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Analyses of Simple and Intercooled Recuperated Direct Brayton Helium Gas Turbine Cycles for Generation IV Reactor Power Plants

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Abstract

As a non-greenhouse gas-emitting source, the benefits of nuclear as a main power generation alternative are yet to be fully explored; part of the reason is due to the significant implementation costs. However, with cycle efficiencies of 45% to 50% in current studies, it can be argued that the long-term benefits outweigh the initial costs, if developed under the Generation IV framework. The main objective of this study is to analyse the effects of pressure and temperature ratios including sensitivity analyses of component efficiencies, ambient temperature, component losses and pressure losses on cycle efficiency and specific work. The results obtained, indicate that pressure losses and recuperator effectiveness have the greatest impact on cycle efficiency and specific work. The analyses intend to aid development of the Simple Cycle Recuperated (SCR) and Intercooled Cycle Recuperated (ICR) cycles, applicable to Gas Cooled Fast Reactors (GFRs) and Very-High-Temperature Reactors (VHTRs), where helium is the coolant.

Keywords: Gen IV, Efficiency, Specific Work, Cycle, Nuclear Power Plants, Performance, Simple, Intercooled.

Nomenclature

Notations

A	Area (m^2)
Cp	Spec. Heat of Gas at Constant Pressure (J/kg K)
CW	Compressor Work (W)
m	Mass Flow Rate (kg/s)
Q	Reactor Thermal Heat Input
q	Heat Flux (W/m^2)
P	Pressure (Pa)
PR	Pressure Ratio
SW	Specific Work/Power Output (W/Kg/s)
T	Temperature (K or ℃)
TR	Temperature Ratio (T_4 / T_1; expressed in Kelvin)
TW	Turbine Work (W)
W	Work (W)
UW	Useful Work (W)

Greek Symbols

γ	Ratio of Specific Heats
Δ	Delta, Difference
ε	Effectiveness (Heat Exchanger)
η	Efficiency

Subscripts

c	Compressor
c_{in}	Compressor Inlet
c_{out}	Compressor Outlet
e	Power for Electrical Conversion
he	Helium
he_{min}	Helium with minimum gas conditions
ic	Intercooled Cycle; intercooled coefficient
is_c	Isentropic (Compressor)
is_t	Isentropic (Turbine)
MHR	Reactor (Heat Source)
MHR_{in}	Reactor (Heat Source) Inlet
MHR_{loss}	Reactor (Heat Source) Pressure Losses
MHR_{out}	Reactor (Heat Source) Outlet
pc_{in}	Precooler Inlet (also applicable to intercooler)
pc_{loss}	Precooler Pressure Losses (same as above)
pc_{out}	Precooler Outlet (same as above)
re	Recuperator
re_{cold}	Recuperator cold side
re_{hot}	Recuperator hot side
re_{HPloss}	Recuperator High Pressure Losses
re_{LPloss}	Recuperator Low Pressure Losses
re_{real}	Recuperator Real (specific heat transfer)
re_{max}	Recuperator Max (specific heat transfer)
th	Thermal Power
t	Turbine
t_{out}	Turbine Outlet
t_{in}	Turbine Inlet

Superscripts

'	Recuperator inlet conditions

Abbreviations

C	Compressor
CH	Precooler (Figure 1)
COT	Core Outlet Temperature

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DP	Design Point
GEN IV	Generation Four
GFR	Gas-Cooled Fast Reactors
GIF	Generation IV International Forum
HE	Heat Exchanger (Recuperator)
HP	High Pressure
HPC	High Pressure Compressor
ICR	Intercooled Cycle Recuperated
LP	Low Pressure
LPC	Low Pressure Compressor
NPP	Nuclear Power Plant
NTU	Number of Transfer Units
OPR	Overall Pressure Ratio
R	Reactor
RPV	Reactor Pressure Vessel
SCR	Simple Cycle Recuperated
T	Turbine
TET	Turbine Entry Temperature
TUR	Turbine
VHTR	Very-High-Temperature Reactor

Introduction

Generation IV reactors intend on revolutionising the designs of Nuclear Power Plants (NPP) with one key aspect being the improvement of cycle thermal efficiency in comparison to the incumbent designs [1]. However, the simplification of the plant design is critical to better life cycle and energy production costs [2]. Complicated designs derived from complex arrangements may increase plant capacity but may not provide sound economics if the overall efficiency of the plant does not provide the necessary cost justification. The objective is to conduct a thermodynamic study using a performance simulation tool to analyse the SCR and ICR in a closed Brayton direct configuration using helium as the working fluid.

Generation IV (Gen IV) Systems

The Gen IV systems applicable to this study are the Gas-Cooled Fast Reactor System (GFR) and Very-High-Temperature Reactor System (VHTR). The GFR is helium cooled, with the objective of the technology lying in its ability to bring a high temperature reactor and a fast spectrum nuclear core. With a Core Outlet Temperature (COT) of 850-950°C made possible through an efficient Brayton cycle, a direct thermodynamic cycle is easily adopted. Helium as a working fluid has benefits such as single phase cooling in all circumstances, chemical inertness and neutronic transparency [3]. The VHTR is a high temperature thermal reactor, which is cooled by helium in gaseous phase and moderated by graphite in the solid state. The core has a COT of 750-1000°C, which signifies increase in thermal efficiency due to high temperature. This is because helium will not induce a chemical reaction within the moderator and graphite retains good mechanical properties at high temperature [4]. According to the Gen IV Forum (GIF) [5], several demonstrator projects planned for the GFR and VHTR are currently in the viability phase – relating to testing of basic concepts or in the performance phase. Descriptions of planned demonstrator reactors are discussed in [1].

