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Analysis of Factors Affecting Thermodynamic Efficiency in Generation III+ PWR Nuclear Power Plants.

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Abstract: Generation III+ reactors are the latest generation of Nuclear Power Plants to enter the market. The key evolution in these reactors is the introduction of stringent safety standards. This is done through thorough incident scenario analysis and preparation, resulting in the addition of novel active and passive auxiliary safety systems, affecting the power consumption in the balance of plant. This paper analyses the parameters of PWR power plants of similar design, to determine the parameters for optimal efficiency, regarding gross and net electrical output, determining the impact the balance of plant has on this efficiency.

While two of the three main factors affecting the Rankine cycle – boiler pressure and steam temperature – behaved as theoretically expected, there was a notable point of departure with the third parameter – condenser pressure. The relationship between steam temperature and gross electrical efficiency was linear across all reactors but the relation between the steam temperature and the net electrical efficiency ceased to be linear for secondary loop steam temperatures above 290°C. The relationship between boiler pressure and both gross and net electrical efficiency was linear, proving the Rankine cycle. A relationship was not observed between the condenser pressure and either the gross or net electrical efficiency

Keywords: Efficiency; Nuclear Fission; Rankine Cycle; Boiler; Condenser; Steam; Pressure; Temperature; Generation III+; Thermodynamics; Advanced Nuclear Reactor; Pressurised Water Reactor;

Table 1. Abbreviations

PWR	Pressurised water reactor
LWR	Light water reactor

Table 2. Nomenclature

ε	Thermal efficiency (%)
W	Work done
Q_c	Cold reservoir enthalpy
Q_H	Hot reservoir enthalpy
W_{net}	Total work generated
Q_b	Heat in the boiler
Q_{c_1}	Negative heat in the boiler
W_t	Work output of the turbine
W_p	Work input for the pump

Table 3. Definitions

Primary loop	Loop transmitting heat from Reactor Core to Secondary Loop
Secondary loop	Loop converting thermal energy to mechanical work via turbine
Enthalpy	Heat content of a system
Isentropic	A process with no change in entropy
Generation III$^+$ Reactor	Improved Generation III reactor designs entering operation at the time of publishing
Small Modular Reactor	Smaller reactors designed to work in connected arrays or for smaller power needs in remote areas
Pressurised Water Reactor	Reactors with light water coolant in the primary loop kept at a constant, high pressure
Rankine Cycle	Thermodynamic cycle in the secondary loop
T-S diagram	A diagram comparing the temperature and entropy of a system
Balance of Plant	All supporting components and auxiliary systems needed to operate the plant, aside from energy generating system itself.

1. Introduction

1.1 Background

Nuclear Fission power generation has been a longstanding competitive market since it first entered commercial viability which can be dated to the first operational commercial plant in 1957(1). Problematically, a prolonged period of stagnation due to the lack of long-term and economically viable progress throughout the 20th century limited the commercial market in the west while high profile failure incidents like Chernobyl and Three Mile Island contributed to a cultural and political alienation of fission power generation.

This renewed interest in reactor design and the continuing pressure of old reactors being decommissioned has led to the implementation of early Generation III reactors, however there was a general sense of disappointment over the physical implementation of these designs as stringent yet constantly changing safety guidelines defocused innovation and acted as a stumbling block to wide acceptance of these reactors.(2)

The focus for development of Gen III+ Nuclear Reactors for commercial electricity generation is safety innovation over previous generations such as PHRS(3)(Passive Heat Removal Systems) and a turn to options suitable for remote areas where smaller more affordable reactors are required for power generation. These features have particularly become more relevant in the 21st century following the aftermath of Fukushima Daiichi(4) and current iteration advanced reactors will attempt to engage these design focuses.(5)

This paper will explore the relative thermodynamic efficiencies of such advanced PWR SMR and Large Reactor systems. This will be especially important as many of these reactors enter a more concrete construction stage of development in the coming few years. An analysis of existing literature will be used to facilitate an evaluation of the prototype systems in question and a comparison of their viability on a thermodynamic level.

