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Analyses of the Costs associated with Very High Turbine Entry Temperatures in Helium Recuperated Gas Turbine Cycles for Generation IV Nuclear Power Plants

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ABSTRACT

Previous analyses of Generation IV (GEN IV) helium gas turbine cycles indicated the possibility for high Turbine Entry Temperatures (TETs) up to 1200°C in order to improve cycle efficiency, using improved turbine blade material and optimum turbine cooling fractions. The purpose of this paper is to understand the effect on the Levelised Unit Electricity Cost (LUEC) of the Nuclear Power Plant (NPP), when the TET is increased to 1200°C from an original TET of 950°C and when an improved turbine blade material is used to reduced the turbine cooling fraction. The analyses focus on the Simple Cycle Recuperated (SCR) and the Intercooled Cycle Recuperated (ICR). The baseline LUECs of the NPPs were calculated as \$61.84/MWh (SCR) and \$62.16/MWh for a TET of 950°C. The effect of changing the turbine blades improved the allowable blade metal temperature by 15% with a reduction in the LUEC by 0.6% (SCR) and 0.7% (ICR). Furthermore, increasing the TET to 1200°C has a significant effect on the power output but more importantly it reduces the LUECs by 22.7% (SCR) and 19.8% (ICR). The analyses intends to aid development of the SCR and ICR including improving the decision making process on choice of cycles applicable to the Gas-cooled Fast Reactors (GFRs) and Very High-Temperature Reactors (VHTRs), where helium is the coolant.

INTRODUCTION

The design intent of Generation IV (GEN IV) reactors is to advance the designs of Nuclear Power Plants (NPPs), but the design is expected to be underpinned by sound economics in comparison to incumbent technologies. This also applies to conducting design impacts studies. The studies help to understand the effect of improving the solution. However, for GEN IV NPP designs, the economics are not fully understood thus the economic effect of such impact studies are not known. The objective of this paper to understand the effects on the Levelised Unit Electricity Cost (LUEC) when the Turbine Entry Temperature (TET) is increased to 1200°C from an original TET of 950°C and when an improved turbine blade material is used to reduced to turbine cooling fraction based on an earlier study in [1]. The study applies to the Simple Cycle Recuperated (SCR) and Intercooled Cycle Recuperated (ICR) in a closed Brayton direct configuration using helium as the working fluid.

NOMENCLATURE

Notations

A	Area (m ²)
C	Cash Flow
C_p	Spec. Heat of Gas at Constant Pressure (J/kg K)
CW	Compressor Work (W)
F	Fuel Cycle Component
J	Number of Periods
m	Mass Flow Rate (kg/s)
P	Pressure (Pa) or Power (W) (Economic Analysis)
PW	Power (W)
PR	Pressure Ratio
Q	Reactor Thermal Heat Input (W)
q	Heat Flux (W/m ²)
r	Discount Rate (%)
SW	Specific Work/Power Output (J/Kg/s)
T	Temperature (K or °C) or Time/Date (Econ. Analysis)
TW	Turbine Work (W)
t	Time or Date
W	Work (W)
UW	Useful Work (W)
X	Real Discount Rate (%)

Greek Symbols

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

Subscripts

c	Compressor
c_{in}	Compressor Inlet
c_{out}	Compressor Outlet
$e/elec$	Power for Electrical Conversion
$elec_annual$	Annual Electricity
he	Helium
he_{min}	Helium with minimum gas conditions
ic	Intercooled Cycle; intercooled coefficient
is_c	Isentropic (Compressor)

i_{s_t}	Isentropic (Turbine)
j	Period number
MHR	Reactor (Heat Source)
MHR_{in}	Reactor (Heat Source) Inlet
MHR_{loss}	Reactor (Heat Source) Pressure Losses
MHR_{out}	Reactor (Heat Source) Outlet
op	Operation
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
L/L_{econ}	Plant Operational Life

Abbreviations

BCC	Baseline Capital Costs
C	Compressor
CDD	Decomm. Cost
CFC	Capitalised Financial Cost
CH	Precooler
CIT	Core Inlet Temperature
COT	Core Outlet Temperature
DD/D&D	Decontamination and Decommissioning / Constant
Dollar D&D	Payment
DP	Design Point
EMWG	Economic Modelling Working
FCR	Fixed Charge Rate
GEN	Generation
GFR	Gas-Cooled Fast Reactor
GIF	Generation IV International Forum
HP	High Pressure
HE	Recuperator
IC	Intercooler
ICR	Intercooled Cycle Recuperated
IDC	Interest During Construction
JAEA	Japan Atomic Energy Agency
LCC	Levelised Capital Cost
LFCC	Levelised Fuel Cycle Cost
LP	Low Pressure
LUEC	Levelised Unit Electricity Cost
LWR	Light Water Reactor
MOX	Mixed Oxide
NOAK	Nth Of A Kind