Simple and Intercooled Recuperated Brayton Cycles

The SCR requires a compressor and a turbine as part of the turbomachinery. Compressor work is lower than turbine work, thus useful work can be used to drive the generator load but due to component inefficiencies, the compression and expansion phases are not isentropic. As a result, heating and cooling of the cycle (without considering heat exchangers) is not achieved at constant pressure, hence losses are observed in the cycle. The losses translate into additional work input required for the compression process due to increase in temperature, resulting in a higher exit temperature. The heat addition into the cycle is not isobaric, which reduces total gas exit pressure. Thus, possible total power extraction is reduced due to reduced gas exit pressure and reduced component efficiencies. The turbine exit heat is typically hotter than expected, which makes compression inlet temperature hotter than ideal.

A precooler and a recuperator are included in a typical NPP, which is utilised in SCR, in addition to the turbomachinery. The addition of the precooler ensures the working fluid can be cooled by a cooling medium (usually seawater) at the compressor entry to achieve the necessary cycle inlet temperature. This reduces the compressor work but reduces the compressor exit temperature, which will increase the input thermal power. Due to the reactor thermal power being fixed for a given COT, the precooler alone will not yield the specific work required for the NPP, which devalues the economics of the plant. To mitigate this, the recuperator is introduced. Heat from the turbine outlet gas is used to preheat the working fluid downstream of the compressor, thus raising the temperature to reduce the amount of thermal heat input into the cycle, which positively impacts cycle efficiency.

The ICR encompasses all of the aforementioned components in addition to an intercooler and a second compressor, which is downstream of the first compressor. Improving the specific and useful work in the ICR requires a reduction of the compressor work. The working fluid downstream of the first compressor is reduced to a lower temperature in the intercooler, prior to entry into the second compressor, with negligible reduction in pressure.

Thermodynamic consequences of parameters as a result of changing from air to helium in a nuclear gas turbine have been extensively covered in [6]. Although the study, which is also documented in [7] and [8] focuses on off-design, control and transient operational modes of a helium gas turbine, it provides good bases for future off-design analyses, which will be applicable to the SCR and ICR configurations.

Figures 1 and 2 respectively, illustrates typical schematics of the Simple Cycle Recuperated (SCR) and Intercooled Cycle Recuperated (ICR) NPPs. Table 1 provides key design point values for modelling using the performance simulation tool.

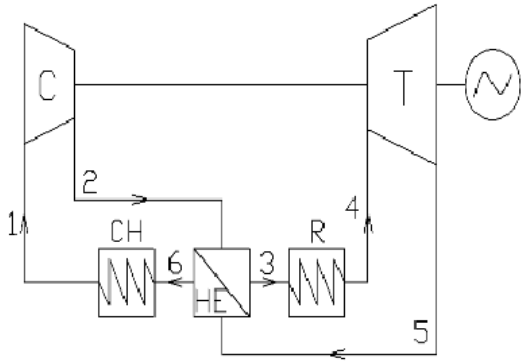


Figure 1 – Typical Simple Cycle with Recuperator [9]

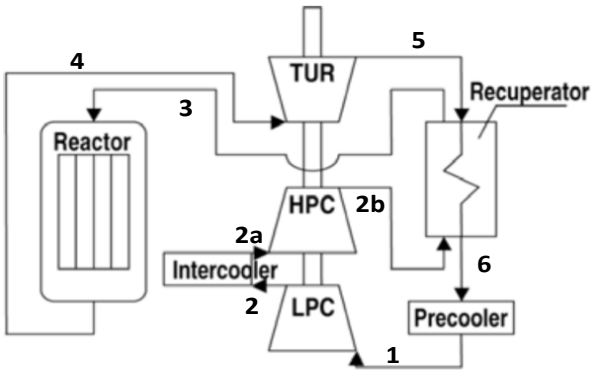


Figure 2 – Typical Intercooled Cycle with Recuperator [10]

The performance of a typical helium cooled NPP utilising SCR or ICR under the conditions in table 1 were modelled and simulated using a FORTRAN based tool, which was developed as part of this study. The equations implemented within the code environment are described in the proceeding sections for steady state design point calculations against each component and cycle.

Compressor

Prerequisite parameters for performance design considerations of the compressor include the compressor pressure ratio, compressor inlet conditions (temperature, pressure and mass flow rate), component efficiency and the working fluid gas properties (Cp and γ). The compressor outlet pressure (Pa) is:

$$P_{c_{out}} = P_{c_{in}} \cdot PR_c \quad (1)$$

Table 1 – SCR and ICR Input Values for Modelling

Inputs	Values	Units
Inlet Temp.	28	°C
TET (Core outlet temp)	950.0	°C
Core inlet temp (SCR)	678	°C
Core inlet temp (ICR)	677	°C
Inlet Pressure	3.21	MPa
OPR	2	-
Mass flow rate at inlet	410.4	kg/s
Compressor Efficiency (Isentropic)	90	%
Turbine Efficiency (Isentropic)	94.5	%
**Recuperator Effectiveness	96	%
Pressure Loss (Precooler)	2.5	%
Pressure Loss (Intercooler ICR only)	2.5	%
Pressure Loss (Reactor)	2	%
Pressure Loss (Recup. HP side)	6 combined	%
Pressure Loss (Recup. LP side)		
Turbine Cooling flow (% of Mass flow rate)	1	%
Reactor Cooling flow (% of Mass flow rate)	0.25	%

***Recuperator Effectiveness is based on technological improvements in* [11]

The isentropic efficiency of the compressor is $\frac{T_{rise_{ideal}}}{T_{rise_{actual}}}$ and is also indicative of the specific work input or total temperature increase. Thus, the temperature (°C) at the exit can be derived from the inlet temperature, pressure ratio, isentropic efficiency and ratio of specific heats:

$$T_{c_{out}} = T_{c_{in}} \cdot \left[1 + \frac{\left(\frac{P_{c_{out}}}{P_{c_{in}}}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\eta_{is_c}} \right] \quad (2)$$

The mass flow rate (kg/s) at inlet is equal to the mass flow rate as there are no compositional changes:

$$m_{c_{out}} = m_{c_{in}} \quad (3)$$

The compressor work (W) is the product of the mass flow rate, specific heat at constant pressure and the temperature delta:

$$CW = m_c \cdot Cp_{he} \cdot (\Delta T_c) \quad (4)$$

whereby $\Delta T_c = T_{c_{out}} - T_{c_{in}}$ (5)

Bypass splitters are incorporated within the performance simulation tool to allow for compressed coolant to be bled for reactor and turbine cooling.

