Closed-Cycle Gas Turbine for Power Generation: A State-of-the-Art Review

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Abstract

In the last few years there has been considerable interest in closed-cycle gas turbine power plant due to the important contribution it can make to meeting worldwide energy demands. Closed-cycle gas turbine has the potential to serve as power conversion system for a wide range of energy sources such as fossil, concentrated solar power, nuclear, biomass and waste heat. However, there is a need to provide an update on the development of closed-cycle gas turbine with a view to identifying the challenges and the opportunities for future commercialisation. This paper is a review of research activities and studies carried out so far on closed-cycle gas turbine. The historical development in chronological order was presented first, followed by a review of some fundamental features such as heat sources, working fluids, compact heat exchangers and cycle layouts/configurations. Important research programmes and experimental/pilot plants as well as previous commercially operated plants are reviewed. Moreover, various studies based on modelling and simulation of closed-cycle gas turbine were reviewed, in addition to the operation and control strategies. Based on the review studies, the challenges ahead and potential future breakthroughs were highlighted in different aspects such as heat source technologies, power conversion system and demonstration plant.

Keywords

Closed-cycle gas turbine

Brayton cycle

Compact heat exchanger

Research programmes

Fossil fuel

Nuclear reactor

Highlights

- Closed-cycle gas turbine applicable to a wide range of fuels
- Working fluids include air, nitrogen, S-CO_2 and helium
- Review of important R&D programmes and operated plants
- Heat exchangers are significant driver in the capital cost and technical viability
- Demonstration plant essential before commercial deployment

1 Introduction

1.1 Background and Motivations

Closed-cycle gas turbine power plant has the potential to complement the conventional coal-fired power plant and internal combustion (open cycle) gas turbine (GT) power plants. Early popularity of the closed-cycle GT in the 1950s to the 1970s was over shadowed by the more matured open cycle GT, which gives higher efficiency due to its higher firing temperature. However in the recent past, there has been a revival of interests in the study of closed-cycle GT as an alternative or as an additional power conversion system (PCS).

Contributing to the renewed interest is the enormous achievement in the areas of high temperature small modular reactors (SMRs), the development of next generation nuclear reactors by Generation IV consortium and the improvement of solar receivers. While these new promising heat sources share the common features of moving to higher operating temperatures, the conventional power conversion systems (PCSs) cannot be adapted to exploit some of these higher temperatures. Hence, the door is open for the closed-cycle GT to be more competitive and will have billions of US dollars of commercial market. A previous drawback of the closed-cycle GT has been the lack of suitable heat source since light water reactors (LWRs) could not meet the high temperature requirement necessary for the cycle to be competitive. Similarly, the closed cycle GT was not well suited for conventional fossil-fired heat sources [1,2].

Previous hindrances to the commercialisation of closed-cycle GT such as material limitations for the high temperature and high pressure applications, the non-availability of suitable compact heat exchangers (CHEs) and the lack of sufficient turbomachinery experience are no longer major concerns [1,3]. For instance, the high pressure and high temperature are no longer considered as a drawback since power plant operators have acquired much experience with supercritical and ultra-supercritical steam units with operating conditions up to 320 bar and 600/610 °C [4,5]. CHEs such as the printed circuit heat exchanger (PCHE) with high effectiveness and ability to withstand high pressure and temperature are now available as replacement for the classical shell and tube design [3,6]. In the field of gas turbomachinery, introduction of magnetic bearing in 1985 means heavy rotor can be sustained and oil ingress in nuclear reactor eliminated [7,8]. The development of solid state frequency converters removes the restriction to always design the gas turbomachinery for synchronous speed and allows optimisation of turbomachinery performance on common shaft with the generator [9]. Also the availability of advanced numerical computational tool now allows improved design of the heat exchangers and the turbomachinery aerodynamics.

Furthermore, a unique feature of closed-cycle GT is its potential to serve as PCS for non CO_2 emission energy sources such as nuclear reactor, concentrated solar power (CSP), biomass, geothermal and fuel cell [10-12]. As shown in **Figure 1**, global energy production has been increasing and it is projected to continue to increase in the future due to increasing world population and economic growth [13-15]. Associated with the increased energy demand is also increase in fuel prices [16]. Although there is currently a drop in the price of oil, the future is still unknown. It is expected that the percentage of power generated by renewables sources and possibly nuclear energy will increase in an attempt to reduce carbon dioxide (CO_2) emission [16]. Therefore, the current global efforts geared towards the generation of electricity in a more efficient and environmentally benign manner through the research and development of alternative energy sources and PCSs will provide more market for closed-cycle GT [17].

