power_th	100	MWt
T_in	515	°C
T_feed	208	°C
P_in	140	Bar
P_i1	3	Bar
P_i2	1.5	Bar
P_cond	0.1	Bar

Parameter	Value	Unit
Eta_t	0.9	—
Eta_p	0.8	—
Eta_mech	0.99	—

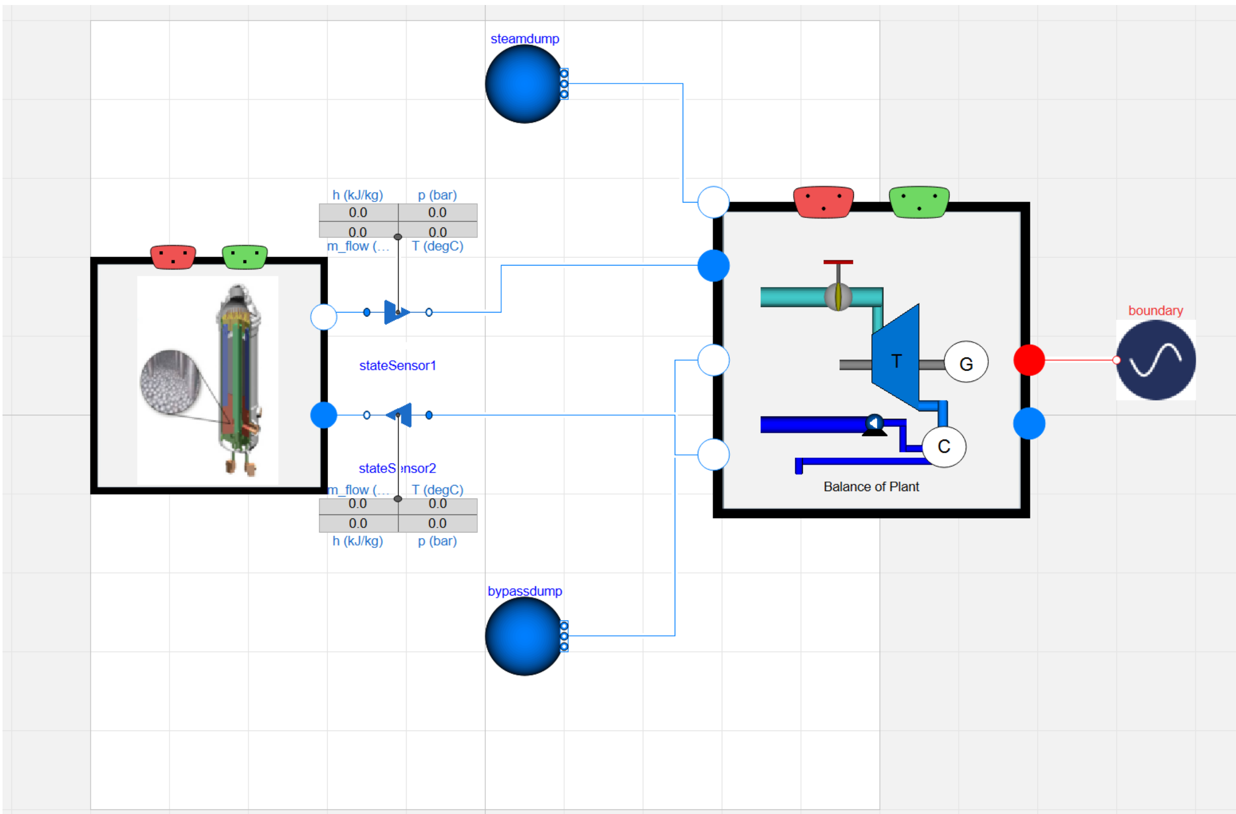


Figure 8. NHES.Systems.PrimaryHeatSystem. HTGR.HTGR_Rankine. Rankine_HTGR_ThreeStageTurbine_OFWH.

3.3 Sodium-Cooled Fast Reactor

Table 6 shows the input conditions for the sodium-cooled fast reactor (SFR) system. Figure 9 shows the Modelica model of the system with SFR, intermediate sodium loop and BOP models.

Table 6. SFR nominal conditions.

Parameter	Value	Unit
Power_th	100	MWt
T_in	364	°C
T_feed	210	°C
P_in	123	Bar
P_i1	3	Bar
P_i2	1.5	Bar
P_cond	0.1	Bar
Eta_t	0.9	—

