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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

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Abstract

An important requirement for Generation IV Nuclear Power Plant (NPP) design is the control system, which enables part power operability. The choices of control system methods must ensure variation of load without severe drawbacks on cycle performance. The objective of this study is to assess the control of the NPP under part power operations. The cycles of interest are the Simple Cycle Recuperated (SCR) and the Intercooled Cycle Recuperated (ICR). Control strategies are proposed for NPPs but the focus is on the strategies that result in part power operation using the inventory control method. Firstly, results explaining the performance and load limiting factors of the inventory control method are documented; subsequently, the transient part power performances. The load versus efficiency curves were also derived from varying the load to understand the efficiency penalties. This is carried out using a modelling and performance simulation tool designed for this study. Results show that the ICR takes ~102% longer than the SCR to reduce the load to 50% in Design Point (DP) performance conditions for similar valve flows, which correlates to the volumetric increase for the ICR inventory tank. The efficiency penalties are comparable for both cycles at 50% part power, whereby a 22% drop in cycle efficiency was observed and indicates limiting time at very low part power. The analyses intend to aid the development of cycles for Generation IV NPPs specifically Gas Cooled Fast Reactors (GFRs) and Very High Temperature Reactors (VHTRs), where helium is the coolant.

Keywords: Gen IV, Efficiency, NPP, Cycle, Part Power, Performance, Simple, Intercooled, Inventory, Control.

Nomenclature

Notations

A	Area (m^2)
Cp	Spec. Heat of Gas at Constant Pressure (J/kg K)
CW	Compressor Work (W)
CN	Corrected Speed (Non-Dimensional)
m	Mass Flow Rate (kg/s)
N	Speed (Non-Dimensional)
$NDMF$	Non-Dimensional Mass Flow
Q	Reactor Thermal Heat Input (W)
q	Heat Flux (W/m^2)

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P	Pressure (Pa)
PR	Pressure Ratio
R	Gas Constant (J/kg K)
SW	Specific Work (W/kg/s or MW/kg/s)
T	Temperature (K or °C)
TW	Turbine Work (W)
V	Volume
W	Work (W)
UW	Useful Work/ Power Output (W)

Greek Symbols

γ	Ratio of Specific Heats
Δ	Delta, Difference
ε	Effectiveness (Heat Exchanger; cooling)
η	Efficiency
θ	Referred Temperature Parameter
δ	Referred Pressure Parameter

Subscripts

0	Initial State
1	Final State
$blade$	Turbine Temperature (also known as Blade Temp.)
c	Compressor
c_{in}	Compressor Inlet
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
HP	High Pressure
HP_0	Initial High Pressure Condition
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)
s_{in}	Station number at Inlet
th	Thermal Power
t	Turbine
t_{out}	Turbine Outlet
t_{in}	Turbine Inlet
$tank$	Helium Inventory
$tank_0$	Initial Tank Conditions
$withdrawn$	Withdrawn Helium Inventory

Superscripts

’	Recuperator inlet conditions

Abbreviations

C	Compressor

CH	Precooler
CIT	Core Inlet Temperature
COT	Core Outlet Temperature
CV	Control Valve (Figure 3)
DP	Design Point
GEN IV	Generation IV
GFR	Gas-Cooled Fast Reactor
GIF	Generation IV International Forum
GTHTR	Gas Turbine High Temperature Reactor
HP	High-Pressure
HE	Recuperator
HPC	High Pressure Compressor
IC	Intercooled Cycle
ICR	Intercooled Cycle Recuperated
ISA	International Standard Atmosphere
LP	Low-Pressure
LPC	Low Pressure Compressor
NPP	Nuclear Power Plant
NTU	Number of Transfer Units
OD	Off-Design
ODP	Off-Design Point
OPR	Overall Pressure Ratio
R	Reactor
RPV	Reactor Pressure Vessel
SCR	Simple Cycle Recuperated
T	Turbine
TET	Turbine Entry Temperature
VHTR	Very High Temperature Reactor

Introduction

Generation IV reactors are key to advancements in the designs of Nuclear Power Plants (NPPs), with one of the main focuses being on part power cycle efficiency and control systems. Cycle economics stipulate for necessary improvements in comparison to the incumbent designs. Furthermore, beyond deriving better plant efficiencies at Design Point (DP) and Off-Design Point (ODP) for equilibrium performance, the control of the NPP is inherent in the safe and reliable operational strategy, which is critical to Gen IV system development. The objective of this study is to demonstrate the control performance at part power operation. A set of control methods are proposed and discussed in line with the strategies but control performance analyses shall be based on inventory control. The cycles of interest are the Simple Cycle Recuperated (SCR) and Intercooled Cycle Recuperated (ICR), which are analysed in a closed Brayton direct configuration using helium as the working fluid.

