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Analyses of Long Term Off-Design Performance Strategy and Operation of A High Pressure Ratio Intercooled Brayton Helium Gas Turbine Cycle for Generation IV Nuclear Power Plants

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ABSTRACT

The Intercooled Cycle (IC) is a simplified novel proposal for Generation IV Nuclear Power Plants (NPP) based on studies demonstrating efficiencies of over 45%. As an alternative to the Simple Cycle Recuperated (SCR) and the Intercooled Cycle Recuperated (ICR), the main difference in configuration is no recuperator, which reduces its size. It is expected that the components of the IC will not operate at optimum part power due to seasonal changes in ambient temperature and grid prioritisation for renewable sources. Thus the ability to demonstrate viable part load performance becomes an important requirement. The main objective of this study is to derive Off-Design Points (ODPs) for a temperature range of -35 to 50°C and COTs between 750 to 1000°C. The ODPs have been calculated using a tool designed for this study. Based on results, the intercooler changes the mass flow rate and compressor pressure ratio. However, a drop of ~9% in plant efficiency, in comparison to the ICR (6%) was observed for pressure losses of up to 5% . The reactor pressure losses for IC has the lowest effect on plant cycle efficiency in comparison to the SCR and ICR. Characteristic maps are created to support first order calculations. It is also proposed to consider the intercooler pressure loss as a handle for ODP performance. The analyses brings attention to the IC an alternative cycle and aids development of cycles for Generation IV Nuclear Power Plants specifically Gas Cooled Fast Reactors (GFRs) and Very High Temperature Reactors (VHTRs), using helium.

INTRODUCTION

A simplified configuration and an efficient cycle for Nuclear Power Plants (NPPs) are necessary for Generation IV (Gen IV) development in order to deliver low cost NPPs [1]. The Intercooled Cycle (IC) has been the subject of technological improvements using air gas turbines such as the General Electric LMS100 to achieve 46% efficiency therefore prompting studies as documented in [2]. Incorporating a cycle without a recuperator has never been explored for Gen IV. This is based to the perception of the nuclear gas turbine cycle not being economical without a recuperator i.e. the exhaust heat is not transferred back into the cycle [3]. Nonetheless, a study was undertaken whereby analyses were conducted on a high efficient Brayton helium cycle for Gen IV, with a derived Design Point (DP) cycle efficiency of 45.88% [4]. With improvements in cooling and turbine blade material, the plant efficiency can be improved further if the Core Outlet Temperature (COT) is in excess of 1000°C. Since there is no recuperator, the excess temperature is judged to be within the operating experience of the plant, when the turbomachinery and reactor alone are considered [5]. Beyond deriving better plant efficiencies at Design Point (DP), the Off-Design Point (ODP) is just as critical to ensure the plant runs efficiently for long term periods when ambient conditions change and grid prioritisations are in favour of renewable sources. However, this is challenging because the coupled individual components limit the amount of optimum ODPs that the plant can run at [3]; finding these ODPs require very complex iterative calculations. The objective is to use a DP to calculate a set of ODPs when the ambient or compressor inlet temperature is in the range of -35°C to 50°C and the reactor COT range is 750°C to 1000°C. In addition to deriving the ODP, study analyses of the component effects on the ODPs. The cycle of interest is the IC, with comparisons to a similar study (Ref [6]) of the Intercooled Cycle Recuperated (ICR) and the Simple Cycle Recuperated (SCR).

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)
$NDMF$	Non-Dimensional Mass Flow
Q	Reactor Thermal Heat Input (W)
P	Pressure (Pa)
PR	Pressure Ratio
SW	Specific Work (J/kg s)
T	Temperature (K or ℃)
TW	Turbine Work (W)
W	Work (W)
UW	Useful Work Power Output (W)

Greek Symbols

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

θ	Referred Temperature Parameter
δ	Referred Pressure Parameter

Subscripts

$blade$	Turbine Temperature (also known as Blade Temp.)
c	Compressor
c_{in}	Compressor Inlet
c_{map}	Compressor Map
c_{out}	Compressor Outlet
$cool$	Cooling
$coolant$	Compressor Exit Coolant
e	Power for Electrical Conversion
gas	Turbine Entry Temperature
he	Helium
he_{min}	Helium with minimum gas conditions
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
$NDMF_{Plant}$	Plant Non-Dimensional Flow Conditions
pc_{in}	Precooler Inlet (also applicable to intercooler)
pc_{loss}	Precooler Pressure Losses (same as above)
pc_{out}	Precooler Outlet (same as above)
s	Station number
S_{in}	Station Inlet
th	Thermal Power
t	Turbine
t_{map}	Turbine Map
t_{out}	Turbine Outlet
t_{in}	Turbine Inlet

Abbreviations

C	Compressor
CH	Precooler
CIT	Core Inlet Temperature
CN	Corrected Speed
COT	Core Outlet Temperature
DP	Design Point
GEN IV	Generation Four
GFR	Gas-Cooled Fast Reactor
GIF	Generation IV International Forum
HP	High-Pressure
HPC	High Pressure Compressor
IC	Intercooled Cycle
ICR	Intercooled Cycle Recuperated
ISA	International Standard Atmosphere
LP	Low-Pressure
LPC	Low Pressure Compressor
M	Mixer (Fig. 4)
NPP	Nuclear Power Plant
NTU	Number of Transfer Units
ODP	Off-Design Point
OPR	Overall Pressure Ratio
R	Reactor
RPV	Reactor Pressure Vessel
S	Splitter (Fig. 4)
SCR	Simple Cycle Recuperated
TET	Turbine Entry Temperature
VHTR	Very High Temperature Reactor