NPP	Nuclear Power Plant
NTU	Number of Transfer Units
O&M/OM	Operation and Maintenance
OPR	Overall Pressure Ratio
R	Reactor
RPV	Reactor Pressure Vessel
SCR	Simple Cycle Recuperated
SFF	Sink Fund Factor
SOC	Specific Overnight Costs
TCC	Total Capital Costs
TCIC	Total Capital Investment Costs
TET	Turbine Entry Temperature
TOCC	Total Overnight Construction Cost
VHTR	Very High Temperature Reactor

Generation IV (Gen IV) Systems

The Gas-Cooled Fast Reactor System (GFR) and Very-High-Temperature Reactor System (VHTR) are the focus of this study. The GFR utilises helium as the coolant with high temperature and a fast spectrum nuclear core. The Core Outlet Temperature (COT) is between 850-950°C (950°C is considered in this study). The high temperature is enabled by an efficient direct thermodynamic Brayton cycle. Single phase cooling is provided by the helium coolant which is also chemically inert, stable and neutronically transparency. The VHTR is also a high temperature thermal reactor which is also cooled by helium in gaseous phase and moderation that is provided by graphite in the solid state. The core delivers a COT of 750-1000°C (950°C is considered in this study). This means that significant increases in cycle efficiency are expected with helium not altering its gas properties due to increased temperature. Graphite also possesses the necessary mechanical properties for moderation. The list of on-going and planned demonstration projects are described and discussed in [2].

Simple and Intercooled Recuperated Brayton Cycles

The SCR includes a compressor and a turbine, which make up the turbomachinery. The Compressor Work (CW) is lower than Turbine Work (TW), thus Useful Work (UW) generated is used to drive the generator load. However, due to component inefficiencies during the compression and expansion phases, the processes are not isentropic [3]. Consequentially, the heating and cooling stages of the cycle (without consideration of the heat exchangers) are not achieved at constant pressure. This results in losses in the cycle. These losses translate into additional work input that is required for the compression of the helium due to the increase in temperature, therefore resulting in a higher than preferred exit temperature. The heat added into the cycle is not isobaric, thus total gas exit pressure is reduced accordingly [3]. Thus, the potential total power extraction is not realised due to the reduced gas exit pressure and reduced component efficiencies. The turbine exhaust heat is hotter than expected, which in turn influences the inlet compression temperature as it becomes hotter than ideal.

A typical NPP would include a precooler and a recuperator in addition to the turbomachinery. The precooler cools down the helium using a cooling medium such as seawater. The cooled helium at the compressor entry is necessary at the cycle inlet temperature. This is because it reduces the CW but in turn, the compressor exit temperature rises, which results in increases in the reactor input thermal power. Due to the thermal power being fixed for a given COT, the precooler as a lone component will not provide the necessary specific work required for the NPP. This devalues the economics of the plant and therefore falls short of the Generation IV International Forum (GIF) requirements. As mitigation, the recuperator is introduced to improve the economics. The heat from the turbine exhaust gas is used to exchange heat to the helium upstream at the inlet of the reactor. This significantly raises the temperature of the helium and reduces the amount of thermal heat input and reactor power, which positively impacts cycle efficiency.

At simplified baseline configurations, the SCR and ICR feature all of the aforementioned components. However, in addition, the ICR includes an intercooler and a second compressor, which is downstream of the first compressor. The reason is the ICR improves the Specific Work (SW) and UW by reducing the compressor work. The helium downstream of the first compressor is reduced to a lower temperature as it passes through the intercooler, before entering the second compressor upstream, with some negligible reductions in pressure observed.

The thermodynamic consequences resulting from changing to helium in a nuclear gas turbine have been extensively covered in [4]. The study is also documented in [7] and [8] and focuses on off-design, control and transient operational modes of a helium gas turbine, which is also applicable to the plant operations for this study.

Technical Performance Modelling and Simulation of Nuclear Power Plants

When the focused is on the modeling capabilities, the technical model was created using FORTRAN in [7]. The tool is able to determine the temperatures, pressures and mass flow rate for every component based on known cycle inlet conditions and COTs, with consideration of component efficiencies, pressure losses and cooling requirements. This enables the NPP output and cycle efficiency to be derived. The tool is also capable of analysing the effects on cycle output, capacity and efficiency by investigating changes to any of the above parameters. In addition to the Design Point (DP) capabilities, the tool includes component maps and algorithms to calculate the optimal Off-Design Points (ODPs) for long term operation at reduced power or where changes in ambient temperature DP are observed. In situations where changes in ambient temperature vary and demand load-following or reduced power is required for short term operation, the NPP can be controlled using Inventory Pressure Control (IPC). This requires the tool to model the typical load-following characteristics. The model has been used in studies documented in [3], [8], [1], [9]–[13]. Figures 1 and 2 illustrate typical schematics of the SCR and the ICR. Table 1 provides the key technical DP values, which underpins the

configurations for the economic analyses in this study. The equations implemented within the code environment of the technical model are described in the proceeding sections for steady state design point calculations against each component and cycle. The model was used to match known NPPs configurations in the public domain. The results were satisfactory.

Compressor

Prerequisite parameters for DP considerations of the compressor include the compressor PR , compressor inlet conditions (temperature, pressure and mass flow rate), component efficiency and the working fluid gas properties (C_p and γ).