Parameter	Value	Unit
Eta_p	0.8	—
Eta_mech	0.99	—

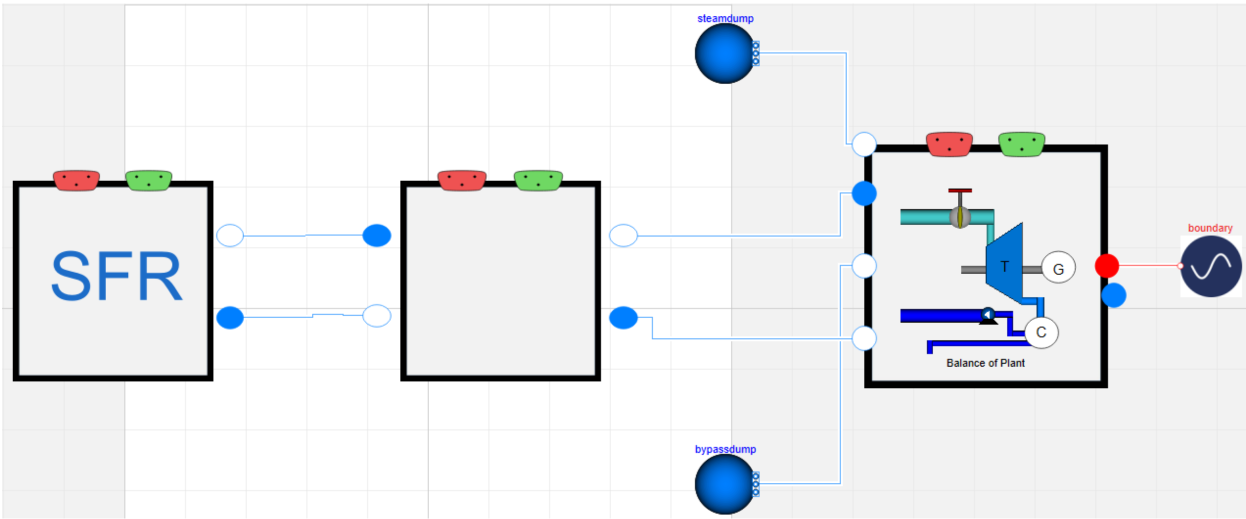


Figure 9. NHES.Systems.PrimaryHeatSystem.SFR.SFR_Example3TSBOP.

4. THERMAL EXTRACTION ANALYSIS USING RAVEN

The analysis required a parametric study running the Modelica models with different sets of input parameters. Risk Analysis and Virtual ENvironment (RAVEN) [4] was used to perform these tasks.

4.1 Workflow

Integrated steam users and turbomachinery manufacturers may need to identify desirable steam extraction pressures and flow rates to meet conditions mentioned in Section 3. To understand the effects of thermal extraction on the system, a thermal extraction analysis workflow was created to flex the system model with a large range of parameters. Figure 10 shows a thermal extraction analysis workflow using RAEVN.

Figure 10 shows the workflow of thermal extraction analysis using RAVEN. First, the system specifications including control setpoints such as thermal power, feedwater temperature, and steam generator outlet pressure are inserted to the design thermodynamic model. The design thermodynamic model also receives a set of design extraction pressure, demand pressures, and extraction flow rates from the RAVEN sampler. Nominal fluid density at the extraction point, i.e., input parameter of the low-pressure turbine (LPT), is then taken by the RAVEN sampler as input process variables of the Modelica model before running it. As such, steady state model is flexed using the RAVEN sampler and response surface analysis and its visualization are followed next.

To identify operational ranges (i.e., extraction pressure and extracted steam mass flow) given demanded pressure for heat demand, two separate thermal extraction analyses are performed. First, the demand pressure is set to be 1 bar, the lowest demand pressure considered, as demand temperatures below 100°C are not considered. Then the simulation is run through a range of different extraction pressure and mass flow rates going from minima (zero mass flow rate, 1 bar extraction pressure) up to their physical maximums. Physical maximum is considered to be the point at which nominal design values within the steam generator (steam pressure, feedwater temperature, and steam temperature) can no longer be met during operation. Multiple demand pressures are not needed for this set of runs as the demand pressure does not affect the resulting thermal efficiency of the system (only affects the cut-off point, beyond which more steam cannot be extracted with the current configuration). Second, the extraction mass flow rate is set to be the total nominal flow rate of the system (i.e., all steam passing the turbine) with a set of different extraction and demand pressures. The system cannot realistically reach this flow rate and will find out actual maximum flow rate, where key design setpoints are still met, as a function of the extraction and demand pressures. This is done to find the maximum flow rate for each set of pressures. Only simulations where the extraction pressure was higher than the demand pressure were run in the second analysis. All results from the first and second analyses are compiled into a two-dimensional (2D) map with contour lines for both the extraction pressures and demand pressures, named the whale chart.

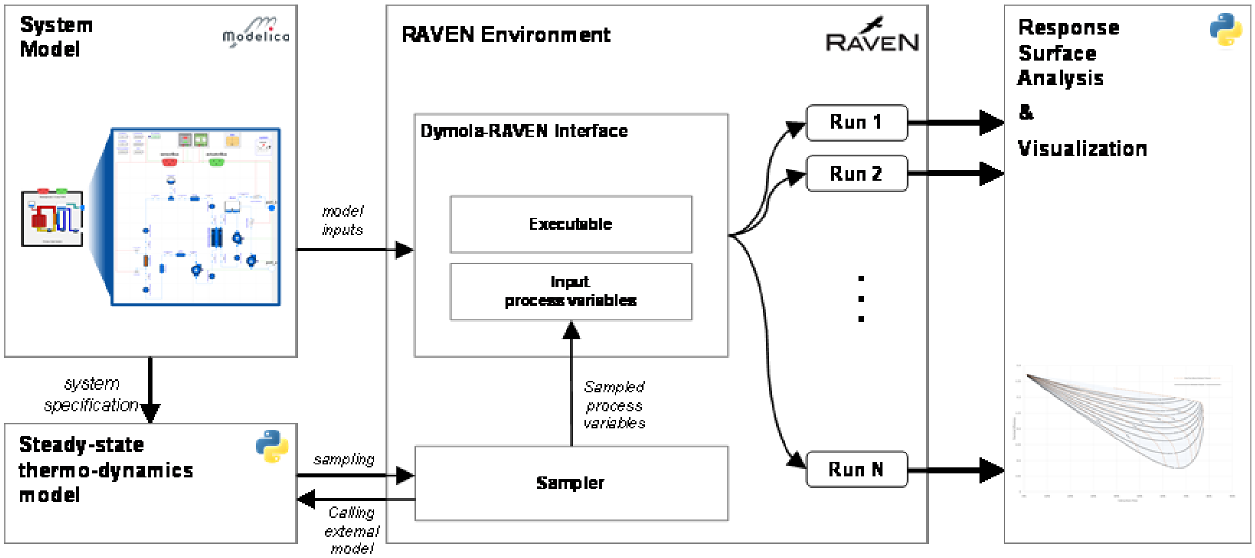


Figure 10. Thermal extraction analysis workflow using RAVEN.