Generation IV (Gen IV) Systems

The Generation IV (Gen IV) systems of interest are the Gas-Cooled Fast Reactor Systems (GFRs) and Very-High-Temperature Reactor Systems (VHTRs). The GFR configuration is gas cooled by a medium such as helium. It includes a fast breeder reactor with high temperature capability and a nuclear core. The COT is between 850-950°C and is coupled in a Brayton cycle for efficiency purposes. Helium as a coolant is beneficial as a working fluid because it ensures single phase cooling in all circumstances, chemical inertness and neutronic transparency [7], [8]. The VHTR in this scenario is also cooled by helium in a gaseous phase with a high temperature thermal reactor that utilises graphite as a moderator in solid state. Graphite exhibits good mechanical properties at very high temperature and with helium as a stable coolant, there are no issues of a chemical reaction with graphite moderator. There are planned and on-going development projects for the GFR and VHTR. These projects relate to testing of basic concepts and performance phase validation. These demonstrators are discussed in [1].

The Intercooled Brayton Cycle (IC)

The IC configuration is extensively documented as part of studies in reference [4]. The IC incorporates x2 compressors and a turbine as part of the turbomachinery, the precooler, reactor and an intercooler. The intercooler is aft of the first compressor. The working fluid downstream of the first compressor experiences a reduction in temperature as it passes through the intercooler. The temperature is reduced to the same inlet temperature as the first compressor, prior to entry into the second compressor [5]. Although the efficiency derived in [4] for the IC is lower by 3.8% and 5.9% when compared to the SCR and ICR, there is scope for increasing the COT to a temperature in excess of 1000°C, which would significantly increase the cycle efficiency [3]. This is above the limits of the current recuperator designs and gives the IC the advantage of a simpler configuration that can have comparable cycle efficiencies with the other cycles in the immediate term. The benefits of changing from air to helium in a nuclear gas turbine, including the thermodynamic consequences, have been extensively covered in [9], [10] and [11]. The papers focus on off-design operation, control and transient operational modes of a helium nuclear gas turbine plant. The papers do not analyse conditions as proposed in this study but provides good theoretical bases for application.

Long Term Off-Design Performance Strategy and Operation.

Ref [12] describes control system strategies to be considered for Gen IV NPPs. The applicable control strategies concerned with this study adopt methods that require change of mass flow rate and adjusting the reactor COT. For strategies where the power regulation is based on ambient temperature changes or pressure losses in the cycle, changes in mass flow to alter the effect of temperature is preferred. This is based on achieving a high efficiency of the NPP as observed in [12], [13]. Whereby there is prioritisation of the grid in favour of other generating sources such as renewables, the COT can be reduced to reduce the power level.

Modelling of Nuclear Power Plants and Performance Simulation Tool

The schematics of the IC is provided in Figure 1. The Design Point (DP) values for the cycles are in Table 1. The modelling was performed using a FORTRAN tool designed specifically for this study. In relation to DP performance, the tool has been designed to calculate the mass flow rate, pressures and temperatures for each cycle component using Table 1 inlet conditions and COT, with consideration of component efficiencies, pressure losses and cooling requirements. This derives the NPP output and efficiency for DP. The tool also aids analyses by investigating the effects on cycle output, capacity and efficiency through changes to parameters in Table 1.

For Off-Design Point (ODP) performance, the model comprises the turbomachinery component maps, configured as polynomial curves within the code algorithm. Firstly, compressor map polynomial plots (applies to the LPC and HPC), are characterised as corrected non-dimensional speed curves, which are plots of the individual compressor Pressure Ratio (PR) as a function of the non-dimensional mass flow (NDMF) [3]. Secondly, isentropic efficiency lines are plotted with the compressor efficiency as a function of the compressor PR [3]. The turbine is characterised by a single curve plotted for a specific NPP configuration, with the NDMF as a function of the enthalpy drop ratio (also an indicator of the heat rise in the reactor) [3]. Similarly, to the compressor, the turbine isentropic efficiency curves can be presented by the component efficiency as a function of the turbine PR or the enthalpy drop ratio [3]. The maps are illustrated in Figs. 2 and 3 for the compressors and turbine respectively. The turbine map NDMF for any constant speed line rises to a certain level of enthalpy drop ratio or turbine PR and remains constant in the choking region [3]. This means that the highest level of mass flow rate is reached at an enthalpy drop ratio. Another way to look at it is the turbine PR that produces choking conditions in the turbine is dependent on reaching the maximum mass flow rate. The curves in the turbine map relate to a turbine configuration where the choking is dependent on speed i.e. happens in the rotor [3]. However a single curve is used for this study, which denotes that choking happens in the stators and is not dependent on speed due to running at a constant speed. The turbomachinery maps are generic and use relative values based on open source experimental data. The maps used in the model do not relate to any NPP tests. However, turbomachinery components behave in the same way. The maps were also corrected from air to helium and adapted for the different cycles using scaling factors. This approach was considered satisfactory for the study.