Turbine

Prerequisite parameters of the turbine include the turbine inlet conditions (temperature, pressure and mass flow rate), the pressure at outlet, component efficiency and the working fluid gas properties (Cp and γ).

The temperature (°C) at the outlet is derived from the following expression:

$$T_{t_{out}} = T_{t_{in}} \cdot \left\{1 - \eta_{is_t}\left[1 - \left(\frac{P_{t_{out}}}{P_{t_{in}}}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\} \quad (6)$$

As with the compressor, eqs (3) and (4) also apply to the turbine for mass flow rate (kg/s) conditions and turbine work (W) but:

$$\Delta T_t = T_{t_{in}} - T_{t_{out}} \quad (7)$$

A mixer is incorporated within the performance simulation tool to allow for the coolant to mix with the hot gas to simulate turbine cooling.

Recuperator

The calculation method for the rate of heat transfer is based on the Number of Transfer Units (NTU) method, which has been documented by [12] and applied for complex cross flow heat exchangers by [13]. The algorithm in the code ensures satisfactory results and numerical stability.

Prerequisite parameters include the recuperator effectiveness, hot and cold inlet conditions (pressure and temperature) and the delta pressures due to losses at high and low pressure sides.

The effectiveness of the recuperator is given as:

$$\varepsilon_{re} = \frac{q_{re_{real}}}{q_{re_{max}}} \quad (8)$$

The maximum amount of heat flux (W/m^2) of the recuperator $q_{re_{max}}$ must consider the hot and the cold inlet conditions. It must also consider the minimum specific heat because it is the aspect of the fluid with the lowest heat capacity to experience the maximum change in temperature. This is expressed as:

$$q_{re_{max}} = \frac{Cp_{he_{min}} \cdot \left(T'_{re_{hot}} - T'_{re_{cold}}\right)}{A} \quad (9)$$

and the real heat flux (W/m^2) is:

$$q_{re_{real}} = \frac{Cp_{he_{hot}} \cdot \left(T'_{re_{hot}} - T_{re_{hot}}\right)}{A} = \frac{Cp_{he_{cold}} \cdot \left(T_{re_{cold}} - T'_{re_{cold}}\right)}{A} \quad (10)$$

With helium as the working fluid, Cp is considered to be constant, thus $Cp_{he_{min}} = Cp_{he_{cold}} = Cp_{he_{hot}}$ in the energy balance equation. The temperatures at the hot and cold ends can be obtained when considering eq (10) (either hot or cold sides) and considering an arbitrary effectiveness. The temperature for the cold end (°C) is then expressed as:

$$T_{re_{cold}} = T'_{re_{cold}} + \left[\varepsilon_{re} \cdot \left(T'_{re_{hot}} - T'_{re_{cold}}\right)\right] \quad (11)$$

With $Cp_{he_{min}} = Cp_{he_{cold}} = Cp_{he_{hot}}$, the energy balance is:

$$\left[m_{re_{cold}} \cdot \left(T_{re_{cold}} - T'_{re_{cold}}\right)\right] = \left[m_{re_{hot}} \cdot \left(T'_{re_{hot}} - T_{re_{hot}}\right)\right] \quad (12)$$

thus, the hot outlet (°C) is:

$$T_{re_{hot}} = T'_{re_{hot}} - \left[\frac{m_{re_{cold}} \cdot \left(T_{re_{cold}} - T'_{re_{cold}}\right)}{m_{re_{hot}}}\right] \quad (13)$$

With regard to pressures, the exit conditions can be calculated if the pressure drops (%) across the hot and cold sides are known:

$$P_{re_{cold}} = P'_{re_{cold}} \cdot \left(1 - \Delta P_{re_{HPloss}}\right) \quad (14)$$

$$P_{re_{hot}} = P'_{re_{hot}} \cdot \left(1 - \Delta P_{re_{LPloss}}\right) \quad (15)$$

Due to no compositional changes, mass flow rate (kg/s) conditions are:

$$m_{re_{hot}} = m'_{re_{hot}} \quad (16)$$

$$m_{re_{cold}} = m'_{re_{cold}} \quad (17)$$

Precooler and Intercooler

Prerequisite parameters for the precooler and intercooler (ICR only) take into account that both components are upstream of the first and second compressors, thus compressor inlet temperature and pressure are of importance including the pressure losses.

The conditions for the precooler are as follows:

$$T_{pc_{out}} = T_{c_{in}} \quad (18)$$

$$P_{pc_{in}} = P_{pc_{out}} \cdot \left(1 + \Delta P_{pc_{loss}}\right) \quad (19)$$

$$m_{pc_{out}} = m_{pc_{in}} \quad (20)$$

With regard to the intercooler, eqs (18), (19) and (20) also apply. An addition of a second compressor for the intercooled cycle means that the pressure ratio for both compressors is determined as:

$$PR_{ic} = \sqrt[ic]{PR} \quad (21)$$

whereby the ic coefficient denotes the number of intercoolers in the cycle +1, leading to a reduction in the pressure ratio per compressor.