1.2 Basic characteristics of a pressurised water reactor

1.21 Heat engine principles

In a nuclear power plant, power is generated by converting the thermal energy released from nuclear fission reaction into mechanical work, which is then used to turn a turbine, rotating an alternator to produce electrical power. In the case of a PWR, the medium used to transmit this energy is steam. The ideal thermodynamic cycle for a steam engine is the Rankine cycle, all power plants reviewed operate under such principles.

The Temperature-Entropy (TS) diagram shown in Fig.1 displays the overall process for the ideal Rankine cycle. A TS diagram is a tool for visualising the parameters related to increasing or decreasing the efficiency of an engine. The curve on the TS diagram represents the saturation dome in a 2d plane. To the left of the saturation curve, the working medium, in this case, H_2O, is in a liquid state. Inside the saturation curve, the medium is in a 2-phase state, consisting of liquid and vapor. To the right of the saturation curve, the medium is entirely gasseous, so called 'dry stream.'

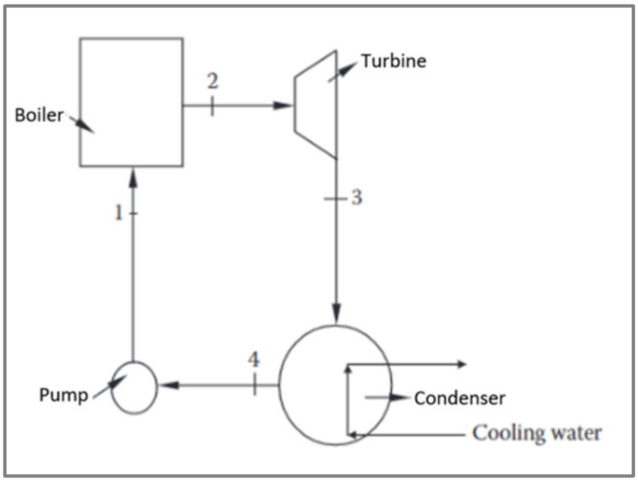

Figure 1. *Rankine cycle flow chart(6)*

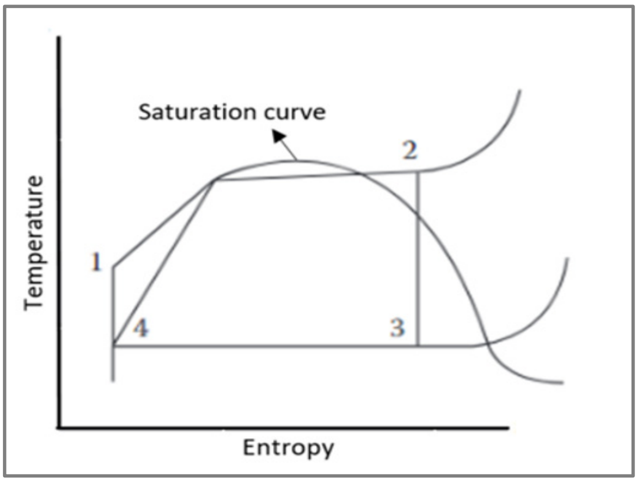

Figure 2. *T-S diagram of Rankine cycle(6)*

The work produced by the engine cycle is represented by the area of the shape plotted from the combined steps in the thermodynamic cycle. The work required to be inputted into the engine from an external source is represented by the area underneath the cycle. It follows therefore that maximising the area inside the shape while reducing the area below the shape will give us a greater efficiency by increasing the work output.

This means that there are three ways to increase the efficiency of a Rankine engine (7); firstly, increasing boiler pressure [process 1-2], secondly increasing the steam temperature [process 2-3], or thirdly decreasing the condenser pressure [process 3-4].