4.2 Results

Thermal extraction analyses were performed for each of the three reactor types shown before. Some of the detailed reactor models were replaced with heated volumes and hydraulic resistances to improve computational speed. The heated volumes and resistances simulate the steam generator. Where the pressure and feedwater conditions are met with design values, a nominal nuclear heat generation rate is well estimated by a constant heat rate imparted on the secondary side flow. It is important to note that the results of these analyses are steady-state results, and so steady-state simplifying assumptions can appropriately describe the system. The detailed steam generation and nuclear steam supply system modeling will be reinstated before any transient analyses are done.

Figure 11 shows as an illustrative example of several specific curves of flow rate and extraction pressure, instead of the full range for illustration of the whale chart, to help describe to readers how to read the full whale chart. Two kinds of curves are plotted: the solid black lines show the thermal-to-electric efficiency of the BOP at a dictated design extraction pressure. This pressure can be thought of as effectively the pressure at the inlet of the LPT. Orange dashed lines show the maximum mass flow rate that can be extracted with a given thermal demand pressure outside of the BOP. Due to pressure losses across components, these extraction flow rate lines are necessarily below the extraction pressures of the same value. The key points on the whale chart are where the dashed lines cross over the solid lines: these indicate extraction flow rates from an extraction pressure to a demand pressure. In Figure 11 this means that from extraction pressures of 35, 50, and 110 bar the maximum flow rates that can be extracted to a 20 bar process are around 41%, 58%, and 80% of nominal steam flow. These values are specific to the BOP system being analyzed: feedwater heating methods and setpoints along with design steam pressure setup the line contours on the whale charts.

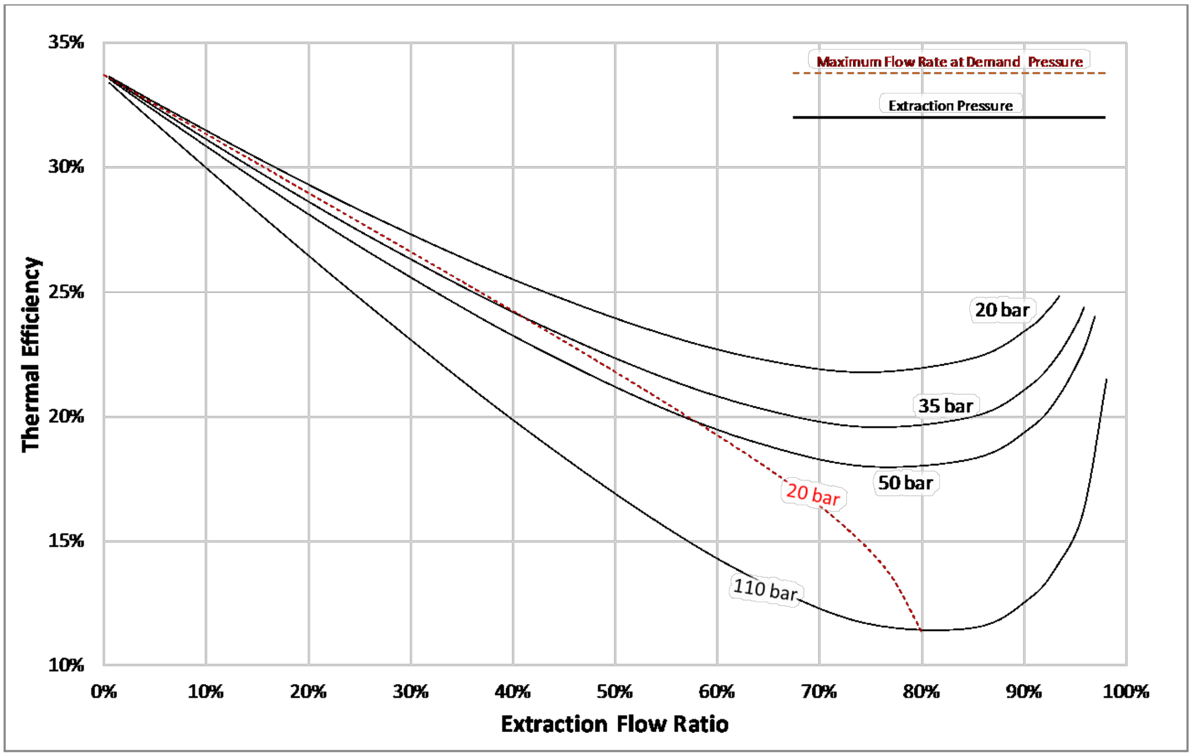


Figure 11. Snippet of the whale chart.

To better explain the pressure parameters within the system and their impact on the performance, Figure 12 shows the relationship between the maximal extraction steam flow and the required extraction nominal pressure for given demand pressure. The ends of curves in Figure 12 for a given extraction pressure indicate that removing additional mass flow from the system will force the BOP to not meet design setpoints. Figure 13 shows the thermal efficiency of the system for the combination of the nominal extraction and desired delivery demand pressures. Figure 13 curves are not on the whale charts, but the chart demonstrates how a single rule solution (such as always minimize the design extraction pressure relative to the demand pressure) is insufficient to describe all systems.