Generation IV (Gen IV) Systems

The Gas-Cooled Fast Reactors (GFRs) and Very-High-Temperature Reactors (VHTRs) are pertinent to this study. The GFR is helium cooled and encompasses a reactor with high temperature capability and a nuclear core with fast spectrum. The Core Outlet Temperature (COT) is between 850-950°C and is based on an efficient Brayton cycle design. The benefits of using helium include single phase cooling in all circumstances, chemical inertness and neutronic transparency [1]. The VHTR is cooled by helium in the gaseous phase and utilises a high temperature thermal reactor and graphite moderation in solid state. The mechanical properties of graphite at high temperature make it a good choice for moderation. The chemical inertness of helium is also key to this reactor configuration to avoid a chemical reaction with the 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 [2].

Simple and Intercooled Recuperated Brayton Cycles

The SCR and the ICR NPP configurations have been described extensively in [3] and are illustrated in figures 1 and 2. The SCR and the ICR both have the compressor and turbine as part of the turbomachinery, the precooler, reactor and recuperator. The main physical difference is the ICR employs an intercooler aft of the compressor in addition to a second compressor. Another notable difference is their respective plant cycle performances. The ICR improves the specific and useful work by reducing the compressor work. The helium coolant downstream of the first compressor is subjected to a reduction in temperature in the intercooler. The temperature is reduced to the same

inlet temperature as the first compressor, prior to entry into the second compressor [4]. This translates into an increase of 3% and upwards with regard to cycle efficiency, in comparison to the SCR when optimised turbine cooling methods are utilised [4]. A big disadvantage is the increased capacity of the plant due to additional components, which adds complexity to the plant configuration. The benefits of changing from air to helium including the thermodynamic consequences, have been extensively covered in [5], [6] and [7]. The papers provide good theoretical bases for off-design operation, control and transient operational modes of a helium nuclear gas turbine plant.

Control Systems Strategy

In terms of current operational strategies, fossil fuel power plants are preferred for meeting peak load, whilst NPPs are mostly utilised for base load. However, to eliminate the negative impact on the environment by displacing polluting energy sources, NPPs will need to demonstrate part load operational capability to meet grid demand.

It is acknowledged that NPPs do have the capability for part power operations. However, it is not widely adopted because of the perceived economics. There is also the issue of reactor core integrity, which could be compromised if hot spots appear due to repeated control rod insertion, thereby distorting the neutron flux. As such, the following strategies below; some of which are based on previous studies by [8], are taken into account:

1) Power Regulation based on Precooler Outlet/Compressor Inlet Temperature –(Normal Daily Operation)

The temperature of the coolant at the precooler outlet/compressor inlet is crucial for performance conditions of the NPP especially meeting grid demand. Variations in ambient temperature and the precooler hot gas inlet temperature will affect Design Point (DP) operation, which will impact the power output [9], and the effects are detailed in [10]. This will require the control system to regulate mass flow rate to effect changes without altering the Pressure Ratio (PR). This will be required to meet the optimum equilibrium Off-Design Point (ODP) operation for power output, without significantly compromising reactor core integrity.

2) Power Regulation based on Component Pressure Losses

In terms of operating at equilibrium, the recuperator High Pressure (HP) and the intercooler losses do alter the DP inlet conditions for mass flow rate and compressor pressure ratio. This is based on studies performed in [9], [11], whereby ODP performance calculations to establish equilibrium operating points for the purpose of optimum cycle efficiencies, yielded changes to mass flow rate and compressor pressure ratio. The study which is part of this research contribution also concluded that the reactor pressure losses do alter the mass flow rate and compressor pressure ratio but also acknowledged that conditions for ODP performance needed to ensure the reactor thermal power is below or close to the DP reactor thermal power to limit thermal stresses on the reactor. It is necessary for the control system to consider changes in pressure losses of the recuperator HP, intercooler and the reactor but as second order parametric inputs. i.e. only considered if precooler outlet/compressor inlet temperature is at DP condition. If the inlet temperature condition is as close as possible to DP, then the plant mass flow rate could be adjusted to counteract pressure losses for efficiency purposes.