In the first case – increasing boiler pressure shifts the cycle to the left and with fixed volume increases the work output of the turbine and the work input of the pump. I.e. there is a heat supply increase and a heat rejection increase, implying greater thermodynamic efficiency.

In the second case – increasing the steam temperature at fixed pressure will raise a corresponding increase in the area within the cycle, this also decreases the moisture content in the steam which increases the Work output of the turbine without the often corresponding increase in work input required by the pump.

Finally, in the third case – decreasing the condenser pressure increases the area within the cycle, however, this will also increase the moisture content of the steam as it enters the turbine and therefore decreases the efficiency of the turbine (as well as introduce issues of corrosion).

This can also be understood formulaically using the equation of net work in a Rankine cycle engine;

$$W_{net} = Q_b - Q_{c1} = W_t - W_p \qquad Eq.1\ (6)$$

1.22 Fission chain reaction

The neutrons released in the fission reaction interact with the core itself to fission further neutrons, thus creating a chain reaction. When this reaction can sustain itself, the core is said to be critical. A certain "critical" amount of material is thus required to release enough neutrons to continue the fission reaction.

1.23 Neutron Moderator

The fast neutrons released from the fission reaction often 'escape' the reactor core material without creating further fission products. A way to ensure a higher efficiency of neutrons engaging in the chain reaction (neutron economy) is to slow down these neutrons to thermal energies, that is, to an energy level in which they are in thermal equilibrium with the surrounding material. This is done by the introduction of a moderator. The moderator consists of a material with lightweight nuclei which absorb the kinetic energy of the neutrons, slowing them to thermal energies, increasing neutron economy and reducing the critical mass required in the core.

1.24 Coolant

In a PWR, water acts as both coolant and moderator. In the process of neutron moderation, the kinetic energy imparted to the water's nuclei increases its thermal energy. This is the mechanism by which the thermal energy is removed from the core. The heated coolant water is kept under constant pressure to prevent it from boiling via a pressuriser. This is to prevent any changes in density of the coolant system, sustaining a steady flow of the coolant in an out of the reactor core. The water coolant system that is in contact with the reactor is kept in a contained loop within the reactor vessel. This is done to minimise radioactive products exiting the reactor vessel and increased containment safety.

1.25 Steam Generator

The heat from the coolant loop is transferred to a secondary water loop (feedwater loop), which is allowed to vaporise. The steam produced in the feedwater loop is then used to turn a steam generator turbine, thus converting the work from the heat engine into electrical energy. The steam is then cooled via a condenser back to the liquid phase and the cycle repeats. (7)