Modular Helium Reactor

As a heat source with inevitable pressure losses, the prerequisites are the thermal heat input from burning the fuel and the known reactor design pressure losses.

The heat source does not introduce any compositional changes thus mass flow rate (kg/s) is:

$$m_{MHR_{out}} = m_{MHR_{in}} \quad (22)$$

Pressure taking into account losses (%):

$$P_{MHR_{out}} = P_{MHR_{in}} \cdot \left(1 - \Delta P_{MHR_{loss}}\right) \quad (23)$$

and the thermal heat input (Wth) is:

$$Q_{MHR} = m_{MHR_{in}} \cdot Cp_{he} \cdot \left(\Delta T_{MHR}\right) \quad (24)$$

whereby $\Delta T_{MHR} = T_{MHR_{out}} - T_{MHR_{in}}$ (25)

A mixer is incorporated within the code to allow for coolant to be mixed with the heated fluid upstream of the reactor to simulate reactor vessel cooling.

Cycle Calculations

The useful work, specific work and thermal efficiency output values are of interest after executing each set of station parametric calculations. The useful work (We) that is the work available for driving the load is:

$$UW = TW - CW \quad (26)$$

whereby eq (26) is also applicable to ICR but CW is the summation of both compressors' work requirement to be delivered by the turbine.

The specific work or capacity of the plant (W/kg/s) is:

$$SW = UW/W \quad (27)$$

and the thermal efficiency (%) of the cycle is:

$$\eta_{th} = UW/Q_{MHR} \quad (28)$$

Figure 3 denotes the typical structure of the performance simulation code for SCR. The structure is interchangeable for ICR but the calculation algorithms are tailored to the conditions driven by the requirements of each cycle. The tool was used to match design point conditions of known SCR & ICR NPPs in open literature in order to verify its functionality. The matching results were considered satisfactory for the purpose of this study.

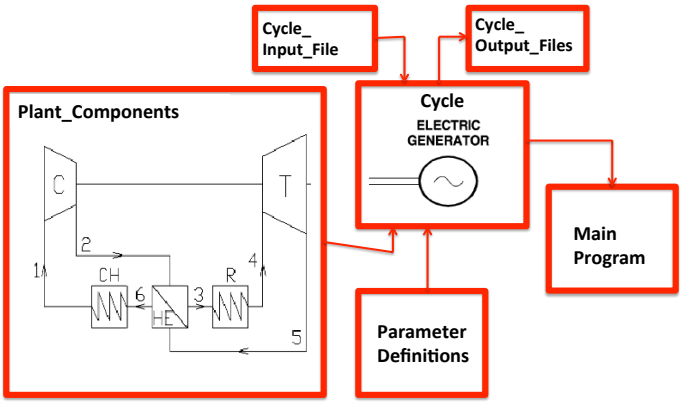


Figure 3 – Performance Simulation Tool Structure for SCR

Results and Discussion

Input data were taken from table 1. Table 2 lists the mass flow rates, pressures and temperatures, which is in line with the cycle schematics in figures 1 and 2. Table 3 lists the output results of the cycles. Both tables provide delta values for quantitative comparison of the SCR to the ICR.

Table 2 – SCR and ICR Station Output Values

St No	m [kg/s]			P [MPa]			T [Deg C]		
	SCR	ICR	Δ (%)	SCR	ICR	Δ (%)	SCR	ICR	Δ (%)
1	410.4	410.4	0.0	3.21	3.21	0.0	28	28	0.0
2	405.28	406.3	-0.3	6.42	4.54	41.4	135	78	73.1
2a	-	406.3	-	-	4.54	-	-	28	-
2b	-	406.3	-	-	6.42	-	-	78	-
3	405.28	405.28	0.0	6.36	6.36	0.0	678	677	0.1
4	406.3	406.3	0.0	6.23	6.23	0.0	950	950	0.0
5	410.4	410.4	0.0	3.45	3.45	0.0	701	702	-0.1
6	410.4	410.4	0.0	3.29	3.29	0.0	164	110	49.1

Table 3 – SCR and ICR Cycle Output Results

CW [MW]			TW [MW]			UW [MW]			SW [MW/kg/s]			Heat Input [MWt]			η %		
SCR	ICR	Δ (%)	SCR	ICR	Δ (%)	SCR	ICR	Δ (%)	SCR	ICR	Δ (%)	SCR	ICR	Δ (%)	SCR	ICR	Δ (%)
227.27	210.52	8.0	513.21	510.64	0.5	285.94	300.12	-4.7	0.70	0.73	-4.7	575.97	579.78	-0.7	49.65	51.76	-2.1

The ICR has 2 additional stages denoted as 2a and 2b that enable the coolant to be cooled to the same inlet temperature as observed at the first compressor, but retaining the higher exit pressure of the first compressor, although with some pressure losses observed, prior to entering into a second compressor. The arrangement shows a lower exit temperature at 2b for the ICR; the SCR registering a 73.4% increase in overall exit temperature. The SCR compressor work is 8% higher for the same PR, which translates into a decrease in useful work of about 4.7%. Negligible decrease in thermal heat input from the burning of nuclear fuel is observed in the ICR, but the main reason for the increase of 2.1% in thermal efficiency in comparison to the SCR, stems from the direct correlation between the additional plant capacity also known as the specific work and the useful work.