3) Constant Thermal Power of the Reactor during Operation

Keeping the reactor thermal power constant is preferred for cycle economics. The thermal power due to the product of the mass flow rate of the helium taking into account specific heat at constant pressure and the delta between the core inlet and outlet temperatures, could vary as a result of changes in compressor inlet temperature. Maintaining the reactor thermal power will require increasing or reducing the plant output through increasing or reducing the inventory, which for a given COT and pressure ratio, will regulate the reactor thermal power.

4) Minimise Reactor Thermally Induced Stresses during Operation.

Maintaining a constant COT is key to minimising stresses within the reactor. This will in turn ensure structural integrity and fatigue of components are not compromised. The precooler ensures the temperature of the hot gas is reduced to the predefined inlet temperature. Nonetheless, it is acknowledged that the heat sink temperature conditions may not be controllable, if driven by ambient conditions. In such cases, the reactor coolant

amount could be varied to minimise the thermally induced stresses.

5) Minimise Turbomachinery Turbine Blade Thermally Induced Stresses during Operation

The turbine blade life is critical to the expansion process of the hot gas, whereby the work is created to drive the compressor and provide mechanical drive to the generator. The life of the blade could be severely reduced during load-following operations if there is variation in the thermal flux seen by the turbine blade, coupled with the centrifugal stresses. Apart from ensuring a suitable blade material is incorporated in the turbine, the way the turbine is cooled could be optimised using the blade metal temperature to calculate the optimum cooling flow as demonstrated in [4]. This is preferred in order to improve cycle efficiency for economic purposes; the ICR plant cycle efficiency was also improved by an additional 1% (3% in total) when the cooling was optimised, in comparison to 2% as stated in [12].

6) Maintaining High Efficiency during Load Following and Part Power Operations.

The efficiency of the plant from an economic stance remains the most critical of requirements. Operating the NPP at the equilibrium ODPs if changes are observed in inlet temperature or component pressure losses, ensures that the efficiency is maximised for those conditions. Again, the key here is to define the settings for regulating the mass flow rate in accordance with the ODP for power output, but without changes to the compressor pressure ratio.

7) Isolate Reactor and Remove Coolant from the Fluid Circuit in Emergency Conditions

In the event of an initiation of a rapid shutdown, the control system is expected to be able to isolate the reactor from the flow circuitry. This is achieved by diverting the flow upstream of the reactor and introducing it either at the inlet of the recuperator or the precooler. This ensures that the speed of the shaft is kept constant whilst the rapid load change takes place. In terms of introducing it before the recuperator LP inlet, it counteracts the increase of the turbine outlet temperature due to decrease in the turbine head [13], therefore minimising thermal transients in the recuperator Low Pressure (LP) side. This can be achieved by using bypass control valves in various configurations as described in [13]–[15]. For big NPPs, which perhaps utilise the ICR configuration, quick part load responses could be achieved by supplementing the flow using bypass control valves, but the cost of efficiency penalties do compromise the cycle economics.

Control Systems Design

The studies undertaken by [16] for GTHTR300C Cogeneration VHTR utilising SCR, provide control systems design solutions for some of the aforementioned strategies; these design solutions can also be applied for the ICR. Reduction of reactor and turbine thermally induced stresses using compressor coolant are demonstrated in the studies conducted as part of this research work and are documented in [3] and [4] for design point operation. The cooling methods are also employed in this study for part power operation.

Inventory Pressure Control

For strategies 1, 2, 3 and 6, which can be achieved by regulation of the flow, inventory pressure control is the focus and is proposed for steady regulation in this study. The notion of regulating the mass flow rate is intended to vary the pressure levels in the helium circuit, without changing the speed setting or the pressure ratio of the compressor. Thus the regulation takes place down stream of the compressor(s). As mathematically demonstrated later in this paper, the power output regulation is almost linear to the flow up to a certain level due to the change in working fluid density. It has negligible effect on the plant cycle efficiency if temperatures are kept constant and velocity of flow remains unchanged, whist maintaining other critical parameters such as shaft speed and compressor pressure ratio.