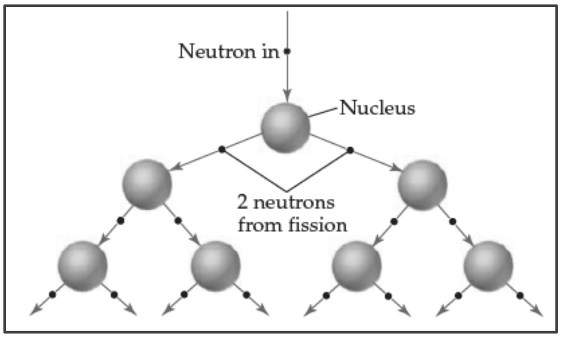

Figure 3. *Neutron fission chain reaction(8)*

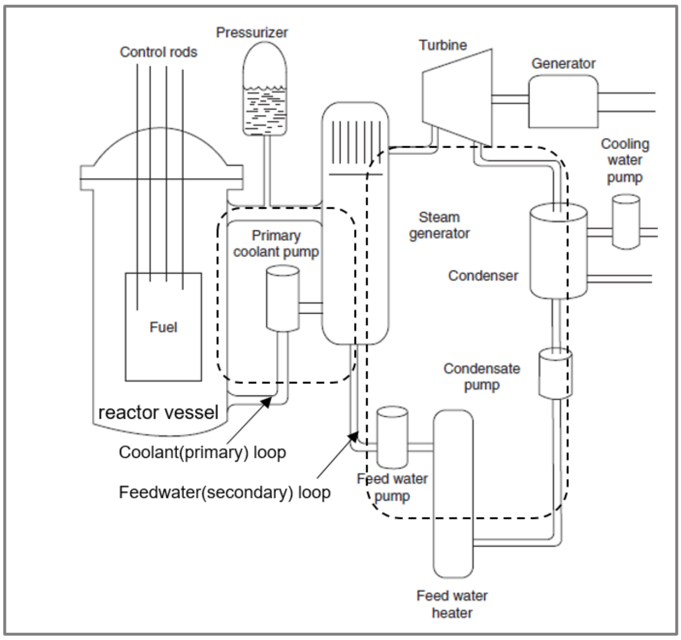

Figure 4. *Conceptual design of a PWR reactor plant(7)*

2. Methods

This paper is a meta-analysis of existing literature in the field of Nuclear Engineering and as such is a study of multiple papers, both on the topic and for wider understanding and appreciation. This research was conducted by accessing a variety of databases – Scopus, Science Direct, Access Science and Google Scholar – along with a selection of journals – 'Nuclear Engineering and Design,' 'Progress in Nuclear Energy,' 'Annals of Nuclear Energy' and 'Nuclear Engineering and Technology.'

A major source of individual reactor parameters was the 'International Atomic Energy Agency's' 'Advanced Reactors Information System.' Information from this source was collated and then systematically cross-referenced against other sources to ensure accurate recordings. This allowed for the construction of a large single table containing parametric data on many reactors, included in the appendix for posterity and future research. This, in turn, enabled rapid data mining for relevant factors for the paper.

The scope of all research was restricted to plants currently in late stage development, under construction or already operational to maintain a reflection of reality and move away from entirely theoretical design choices that had not properly been experimentally verified. This link to more concrete reactors served an additional purpose as it meant that the majority of reactors being analysed functioned and therefore had fairly rigid thermodynamic parameters.

This research process was conducted by alternately widening and narrowing the scope of the search. Starting with a general perusal of Fission Power Generation the search was then narrowed to an analysis of Passive Heat Removal Systems before expanding back outwards to a more general analysis of plant efficiency in Gen III+ reactors. By this method, it was possible to ensure that the majority of independent and original research retained a use in the finished paper.

Over the course of this research data was located about a wide variety of plant parameters and to define a thesis topic these parameters were compared and graphed against each other. Of particular interest was the amount of electrical power that made it into the grid against the total electrical power generated by the turbines. It can be assumed that the difference between these figures is the total power required by the plant during general operation.

In order to graph the efficiency versus the various parameters investigated, it was necessary to calculate the nominal thermal efficiencies of the reactors, explained here;

The thermal efficiency of a heat engine such as a fission reactor is defined as the efficiency ε as shown:

$$\varepsilon = \frac{W}{Q_H} \qquad \textit{Eq.2(9)}$$

More constructively since W (work produced) and Q_H (heat from the hot reservoir) can be expressed as:

$$Q_c = Q_H - W \qquad \textit{Eq.3 (9)}$$

It follows then that the thermal efficiency ε can also be expressed as:

$$\frac{Q_c}{Q_H} = 1 - \varepsilon \qquad \textit{Eq.4 (9)}$$

3. Results and Discussion

In figures 5-7 displayed below, each coloured marker represents a reactor, with its gross and net efficiency denoted by a solid dot and a black outlined dot, respectively. Details of reactors can be found in the appendix.