The model calculation method is extensively described in [3]. This method incrementally selects the each compressor PR and the enthalpy drop ratio (also used to determine the level of heat rise by the reactor) to calculate the ODPs. This requires a primary, secondary and tertiary looping algorithm to achieve this. Figure 4 shows the modelling code structure for IC. The equations introduced within the code environment are described in the proceeding sections and are based on Refs [3], [5].

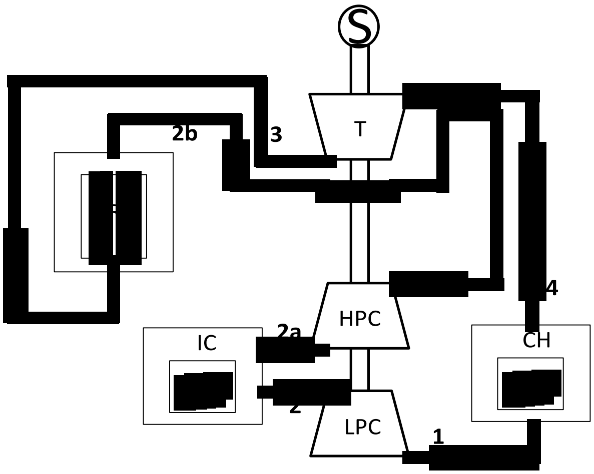

Figure 1 – Typical Intercooled Cycle without Recuperator (IC) [5]

LPC & HPC

Prerequisite parameters for performance design considerations of both compressors include the compressor PR, 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:

$$P_{c_{out}} = P_{c_{in}} \cdot PR_c \tag{1}$$

The isentropic efficiency of the compressor is the ΔT 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, PR, isentropic efficiency and ratio of specific heats:

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

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

$$m_{c_{out}} = m_{c_{in}} \tag{3}$$

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

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

$$\text{whereby } \Delta T_c = T_{c_{out}} - T_{c_{in}} \tag{5}$$

Bypass splitters are incorporated within the performance simulation tool, to allow for compressed coolant to be bled from the LPC for reactor cooling, and from the HPC for turbine cooling. The reactor cooling demands negligible cooling flow at moderate pressures because it is assumed that the opposing pressures within the reactor outer wall and pressure vessel inner wall will not restrict cooling flow for the reactor. The HPC must be used to deliver coolant for turbine cooling because the coolant must be at a higher pressure than that observed in the turbine, in order to be delivered effectively.

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:

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

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:

$$\Delta T_t = T_{t_{in}} - T_{t_{out}} \tag{7}$$

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

Precooler and Intercooler

Prerequisite parameters for the precooler and intercooler take into account that the precooler is upstream of the LPC and the intercooler is downstream of the LPC and upstream of the HPC, thus compressor inlet temperature and pressure are of importance including the pressure losses. The conditions for the precooler are as follows:

$$T_{pc_{out}} = T_{c_{in}} \tag{8}$$

$$P_{pc_{in}} = P_{pc_{out}} \cdot \left(1 + \Delta P_{pc_{loss}}\right) \tag{9}$$

$$m_{pc_{out}} = m_{pc_{in}} \tag{10}$$

With regard to the intercooler, Eqs. (8), (9) and (10) apply but are differentiated within the code to ensure exclusivity to the respective components.

Modular Helium Reactor

As a heat source with inevitable 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:

$$m_{MHR_{out}} = m_{MHR_{in}} \tag{11}$$

Pressure taking into account losses (%):

$$P_{MHR_{out}} = P_{MHR_{in}} \cdot \left(1 - \Delta P_{MHR_{loss}}\right) \tag{12}$$

and the thermal heat input (W*t*) is:

$$Q_{MHR} = m_{MHR_{in}} \cdot Cp_{he} \cdot (\Delta T_{MHR}) \tag{13}$$

$$\text{whereby } \Delta T_{MHR} = T_{MHR_{out}} - T_{MHR_{in}} \tag{14}$$

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

Cooling Calculations

Prerequisites to calculate the cooling flow from the compressor exit, which is required for the cycle (cooling flow is taken as a percentage of mass flow rate) 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:

$$\varepsilon_{cool} = \frac{(T_{gas} - T_{blade})}{(T_{gas} - T_{coolant})} \tag{15}$$

In the case of this study, Eq. 15 is ignored because no turbine or reactor core cooling is considered for the purpose of simplifying the ODP performance calculations. This is because the debited cooling flows will have to be added to the total flow for ODP matching. Thus, the COT and the TET are the same temperature.

Cycle Calculations

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

$$UW = TW - CW \tag{16}$$

whereby CW is the summation of both compressors' work requirement to be delivered by the turbine. The specific work or capacity of the plant (J/kg s) is:

$$SW = UW/W \tag{17}$$

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

$$\eta_{th} = UW/Q_{MHR} \tag{18}$$

The DP performance values for the IC are provided in Table 1. They were derived based on average HP compressor efficiencies for the purpose of having comparable efficiencies with the experimental maps used for this study. This was considered satisfactory because the study is focused on the effects of variation of the handles and sensitivities of components.

Expressions for ODP Performance Calculations

When calculating the ODP performance, the maps become part of the process. Furthermore, they are scaled for capacity purposes to suit the particular plant cycle configuration, thereby avoiding the use of multiple maps. For constant speed steady state ODP performance, the temperature inlet conditions into the compressor for station 1 (ignoring compressor geometry measurements) is expressed as a referred parameter for standard ISA conditions of temperature for the purpose of determining the reference speed curve.