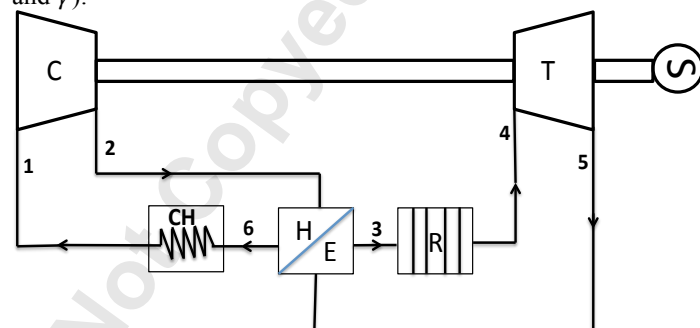


Figure 1 – Typical Simple Cycle with Recuperator (SCR)

The compressor outlet pressure (in Pa) is:

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

The isentropic efficiency of the compressor is ΔT and is also indicative of the specific work input or total temperature increase.

Thus, the temperature ($^{\circ}C$) at the exit can be derived from the inlet temperature, PR , isentropic efficiency and ratio of specific heats:

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

The mass flow rate (kg/s) at inlet is equal to the mass flowrate at outlet 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:

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

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

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

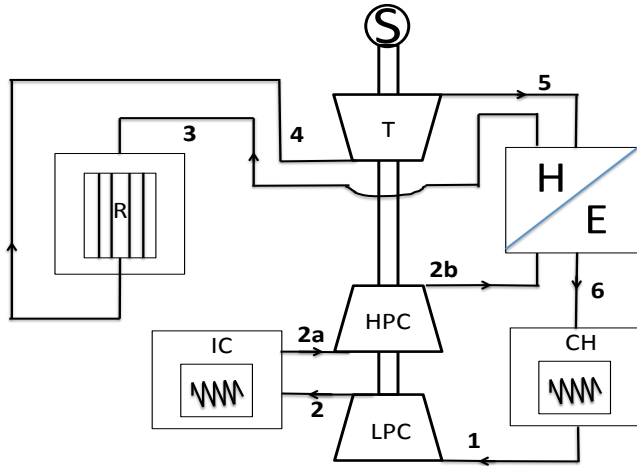


Figure 2 – Typical Intercooled Cycle with Recuperator (ICR)

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 (C_p and γ).

The temperature ($^{\circ}\text{C}$) at the outlet is derived from the following expression:

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

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 [14] and applied for complex cross flow heat exchangers by [15]. 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 the high and low pressure sides.

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 fluid with the lowest heat capacity to experience the maximum change in temperature. This is expressed as:

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

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

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

With helium as the working fluid, C_p 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 ($^{\circ}\text{C}$) is then expressed as:

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

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

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

Thus, the hot outlet ($^{\circ}\text{C}$) is:

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

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

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

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

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

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

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

Precooler and Intercooler

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

$$T_{pcout} = T_{cin} \quad (18)$$

$$P_{pcin} = P_{pcout} \cdot (1 + \Delta P_{ploss}) \quad (19)$$

$$m_{pcout} = m_{pcin} \quad (20)$$

With regard to the intercooler, Eqs. (18), (19) and (20) also apply, but are differentiated for the intercooler. An addition of a second compressor for ICR only, means that the PR 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 PR per compressor (ICR only).

Modular Helium Reactor

The helium reactor is a heat source with pressure losses. The prerequisite 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:

$$m_{MHRout} = m_{MHRin} \quad (22)$$

Pressure taking into account losses (%):

$$P_{MHRout} = P_{MHRin} \cdot (1 - \Delta P_{MHRloss}) \quad (23)$$

and the thermal heat input (Wt) is:

$$Q_{MHR} = m_{MHRin} \cdot C_{phe} \cdot (\Delta T_{MHR}) \quad (24)$$

$$\text{whereby } \Delta T_{MHR} = T_{MHRout} - T_{MHRin} \quad (25)$$

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.

Cooling Calculations

As described in [1], compressor bleed air is used to cool the turbine and the reactor. Steady state conditions for the reactor operation stipulates a steady state cooling requirement that does not require regulating. Turbine cooling requires regulating due to variation in cycle conditions. The prerequisites to calculate the cooling flow are the turbine metal temperature (simply known as blade metal temperature), compressor exit coolant temperature, COT/TET (simply known as gas) and cooling effectiveness. The cooling effectiveness (<1) is expressed as:

$$\varepsilon_{cool} = \frac{(T_{gas} - T_{blade})}{(T_{gas} - T_{coolant})} \quad (26)$$

Cycle Calculations

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

$$UW = TW - CW \quad (27)$$

whereby Eq. (27) is also applicable to the ICR and IC cycles but the CW is the summation of the LPC and HPC work requirements to be delivered by the turbine. The specific work or capacity of the plant ($J/kg/s$) is:

$$SW = UW/m \quad (28)$$

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

$$\eta_{th} = UW/Q_{MHR} \quad (29)$$

Economical Modelling of Nuclear Power Plants

With regard to the economic model, the main equations that define the Total Capital Investment Costs (TCIC), the Specific Overnight Costs (SOC) and the levelised costs for the economic model are described in the proceeding sections and considers the plants to be Nth Of A Kind (NOAK). The calculation of the TCIC takes into consideration typical cash flow, the Total Capital Costs (TCC) and the Interest During Construction (IDC) in accordance with [16], [17]. The economic model is part of the work in [7].