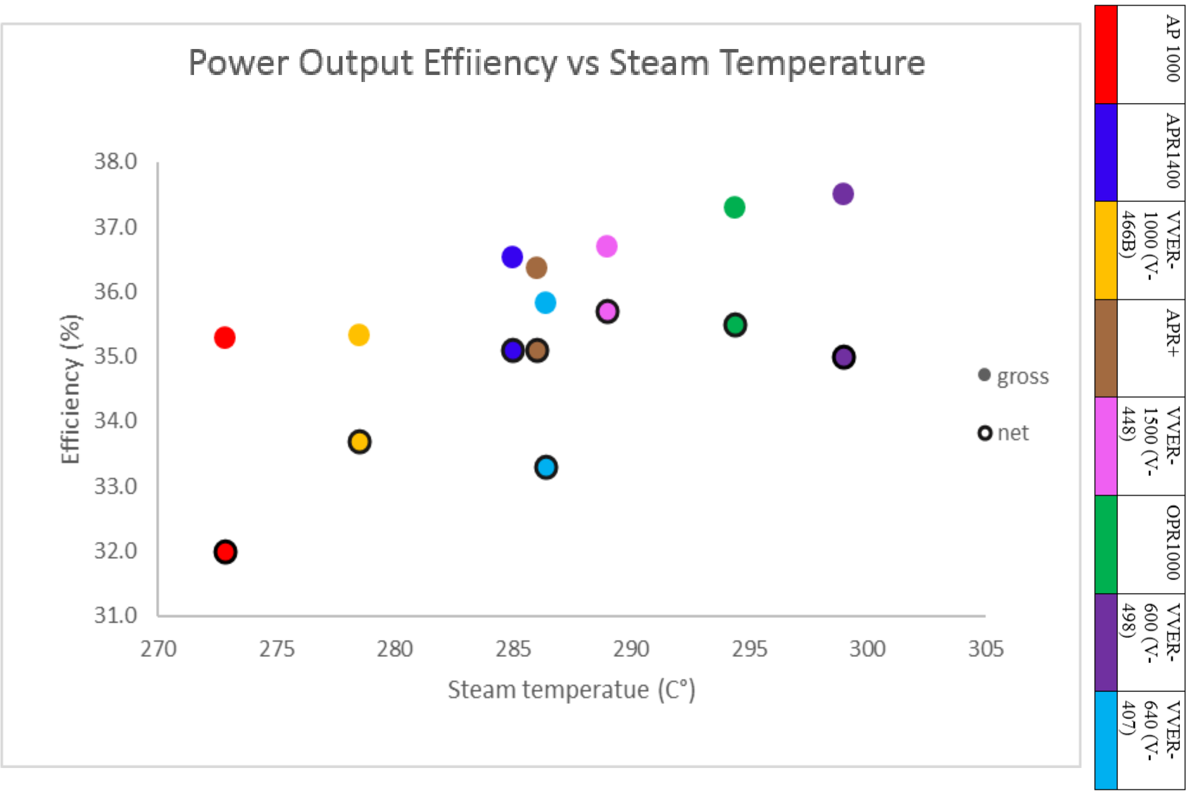

Figure 5. *Steam temperature vs efficiency*

There is a strong linear relationship between steam temperature and the efficiency of the gross electrical power output of the plants in question. It would be expected that the Rankine cycle would increase the gross output of such an engine, but an increase in efficiency also implies an engineering advancement in the heat exchanger, as the heat driving the engine is supplied by the exchange between the primary loop and the secondary loop. Therefore, this result can alternatively be read as an affirmation that a more efficient heat exchanger effectively creates more work on the turbine at no extra work into the system.

Net efficiency appears to follow a linear relation up until 290℃, above this temperature the net efficiency begins to decline. A possible reason for this phenomenon could be that the extra thermodynamic work created on the turbine by the higher steam temperatures is not enough to offset the economies of scale involved in plant engineering. This relative inefficiency appears to be a result of the fact that most reactors examined have a similar absolute operating power requirement (approximately 50MWe), but do not necessarily generate similar amounts of electricity. Therefore, in smaller power plants a higher percentage of its power output must be used just to keep the plant operating than in larger plants – this can be understood as both a thermodynamic and mechanical issue.