Inventory pressure control requires a storage tank, where helium is delivered to for part power performance and released from, if the power needs to be increased. The flow is controlled using valves to an acceptable limit. Figure 3 illustrates a simplified schematic of the SCR with inventory control; there are two methods of utilising inventory control (see figure 3, SCR). The first method removes the helium using Control Valve 1 downstream of the compressor and into the storage tank to reduce the power. To increase the power, the helium is returned back to the cycle at the inlet to the precooler (Control Valve 2). The returned helium momentarily increases the pressure in the cycle, which reduces the speed. This instability in the

operation can be avoided if the helium is returned to the HP side of the cycle (Control Valve 4), which has the opposite effect and is favourable. However, the drawback is the second method requires a compressor when removing the helium from the circuit via Control Valve 3, to ensure that the helium is always at a higher pressure than the cycle. Another disadvantage when considering the ICR is the aerodynamic stability of the second compressor if the helium is returned downstream of the intercooler and upstream of the second compressor. This can be overcome by minimised flow to operate below the surge line [17] or the flow being returned downstream of the second compressor. The inventory management in [17] analysed the use of multiple storage vessels with smaller storage volumes rather than one tank, to overcome charging of all the pressure in a single tank, thus reducing the amount of pressure required to maintain the storage pressure. However, this study is not concerned with the inventory arrangement but rather the performance of the cycle. The modelling in this study assumes the inventory is being returned downstream of the compressor(s) but in reality, method 1 is recommended to avoid complex arrangements.

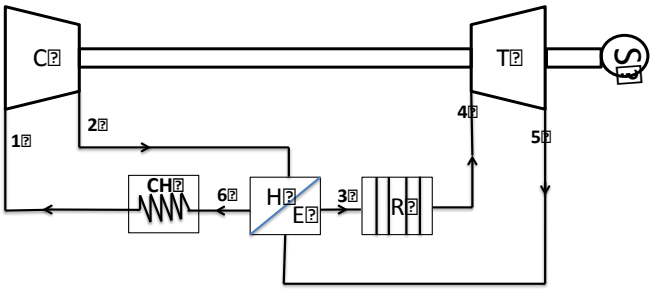

Figure 1 – Typical Simple Cycle with Recuperator (SCR) [18]

Modelling of Nuclear Power Plants and Performance Simulation Tool

Figures 1 and 2 respectively illustrate typical schematics of the SCR and the ICR respectively. Table 1 provides the key DP values for modelling, using the FORTRAN based modelling and performance simulation tool designed specifically for this study. With regard to DP performance, the tool has been designed to calculate the mass flow rate, temperature and pressures for each 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 can also analyse the effects on cycle output, capacity and efficiency by investigating changes to any of the above parameters.

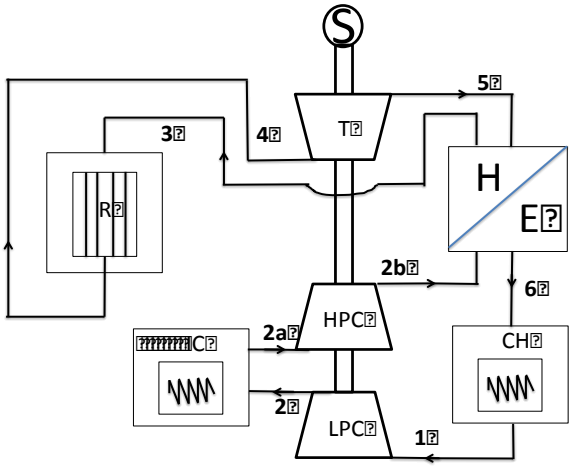

Figure 2 – Typical Intercooled Cycle with Recuperator (ICR) [19]

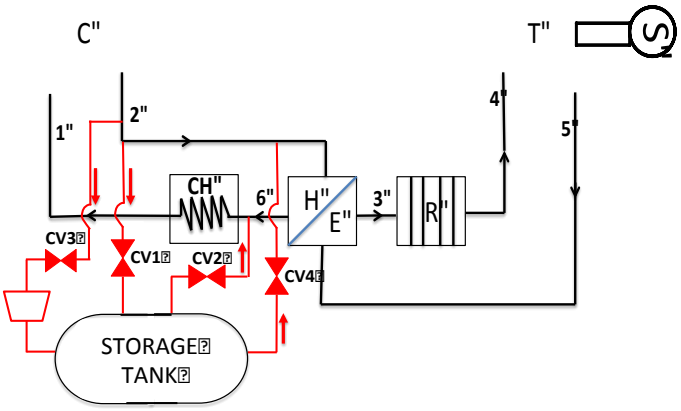

Figure 3 –Simple Cycle with Recuperator (SCR) with Inventory Pressure Control Schematic

When focusing on ODP performance, the model encompasses the turbomachinery component maps, which are represented as polynomials within the model. The process of calculation is iterative because a state of equilibrium for all components is required for successful matching. This is described in greater detail in [9]. With regard to demonstrating the capabilities for steady state and transient inventory pressure control, the model debits and credits the flow at the subject stations. For transient conditions, the calculations are repeated to represent incremental changes of the mass flow rate (kg/s) to

simulate the control method. The approach was considered satisfactory for the analysis conducted in this study. The equations implemented within the code environment are described in the proceeding sections and also feature in [3], [4], [9], [10], [11], [20] for steady state DP and ODP calculations, which are part of the overall research work conducted by the same authors of this study. The inventory control transient calculations are newly introduced in this paper.