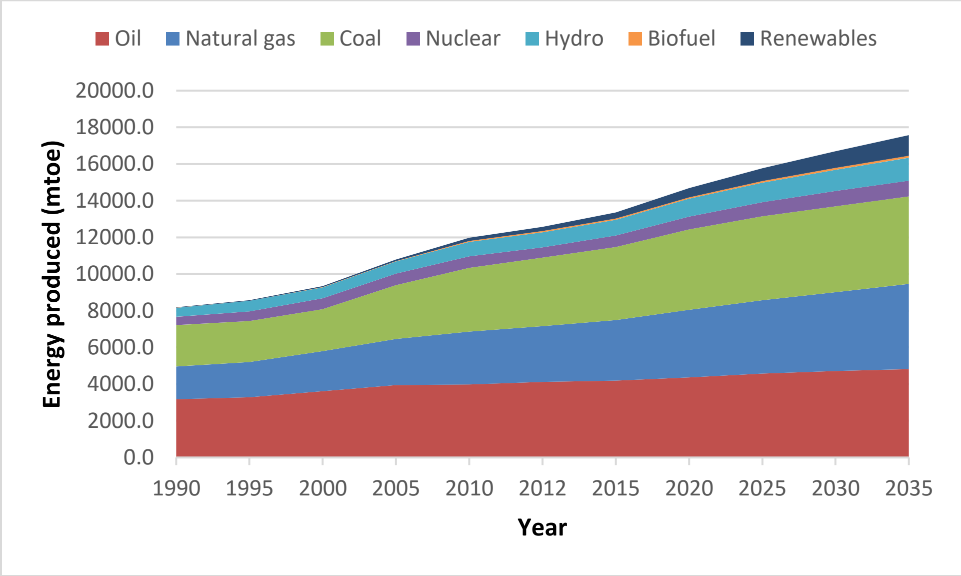


Figure 1 Global energy production by fuel

1.2 Gas turbine: Open versus closed cycle

All gas turbines operate on the thermodynamic cycle called the Brayton cycle to produce mechanical power. Based on the path of the gases, gas turbines can be classified as shown in Figure 2 as: (a) open cycle with air as the working fluid; (b) closed cycle with air or other fluids with better properties as the working fluid and (c) Semi closed cycle.

In a closed cycle GT or closed Brayton cycle (CBC), the turbine exhausts are not thrown out but recirculated. The layout and Temperature-Entropy (T-S) diagram of a simple regenerative closed cycle GT is shown in **Figure 3** (b). The working fluid is compressed in the compressor from point 1 to 2. Then it enters the recuperator where some of the heat content of the turbine exhaust is regenerated (point 2 to 3). After regeneration the fluid passes through the heat source, which could either be a nuclear reactor core, an intermediate heat exchanger (IHX) or a gas heater (point 3 to 4). In the heat source the fluid achieves the highest temperature within the cycle. This is followed by an expansion in the turbine (point 4 to 5). The turbine provides the work for the compressor and generator. The turbine exhaust is then used to preheat the fluid coming out of the compressor in the recuperator (point 5 to 6). Finally, the heat is rejected from the cycle in the cooler, where the fluid is cooled to the initial conditions.

Several authors [10,18-20] have highlighted the benefits of closed-cycle GT for power generation which include:

- Closed-cycle GT can achieve higher efficiency than the steam cycle at high temperature
- Simpler than steam Rankine cycle which has many heat exchangers and pumps as well as a lot of piping
- The possibility of operating at higher pressure gives compact components and smaller plant footprint compared to steam turbine plant. Higher power-to-size ratio and reduced capital cost can then be achieved
- Unlike open cycle GT that can only use clean fuel, closed Brayton cycle (CBC) can use solid fuels like coal and biomass as well as solar, nuclear and waste heat.
- Use of different working fluids with favourable thermal and transport properties e.g. helium, nitrogen, carbon dioxide, argon, neon and gas mixtures

- No fouling and corrosion of system components and no need for air filtration in contaminated environment