This idea neatly explains the status of many conflicting data points for the curve of the net efficiency line. The red points on the graph are the AP1000 which has an operating requirement of nearly double every other reactor, so although it superficially seems to be largely less efficient, there are factors involved beyond the thermodynamics of the loops. Conversely, the cyan (VVER 640), green (OPR1000) and purple (VVER 600) reactors are all reactors with a much lower electrical output altogether essentially creating the opposite problem; the fact that they require the same initial input depresses the net electrical efficiency. Such a result implies that for large power requirements it is more thermally efficient to have one larger reactor than it is to have multiple smaller reactors.

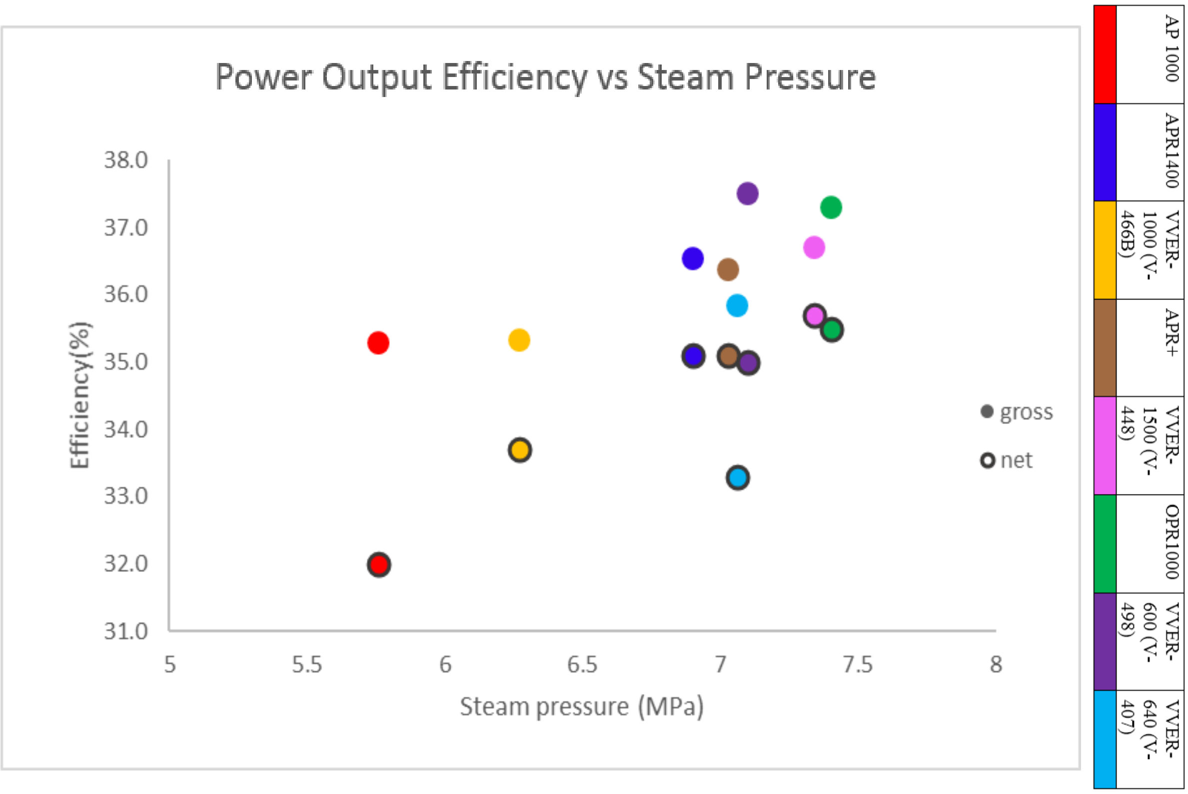

Figure 6. *Steam pressure vs efficiency*

In figure 6, the gross power output of each reactor forms a slight linear trend where most of the data points start limiting around 7 MPa, indicating that most reactors have an optimal pressure range which lies at the 7 MPa pressure. The net power output shows a positive linear trend suggesting that increasing the boiler pressure in a Rankine cycle does increase efficiency which was expected as stated in 1.1. This simply put is due to an increase in entropy allowing a greater electrical output. A reason for this cluster of similar boiler pressures is the increased chance of wet steam formation at higher pressures (6, 10) Wet steam becomes a concern when it forms, as once it condenses in the later steps of the Rankine cycle it causes erosion in the turbine blades.

Figure 7 does not appear to show a linear relationship between condenser pressure and efficiency, net or gross. This is counter to what was established earlier about the Rankine cycle in section 1.2, which tells us that a decrease in efficiency would be seen with an increase in pressure, in other words, it would be expected that any potential trends in data should show a negative gradient. It may be possible to establish many factors that attribute to the lack of relation between the two. One such explanation is the position of the condensing step in Rankine cycle, which can be seen in Fig.1-2. The efficiency of other parameters is dependent on the condenser pressure value, and varying it has a direct effect on all steps in the cycle (11, 12).