Compressor

Prerequisite parameters for DP 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 (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 (°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 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 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 allows 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 [21] and applied for complex cross flow heat exchangers by [22]. 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:

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

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 and IC 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:

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

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

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

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

Modular Helium Reactor

The helium reactor is a heat source with 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 (Wt) 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 allows for coolant to be mixed with the heated fluid upstream of the reactor 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:

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

The method adopted is the film impingement forced convection, which is based on current turbine cooling developments. A detailed description of the cooling process is described in detail in [4].

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 (We), 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 (W/kg/s) is:

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

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

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

The DP performance values for the SCR and ICR are provided in Table 1. These DP performance values vary from the ODP performance analyses detailed in [9].

Expressions for ODP Performance Calculations

For constant speed steady state ODP performance, the temperature inlet conditions into the compressor for station 1 is corrected into a dimensionless parameter for the purpose of adapting the map (see figure 4) for helium and is expressed as:

$$CN = \frac{N}{\theta}_{Map_{Air}} = \frac{N}{\sqrt{(\gamma \cdot R \cdot T_{c_{in}})}}_{Map_{He}} \quad (30)$$

Table 1 – DP Performance for SCR and ICR

Design Point Performance	SCR	ICR	Units
Inlet Temp. (T_1)	28	28	°C
TET (Core Outlet Temp) (T_4)	950.0	950.0	°C
Core inlet temp (T_3)	678	599	°C
Inlet Pressure (P_1)	3.21	3.21	MPa
OPR	2	2.6	-
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	%
Compressor Work	227	299	MW
Turbine Work	512.8	686.8	MW
Heat Input	575.6	743.7	MW
Specific Work (NPP Capacity)	0.7	0.95	MW/ kgs/s
Useful Work	285.7	387.9	MW
Plant Efficiency	49.6	52.2	%

** Based on technological improvements in* [23]

Eq (30) defines the speed as the handle and determines the corresponding polynomial speed curve for the inlet temperature. Once the inlet conditions are defined, the model proceeds to calculate each component station condition. For the benefit of establishing the NDMF across all components, firstly the compressor incorporates the below referred parameter for temperature and pressure,

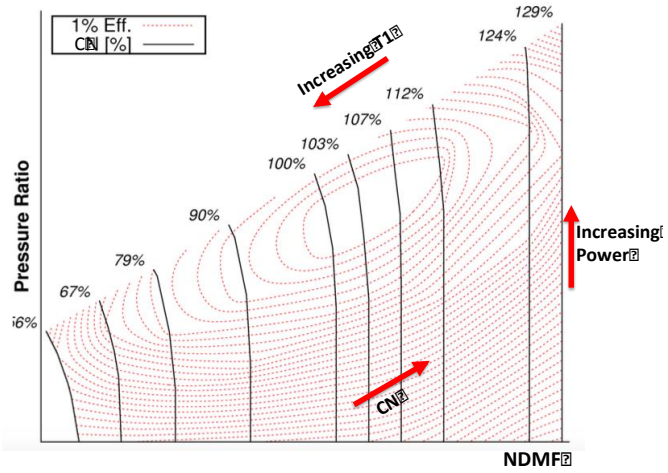

Figure 4 – Compressor Map Showing Corrected Speed Lines and Contours of Efficiency [24]

which is also corrected from the map to a dimensionless expression to get the true NDMF for helium. The NDMF considers the mass flow rate, temperature and pressure at inlet and the gas properties:

$$NDMF = \frac{m \cdot \sqrt{(\theta)}}{\delta}_{Air} = \frac{m \cdot \sqrt{(T_{S_{in}} \cdot R)}}{P_{S_{in}} \cdot \sqrt{(\gamma)}}_{He} \quad (31)$$

Eq (31) also fully applies to the turbine map, whereby it is corrected to give the true NDMF values for helium. The complete calculation sequence and matching process is described in [9].