Interest During Construction (IDC)

The IDC (constant dollars) which is applied to the capital loan for the period the plant is being built is determined as follows:

$$IDC: \sum_{j=1}^{j=J} C_j \cdot [(1+r)^{top-j} - 1] \quad (30)$$

whereby j is the period number, J is the number of periods (quarters or years of construction), C_j is cash flow for year or

quarter and reflects the 'beginning of the borrowing' period, r is the real discount rate expressed annually or quarterly as appropriate and t_{op} is the quarterly or yearly commercial operation.

Total Capital Investment Cost (TCIC)

The TCIC (\$) is determined as:

$$TCIC = BCC + TOCC + CFC \quad (31)$$

whereby BCC is the Baseline Construction Cost derived from estimating the direct and indirect costs using either a top down or bottom up approach, TOCC is the Total Overnight Construction Cost, which includes the cost of the fuel, contingencies e.t.c. and CFC is the Capitalised Financial Cost.

Specific Overnight Cost (SOC)

The SOC (\$/kWe) is the cost derived after the TCIC cost is calculated. This is expressed as:

$$SOC = \frac{TCIC}{\frac{1000}{PW_{elec}}} \quad (32)$$

whereby the PW_{elec} is the power output at the generator (We).

Levelised Capital Cost (LCC)

As part of the assumptions of equal energy generation as advised by the GIF Economic Modelling Working Group (EMWG) [16], the LCC (\$/kWh) is:

$$LCC = \frac{FCR \cdot TCIC}{P_{elec_annual}} \quad (33)$$

whereby the FCR is the Fixed Charge Rate and P_{elec_annual} is the annual electricity production for a single plant (kWh/year). The FCR is typically used to account for various entities such as the interim replacements, return on capital, income and property tax and depreciation. For Gen IV NPP projects, the cost estimation tax and depreciation are ignored. This is due to the process being generalised and is not inclusive of tax [16]. For this reason, it is calculated as a capital recovery factor or the principal loan repayment over a time period:

$$FCR = \frac{X}{[1-(1+X)^{-L_{econ}}]} \quad (34)$$

whereby X represents the real discount rate of 5% or 10%, and L_{econ} represents the operational life of the plant. The TCIC plus the cost of the construction loan is converted into a mortgage-type loan, which recuperates the capital investment (principal loan including the interest) over the life of the plant [16].

Levelised Operation and Maintenance (O&M) Cost

The levelised O&M cost (\$/kWh) is the overall total annual costs divided by the annual electricity produced. The main

assumption here is that the constant dollar costing will be the same for the entire plant life.

Levelised Fuel Cycle Cost

The Levelised Fuel Cycle Cost (LFCC) is expressed as:

$$LFCC = \sum_i \sum_{t=t_0-T_1}^{t=t_0+L+T_2} \frac{F_i(t)}{(1+r)^{(t-t_0)}} \quad (35)$$

whereby t_0 is the reference commissioning date, L is the operational life of the plant, T_2 is the maximum value of lag time (in the back-end), T_1 is the maximum value of lead time (in the front end) and r is the discount rate. A simplified method of estimating the fuel costs prior to levelising the annual costs is detailed in [16].

Levelised Decontamination and Decommissioning (D&D) Costs

The D&D funds accumulate over the operational life of the plant into the sink fund as expressed below:

$$DD = CDD \cdot SFF(r_{real}, L_{econ}) \quad (36)$$

whereby DD is the annual constant dollar payment to the D&D sinking fund, CDD is the decommissioning costs, $SFF(r_{real}, L_{econ})$ is the sinking fund factor at a rate of r for a time period in years of t , which is expressed as:

$$SFF(r, t) = \frac{r}{[(1+r)^t - 1]} \quad (37)$$

Thus, the D&D can be levelised and expressed as:

$$LDD = \frac{DD}{P_{elec_annual}} \quad (38)$$

Levelised Unit Electricity Cost (LUEC)

The LUEC is calculated after deriving the aforementioned components of the economic model. This is expressed as:

$$LUEC = LCC + \sum \frac{[(OM+FCC+DD)(1+r)^{-t}]}{[P_{elec_annual}(1+r)^{-t}]} = LCC + \frac{[(OM+FCC+DD) \sum (1+r)^{-t}]}{[P_{elec_annual} \sum (1+r)^{-t}]} = LCC + \left[\frac{(OM+FCC+DD)}{P_{elec_annual}} \right] \quad (39)$$

Results and Discussion

Calculate Efficient Cycle Configurations

Table 1 provides the input values for the SCR and the ICR, which were used to calculate the cycle configurations for this study. The aim was to create a design space for a range of Core Outlet Temperatures (COTs) and compressor Overall Pressure

Ratios (OPRs). The effects of the cooling have been discussed and the results of the technical performance calculations are partly provided in an earlier study by the authors, which is documented in [1]. The results are also provided in this study to aid the analyses.