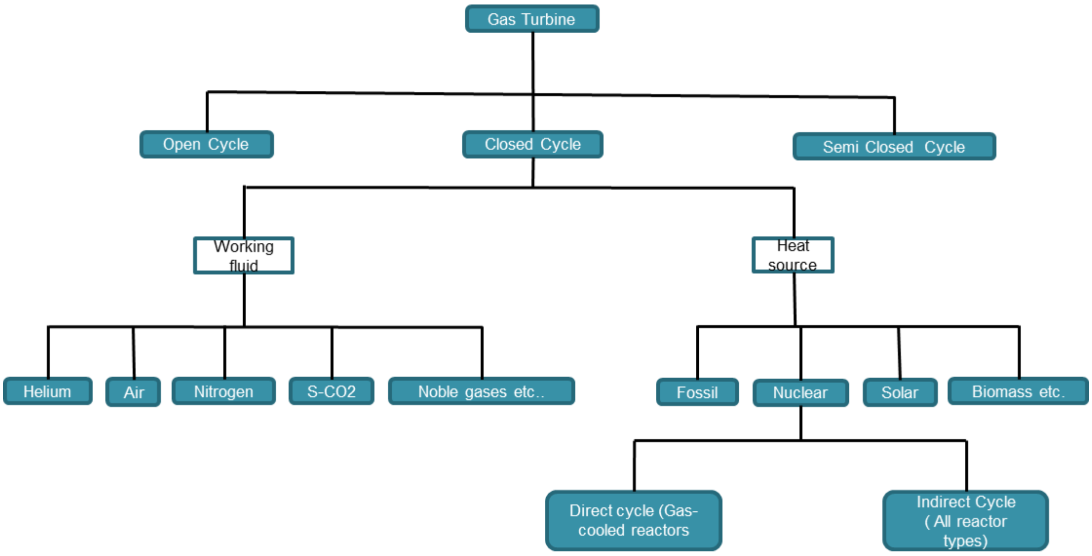
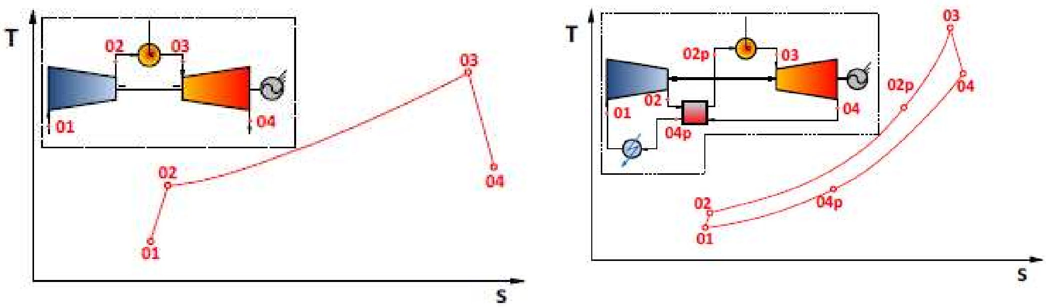


Figure 2 Gas turbine classification



(a) Open cycle gas turbine (b) Closed cycle gas turbine

Figure 3 Open and closed-cycle gas turbine schematic and T-S diagram [21]

Despite the many benefits of closed-cycle GT, the open cycle has been more popular due to its capability to achieve very high turbine inlet temperature (TIT) making it more efficient, more compact and less costly. **Figure 4** produced by [22] shows the trends of the increase in firing temperature of open cycle and closed-cycle GTs. While closed-cycle GT firing temperature is limited by the allowable maximum temperature of the metallic heat exchanger, open cycle GT takes advantage of increase in firing temperature and the availability of natural gas in abundant. Therefore, closed-cycle GT might not be able to replace open cycle GT with the current technology but it could still find usefulness in applications where open cycle GT cannot be deployed such as nuclear. Closed-cycle GT also has the potential to operate at higher temperature than steam Rankine cycle.

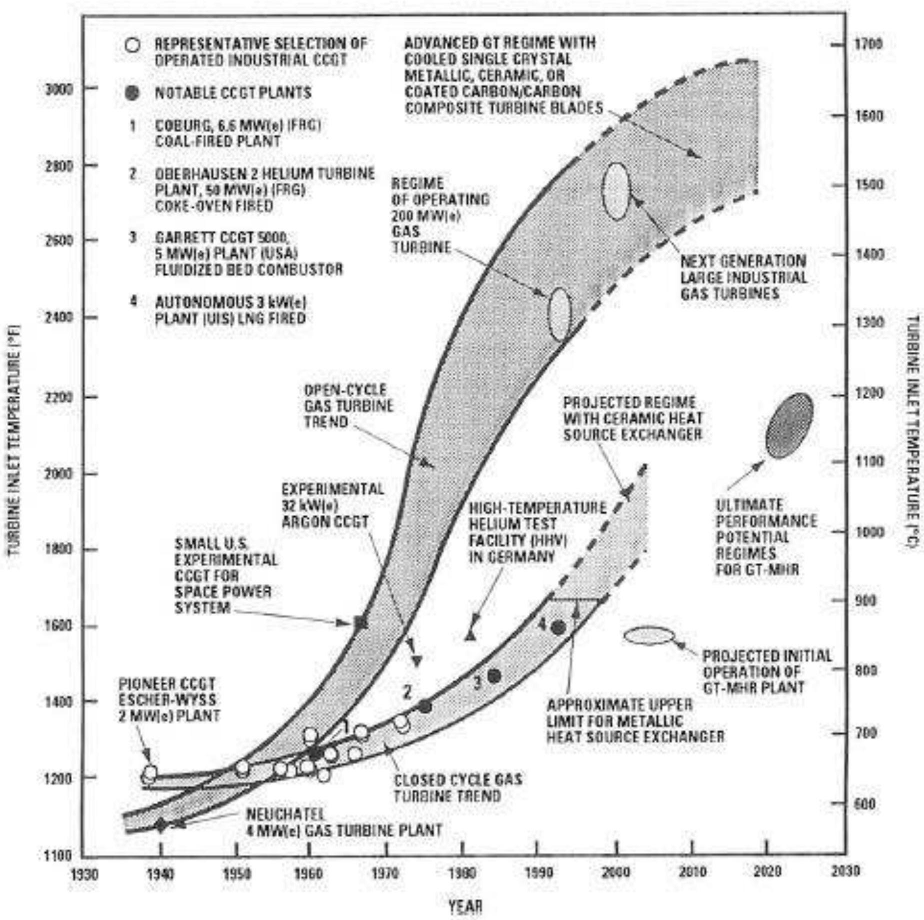


Figure 4 Gas turbine firing temperature trends [22]