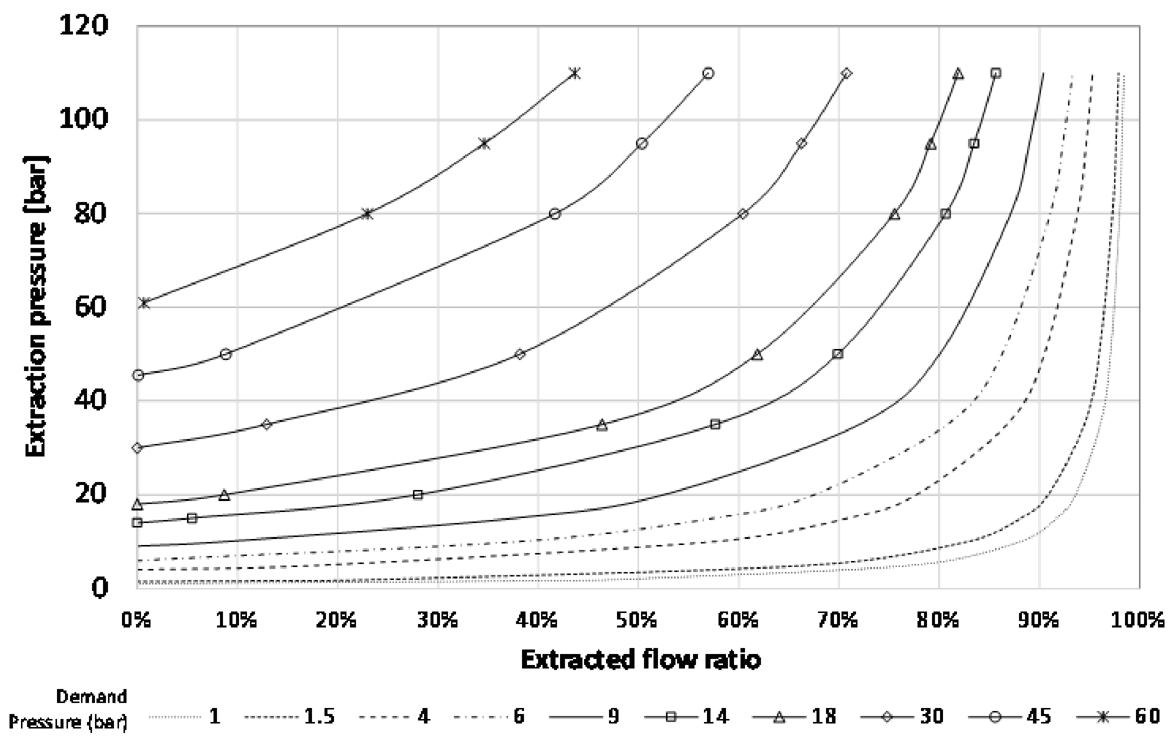


Figure 12. Extraction pressures for required demand steam flow and demand pressure.

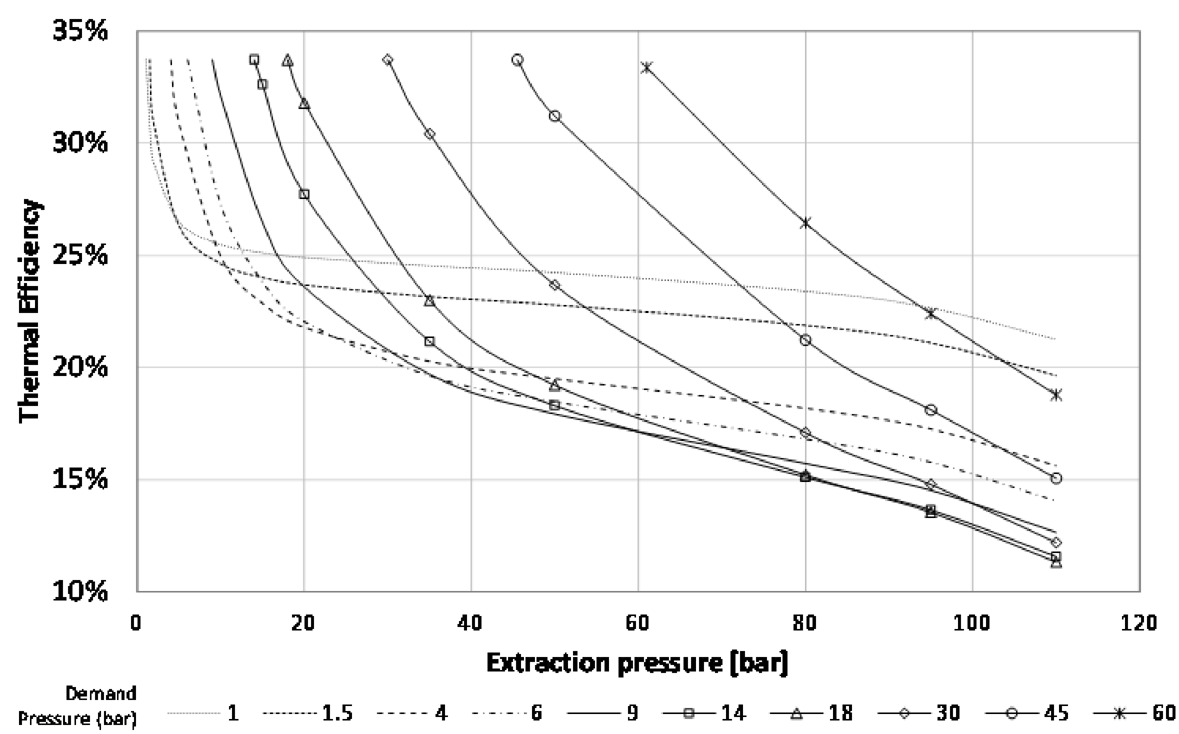


Figure 13. Thermal efficiency as a function of demand and extraction pressure.