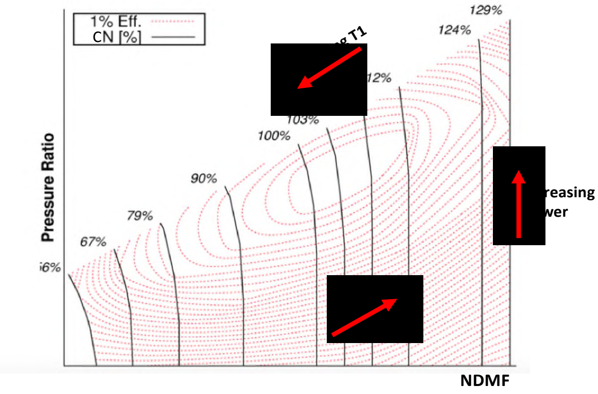

Figure 2 – Compressor Map Showing Corrected Speed Lines and Contours of Efficiency [14].

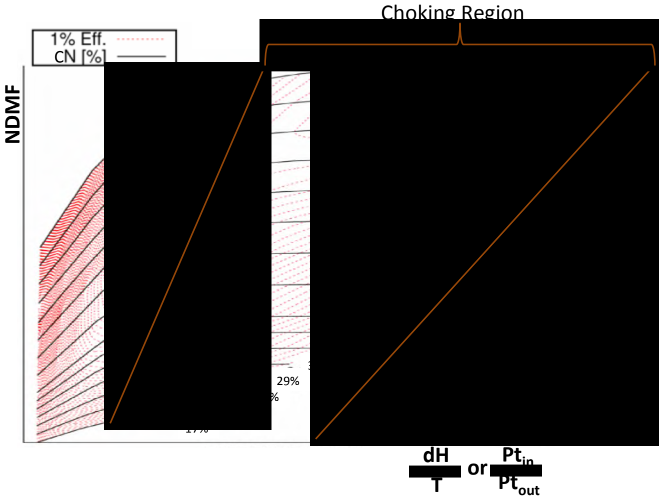

Figure 3 – Turbine Map Compressor Map Showing Corrected Speed Lines and Contours of Efficiency [14].

This is corrected into a dimensionless parameter for the purpose of adapting the map for helium and is expressed as:

$$CN = \frac{N}{\theta}_{Map_{Air}} = \frac{N}{\sqrt{(\gamma \cdot R \cdot T_{c_{in}})}}_{Map_{He}} \tag{19}$$

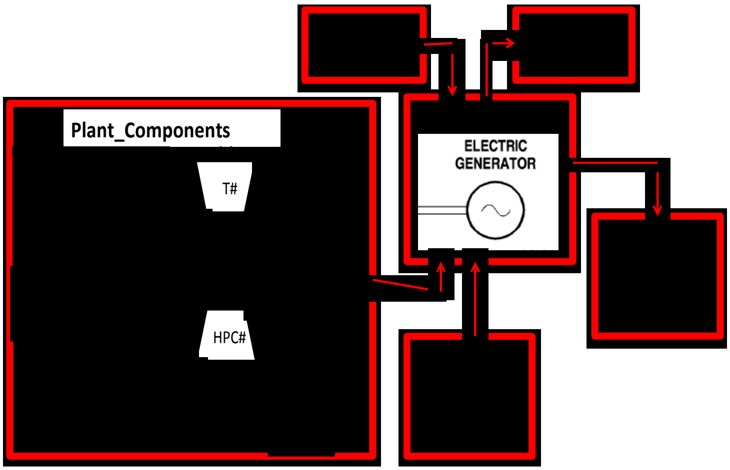

Figure 4 – Performance Simulation Tool Structure for SCR [4]

Equation 19 defines the speed as the handle and determines the corresponding polynomial speed curve for the inlet temperature (see Fig. 2).

Once the inlet conditions are defined, the model proceeds to calculate each component station condition. The below referred parameter is also corrected from the map to a dimensionless expression to get the true NDMF for helium. Ignoring component geometry, the NDMF for helium is:

$$NDMF = \frac{m \cdot \sqrt{(\theta)}}{\delta}_{Air} = \frac{m \cdot \sqrt{(T_{S_{in}} \cdot R)}}{P_{S_{in}} \cdot \sqrt{(\gamma)}}_{He} \qquad (20)$$

Equation 20 also fully applies to the turbine map; the dimensionless part of Eq. 20 is calculated in the absence of component maps for the intercooler and the reactor. This is made possible because the compressor has established the flow conditions upstream. For the actual ODP calculation process, the sequence of calculations commences by scaling the map using scaling factors, then Eq. 19 to define the inlet temperature by selecting the specific speed curve polynomial. Subsequently, Eqs. 1 to 18 are used to calculate the component and station ODP performance values, with the dimensionless part of Eq. 20 utilised to calculate the NDMF for each component of interest..