1.3 Aim of this paper and its novelty

Some authors have reviewed the development of closed-cycle GT for power generation. [20] attempted to establish the maturity of closed-cycle GT technology by highlighting the operating experiences of the early closed-cycle GT using heat from fossil fuel and air as working fluid. A textbook by [23] also reported the operating experiences and future outlook of different closed-cycle GTs with different heat sources such as coal, light oil, nuclear and waste heat and different working fluid such as air, helium and nitrogen. A review of helium as working fluid for high temperature gas reactors (HTGRs) based on experiences in Germany and Japan was presented by [24]. [25] gave a detailed review and historical background of operated helium GT demonstration facilities. Recently, [11] reviewed both closed-cycle and open cycle externally-fired GTs focussing on a wide range of thermal sources, high temperature heat exchangers and technologies for externally-fired GTs. However, most previous reviews has tended to focus on air and helium GTs. There is also the need to highlight the latest developments in closed-cycle GT technology as well at its future applications.

This paper aims to provide a state-of-the-art assessment of the research activities and development of closed-cycle GT. For those with little knowledge of closed-cycle GT, this paper will give an introduction of the relevant concepts necessary to achieve basic understanding. For those already acquainted with the technology, this paper will review past experiences, recent progress and give an outlook of the future research directions based on current developments.

The distinctions between this paper and previous review work such as Keller (1978), Frutschi (2005) are: (a) this paper is to provide an update of major demonstration and test facilities worldwide (b) this paper is to provide a critical review of important research programmes and research studies in modelling and simulation, and operation and control of closed-cycle GTs and (c) this paper is to highlight the challenges ahead and tries to predict the future potential breakthrough.

1.4 Outline of the paper

In Section 2, the historical development is enumerated. The relevant technology concepts (e.g. heat sources, working fluids, configuration and layout) for the understanding of closed-cycle GT is reviewed in Section 3. Then the major plants, demonstration and experimental test facilities, and research activities worldwide are reviewed in Section 4. This is followed by an overview of the various studies based on modelling, simulation, operation and control in Section 5. Section 6 highlights the challenges ahead and tries to predict the future potential. Finally, conclusion is drawn in Section 7.

2 Historical development

Table 1 shows the historical development of closed-cycle GT in chronological order. In 1935, at a time when the development of GT technologies was just emerging, Ackeret and Keller patented the closed-cycle GT [23,25]. Four years later, the pioneering closed-cycle GT, the AK-36 test plant, was built [23]. However, no industrial plant was built until about a decade later as a result of the Second World War and the following economic recession [25]. In 1949, the first industrial closed-cycle GT power plant reported in literature [23] was commissioned in the city of Coventry UK. By the early 1970s, about 20 fossil fired air closed-cycle GT plants had been constructed in Europe with a total operating time of about 750,000 hours [23,25,26]. The ability to operate on different fuels and the possibility for the cogeneration of heat and power contributed to the popularity of the power plants at that time [25].

With the successful operation of the small air closed-cycle GT power plants in Europe, efforts were directed toward the design of plants with larger rated power output [20]. However above 30 MW, helium was considered a more suitable working fluid than air and more so it can serve as coolant in HTGRs. The first helium closed-cycle GT, with no output power generation, was developed in 1962 by James La Fleur for driving a cryogenic air separation process in the USA [27]. Earlier in 1942, Ackeret and Keller proposed the application of helium closed-cycle GT to HTGR with direct cycle [20]. In the following four decades, various conceptual design studies were done on the possibility of coupling helium CBC to HTGR in the USA, Germany, the UK and France. This is as a result of recognising that its adaptability to HTGR would contribute to future acceptance. The first of the German-Swiss High Temperature Reactor Helium GT (HHT) project, the coke oven gas fired Oberhausen II helium turbine cogeneration plant, was built in 1974. The second demonstration facility for the HHT project, the high temperature helium turbomachine test facility (HHV), was built in 1981. These large nuclear GT power plant concepts were not pursued further due to lack of technology readiness. Hence from 1981, investigation of nuclear GT was limited to paper studies [25].

Research focus on helium GT was shifted to the high temperature SMR GT system from the early 1980s. By 1987, studies at MIT resulted in a conceptual design of the Modular High-temperature Gas-cooled Reactor Gas Turbine, MGR-GT [9]. General Atomics (GA) of USA developed the first design of the Gas Turbine-Modular Helium Reactor (GT-MHR) in 1990 [28]. ESKOM Company of South Africa in 1994 started the development of a 400 MWt Pebble Bed Modular Reactor (PBMR) with direct helium Brayton cycle [28]. The Japan Atomic Energy Research Institute (JAERI) started in 2001 the Gas Turbine High Temperature Reactor (GTHTR300) programme [29]. In China, the Institute of Nuclear and New Energy Technology (INET) at Tsinghua University in 2003 started the experimental 10 MW helium cooled High

Temperature Reactor Gas Turbine (HTR-10GT) project [30]. Mid 2003, development began on the French High Temperature Reactor/Very High Temperature Reactor (HTR/VHTR) project, the ANTARES (AREVA New Technology Advanced Reactor Energy Supply) combined cycle cogeneration concepts, comprising a topping helium/nitrogen mixture CBC [31].