From Figure 14 to Figure 17 the whale charts were generated from these results. These figures show the relationship between extraction pressure, demand pressure, extraction flow rate, and thermal efficiency. Mass flow rate is given as a ratio of extraction flow rate to HPT inlet mass flow rate. Thermal efficiency does not take into account the thermal utilization of the steam application, only the net electrical work of the Rankine cycle.

Figure 14 shows the whale chart for the OFWH BOP with A-LWR conditions. Figure 15 and Figure 16 show the whale charts of HTGR with OFWH and CFWH BOP. Note that reduced thermal efficiency can be observed in HTGR with CFWH. Figure 17 shows the whale chart of a sodium-cooled fast reactor (SFR) BOP. Note that for the SFR BOP the highest extraction pressure in the explored range was relatively low compared to the HPT inlet pressure than in other cases, causing the whale to be visually narrower. This is due to the combination of lower steam pressure than HTGRs and still high feedwater temperatures relative to A-LWRs.

Dashed orange lines are extraction contours of maximum flow ratio that can be extracted at a given demand pressure. The operating pressure at the extraction point must be higher than the demand pressure. The limit is a point when the actual extraction pressure decreases to demand pressure (plus pressure drop across extraction valve). As more flow is extracted, the flow rate through the LPTs (with original full-flowrate swallowing capacity) is reduced, which, in turn, decreases the pressure at the extraction point. For any given demand pressure, the system can only operate below the dashed line. The solid black line shows the thermal efficiency of the system at a given extraction pressure and flow rate. The demand pressure has no effect on the electrical efficiency of the system, only the extraction pressure and flow rate do. The demand pressure only needs to be below operational (off-design) extraction pressure. Any difference between these two pressures takes place as a pressure drop across the extraction valve.

Except for work potential lost due to the steam extracted at the demand pressure, there are two additional losses resulting from the off-design system operation. As the intermediate pressure at the extraction point is decreased, the turbine could handle a larger flowrate (higher pressure difference). Since a larger flowrate is not available with the fixed amount of thermal power from the reactor, the pressure at the HPT inlet needs to be decreased; this is performed by throttling in the turbine control valve. The second loss is a result of throttling across the valve controlling steam extraction. This throttling loss takes place every time there is a difference between operation extraction pressure and demand pressure, as the extraction valve reduces the pressure sent to the theoretical process demand. Extraction throttling decreases with additional mass extraction as the extraction pressure decreases to match the demand pressure. This decrease in extraction pressure means that the full amount of steam in the HPT section expands across a larger pressure difference. The throttling losses are not obviously present in the whale charts.

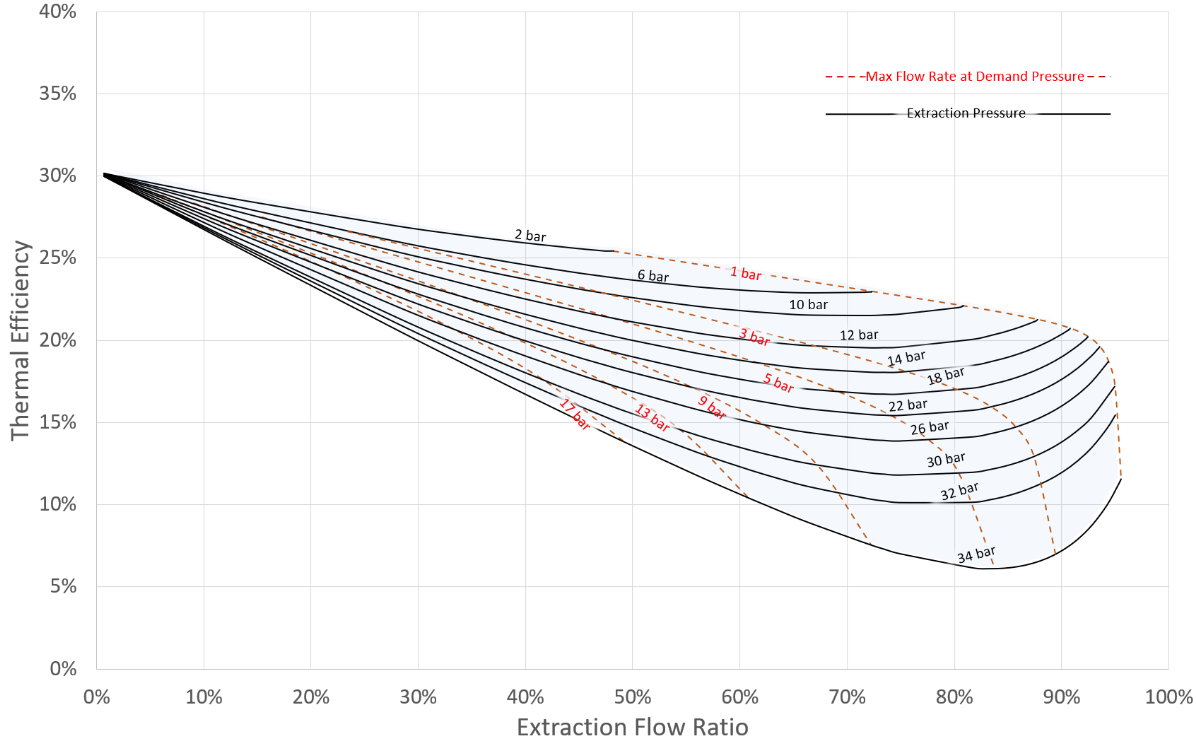


Figure 14. OFWH BOP with A-LWR conditions whale chart.