Realistically, the losses for an ICR will be less during compression and heat exchange in the recuperator, but the addition of an intercooler relinquishes some those benefits. An additional point to note for the ICR is the improved exchange of the heat. This reduces the penalties of low compressor exit temperature, which usually translates to additional thermal heat input from the reactor to compensate for the cycle balance. Instead, only a 0.7% delta in thermal heat from the reactor as aforementioned is noted due to the heat from the turbine exit being transferred back into the cycle. This also means that the amount of heat sink in the precooler for the re-circulated helium is minimised by over 49% in the ICR. Nonetheless, the ICR requires additional capital costs and increases in capacity, translate into additional complexities. This means that the SCR, especially in a modular arrangement, provides an attractive option for consortia investing in nuclear projects, although the net value cost quantification is yet to be undertaken to provide substantiation.

Effects of Pressure and Temperature Ratio on Thermal Efficiency and Specific Work

Figures 4 and 5 provide pressure ratios versus efficiency curves for a range of temperature ratios (T_4/T_1 expressed in degrees Kelvin), for both SCR and ICR respectively. No turbine cooling was included during this stage in the analyses. It is evident from figures 4 and 5 that increases in temperature ratio (TR) denote increases in thermal efficiency. At optimum PR, both ICR and SCR have a 21% increase in thermal efficiency between TRs of 2.6 to 4.1. However, the rate of efficiency increase to maximum achievable and the rate of deterioration from maximum efficiency achieved, is favourable for the ICR in comparison to the SCR at higher temperatures. This is because incremental increases in PR for ICR, lead to bigger increases in thermal efficiency and it also experiences less deterioration. This indicates that the SCR does not offer a significant marginal gain in efficiency and may be suited at a lower PR to limit the compressor work or a lower TR at optimum PR. This is substantiated by an observed increase in efficiency of 0.006% to achieve maximum efficiency, which is low when compared to 0.1% for the ICR at a TR of 4.1. A lower PR for the SCR yields 0.6%; a lower TR of 3.9 also yields approximately the same increase. Further increases in TR from current technology would be limited by thermal material capability of the turbine, the level of turbine cooling required to mitigate damage of the turbine and achievable compressor PR, when aerodynamic losses and mechanical stresses on the blades are considered.

However, because helium has a higher ratio of specific heats in comparison to air, a lower pressure ratio for the compressor is observed for both cycles, thus less aerodynamic losses and reduced mechanical stresses on the compressor when compared to air. The components efficiencies and losses employed in the calculations are as per table 1.

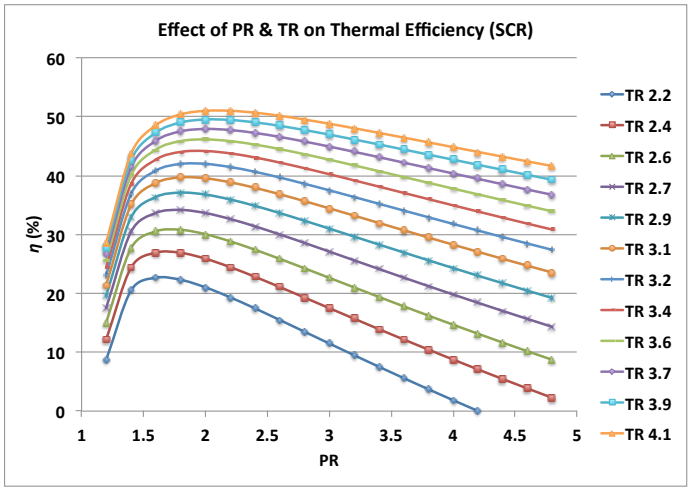


Figure 4 – PR vs. Efficiency for given TRs (SCR)

Figures 6 and 7 show the effect of PR and TR on SW with no turbine cooling considered. There is a 257% increase in SW for the SCR when compared to 213% increase for the ICR between TRs of 2.6 to 4.1. This would indicate that the SCR achieves more plant capacity

utilisation for its size than the ICR between TR of 2.6 to 4.1. As also observed, the maximum SW achievable does not correspond to optimum PR of both cycles, which is a stark contrast to open cycles.

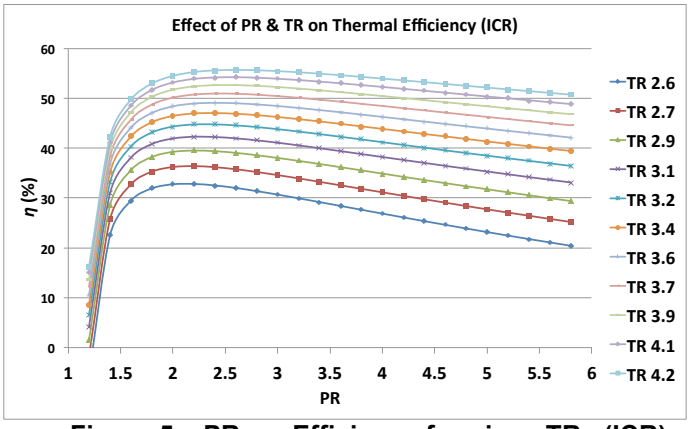


Figure 5 – PR vs. Efficiency for given TRs (ICR)

This stipulates the addition of the recuperator to recover the exhaust heat back into the cycles. Cycle economics do not prioritise the amount of power a plant can deliver, which will require significant scaling up of components and incorporating smaller fuel schedules or increasing the size of the reactor to accommodate more fuel to increase output, at the expense of thermal efficiency. Closing the fuel cycle or lessening of the refuelling schedule is key to achieving the sustainability goal as part of the Gen. IV objectives, thus a change in refuelling demand will not be preferred. Scaling up in plant size will increase the capital costs and subsequent maintenance costs, which is less favourable and not justifiable, when it compromises thermal efficiency.