Table 1 – Input Parameters for Design Point (DP)

Design Point Performance Input Parameters	SCR	ICR	Units
Inlet Temp. (T_1)	28	28	°C
Inlet Pressure (P_1)	3.21	3.21	MPa
Mass flow rate at inlet (m_1)	410.4	410.4	kg/s
Compressor Efficiency (Isentropic)	90	90	%
Turbine Efficiency (Isentropic)	94.5	94.5	%
Recuperator Effectiveness	96	96	%
Pressure Loss (Precooler)	2.5	2.5	%
Pressure Loss (Intercooler ICR only)	-	2.5	%
Pressure Loss (Reactor)	2	2	%
Pressure Loss (Recup. HP side)	6 combined	6 combined	%
Pressure Loss (Recup. LP side)			
Reactor Cooling flow (% of Mass flow rate)	0.25	0.25	%

NB: The conditions such as mass flow rate, pressure losses and component efficiencies are based on GTHTR300 JAEA reactor [18][19]. Pressure losses are based on the 850°C, which were scaled upwards (where necessary) to meet requirements for the COTs analysed in this study

The cycle cooling optimisation analyses considered 2 types of turbine blades with different allowable blade metal temperatures. Blade A is derived from direct solidification casting with thermal barrier coating and film impingement, forced convection cooling technology. Blade A has an allowable blade metal temperature of 755°C because of the material, grain structure and casting process. Blade B is derived from a single crystal material with no grain boundaries and employs film impingement, forced convection cooling technology. Blade B has an allowable blade metal temperature of 870°C. The use of 2 blades with different blade metal temperatures demonstrates the effect of material on the minimum turbine cooling fraction and the overall effect on cycle efficiency for the various cycles.

Table 2 provides the results for the SCR and the ICR. The results show the calculated Overall Pressure Ratios (OPRs), output power and plant efficiencies for both blades at 950°C and 1200°C. From the results in table 2, it is clear that blade B provides an advantage for both cycles. However, the increase in TET had a significant effect on the cycle power outputs. However, due to the fact that the calculation algorithm optimised plant efficiency over capacity, the ICR had a reduced power output for blade B at 1200°C, when compared to blade A. This was a contrast in the results when compared to other results. The reason for this was because the OPR was reduced for blade B as a larger OPR did not result in a more efficient plant. As stated in the previous study [1], the difference the intercooler and the

second compressor makes to the efficiency of the ICR plant is ~3%, which is evident in table 2. The benefit of the TET increase is ~5% in efficiency for both cycles with the SCR experiencing ~36% increase in power compared to ~34% for the ICR.

Table 2 – Results of Design Point (DP) Calculations

SIMPLE CYCLE RECUPERATED				
TET (°C)	950		1200	
Blade	Blade A	Blade B	Blade A	Blade B
Overall Pressure Ratio	2.2	2.2	2.6	2.6
Output Power (MW)	322	325	503	514
Plant Efficiency (%)	50	51	54	55.8

INTERCOOLED CYCLE RECUPERATED				
TET (°C)	950		1200	
Blade	Blade A	Blade B	Blade A	Blade B
Overall Pressure Ratio	2.6	2.6	3.2	3
Output Power (MW)	406	410	628	611
Plant Efficiency (%)	53.3	54.1	57.6	59

Calculate the Baseline Economic Cost of the Plant.

Table 3 lists the economic assessments for both plant cycle at 950°C, with a turbine that uses blade A. The cost of components such as the reactor and services are based on data in [20] and enabled for the costs for year 2020 to be derived. The costs are based on an inflation factor of 2% per year from the year the data was first published. Furthermore, the costs have been scaled using the ratio of the thermal power for the reactor and power outputs for applicable components of the SCR and ICR. The cost of the heat exchangers, pumps and turbomachinery have been derived using methods developed in [7]. A 25% contingency is included in the BCC to mitigate the risks associated with underestimation and reactor performance.

The SCR has a lower BCC of 21% when compared to the ICR. This is due to the cost of the turbomachinery and the reactor. The same difference in price is also reflected in the TCIC and takes into account the first fuel load, the IDC for a 5 year construction period and the scheduled contingency. The SOC is comparable for both plants with the ICR slightly more expensive per kWe by less than 1%. The fuel cycle is based on the methods in the guideline [16] and utilises a Mixed Oxide (MOX) fuel cycle. The MOX fuel cycle utilises recycled plutonium mixed with depleted uranium and is in line with the non-proliferation and spent fissile waste reduction objectives of Gen IV. The D&D costs are based on costs in [21] for 2007 constant dollars for a Light Water Reactor (LWR). However, it was judged that the D&D costs will be greater for the GFRs and VHTRs due to more systems and structures in direct contact with the working fluid. For this reason, the cost was assumed to be 1992 constant dollars inflated to year 2020.