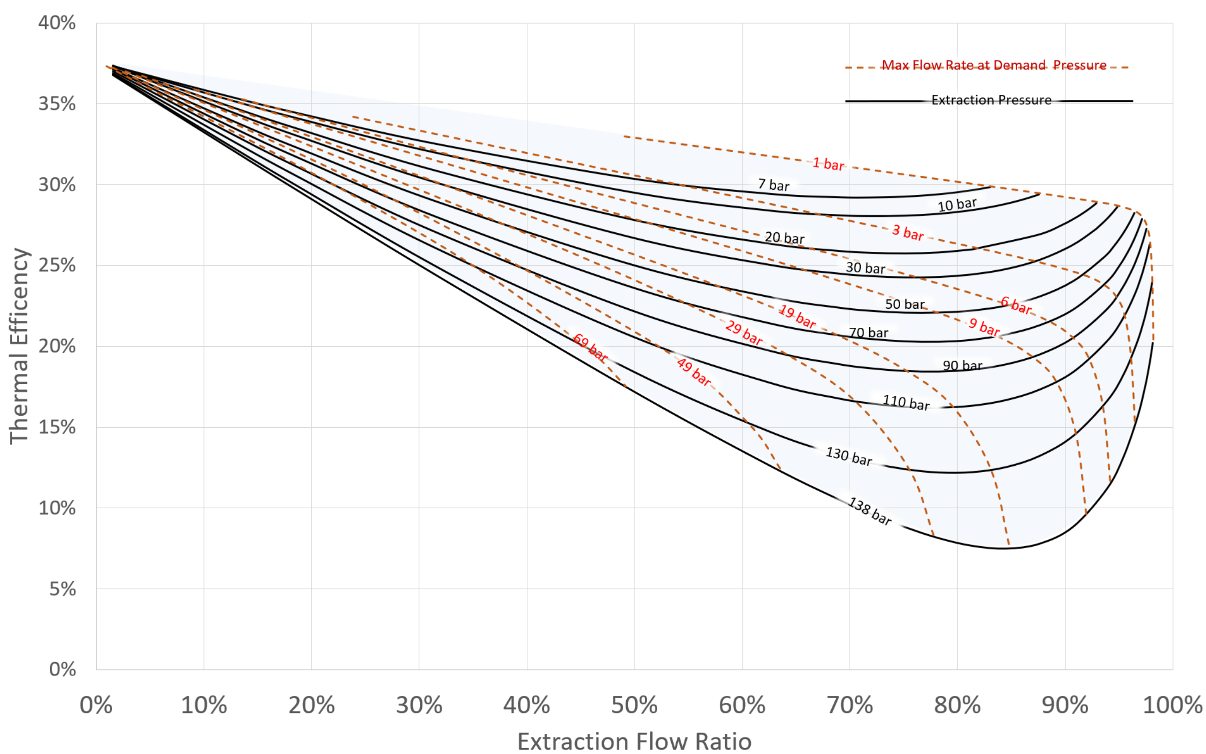


Figure 15. OFWH BOP with HTGR conditions whale chart.