In 1950, a partial condensation carbon dioxide closed-cycle GT was patented by G. Sulzer [32]. In the 1960s and early 1970s, the benefits of the unique features of CO_2 gave rise to increase interest in its potential use as working fluid among researchers in the Soviet Union [33], Italy [34], the United States [35] and Switzerland [36]. In 1970 Hoffman and Feher designed a 150 kWe supercritical carbon dioxide (S-CO_2) test loop for small terrestrial nuclear reactor [4,37]. After this period, development of S-CO_2 cycle was delayed with no deployment of the plant taking place because of the lack of technology maturity for the high pressure and high temperature system. However in the late 1990s and early 2000s, a renewal of interest in the S-CO_2 cycle was kindled by research at institutions such as the MIT in collaboration with Sandia National Laboratories (SNL), Idaho National Laboratories (INL) and Argonne National Laboratories (ANL) [3,38]. Other institutions included the Czech Technical University in 1997 and the Tokyo Institute of Technology, TIT [38,39]. The renewed interest was aided by the relative maturity of the turbomachinery, compact heat exchanger and heat source technologies. TIT built a test loop for corrosion studies of S-CO_2 cycle materials. In April 2012, the final design and installation of a megawatt class S-CO_2 recompression Brayton cycle test assembly was realised by SNL contractor Barber-Nichols Inc. [40]. An 8 MW closed power cycle using S-CO_2 as working fluid was presented for commercial demonstration by Echogen Power Systems in December 2014 [41].

Table 1 Historical development of closed-cycle GT

Date	Development
1935	Prof Curt Keller and Prof J. Ackeret patented the closed-cycle GT in Berne, Switzerland
1939	The AK-36, the pioneer closed-cycle GT, was built by Escher Wyss AG in Zurich, Switzerland.
1949	An industrial closed-cycle GT with waste heat source and using air as working fluid was commissioned in Coventry UK
1950	G. Sulzer patented a partial condensation CO_2 Brayton cycle
1960	In Germany, the Oberhausen I air closed-cycle GT cogeneration plant was commissioned
1962	The US Army's ML-1, the only nuclear reactor coupled CBC ever built, was built for mobile power generation. In the USA, the pioneering helium closed-cycle GT was built for air liquefaction by James La Fleur
1970	A 150 kWe S-CO2 loop was designed by Hoffman and Feher to investigate the possibility of using S-CO_2 cycle for small terrestrial nuclear reactor
1972	The biggest and the last air closed-cycle GT was built by Escher Wyss for the City of Vienna
Early 1980s	GA conducted an assessment of a large size (2000 MWth) HTGR-GT OKBM in USSR investigated the replacement of steam cycle with CBC for their 1000 MWth nuclear power plant
1974	The first HHT project, the Oberhausen II, started operation in German. Operation stopped in 1988.
1981	The second HHT project, the HHV test facility, was built in Germany
1987	Years of studies at MIT resulted in a conceptual design of the MGR-GT
2001	The GTHTR300 programme was started by the JAERI in partnership with Toshiba and Mitsubishi
2003	The experimental HTR-10GT project was started in China by INET
1995	A joint programme for the development of the GT-MHR was started by GA of USA and Minatom of Russia with the support of the Russian and U.S. Department of Energy (DOE). Framatone (France) and Fuji Electric (Japan) later joined the programme
1994	The South African company, ESKOM, started the development of PBMR helium GT plant. Later changed to indirect steam Rankine cycle in 2009.
1995	In Britain, a natural gas-fired closed cycle GT test facility using mixture of nitrogen and oxygen (2%) as working fluid was installed by British Gas.
2000	MIT in collaboration with INL, SNL and ANL revived interest in SCO_2 cycle study
2003	A 1/3-scale test model of the GTHTR300 compressor was designed and fabricated in Japan to investigate the performance and design
2003	Development of ANTARES (France) combined cycle cogeneration plant concept with a topping CBC.
2012	After previous installation of small S-CO_2 compression test loops and the CBC test bed (SBL-30), SNL contractor Barber-Nichols Inc. completed the design and installation of a megawatt class S-CO_2 recompression cycle test assembly
2014	Echogen announced the commercialisation of 8 MW EPS100 heat engines, that uses S-CO_2 as working fluid for waste heat recovery

3 Review of relevant concepts and major features

The fundamental concepts and features relating to the design consideration of close-cycle GT involve: the selection of heat source; the choice of working fluid and the adoption of a physical layout/configuration for the cycle. An understanding of the cycle components is also required.