Table 1 – DP Performance for IC

Design Point Performance	IC	Units
Inlet Temp. (T_1)	28	°C
TET (Core Outlet Temp) (T_3)	950.0	°C
Core inlet temp (T_{2b})	148	°C
Inlet Pressure (P_1)	3.21	MPa
OPR	2.81	-
Mass flow rate at inlet (m_1)	413.9	kg/s
LP Compressor Efficiency (Isentropic)	83	%
HP Compressor Efficiency (Isentropic)	63	%
Turbine Efficiency (Isentropic)	81	%
Pressure Loss (Precooler)	2.5	%
Pressure Loss (Intercooler ICR only)	2.5	%
Pressure Loss (Reactor)	2	%
Turbine Cooling flow (% of Mass flow rate)	-	%
Reactor Cooling flow (% of Mass flow rate)	-	%
Compressor Work (Combined)	418.97	MW
Turbine Work	678.59	MW
Heat Input	1723.85	MW
Specific Work (NPP Capacity)	0.63	MW/ kgs/s
Useful Work	259.62 i	MW
Plant Efficiency	15.06	%

ODP Component Matching Process

For NDMF compatibility, the plant NDMF, which is based on the conditions between station 1 to station 3 must equal the respective NDMF on the turbine map, which corresponds to the actual enthalpy drop ratio. With consideration of a given matching tolerance, the NDMF compatibility is expressed as:

$$NDMF_{HPC_{map}} \cdot \frac{P_{2a}}{P_{2b}} \cdot \frac{P_{2b}}{P_3} \cdot \sqrt{\frac{T_3}{T_{2a}}}_{NDMF_{Plant}} = NDMF_{t_{map}} \qquad (21)$$

Figure 5 describes the process of matching and calculating the ODP performance.

Results and Discussion

Variation of Inlet Temperature (T_1)

The ODP performance results for the handle variation of T_1 (-35°C to 50°C) for IC are provided in Table 2. This analysis simulates a long term operation at temperatures outside the DP. It denotes an increase in in the compressors' OPR from the DP (28°C), as T_1 moves to the right (reduction in ambient temperature), which indicates that the temperature is reduced (see Fig. 3). The ODP with T_1 at 50°C indicates a move to the left of the map whereby the OPR is reducing as expected. An increase in in compressors' OPR is proportional to increases in mass flow rate and correlates to a move to the right of the compressor map. Equation (20) denotes that the changing parameter in the expression is the mass flow rate, which has to change in line with the OPR. The effect on the IC suggests that when T_1 is less than the DP value of 28°C, the ODP equilibriums showed increases in cycle efficiency at an inlet of 2°C or lower. This effect is similar to the results from the study of the ICR [6] but the effect as noted in this study is less pronounced. The effect is quantified in the drop in efficiency; a reduction of 0.27% in efficiency at 9°C (IC), in comparison to 18% for ICR at the same reference temperature. Given that this observation was not noted for the SCR, it is judged that the intercooler drives the effect. The reason is because the design intent of the intercooler in the Brayton gas turbine cycle is to reduce the compressor work of the IC and ICR but there are notable, non-linear changes in compressor work. The extent of non-linearity is dependent on increasing complexity (additional components) during matching especially when the recuperator is considered. It also provides justification for the simplified IC to be considered. The overall changes in power output and efficiency are considered (including results from [6]), the analyses concludes that the SCR ODPs provide the least compromise of power an efficiency for long term OD operation, with the ICR providing the most compromise. This is based on 19% and 5% average increases in power and efficiency respectively (IC), compared to 56% and 11% increases (SCR), and 7% and 6% decreases (ICR).

Variation of COT/TET (T_3)

This analysis simulates when part power is required for long term operation due to grid prioritisation for other generating sources, for instance renewable sources. The ODP performance results for the handle variation of the COT (750°C to 1000°C) are listed in Table 3. The trends are as per expectation without changing T_1. The results are comparable to the SCR. However, the ICR has 11% more power output at 750°C COT than the IC but this is reduced to 4% at 900°C. Another significant difference is the change in mass flow rate for change in COT.