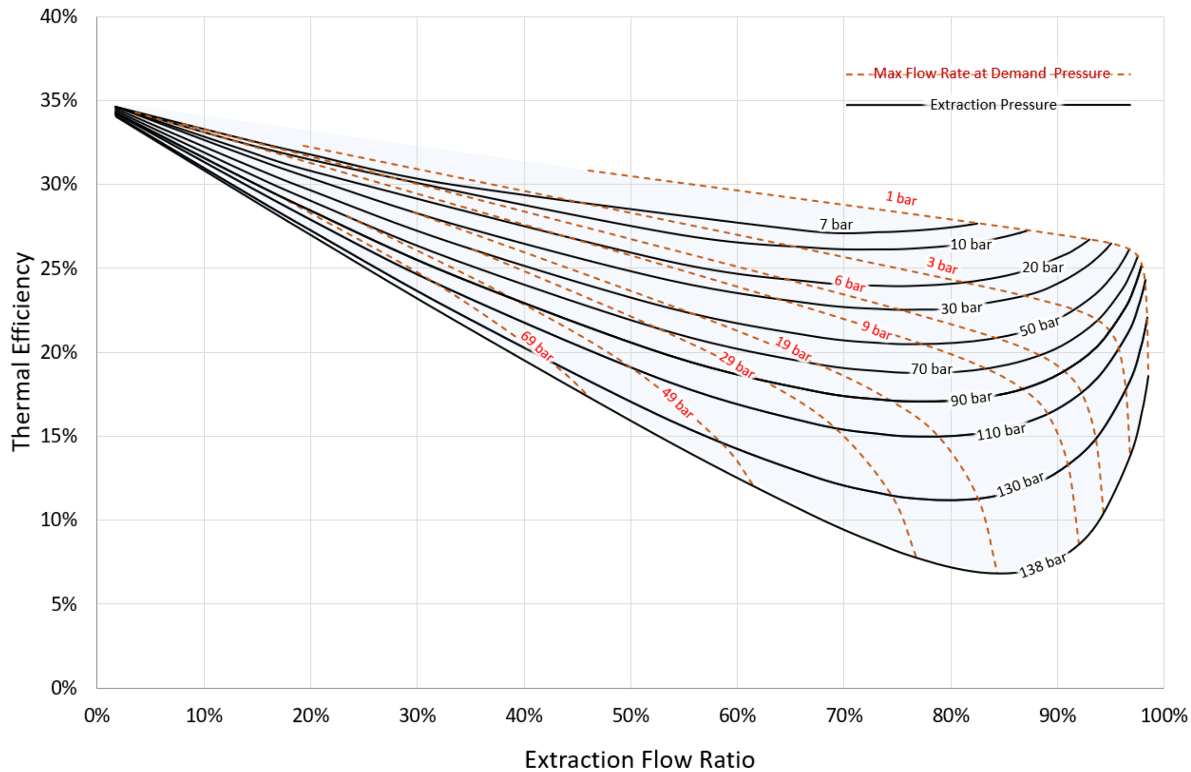


Figure 16. CFWH BOP with HTGR conditions whale chart.

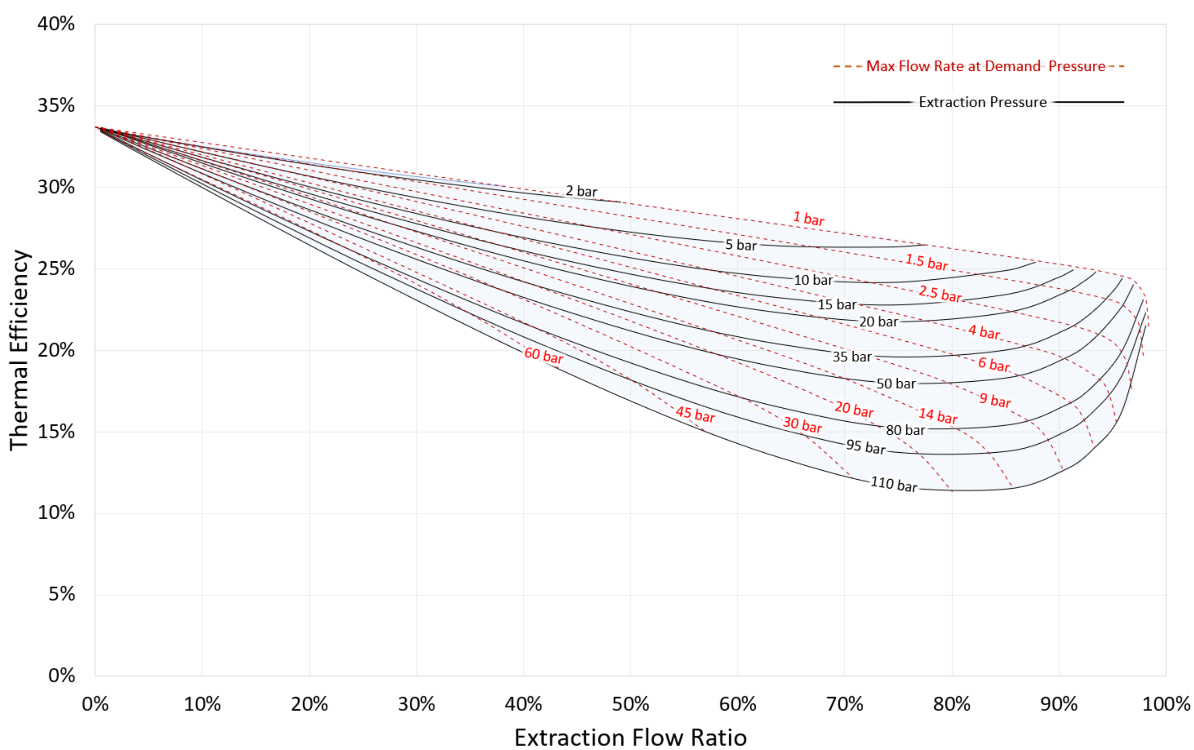


Figure 17. OFWH BOP with SFR conditions whale chart.

5. FUTURE WORK

There are multiple primary activities that still must be done to meet the goals for the 2023 fiscal year. They include completing the development and analysis of a molten salt reactor (MSR) system, which is the final class of advanced reactors needed to complete the suite of technologies within HYBRID. Future activities also include some BOP modeling verification, especially at significantly reduced flows where choked flow may occur.

5.1 Molten Salt Reactor System

A BOP model compatible with a MSR will be developed, as well as integrating the BOP with the MSR model in Modelica. Parameters, including those for the primary heat exchanger (PHX) and secondary heat exchanger (SHX), that will be used in this integration can be seen in Table 7.

Table 7. Nominal design parameters for the molten salt demonstration reactor [5].