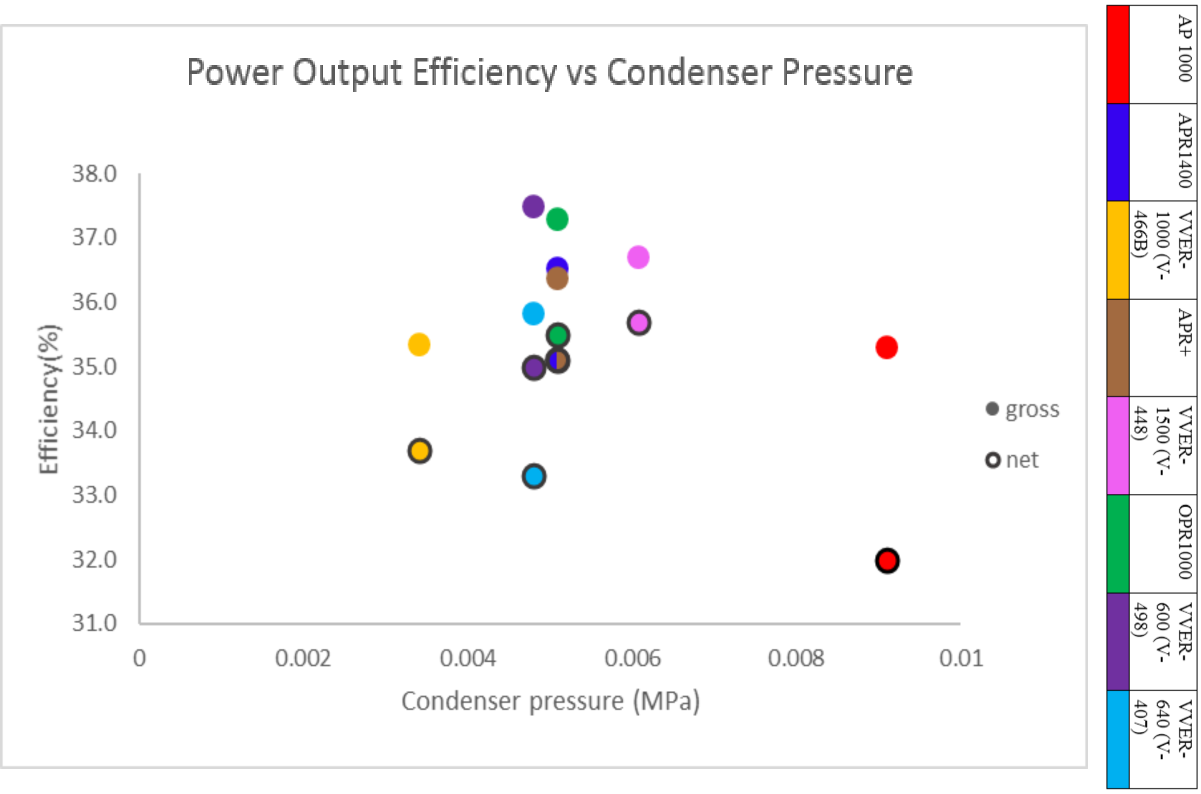

Figure 7. *Condenser pressure vs efficiency*

The complexity of the balance of plant introduced by condenser pressures significantly below atmospheric pressure may also be a factor, introducing working input in machinery and piping that is not considered in the fundamental Rankine cycle TS diagram (13).

4. Conclusions

A direct linear relationship can be seen between the steam temperature at the turbine and the power plant efficiency. This is in concurrence with the thermodynamics of the Rankine cycle. A limiting temperature is observed around 290° for net electrical power efficiency. This may be due to the increased work input required by the power plants at such high temperatures, as well as the disparity in efficiency created by reactors of different power outputs requiring a similar power input.

A weaker but still observable linear relationship is seen between steam pressure and efficiency. It is noted that the steam pressure is effectively equivalent to the boiler pressure as they are part of the same step in the Rankine cycle. A limiting pressure of 7.5MPa is seen, with most reactor pressure fitting in the 7-7.5MPa mark.

No relationship was observable between condenser pressure and efficiency. Previous studies (11-13) and the laws of thermodynamics tell us that this relationship exists; however it appears to be more difficult to optimise directly, due to the complexity of the balance of plant introduced by this parameter, as well as the dependence of other parameters on the value of condenser pressure having a 'knock on' effect.