Table 3 – Results of Baseline Economic Calculations

Items (Year 2020)	SCR	ICR	Units
Total Direct Cost	393.3	496.0	\$ M
Total Indirect Cost	144.6	182.3	\$ M
Baseline Construc. Cost (BCC) Inc. Overnight	537.8	678.3	\$ M
Total Contingency of BCC @25% of BCC	134.5	169.6	\$ M
First Fuel Load	28.1	44.7	\$ M
Total Capital Investment Cost (TCIC)	700.4	892.5	\$ M
TCIC with IDC & Schedule Contingency	816.1	1034	\$ M
Specific Overnight Cost (SOC)	2534	2548	\$/kWe
Decontamination & Decomm. (D&D)	938	1183	\$ M
Annual Capital Cost to be Recovered (levelised)	43.1	54.7	\$ M
Annual Op. & Maintenance Cost (levelised)	73.3	89.8	\$ M
Fuel Cycle (levelised)	9.3	14.84	\$ M
D&D Sink Fund (levelised)	2.7	3.3	\$ M
TOTAL ANNUAL COST RECOVERY (levelised)	128.4	162.6	\$ M
LEVELISED UNIT ELECTRICITY COST	61.80	62.10	\$/MWh

The D&D cost of the ICR is determined from scaling using ratios of the power output between the ICR and the SCR. The final LUEC is based on the mortgage-style payment method. This means that the costs are recuperated over the operating life of the NPPs. The operating plant life is 60 years with a capacity factor of 92% of total annual electricity generation (kWh). An availability factor of 80% of the capacity factor is assumed to cover any operational and performance shortfalls in the price. The discount rate applied to financing of the capital is 5%. The final LUECs for both cycles were calculated to be \$61.80/MWh (SCR) and \$62.10/MWh (ICR). The prices of both cycle options are estimated to be cheaper than the Generation III+ (Gen III+) technology based on an average price of ~\$100/MWh documented in [22] for the year 2015 and the cost of £92.50 for the UK Hinckley Point C plant [23].

Economic Evaluation of Improved Turbine Blade.

Table 4 shows data from the economic analysis for both plant cycles when the blade is changed to blade B at 950°C. The improved turbine blade means less cooling air is required for the turbine due to an improved metal temperature from 755°C to 870°C. The increases across the cycles include turbine costs and the TCC. The additional benefit of an improved turbine for the SCR and ICR includes fuel cost savings. This translates into savings of 0.6% and 0.7% on the LUEC respectively.

Table 4 – Results of Economic Calculations (Improved Turbine)

SCR	Turbine Cost (\$M)	First Fuel (\$M)	TCC (\$M)	SOC (\$/kWe)	Plant Capacity (MW)	Ann Fuel Comb. (\$M/year)	Ann Cost/ Cap Rec (\$M/year)	LUEC (\$/MWh)
Blade B (870°C)	53.4	27.8	826.1	2565.4	325	9.24	128.8	61.46
Blade A (755°C)	46.4	28.1	816.1	2534.38	322	9.33	128.4	61.84
Delta (%)	15.09%	-1.07%	1.23%	1.22%	0.9%	-1.0%	0.31%	-0.6%

ICR	Turbine Cost (\$M)	First Fuel (\$M)	TCC (\$M)	SOC (\$/kWe)	Plant Capacity (MW)	Ann Fuel Comb. (\$M/year)	Ann Cost/ Cap Rec (\$M/year)	LUEC (\$/MWh)
Blade B (870°C)	55.5	44.4	1044.8	2548.31	410	14.76	163.1	61.7
Blade A (755°C)	48.2	44.7	1034.5	2547.9	406	14.84	162.6	62.13
Delta (%)	15.15%	-0.67%	1.00%	0.02%	1.0%	-0.5%	0.31%	-0.7%

It will be important for Plant Operators to review the maintenance requirements for the SCR and ICR turbines prior to making a decision about whether to introduce an improved turbine. The necessary maintenance requirements have not been considered in this study because it will be plant specific. This will need to be considered in the plant construction phase.

Economic Evaluation of Increased TET.

Table 5 shows a comparison of the baseline economic evaluation at 950°C versus 1200°C for both cycle configurations.

Table 5 – Results of Economic Calculations (Increased TET)

950°C COT (Year 2020)	SCR	ICR	Units
Power Output	322	406	MWe
Specific Overnight Cost	2534.4	2547.9	\$/kWe
Decontamination & Decomm. (D&D)	938.0	1182.7	\$ M
Annual Capital Component Recovery Cost	43.1	54.7	\$ M
Annual Operation Cost	73.3	89.8	\$ M
Fuel Cycle	9.3	14.84	\$ M
D&D Sink Fund	2.7	3.3	\$ M
TOTAL ANNUAL COST RECOVERY	128.4	162.6	\$ M
LEVELISED UNIT ELECTRICITY COST	61.80	62.10	\$/MWh