3.1 Fuel/Heat sources

The closed-cycle GT is applicable to most thermal heat sources for power generation. Hence its potential markets include: electric power generation from nuclear, concentrated solar, biomass, geothermal, waste heat and energy storage system; power plants with carbon capture & sequestration (CCS); space exploration power systems; marine and underwater propulsion and power systems; and terrestrial transportation systems [42,43].

3.1.1 Fossil fuels

All the early operational closed-cycle GTs were fossil fuel fired [23]. The first closed-cycle GT, the AK36 test installation, employed a light oil fired heater. A 2.3 MW plant built in 1956 was fired by pulverised bituminous coal and supplied the Escher Wyss machinery factory in Ravensburg. At a time it was clear that the fossil-fired closed-cycle plants using air as working fluid cannot compete with open cycle due to the small rated power and low firing temperature (below 700 °C). The Oberhausen II plant was built in 1974 to prepare the ground for nuclear closed-cycle GT and demonstrate the use of helium in high temperature large scale plant. The plant was fired by coke oven gas to give hot helium temperature of 750 °C. This was followed by the HHV test facility with hot helium temperature of 850 °C. A detailed description of these plants and others will be presented later.

Closed-cycle GT can be integrated with combustion systems that have low emissions such as fluidized bed combustion (FBC). CO_2 emission can be mitigated by either enabling the GT to operate on a CO_2-neutral fuel like biomass, or using a fossil fuel and then capturing the CO_2 instead of venting it to the atmosphere. A 5 MWe closed-cycle GT burning petroleum coke in Atmospheric FBC (AFBC) was built by Garrett Corporation, USA in 1985 [25]. Under the US DOE programme, Aerojet Rocketdyne (AR) and Southwest Research Institute (SwRI) have been evaluating S-CO_2 closed-cycle GT using fossil fuels with CCS [44,45]. The AR's Zero Emission Power and Steam (ZEPS^{TM}) plant using FBC is an oxy-coal power plant with S-CO_2 Brayton cycle (Figure 5). A technical-economic evaluation of a coal-fired S-CO_2 closed-cycle GT plant with post-combustion CO_2 capture by [46] showed 15% reduction in cost of electricity compared to supercritical steam plant equipped with CO_2 capture.

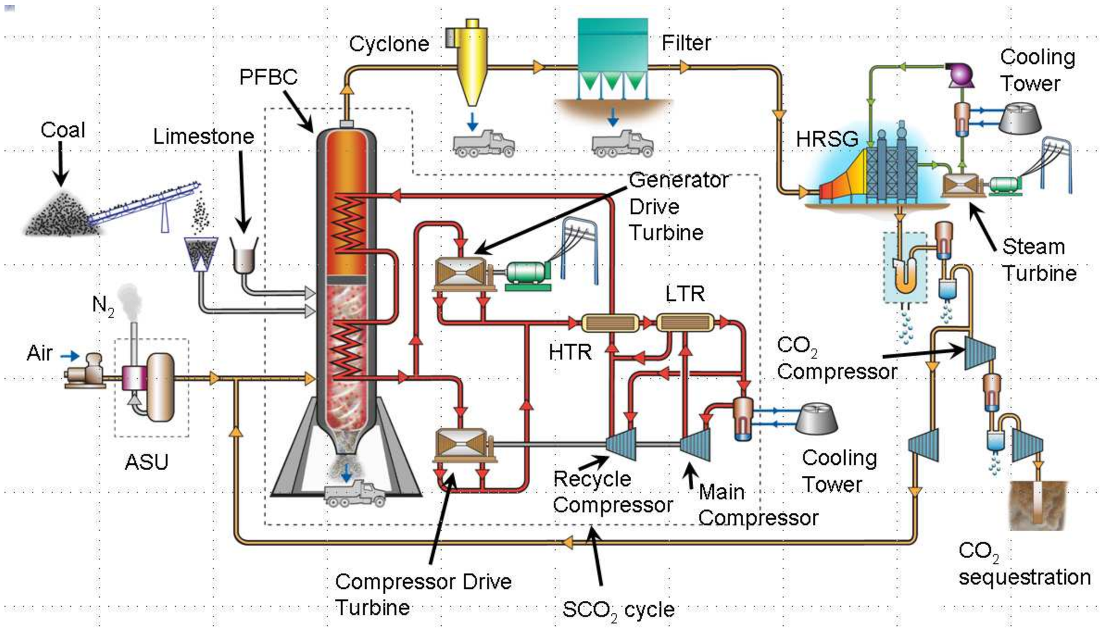


Figure 5 AR's oxy-combustion coal-fired S-CO_2 Brayton cycle [47]

3.1.2 Nuclear heat source

Closed-cycle GT is well suited for nuclear heat source as it prevents release of contaminated fission material to the environment unlike open cycle GT. Also, with efficiency up to 50% at about 1000 °C reactor outlet temperature and the benefit of smaller plant footprint, the closed-cycle GT can compete with steam cycle [48].