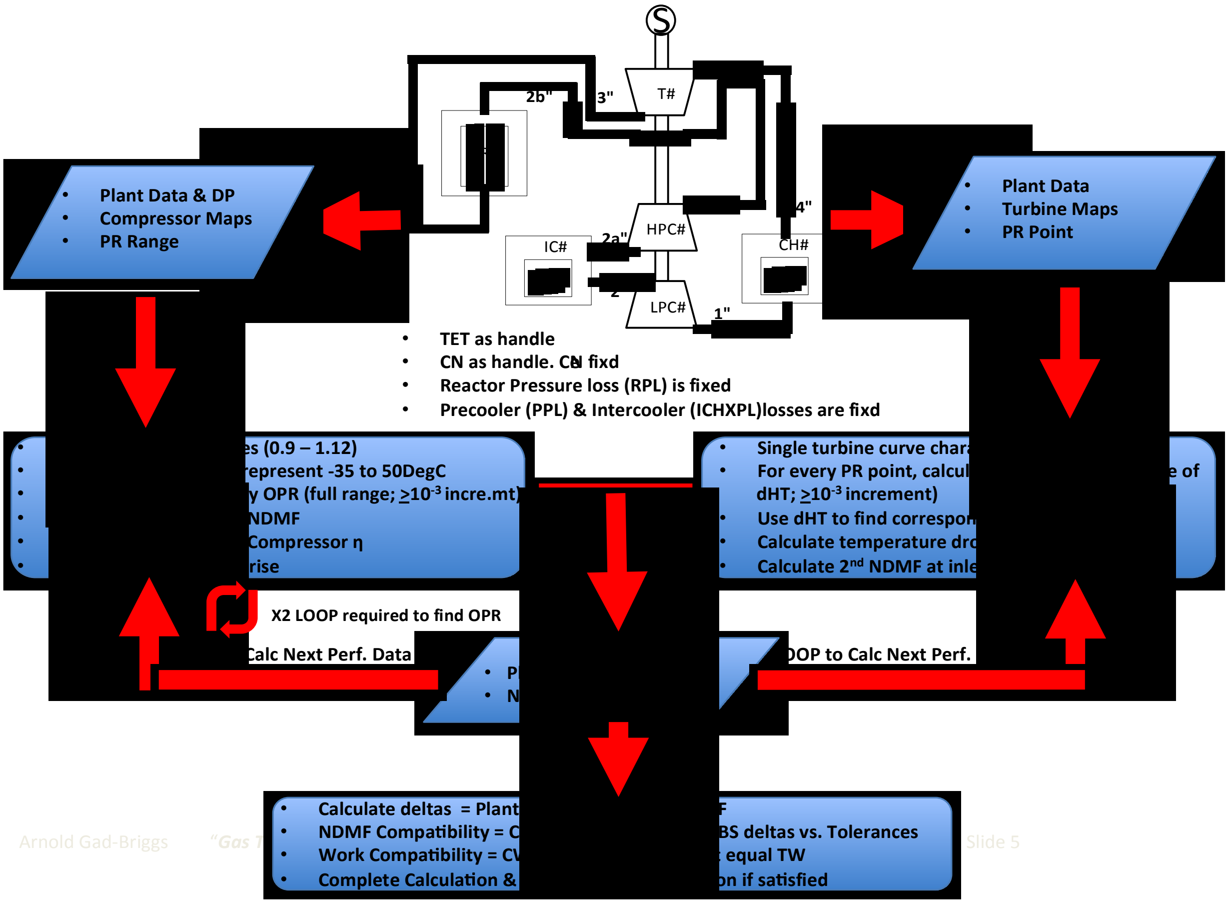

Figure 5 – Plant Matching Process

Table 2 – ODP Performance for IC T_1 (Corrected Speed Line) as Handle

COT	T_1	OPR	m	CW	TW	UW	SW	Heat Input	Cycle η	T η	HPC η	LPC η	Δ_UW_DP
°C	°C	N/A	kg/s	MW	MW	MW	MW/ kg/s	MW	%	%	%	%	%
950	28	2.81	413.87	418.97	678.59	259.62	0.63	1723.9	15.06	81	63	83	
950	50	2.78	384.47	433.62	608.46	174.84	0.45	1438.8	12.15	79	68	80	67
950	9	2.88	444.45	469.15	750.7	281.55	0.63	1875	15.02	82	61	73	108
950	2	2.93	460.54	491.59	792.15	300.56	0.65	1900.8	15.81	82	61	76	116
950	-9	3.02	473.37	503.56	831.42	327.86	0.69	2061.2	15.91	82	60	69	126
950	-35	3.16	511.03	481.01	936.67	455.65	0.89	2289.3	19.9	82	56	89	176

Table 3 – ODP Performance for IC COT (TET) as Handle

COT	T_1	OPR	m	CW	TW	UW	SW	Heat Input	Cycle η	T η	HPC η	LPC η	Δ_UW_DP
°C	°C	N/A	kg/s	MW	MW	MW	MW/ kg/s	MW	%	%	%	%	%
950	28	2.81	413.87	418.97	678.59	259.62	0.63	1723.9	15.06	81	63	83	
750	28	2.62	415.48	387.72	530.33	142.61	0.34	1317.5	10.82	80	63	84	55
800	28	2.67	415.48	395.43	566.76	171.33	0.41	1417.7	12.09	80	63	84	66
850	28	2.72	417	409.33	607.3	197.97	0.47	1505.8	13.15	80	64	85	76
900	28	2.76	415.48	412.6	642.5	229.9	0.55	1616.3	14.22	81	64	84	89
1000	28	2.86	413.87	426.88	717.47	290.59	0.70	1823.4	15.94	81	64	83	112

The IC performance shows an increase of 0.39% in mass flow rate at 750°C in comparison to 0.20% for SCR and 0.26% for the ICR. The derived ODP at 1000°C was at the same mass flow rate as at DP in comparison to the SCR (0.07%) and ICR (0.21%). The results indicate that the IC requires the biggest inventory when operating at lower COTs. This is supported by results from a study which looked at the load-following characteristics in [13]. It is anticipated that COTs will be varied for long term operation but for short term load-following requirements, the reduction in power could be achieved via inventory control. This will affect the level of inventory required for plant performance control. This has been investigated in Refs [12], [13] for all 3 cycles. Peak load requirements for 1000°C would be a short term demand to avoid impacting the reactor mechanical integrity due to the increase in 6% reactor power.

Variation of Reactor Pressure Loss

This analysis investigates if the reactor pressure losses affect the ODP characteristics, when the pressure losses are varied. The results are provided in Table 4 when the reactor pressure losses are varied (1 to 5%), with the COT and T_1 unchanged from DP. The scenario for matching ensures that the heat input is not exceeded beyond the DP values or is as close as possible to the DP due to safety operational reasons. When the

ODP efficiency values in Table 4 are considered, a pressure loss range of 1 to 5% can amount to an average efficiency drop of up to 6% for the IC. However, the IC reactor pressure loss has the lowest effect on cycle efficiency when compared to the SCR (average 11%) and ICR (average 8%). Another consideration is the load-following capabilities of IC to maintain the reactor thermal power. This is also considered for short term operation in [12], [13]. For long term operation, pressure losses should be limited but where this is not the case, it can be considered as a handle.