1200°C COT (Year 2020)	SCR	ICR	Units
Power Output	504	628	MWe
Specific Overnight Cost	2115.7	2182.8	\$/kWe
Decontamination & Decomm. (D&D)	938.0	1182.7	\$ M
Annual Capital Component Recovery Cost	56.3	72.4	\$ M
Annual Operation Cost	73.6	90.16	\$ M
Fuel Cycle	22.9	35.5	\$ M
D&D Sink Fund	2.7	3.3	\$ M
TOTAL ANNUAL COST RECOVERY	155.4	201.4	\$ M
LEVELISED UNIT ELECTRICITY COST	47.80	49.80	\$/MWh

The cost evaluation assumes that the decommissioning costs will remain the same due to a negligible increase in infrastructure. Therefore it can be assumed that there is no increase in the nuclear and turbine island area. As a result, the SCR has the highest decrease of 22.7% in the LUEC, when compared to a decrease of 19.8% for the ICR. When the combination of an improved turbine with an increased TET of 1200°C is considered, the SCR has a LUEC of \$47.40/MWh; the ICR has a LUEC of \$49.40/MWh. The cost benefits as observed at 950°C are improved at 1200°C but a new turbine does not provide a significant improvement for the SCR and ICR. Any advances in design improvements would need to be judged on the merit of the economic improvements and the cost of maintenance as a result of this improvement. This is crucial, especially if the reactor undergoes shorter inspection intervals due to increased Core Outlet Temperatures (COTs).

Conclusion

In summary, the objective of this paper was to understand the effects on the Levelised Unit Electricity Cost (LUEC) when the TET is increased to 1200°C from an original TET of 950°C and when an improved turbine blade material is used to reduce turbine cooling fraction. This was aided by using a modeling, performance simulation and economic tool designed for this study. The cycles of interest are the Simple Cycle Recuperated (SCR) and Intercooled Cycle Recuperated (ICR). The results provide good bases to support the decision-making process on choice of cycles during the preliminary design phases of Gas Cooled Fast Reactors (GFR) and Very High Temperature Reactors (VHTR) for Generation IV NPPs. The main conclusions are:

- From the results, it is clear that blade B provides an advantage for both cycles. However, the increase in TET had a significant effect on the cycle power outputs.
- The difference the intercooler and the second compressor makes to the efficiency of the ICR plant is ~3% increase in efficiency over the SCR.
- The benefit of the TET increase in performance is ~5% in efficiency for both cycles with the SCR experiencing ~36% increase in power and ~34% for the ICR. The benefit of the improved turbine blade is ~1% efficiency improvement at 950°C and ~2% efficiency improvement at 1200°C for both cycles.
- The SCR has a lower Baseline Construction Costs (BCC) of 21% when compared to the ICR. This is due to the cost of the turbomachinery and the reactor. The same difference in price is also reflected in the TCIC and takes into account the first fuel load, the IDC for a 5 year construction period and the scheduled contingency.
- The final LUECs for both cycles were calculated to be \$61.80/MWh (SCR) and \$62.10/MWh (ICR). The prices of both cycle options are estimated to be cheaper than the

Generation III+ (Gen III+) technology based on an average price of ~\$100/MWh for the year 2015 and the cost of £92.50 for the UK Hinckley Point C plant.

- The improved turbine blade means less cooling air is required for the turbine due to an improved metal temperature from 755°C to 870°C. The increases across the cycles include turbine costs and TCC. The additional benefit of an improved turbine for the SCR and ICR includes fuel cost savings. This translates into savings of 0.6% and 0.7% on the LUEC respectively.
- With regard to the effect of increasing the TET, the SCR has the higher decrease of 22.7% (\$47.80/MWh) in the LUEC, when compared to a decrease of 19.8% (\$49.80/MWh) for the ICR. When the combination of an improved turbine with an increased TET of 1200°C is considered, the SCR has a LUEC of \$47.40/MWh, the ICR has a LUEC of \$49.40/MWh. The cost benefits as observed at 950°C are improved at 1200°C but a new turbine does not provide a significant improvement for the SCR and ICR.
- Any advances in design improvements would need to be judged on the merit of the economic improvements and the cost of maintenance as a result of this improvement. This is crucial, especially if the reactor undergoes shorter inspection intervals due to increased Core Outlet Temperatures (COTs).
- Validation is recommended for this tool to enable optimisation and improve the applicability and accuracy. Furthermore, this will encourage its use thereby improving the decision making process for plant operators.

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REFERENCES

- [1] A. Gad-Briggs, P. Pilidis, and T. Nikolaidis, "A Review of The Turbine Cooling Fraction for Very High Turbine Entry Temperature Helium Gas Turbine Cycles For Generation IV Reactor Power Plants," *ASME J. Nucl. Eng. Radiat. Sci.*, vol. 3, no. 2, 2017.
- [2] G. Locatelli, M. Mancini, and N. Todeschini, "Generation IV nuclear reactors: Current status and future prospects," *Energy Policy*, vol. 61, pp. 1503–1520, Oct. 2013.
- [3] A. Gad-Briggs and P. Pilidis, "Analyses of Simple and Intercooled Recuperated Direct Brayton Helium Gas Turbine Cycles for Generation IV Reactor Power Plants," *J. Nucl. Eng. Radiat. Sci.*, vol. 3, no. 1, 2017.
- [4] K. N. Pradeepkumar, A. Tournlidakis, and P. Pilidis,