Coupling of closed-cycle GT to Dragon helium cooled reactor was suggested by Escher Wyss and GHH suggested coupling to the Beach Bottom reactor [20]. GA assessed a large 2000MWth HTGR gas turbine and OKBM in the USSR investigated the replacement of steam cycle with CBC for their 1000MWth VG-400 nuclear reactor [49,50]. The only nuclear reactor coupled closed-cycle GT ever built was the ML-1 for mobile power generation [51].

In order to achieve inherent safety, most modern HTGRs design adopt SMR concept limited to below 600 MWth [48]. Some recent design of HTGR-coupled CBC are GT-MHR (Russia and USA), ANTARES (France), GT-HTR300 (Japan), HTR-10GT (China) and PBMR (South Africa). They all use helium as reactor coolant. The Generation-IV consortium, established in 2000, is developing six categories of next generation nuclear reactors expected to be fully matured for commercialisation in the period between 2020 and 2030 or beyond [52,53]. These reactors, for electricity generation and hydrogen production, would be operating at higher temperature than the current reactors. Various researches on the power cycles for these next generation reactors indicated closed-cycle GTs as promising alternatives to the current steam turbine cycles [4,54-56].

The CBC can be coupled to the reactor in either a direct cycle (in the case of gas-cooled reactors) or an indirect cycle configuration (Figure 6).

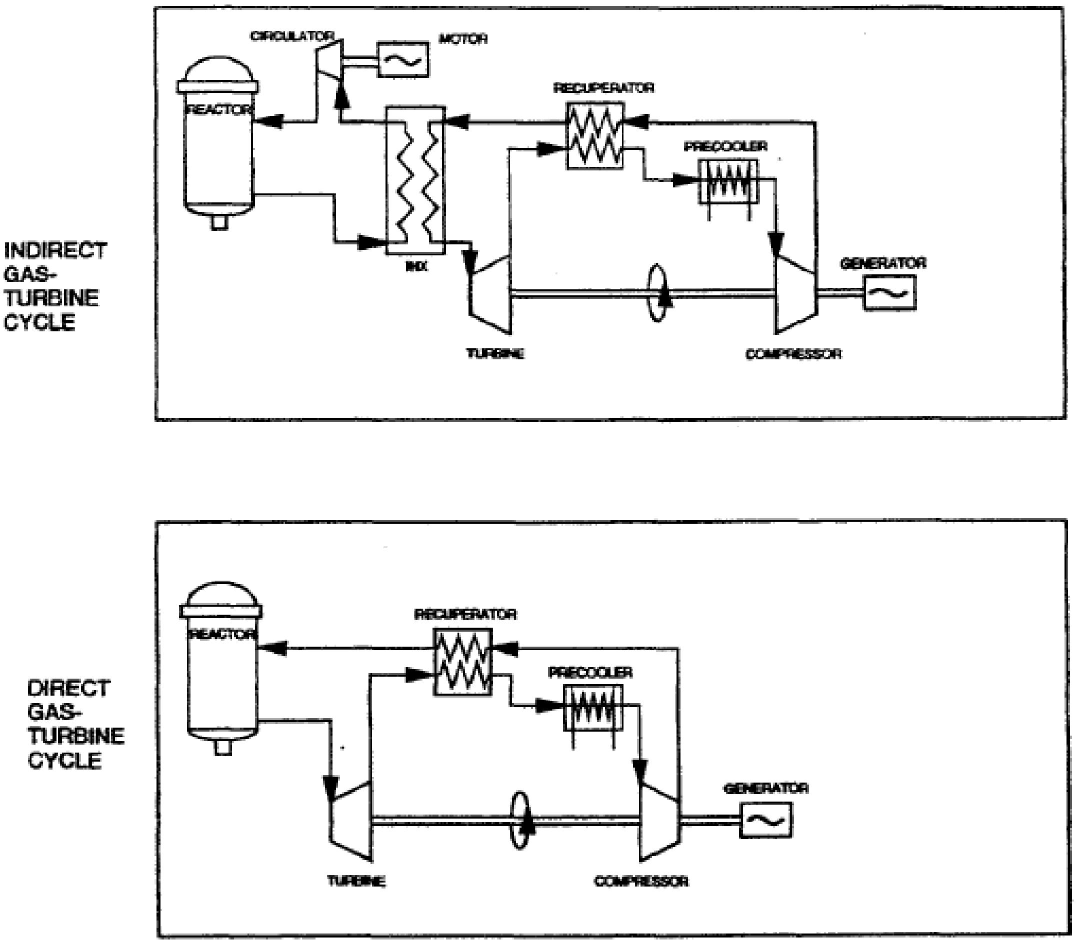


Figure 6 Indirect and direct nuclear GT cycles [57]

3.1.3 Concentrated solar power (CSP)

CSP can provide renewable thermal power at temperature up to and above 1000 °C with the current receiver technologies to drive a power conversion cycle for the generation of electricity [11,58].