Control of the Inventory Pressure

The calculation process considers the parameters of importance by applying the ideal gas model. Consider eqs 4, 5 and 7 for the *CW* and *TW*, eqs (32) and (33) replace ΔT_c and ΔT_t respectively, when using eq (4) for the *CW* and *TW*:

$$\Delta T_c = T_{c_{in}} \cdot PR^{\frac{\gamma-1}{\gamma}} \cdot \left(1 - \frac{1}{PR^{\frac{\gamma-1}{\gamma}}}\right) \cdot \eta_{is_c} \quad (32)$$

$$\Delta T_t = TET \cdot \left(1 - \frac{1}{PR^{\frac{\gamma-1}{\gamma}}}\right) \cdot \eta_{is_t} \quad (33)$$

By replacing the temperature deltas used in eq (4) for *CW* and *TW* with eqs (32) and (33) and combining both equations, the *UW* becomes:

$$UW = m \cdot Cp \cdot \left(1 - \frac{1}{PR^{\frac{\gamma-1}{\gamma}}}\right) \cdot \left(TET \cdot \eta_{is_t} - T_{c_{in}} \cdot \frac{PR^{\frac{\gamma-1}{\gamma}}}{\eta_{is_c}}\right) \quad (34)$$

Due to the known useful work of the cycle, the reactor heat input (*W*t) can be derived from eq (24) and (25) to allow the thermal efficiency to be calculated. For simplification, assuming 100% recuperator effectiveness, CIT is equal to turbine outlet temperature to allow the cycle efficiency to be retrieved from the below expression:

$$\eta_{th} = \frac{\left(1 - \frac{1}{PR^{\frac{\gamma-1}{\gamma}}}\right) \cdot \left(TET \cdot \eta_{is_t} - T_{c_{in}} \cdot \frac{PR^{\frac{\gamma-1}{\gamma}}}{\eta_{is_c}}\right)}{TET \cdot \left(1 - \frac{1}{PR^{\frac{\gamma-1}{\gamma}}}\right) \cdot \eta_{is_t}} \quad (35)$$

The main parameters, which influences the NPP power output according to eq (34) are the mass flow rate, PR, compressor inlet temperature and TET. The same parameters also have an influence on the cycle efficiency, with the exception of the mass flow rate according to eq (35). The proceeding section discusses the effect of these parameters on the power output and cycle efficiency.

Results and Discussion

Demonstrating Key Parameters and their Effect on Power Output and Cycle Efficiency

The control strategies described above implicitly determine what parameters are of importance in order to realise the respective strategies, but for power output, there are several. What is important is to demonstrate the pertinent parameters and their influence on the power output and efficiency.

Using simple calculations on the SCR, it was demonstrated that:

- 20% decrease in mass flow rate = 20% decrease in power and no effect on cycle efficiency
- 20% decrease in COT or TET = 37% decrease in power output and 20% decrease in cycle efficiency
- 20% decrease in compressor PR = 24% decrease in power output, 6.7% decrease in cycle efficiency
- 20% increase in first compressor inlet temperature = 15% increase in power output and cycle efficiency.

It is worth noting that the above results assume a recuperator effectiveness of 1. For the cycles in question, it is expected that the recuperator represents a limiting factor in minimising the efficiency drop. Studies documented in [3] as part of this research work, revealed that the recuperator effectiveness has the greatest component efficiency effect on the plant cycle efficiency. A cycle efficiency drop of 1.56% was reported for the SCR in comparison to 1.80% (ICR), when the recuperator effectiveness is between 0.85 and 0.89 from an initial value of 0.96. The most important aspect to consider however is that the methodology as presented in this section is only applicable to ideal gases such as helium. The mass flow rate is the product of the gas density, geometry area and velocity. With a constant velocity and an unchanged geometry, the mass follow rate becomes proportional to the gas density. Moreover, with a constant temperature, the pressure of the gas is also proportional to the gas density. However, there is a limit to the power range achievable.

Power Limiting Range

With consideration of eq (34) and the fact that the mass flow rate is proportional to the pressure, it is easy to assume that the power reduction achieved in the cycle will always be directly proportional to the mass flow rate. However, this is not the case because either removing helium or returning it to the cycle happens due to the pressure differential, when the pressure in the tank and the cycle acting pressure on the transfer valves are considered. One important aspect to this is the influence of mass, thus if the pressures in the cycle and the storage tank are at equilibrium, then the transfer of gas between the tank and the cycle cannot take place. To describe this fully for a

withdraw scenario in the SCR, the initial conditions of the gas (volume, initial pressure and temperature), if known, can be used to calculate the initial mass in the tank:

$$m_{tank_0} = \frac{P_0}{R \cdot T_0} \cdot V_{tank} \quad (36)$$

When a change in mass is observed due to withdrawing helium from the cycle, the secondary effect is a change in the pressure downstream of the compressor:

$$P_{HP} = \frac{m_1}{m_0} \cdot P_{HP_0} \quad (37)$$

Thus, for the pressure at the ducting point downstream of the compressor to decrease, the final mass M_1 in the cycle is reduced in eq (37) and added to the tank, thereby increasing the pressure and temperature (°K):

$$P_{tank} = \frac{m_{tank_0} + m_{withdrawn}}{V} \cdot R \cdot T_0^4 \quad (38)$$

but to ensure the flow of the gas, $P_{HP} > P_{tank}$; if at equilibrium, then the limit in power control is reached. The results showing the effect of change in mass on the pressures of the tank and the cycle and the ratio of pressures is presented in figure 5. It indicates equilibrium between tank and cycle is achieved typically at 60%, whereby, the cycle can no longer effect the control of the power using mass flow because of the pressure drop in the cycle. On the other hand, the tank's change in mass has resulted in the increase of the pressure, thereby requiring additional compression to effect any reduction in power. In such cases, the flow to the tank can be supplemented by using the bypass valves to achieve lower power settings. The analysis presented in figure 5 is also applicable for the ICR configuration. The storage tank will need to be scaled to meet the volumetric capacity. The difference apart from size is the time taken to withdraw and return helium to the cycle. The delta volume in scaling for the ICR is judged to be proportional to the delta time between both cycles for a given inlet temperature and valve flow rate.

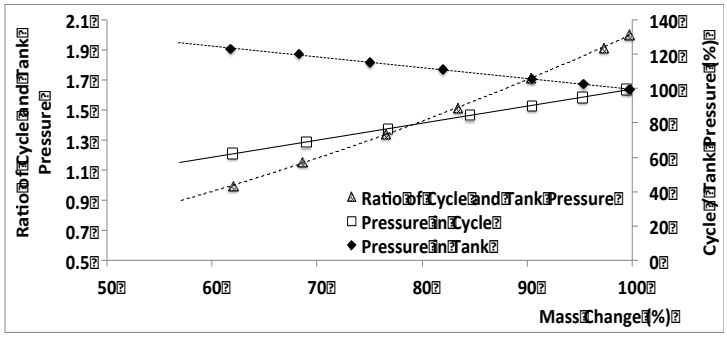

Figure 5 – Effect of Mass Change on Cycle and Tank Pressures

Transient Part Power Performance

Figure 6 illustrates the transient performance of the SCR and the ICR when the inventory is withdrawn during DP operations (Table 1). The flow rate for the withdrawal of helium was set at an average of 0.13 kg/s. This is based on studies conducted by [8], whereby 2 different flow rates (0.09 and 0.18 kg/s) were utilised. The simulation considers the inventory flow to be complemented due to the power-limiting factor, in order to achieve the flow rate. A reduction of up to 50% in power was considered in line with recommendation for inventory use as documented in [25], [26]. The results at 50% part power show that the SCR took 9 minutes 27 seconds to achieve a 50% reduction in comparison to the ICR, which took 19 minutes 8 seconds. The ICR performance at the analysed condition is 102% more than the SCR and also indicates the volumetric up-scaling that is required for the storage tank. This upscale takes into account the complete removal of the inventory from the cycle in emergency conditions. The reason for double the time is indicated in the capacity of both plants. The SCR capacity, which is indicated by the SW, is reduced by 0.16 MW/kg/s from DP; the ICR is reduced by 0.21 MW/kg/s from DP. The ICR had a bigger reduction of 0.05 MW/kg/s in capacity to meet the power demand, primarily due to the amount of the inventory removed. The % reduction in *CW* and *TW* are matched for both cycles. It is expected that the inventory pressure control will be limited to no less than 50% part power operation by NPP operators. Any attempts to increase the flow rate especially in the ICR must consider the aerodynamic stability of the compressors to and must avoid surge conditions.

Plant Part Power Efficiency

Figure 7 illustrates the performance curves of the SCR and the ICR when helium is extracted during DP operation (Table 1). The flow rate for the withdrawal of helium was set at an average of 0.13 kg/s. The simulation considers the inventory flow to be complemented due to the power-limiting factor, in order to achieve the flow rate.