Table 4 – ODPs for IC (Reactor Pressure Loss)

	PR	m	CW	TW	UW	SW	Heat Input	Cycle η	T η	HPC η	LPC η	Δ_UW_DP	Δ Heat Input	Δ_η
	N/A	kg/s	MW	MW	MW	MW/ kg/s	MW	%	%	%	%	%	%	%
ODP (CN 1) MHR 1%	2.76	418.44	420.71	682.97	262.26	0.63	1706.38	15.37	81	64	85	101	99	102
ODP (CN 1) MHR 2% (DP)	2.81	413.87	418.97	678.59	259.62	0.63	1723.85	15.06	81	63	83	100	100	100
ODP (CN 1) MHR 3%	2.77	418.44	423.45	678.19	254.74	0.61	1703.65	14.95	82	64	85	98	99	99
ODP (CN 1) MHR 4%	2.85	415.48	427.65	679.38	251.73	0.61	1709.13	14.73	81	64	84	97	99	98
ODP (CN 1) MHR 5%	2.8	418.44	429.37	675.16	245.79	0.59	1697.73	14.48	82	64	85	95	98	96

Note: For the last 2 columns, divide numbers by 100 to get the actual % increase or decrease.

Variation of Intercooler Pressure Losses for IC and ICR

The analysis assesses if the intercooler affects the DP conditions of the IC and ICR when the pressure losses are varied between 1 to 5%. Tables 5 and 6 present the ODP performances for the IC and the ICR respectively. The COT and T_1 were unchanged from DP. The IC results show that for every increase in pressure losses, there is reduction in part power performance and cycle efficiency due to the rise in compressor work. A different observation was made in the case of the ICR, which established no significant trends. The absence of a recuperator translates into a drop of 9% in cycle efficiency for the IC, with the ICR showing a 6% drop in cycle efficiency. However, at part power performance, it expected that the total pressure loss would reduce due to lower referred coolant inlet mass flow [15]. This hold true because for a reduced mass flow at inlet and no change to heat sink conditions, it is expected that the improved heat removal from the coolant means that pressure losses will be lower at part power. Due the results, it is judged that the intercooler could be considered as a handle if pressure losses become unavoidable.

Variation of Precooler

For ODP performance, a variation precooler pressure losses between 1 to 5% (with COT and T_1 unchanged from DP) does not result in changes to the mass flow rate and pressure conditions effected by the compressor PR OPR. This also means that there is no change in the compressor work, but the turbine work is reduced and will result in lower useful work. The precooler loss results in a hotter coolant at inlet into the compressor and will result in a slightly hotter gas going into the precooler. The effects of hotter gas into the precooler has been investigated in [16]. Given there are no changes in inlet conditions, then losses in precooler do not require ODP considerations. The first order DP performance calculations are also applicable and have been considered and analysed in [4]. It is judged that the intercooler minimises the effect upstream of the cycle, providing the losses in the intercooler are kept to a minimum.

Table 5 – ODPs for IC (Intercooler Pressure Loss)

	PR	m	CW	TW	UW	SW	Heat Input	Cycle η	T η	HPC η	LPC η	Δ_UW_DP	Δ_η	Δ_m
	N/A	kg/s	MW	MW	MW	MW/ kg/s	MW	%	%	%	%	%	%	%
ODP (CN 1) ICHX 1%	2.65	418.44	401.89	670.42	268.53	0.64	1725.21	15.57	82	64	85	103	103	101.10
ODP (CN 1) ICHX 2.5% (DP)	2.81	413.87	418.97	678.59	259.62	0.63	1723.85	15.06	81	63	83	100	100	100.00
ODP (CN 1) ICHX 3%	2.84	418.44	434.73	687.16	252.43	0.60	1692.37	14.92	81	65	85	97	99	101.10
ODP (CN 1) ICHX 4%	2.86	418.44	437.15	685.7	248.55	0.59	1689.95	14.71	81	65	85	96	98	101.10
ODP (CN 1) ICHX 5%	2.81	419.8	437.63	680.53	242.91	0.58	1684.9	14.42	82	65	84	94	96	101.43

Note: For the last 2 columns, divide numbers by 100 to get the actual % increase or decrease.

Table 6 – ODPs for ICR (Intercooler Pressure Loss)

	PR	m	CW	TW	UW	SW	Heat Input	Cycle η	T η	C η	Δ_UW_DP	Δ_η	Δ_m
	N/A	kg/s	MW	MW	MW	MW/ kg/s	MW	%	%	%	%	%	%
ODP (CN 1) ICHX 1%	2.49	411.66	322.13	586.15	264.02	0.64	635.12	41.57	82	80	109	100.4	99.59
ODP (CN 1) ICHX 2.5% (DP)	2.35	413.35	291.31	533.91	242.6	0.59	585.91	41.41	81	82	100	100.0	100.00
ODP (CN 1) ICHX 3%	2.57	410.76	340.14	588.7	248.56	0.61	637.03	39.02	82	78	102	94.2	99.37
ODP (CN 1) ICHX 4%	2.55	410.96	336.05	581.67	245.62	0.60	630.4	38.96	82	79	101	94.1	99.42
ODP (CN 1) ICHX 5%	2.52	411.37	327.84	569.58	241.74	0.59	619.04	39.05	83	79	100	94.3	99.52

Note: For the last 2 columns, divide numbers by 100 to get the actual % increase or decrease.