This suggests that in relation to the first case further focus should be directed towards investigating the optimal scale for thermal reactor output as a function of net electrical efficiency. Whereas in relation to the third case more investigation into condenser pressure as an optimisation for the Rankine Cycle is required.

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Appendix

Acronym	Units	OPR1000 (27-29)	VVER-640 (V-407) (25, 26)	VVER-600 (V-498) (23, 24)	VVER-1500 (V-448)(22)	APR+ (21)	VVER-1000 (V-466) (19, 20)	APR1400 (17, 18)	AP 1000 (14-16)
Reactor thermal output	[MWth]	2815	1800	1600	4250	4290	3000	3983	3400
Power plant output gross	[MWe]	1050	645	600	1560	1560	1060	1455	1200
Power plant output net	[MWe]	1000	603	546	1505	1505	1011	1400	1100
plant efficiency gross	[%]	37.3	35.8	37.5	36.7	36.4	35.3	36.5	35.3
Plant efficiency, net	[%]	35.5	33.3	35	35.7	35.1	33.7	35.1	32
Steam flow rate	[kg/s]	1580	1000	444.4	2390	1218.4	408.33	1130.83	1889
Steam pressure	[MPa]	7.4	7.06	7.1	7.34	7.03	6.27	6.9	5.76
Steam temp	[°C]	294.4	286.4	299	289	286	278.5	285	272.8
Condenser pressure	[Mpa]	0.00508	0.0048	0.0048	0.00608	0.00508	0.0034	0.00508	0.0091
Feedwater flow rate	[kg/s]	-	1000	-	-	1220.84	6000	1134	1889
Feedwater temp	[°C]	232.2	230	230	230	232.2	220	232.2	226.7
Primary coolant flow	[kg/s]	-	14945	13861	31594	21658	23888	20991	14300
Reactor operating	[MPa]	15.5	15.7	16.2	15.7	15.5	15.7	15.5	15.513
Coolant inlet temp	[°C]	296	294.3	299	298	291.7	291	290.6	279.4
Coolant outlet temp	[°C]	327	322.7	325	330	326.1	321	323.9	324.7