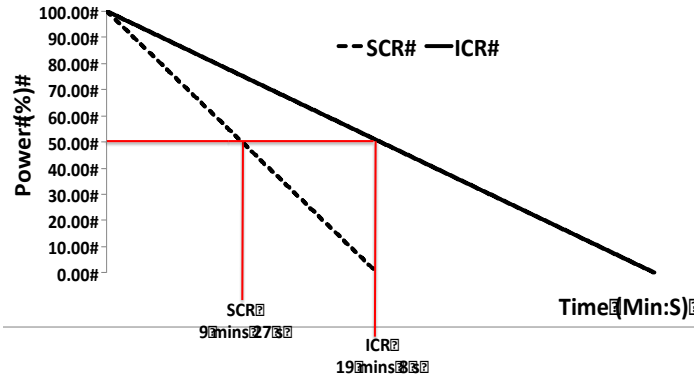

Figure 6 – Transient Part Power Performance (T_1 @ DP)

At the 50% part power level, the plant cycle efficiencies are reduced by ~22% to 38.5% for the SCR and 40.9% for the ICR. When the power is reduced to 80% of full power, the SCR plant cycle efficiency had reduced by 6.7% to 46.33%; the ICR had reduced by 6.4% to 48.8%. When at 90% of full power, the SCR plant cycle efficiency had reduced by 3% to 48.2%; the ICR had reduced by 2.9% to 50.7%. The plant cycle efficiency drops between 90% to 80% of full power are encouraging for part power performances. Operating for very long periods at power settings of ~50% are not recommended in order to maximise efficiency for economic purposes. Furthermore, pressure losses need to be minimised and recuperator effectiveness needs to be maximised to reduce the effect on efficiency. Whereby, recuperator, reactor and intercooler pressure losses and T_1 temperature are different from DP, then the NPP would need to be regulated based on the pre-determined ODP mass flow rates defined for equilibrium operations but more importantly for the economics of the plant.

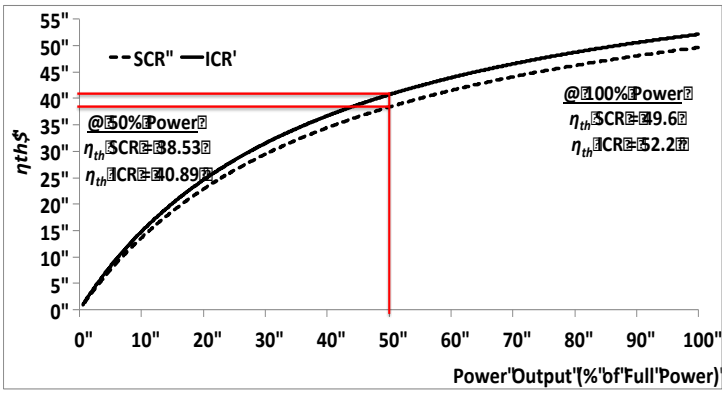

Figure 7 – Part Power versus Plant Cycle Efficiency Curves (T_1 @ DP)

Conclusions

In summary, the objective of this study is to assess the control of the NPP using inventory pressure control based on a set of proposed control strategies but specifically under part power operations. 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:

- Inventory pressure control is proposed to enable steady power regulation based on the following strategies: T_1 variation and pressure losses, constant reactor and power output during load-following operations.
- With no limit on efficiency, mass flow rate is directly proportional to power with no effect on cycle efficiency.
- However, the recuperator effectiveness is considered an efficiency limiting factor. For the plant output, the limiting factor is the ratio of pressures between the cycle and the tank. Based on the illustration provided, a $\geq$60% reduction from full power is achievable with inventory control.
- The ICR requires 102% longer than the SCR to reduce the power by 50% for the same DP conditions and flow rate. The increase in time also represents the level of volumetric scaling that is required for the ICR tank, even for emergency operations using bypass control valves. However, it must be acknowledged that the ICR has a larger power output thus any conclusions must take into account the larger capacity.
- Any attempts to increase the flow rate of the valves especially in the ICR must consider the aerodynamic

stability of the compressors to avoid encroaching on the surge margins.

- At 50% part power level, the plant cycle efficiencies are reduced by ~22% to 38.5% for the SCR and 40.9% for the ICR. At 90% of full power, the SCR plant cycle efficiency is reduced by 3% to 48.2%; the ICR is reduced by 2.9% to 50.7%.
- Operating for long periods at power settings of 50% is not recommended in order to maximise efficiency. Pressure losses also need to be minimised and recuperator effectiveness needs to be maximised to reduce the effect on efficiency.
- The impact on the economics of plants due to reduced availability needs to be assessed under a technoeconomic and environmental risk assessment framework.
- Validation is recommended for the tools such as the one developed for this study. This will enable optimisation to improve the applicability and accuracy and will encourage its use, thereby reducing costs associated with extensive test activities.

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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

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