- “Analysis of 115MW, 3-Shaft, Helium Brayton Cycle using Nuclear Heat Source,” in *Proceedings of ASME Turbo Expo 2001 Land, Sea & Air. June 4-7, 2001.*, 2001.
- [5] K. N. Pradeepkumar, A. Tourlidakis, and P. Pilidis, “Design and Performance review of PBMR Closed Cycle Gas Turbine Plant in South Africa.,” in *International Joint Power Generation Conference. June 4-7 2001.*, 2001.
- [6] K. N. Pradeepkumar, A. Tourlidakis, and P. Pilidis, “Performance Review: PBMR Closed Cycle Gas Turbine Power Plant.,” in *Proceedings of Technical Committee Meeting on HTGR - Power Conversion Systems. International Atomic Energy Agency. 14-16 November 2000, 2001.*, pp. 99–112.
- [7] A. Gad-Briggs, “TERA OF GAS TURBINE HIGH TEMPERATURE REACTOR FOR NEXT GENERATION NUCLEAR POWER PLANTS,” Cranfield University, 2017.
- [8] A. Gad-Briggs, P. Pilidis, and T. Nikolaidis, “Analyses of a High Pressure Ratio Intercooled Direct Brayton Helium Gas Turbine Cycle for Generation IV Reactor Power Plants,” *J. Nucl. Eng. Radiat. Sci.*, vol. 3, no. 1, 2017.
- [9] A. Gad-Briggs, T. Nikolaidis, and P. Pilidis, “Analyses of the effect of cycle inlet temperature on the precooler and plant efficiency of the simple and intercooled helium gas turbine cycles for generation IV nuclear power plants,” *Appl. Sci.*, vol. 7, no. 4, 2017.
- [10] A. Gad-Briggs and P. Pilidis, “Analyses Of Off-Design Point Performances Of Simple And Intercooled Brayton Helium Recuperated Gas Turbine Cycles For Generation IV Nuclear Power Plants,” in *Proceedings of the 2017 25th International Conference on Nuclear Engineering ICONE25, 2017.*
- [11] A. Gad-Briggs and P. Pilidis, “Analyses of the off-Design Point performance of a high pressure ratio intercooled brayton helium gas turbine cycle for generation IV Nuclear Power Plants,” in *International Conference on Nuclear Engineering, Proceedings, ICONE, 2017*, vol. 9.
- [12] A. Gad-Briggs, P. Pilidis, and T. Nikolaidis, “Analyses of the Control System Strategies and Methodology for Part Power Control of the Simple and Intercooled Recuperated Brayton Helium Gas Turbine Cycles for Generation IV Nuclear Power Plants,” *ASME J. Nucl. Eng. Radiat. Sci.*, vol. 3, no. 4, 2017.
- [13] A. Gad-Briggs, P. Pilidis, and T. Nikolaidis, “Analyses of the Load Following Capabilities of Brayton Helium Gas Turbine Cycles for Generation IV Nuclear Power Plants,” *J. Nucl. Eng. Radiat. Sci.*, vol. 3, no. 4, 2017.
- [14] D. R. Pitts and L. E. Sissom, *Theory and Problems of Heat Transfer*, 2nd Editio. New York: McGraw-Hill, 1997.
- [15] H. A. Navarro and L. C. Cabezas-Gomez, “Effectiveness-NTU Computation With a Mathematical Model for Cross-Flow Heat Exchangers,” *Brazilian J. Chem. Eng.*, vol. 24, no. 4, pp. 509–521, 2007.
- [16] GIF EMWG, “Cost Estimating Guidelines,” Boulogne-Billancourt, 2007.
- [17] K. A. Williams, “G4-ECONS: A Model for Calculating the Levelized Unit Electricity Cost (LUEC) for Advanced Nuclear Systems Gen IV EMWG Products and Applications Background,” no. October, 2006.
- [18] X. Yan, K. Kunitomi, T. Nakata, and S. Shiozawa, “GTHTR300 design and development,” *Nucl. Eng. Des.*, vol. 222, no. 2–3 SPEC, pp. 247–262, Jun. 2003.
- [19] H. Sato, X. L. Yan, Y. Tachibana, and K. Kunitomi, “GTHTR300—A nuclear power plant design with 50% generating efficiency,” *Nucl. Eng. Des.*, vol. 275, pp. 190–196, Aug. 2014.
- [20] ABB/Combustion Engineering Inc., Bechtel National Inc., Gas-Cooled Reactor Associates, General Atomics, Oak Ridge National Laboratory, and Stone & Webster Engineering Corp., “Modular High Temperature Gas-Cooled Reactor Commercialization and Generation Cost Estimates,” USA, 1994.
- [21] Y. Du and J. Parsons, “Update on the Cost of Nuclear Power,” Cambridge, Massachusetts, 2009.
- [22] US EIA, “Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2016,” Washington D.C., USA, 2016.
- [23] BBC Radio 4, “The Bottom Line - Britain’s Nuclear Future,” BBC, United Kingdom, 2017.