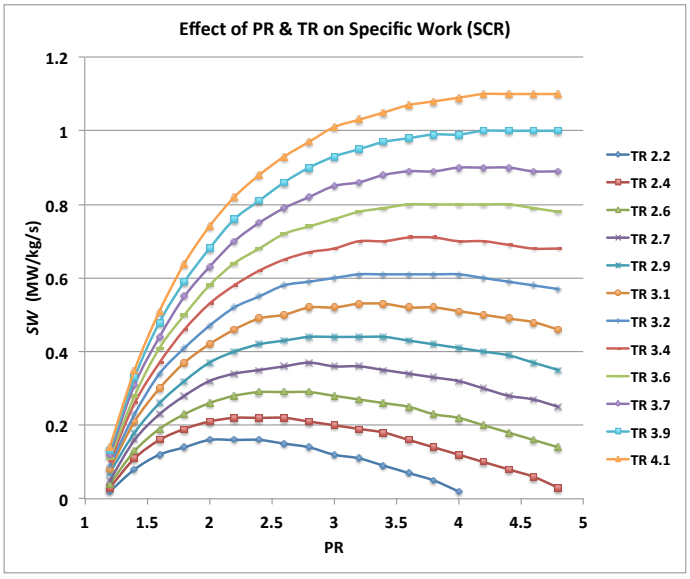


Figure 6 – PR vs. Specific Work for given TRs (SCR)

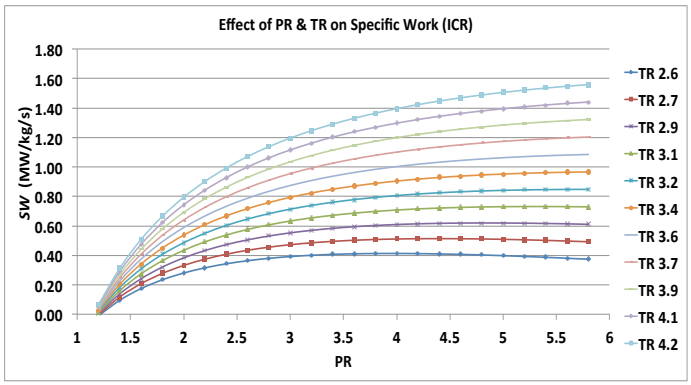


Figure 7 – PR vs. Specific Work for given TRs (ICR)

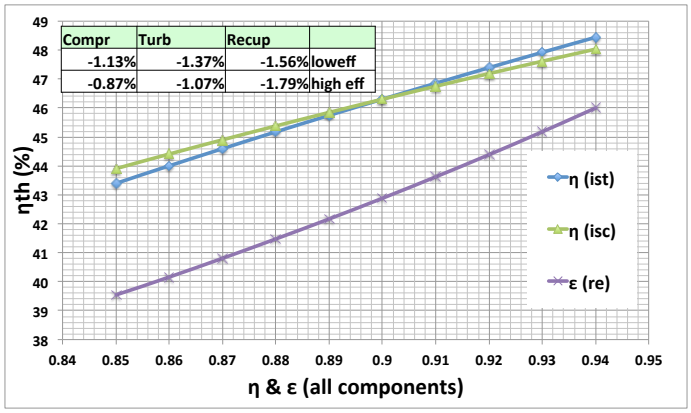


Figure 8 – Sensitivity Analysis – Effect of Component Efficiencies on Cycle Efficiency (SCR)

Sensitivity Analysis – Component Efficiencies

Figures 8 and 9 provide component sensitivity analysis and the effects on cycle efficiency of SCR and ICR.

The analysis provides justification, which expresses the importance of achieving the highest possible efficiencies for SCR and ICR but to also investigate the gains in performance from technological improvements of components versus overall benefit to plant cycles.

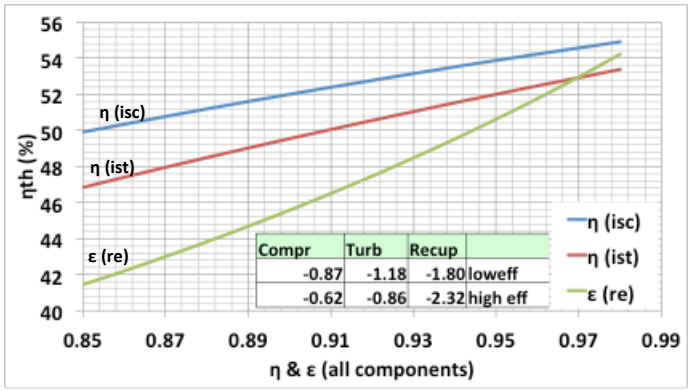


Figure 9 – Sensitivity Analysis - Effect of Component Efficiencies on Cycle Efficiency (ICR)

For each component that was analysed, the other components and conditions not being analysed were unchanged from design point (table 1). The following observations are made from figures 8 and 9:

- The lower ranges of compressor and turbine efficiencies have a greater impact on both cycles. For the compressor, the values are 1.13% (SCR) and 0.87% (ICR) although when it comes to improving the compressor, there are more marginal gains for the SCR per 1% increase in compressor efficiency in comparison the ICR, if the improvement is on a compressor with nominal efficiency <0.89. The other way of looking at it is that efficiency of ICR is negligibly sensitive to compressor efficiency for values >0.85. There is no need to develop the compressors beyond a certain point because it may prove costly to compressor development to design a machine with minimal flow separation, without compromise on the stability limits.
- The ICR (1.37%) is more sensitive to turbine efficiency than the SCR (1.18%) at the lower end of $0.85<\eta<0.89$, but there are still gains to be made for both cycles, if turbine development programmes aimed at improving efficiencies in the range of $0.89<\eta<0.95$.
- The recuperator effectiveness has the greatest effect on cycle efficiency for the SCR (1.56%) and ICR (1.80%) at the $0.85<\varepsilon<0.89$. However, unlike the turbomachinery components, the recuperator has more benefit from further increases beyond 0.95 effectiveness and justifies the need for improvement in design to the highest technological levels achievable to always sustain higher cycle efficiencies. However, there has to be a reasonable compromise between the geometrical scale up versus benefit to cycle performance.