Deriving Characteristic Maps of ODP Performance

Characteristic maps are illustrated in Figures 6 to 7 for the intercooler and the reactor for first order ODP calculations. With regard to Fig. 6, 2 curves are showed on the map, which applies to the IC and ICR. It is based on variation of the intercooler pressure losses. The curves plot the dimensionless value as a function of the pressure losses. The accuracy to within ±1% (error margin). The dimensionless parameter in Fig. 6 considers in all cases the NDMF divided by the mass flow rate at inlet into the intercooler and then that expression is divided the same expression but for the outlet, which will vary based on the station temperature and pressures [3]. Figure 7 applies to the reactor map and covers the IC the SCR and ICR. It characterises the temperature difference between Core Inlet Temperature (CIT) and COT as a function of the reactor heat input divided by the mass flow. An increase in heat input is also based on an increase in mass flow. Thus it is expected that the degree of heat input divided by mass flow, will directly be dependent on the amount of temperature rise required by the reactor to deliver the ODP COT. Based on this, it is clear that the requirements for the reactor are substantially create for IC in comparison to the SCR and the ICR.

It is recommended that a major part of the development activities for Gen IV should be dedicated to validating the tool used for this study and the results and characteristics maps produced. This will require test NPPs to come on line once built and will enable optimization to take place. Improving the accuracy will encourage the use of the tool thereby reducing costs associated with extensive test activities.

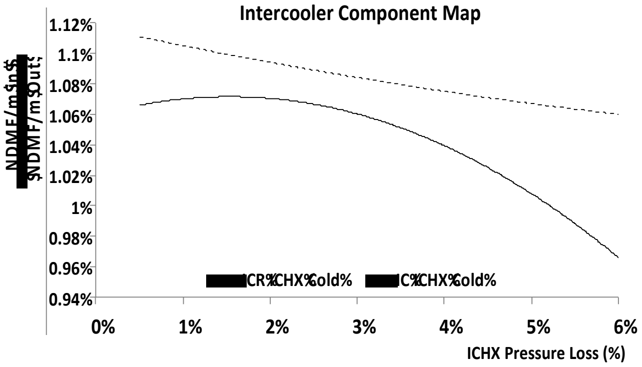

Figure 6 – Intercooler Component Map – IC & ICR

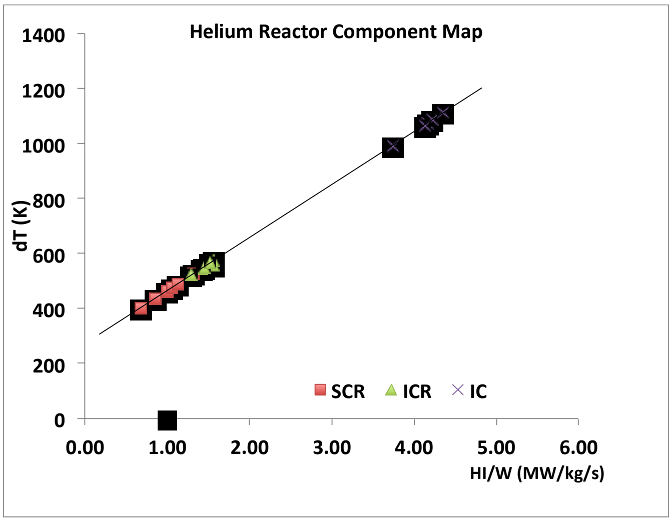

Figure 7 – Reactor Map

Conclusion

In summary, the objective of this study was to use the DP of an IC (260MW rating) to derive the ODP for long term operation in part power mode. For long term seasonal changes to ambient temperature, the analysed temperature range is between -35 to 50°C. Whereby grid prioritisation limits the power demand from the NPP, the power can be limited by reducing the COT. The analysed COT range is between 750 to 1000°C. The analyses was performed using a modeling and performance simulation tool designed for this study. The results provide a good basis to support preliminary cycle part power performance design, testing, validation and verification activities of Gas Cooled Fast Reactors (GFRs) and Very High Temperature Reactors (VHTRs) for Generation IV NPPs. The main conclusions are:

- The ODP showed a drop of 0.27% in efficiency at a modest inlet temperature of 9°C, which is in contrast to the SCR. It is judged that the intercooler is responsible for this effect due to a drop of 18% drop in cycle efficiency for the ICR. The resulting non-linearity is dependent on the increase in complexity during matching of components.
- The IC reactor pressure loss has the lowest effect on cycle efficiency (averaged 5%) in comparison to the SCR and ICR (averaged 11% and 8% respectively). This is for the analysed pressure losses range of 1-5%.
- With regard to the intercooler pressure losses, the absence of a recuperator for the IC means that a drop of 9% in cycle efficiency is observed. The ICR showed a drop of 6% in the cycle efficiency. However, at part power performance, it expected that the total pressure loss would be reduced due to lower referred coolant inlet mass flow.
- It is judged that the intercooler minimises the effect upstream of the cycle, providing the losses in the precooler losses are minimised.
- For economics, the cost of operating the plants at part power for the various scenarios analysed herein, is not understood. To aid better financial decisions on choice of plant configuration for optimum part power cycle efficiencies, a Techno-economic Environmental and Risk Analysis is needed
- Validation is recommended for this tool to enable optimisation and improve the applicability and accuracy. Furthermore, this will encourage its use thereby reducing costs associated with extensive test activities.

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