Parameter	Value	Unit
Thermal power rating	750	MW
Operating pressure	0.1	MPa
Primary hot leg temperature	677	°C
Primary cold leg temperature	566	°C
Secondary hot leg temperature	593	°C
Secondary cold leg temperature	482	°C
Primary total mass flow rate	5000	kg/s
Secondary total mass flow rate	2800	kg/s
Number of heat exchanger loops	3	—
Number of heat exchangers per loop	2	—
Reactor inlet temperature	564.6	°C
Reactor outlet temperature	674.6	°C
Core inlet temperature	564.6	°C
Core outlet temperature	683.0	°C
PHX primary fuel loop side (tube) inlet temperature	662.8	°C
PHX primary fuel loop side (tube) outlet temperature	564.8	°C
PHX primary coolant loop side (shell) inlet temperature	493.0	°C
PHX primary coolant loop side (shell) inlet temperature	592.4	°C
SHX primary coolant loop side (shell) inlet temperature	583.2	°C
SHX primary coolant loop side (shell) outlet temperature	482.9	°C
SHX BOP side (tube) inlet temperature	434.4	°C
SHX BOP side (tube) outlet temperature	540.6	°C
Primary fuel loop mass flow rate	5544	kg/s
Primary coolant loop mass flow rate	2797	kg/s

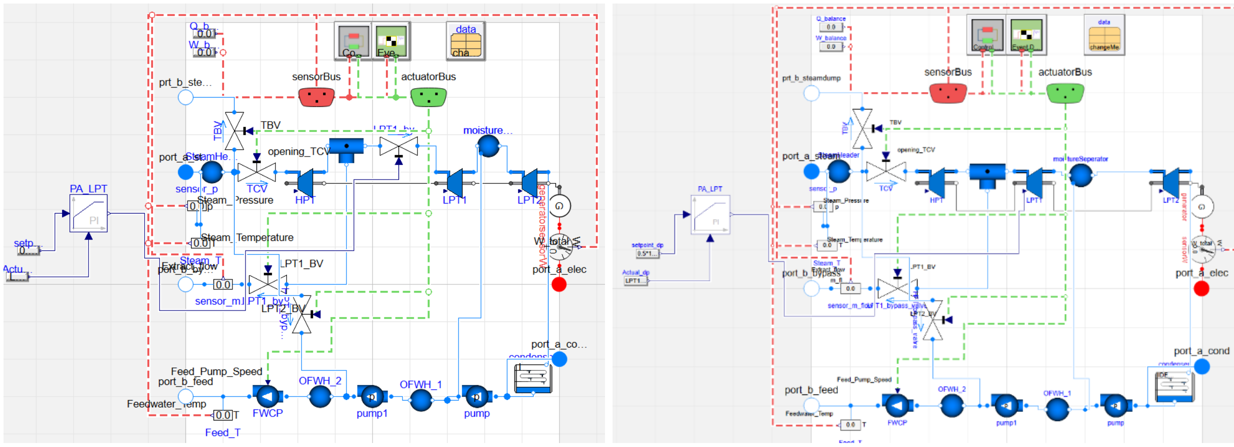
5.2 Continued Improvement of BOP Modeling

The turbine model does not account for potentially choked flow conditions. Therefore, for any deviations in the HPT relative pressure ratio across the turbine higher than the critical pressure ratio, the results may not be physically accurate. Specific design information will be needed to check against systems violating choked flow conditions. Note that the extent of off-design turbine performance would also result in different (typically lower) efficiency, considered here as constant. The team is currently considering possible validation efforts to confirm off-design turbine performance.

The nuclear industry will not be the first industry to employ combined heat and power. Existing experience should be leveraged to employ efficient and cost-effective solutions. Possible additional design features may allow higher flexibility while limiting off-design operation of the turbine. If uncontrolled (referring to LPT inlet pressure) extraction is desired, like in the current model, multiple extraction points flowing to a single node may be a superior configuration. This could allow for selection of the best suited extraction point based on the process pressure and demanded mass flow rate. As flow rates increase beyond maximum cutoff points for lower pressure extractions, valves open allowing higher pressure extraction to meet the demand.

The currently employed models can be changed to operate on controlled extraction once the system has an additional component. Controlled extraction uses a control element (valve) between turbine sections downstream and extraction junction to prevent extraction pressure drop below the desired level. Controlled extraction inevitably causes throttling of the steam going to the LP downstream section which decreases mechanical efficiency.

This loss could be reduced by implementing partial arch admission to the LPT instead of a valve (practically a screen inside the turbine casing). In practical design, this could be achieved also by controlled routing of steam into a separate LP sections, where multiple parallel casings are used. A proof of concept model has been performed for this approach in Modelica, with the BOP depicted in Figure 18. In this model, the valve on the extraction line is still used to control the steam flowrate. Partial admission of the LPT is then controlled to maintain a constant small pressure difference (0.5 bar) across this valve, effectively keeping the extraction pressure constant.



(left) (right)

Figure 18. BOP with controlled extraction realized by a valve before LPT (left) and by LPT partial admission (right).

6. CONCLUSIONS

This work explored the limits of the uncontrolled extraction of stream from the turbine as off-design steady states to simplify steam cycle matching in selected advanced reactor parameters. The results were summarized to show the maximum steam extraction for a given nominal extraction pressure and for a given demand pressure, in relation to the thermal efficiency of the cycle. The resulting charts whale charts show the limits of the extraction and corresponding efficiency. These results can allow analysts to have preliminary mapping of thermal requirements to various reactor types.

Many of the explored limits are, however, pushing turbine operation to highly off-design conditions, where some system assumptions can be questioned. Therefore, additional configurations are proposed for future work, for closer to common practice of CHP steam plants. Future work will also consist of completing the results for system with the MSR model.

7. ACKNOWLEDGEMENTS

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