With regard to the effect of component sensitivity on specific work of SCR and ICR, the following observations are made from figures 10 and 11:

- The turbine has the greater impact on specific work of the plant due to the importance of extracting the power from the hot gas for the purpose of generating useful work. This process is primarily linked to the efficiency of the expansion process, where it is noted that there is a drop of 1.85% in specific work for SCR and 2.63% for ICR, for every 1% drop in turbine efficiency.
- The compressor has less of an impact on the specific work of the plant, where ~1% for SCR and 0.71% for ICR was noted for every 1% drop in compressor efficiency.
- The recuperator effectiveness has no effect on the specific work of the plant. Rather, the heat input has to be increased to maintain compressor and turbine work because they will be unchanged.

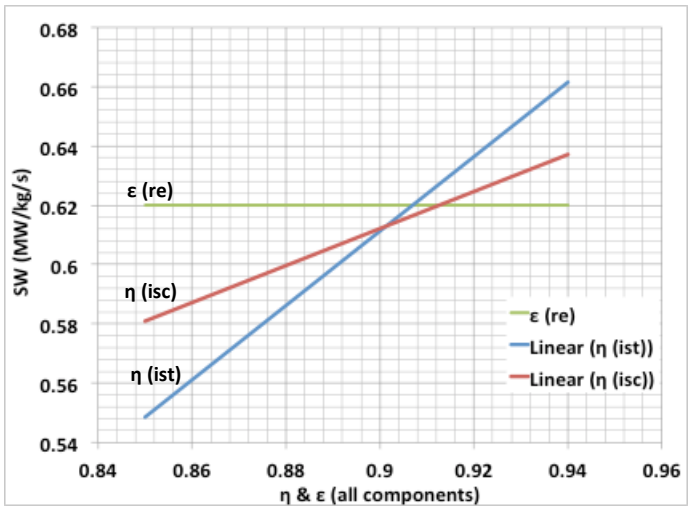


Figure 10 – Sensitivity Analysis – Effect of Component Efficiencies on Specific Work (SCR)

Sensitivity Analysis – Compressor Inlet Temperature

Compressor inlet temperature is important in cycle analysis because it has an effect on the compressor work of the cycle, which affects the cycle efficiency and specific work of the plant. Nuclear plant development is sensitive to ambient conditions especially in hot countries, where higher ambient temperature affects the cooling medium (seawater). With regard to the effect on efficiency, figure 12 shows the trend lines for SCR and ICR for 20-55°C.

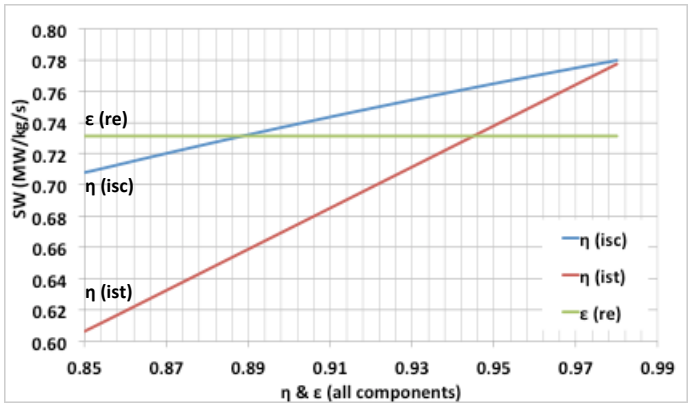


Figure 11 – Sensitivity Analysis – Effect of Component Efficiencies on Specific Work (ICR)

Only the compressor inlet temperature was changed. All other conditions were as per design point values (table 1). The following observations are made:

- The work demand of the compressor is quantified by the fact that for every 1°C rise in temperature, there is a 0.3% increase in compressor work, which affects the useful work available.
- This equates to approximately the same amount of decrease in thermal efficiency, thus a reduction of ~1.3% per 5°C rise.
- The increase in compressor work leads to a reduction in useful work by ~4MW.
- The same negative correlation is observed for the specific work of the cycle.

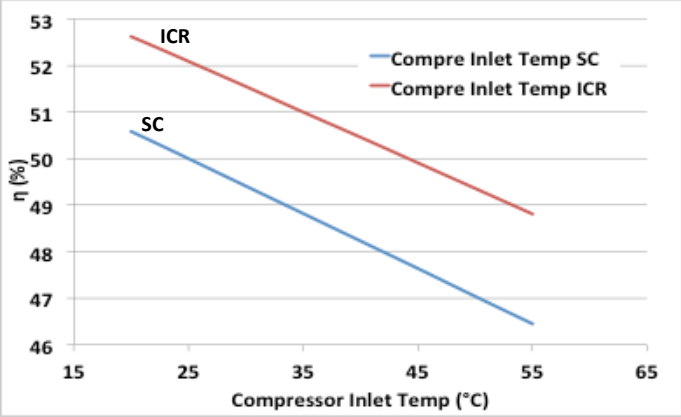


Figure 12 – Sensitivity Analysis - Effect of Compressor Inlet Temperature on Cycle Efficiency

Sensitivity Analysis – Pressure Losses

It is expected that frictional losses will be encountered, when a cycle incorporates heat exchange. The reactor pressure losses also have an effect. All losses within the cycles, reduce the expansion pressure ratio relative to the compression pressure ratio, thus reducing the plant power output due to sensitivity to irreversibilities and thus, having a significant effect on cycle thermal efficiency. Figure 13 illustrates the sensitivities of pressure losses of SCR and ICR at 950°C TET.

Table 4 quantifies the reduction in thermal efficiency based on figure 13 plots for a range of 0.5 - 5% of pressure losses experienced by the relevant components. The main thing noticeable is that the ICR cycle experiences an average total reduction in thermal efficiency of 6.59%, when combining each individual effect in comparison to 5.65% for the SCR. For each component that was analysed, the other components and conditions not being analysed were unchanged from design point (table 1). The specific observations are summarised below:

- It can be observed that for each component, the effects on thermal efficiency are greater at the higher end of the range being investigated.

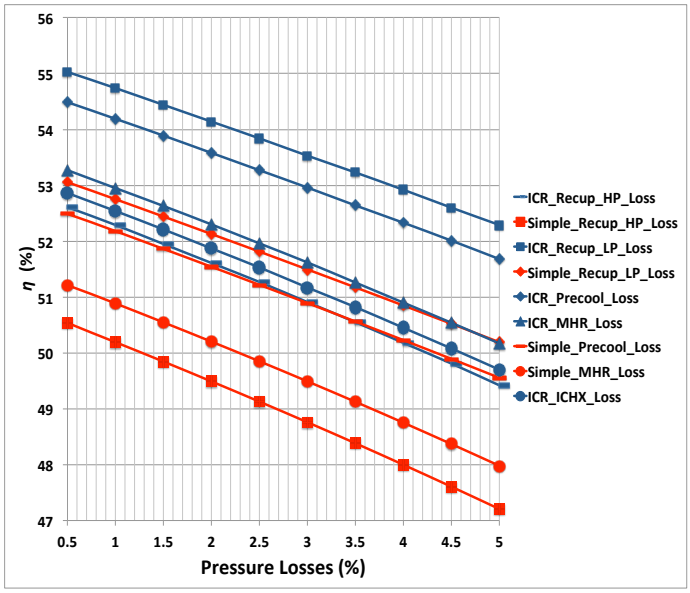


Figure 13 – Sensitivity Analysis – Pressure Losses

- However, the higher range shows higher effects but with variation for each component. For the ICR, the cycle efficiency is more sensitive to recuperator HP side, reactor and intercooler pressure losses. The same holds true for the SCR without an intercooler. This same trend is observed for specific work.
- The effects on thermal efficiency are more pronounced for the SCR cycle (recuperator HP and Reactor) when compared to the ICR although the addition of the intercooler increases the cummulative effect as aforementioned.
- The effect on thermal efficiency of the precooler and recuperator LP side pressure losses are comparable for the SCR and ICR.
- This suggests that nuclear plant design should minimise losses, where possible. Modularising and compacting the design in addition to reducing pipe and duct lengths help to reduce the effect.

Table 4 – Pressure Losses Effect on Cycle Efficiency

950DegC
ICR

	RecupHP	Precooler	RecupLP	Reactor	ICHX	Total
Average (%)	1.43	1.21	1.16	1.37	1.41	6.59
Lower Range (%)	1.27	1.11	1.08	1.22	1.24	5.93
Higher Range (%)	1.54	1.26	1.20	1.46	1.51	6.96
delta (%)	0.27	0.14	0.12	0.24	0.26	

950DegC
SCR

	RecupHP	Precooler	RecupLP	Reactor	Total
Average (%)	1.57	1.32	1.27	1.50	5.65
Lower Range (%)	1.38	1.22	1.18	1.33	5.10
Higher Range (%)	1.68	1.36	1.31	1.61	5.95
delta (%)	0.30	0.14	0.13	0.28	

Conclusion

In summary, the objective of this investigation was to conduct a study using a performance simulation tool to analyse the effects of pressure and temperature ratios, including sensitivity analyses of component efficiencies, ambient temperature, component losses and pressure losses on cycle efficiency and specific work of the Simple Cycle Recuperated (SCR) and Intercooled Cycle Recuperated (ICR), in a closed Brayton direct configuration using helium as the working fluid. The results provide a good basis to support preliminary design, testing, validation and verification activities of Gas Cooled Fast Reactors (GFR) and Very High Temperature Reactors (VHTR) for Generation IV NPPs. The main conclusions are:

- ICR has an increase of 2.1% in thermal efficiency in comparison to the SCR. This stems directly from the correlation between the additional plant capacity of 4.7% also known as the specific work and the useful work.
- The rate of efficiency increase to maximum achievable and the rate of deterioration from maximum efficiency achieved, are more favourable for the ICR in comparison to SCR at higher temperatures. This is due to incremental increases in PR for ICR, leading to bigger increases in thermal efficiency. It also experiences less deterioration, indicating that the SCR does not offer a significant marginal gain when operating close to maximum PR for a given TR.
- Although thermal efficiency provides the main economic basis for a power plant, the plant capacity utilisation is also of interest when comparing both cycles. There is a 257% increase in SW for the SCR, compared to 213% increase for the ICR, between the TR of 18 to 34. This would indicate that the SCR achieves more plant capacity utilisation for its size than the ICR.
- Cooling is a necessity, especially if higher TETs are to be investigated. The optimum cooling amount to minimise thermal stresses versus cost of a better material, requires investigating to understand the relationship of fuel costs versus maintaining efficiency, and cooling optimisation versus improved material selection.
- It is judged that component pressure losses and recuperator effectiveness have the greatest impact on cycle thermal efficiency and specific work. There are more benefits to be realised, if technological advancements for the cycles as part of the Gen. IV initiative prioritises the improvement of the recuperator design to achieve higher effectiveness, without compromising compactness, in addition to minimising pressure losses.

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Analyses of simple and intercooled recuperated direct Brayton helium gas turbine cycles for Generation IV reactor power plants

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