Many researchers are now investigating closed-cycle GT as alternative cycle for CSP offering increased efficiency by taking advantage of the higher temperature [58-62]. According to [58] the use of a single-phase fluid like S-CO_2 as both solar heat transfer fluid and the PCS working fluid will give a simpler plant and is compatible with sensible heat thermal energy storage. Economic and technical analysis of CSP S-CO_2 cycle seems to suggest 5–10 MW as the optimal capacity [58,63]. SwRI has just received a grant of USD 4.9 million (EUR 4.4m) from the US DOE through the SunShot Initiative to fabricate and test the turbine and compact heat exchangers of a S-CO_2 closed cycle for CSP plant. The plant is estimated to reduce the cost of CSP power to USD 0.06 per kWh and raised the efficiency to over 50% (current steam cycle based CSP plant efficiency is less than 35%). The project, running from December 2014 through to mid-2016, will involve other industrial partners like Aramco Services Co, Bechtel Marine Propulsion Corp, Electric Power Research Institute (EPRI), General Electric (GE) and Thar Energy.

3.1.4 Biomass

The non-availability of biomass fuel in large quantity at a single location limits the use of large scale steam cycles or integrated gasification combined cycles to achieve higher efficiencies.

Hence most biomass plants are usually small scale plants that are based on internal combustion engines and Organic Rankine Cycles (ORCs) having low efficiencies [64]. Therefore the possibility of efficiently exploiting a solid renewable source like biomass at the point of fuel production without the need for transportation has increased the potential market of small modular closed-cycle GT [65].

3.1.5 Waste heat recovery

Global opportunity exists for low-grade waste heat recovery in industrial processes, gas turbines exhaust, diesel engines, renewables etc. S-CO_2 power cycles has been investigated and developed as a good option for recovering waste heat [66-71]. In December 2014, Echogen became the first to commercial S-CO_2 power cycle with the introduction of their 8 MW EPS100 waste heat recovery unit that uses S-CO_2 working fluid to convert waste heat into power [41].

Also receiving attention among researchers [72-74] are hybrid systems comprising of high temperature fuel cells and bottoming closed-cycle GTs. The closed-cycle GT generate extra electric power by recouping some of the thermal energy in the fuel cell exhaust gases and thereby improve the system efficiency.

3.2 Working fluids

The choice of working fluid for closed cycle GT will strongly affect the size, geometry and performance of the plant. Some working fluids usually considered for CBCs include air, nitrogen, carbon dioxide, helium and other noble gases. **Table 2** summarises the relative advantages and disadvantages of the working fluids. [75] investigation using helium-nitrogen, helium-argon and helium-xenon mixtures showed that there is drastic reduction in efficiency of the plant as the molecular weight increase but the turbo-machines and shaft length will be significantly smaller than those designed to operate with pure helium. [76] investigated the attributes and limitations of noble gases and binary mixtures as potential coolant for reactor and working fluid for the CBCs.

Early work to compare several real gases for supercritical Brayton cycles by [35] as well as [37] favoured CO_2. [77] presented the result of a comparative design study of turbo-machinery between helium and CO_2 cycles. The CO_2 cycles gas turbo-machinery volume (or weight) was estimated to be about one-fifth compared with helium cycles.

Table 2 Advantages and disadvantages of closed-cycle GT working fluids

Working fluid	Advantages	Disadvantages
Air	• Considerable design experience available • Air is abundant and inexpensive	• High pressure loss • Requires high TIT to achieve attractive efficiency • Poor heat transfer coefficient compared to helium • Likely oxidation of materials at high temperature • Limited plant capacity
Nitrogen	• Composition and properties partly similar to air, can use experience from conventional air GT	• High pressure loss • Requires high TIT • Poor heat transfer property • Likely nitriding and embrittlement of material at high temperature
Helium	• Low pressure loss • Good heat transfer coefficient • Inert and non-toxic • No Mach number restriction in turbomachinery design	• More number of turbomachinery stages • High leakage • Limited turbomachinery design experience • Requires high TIT
S-CO_2	• Good efficiency at moderate TIT • Non-toxic, relatively good thermal stability and inertness • Low leakage rate • Good critical point (7.3773 MPa, 30.978 °C) • Compact and small turbomachinery	• More corrosive than helium at high temperature • Limited design experience • Likely operation and design challenges due to rapidly varying property near the critical point • Possibility of energetic chemical reaction with sodium in sodium cooled reactor

3.3 Compact heat exchangers (CHEs)

Heat exchange devices for closed-cycle GT must have superior performance providing very close temperature approaches and reliable mechanical characteristics at high pressure and temperature to guarantee the cycle efficiency and safety. Moreover geometric constraints are also important for such application in order to limit the size of the system. (Tochon et al., 2004; Li et al., 2011). Selection of potential CHE technologies is based upon their abilities to cope with the operating condition parameters and other parameters such as fouling, nuclear irradiation, corrosion, compactness, weight, maintenance and reliability.

A survey of CHE technologies to determine their suitability is presented in Table 3. The design that meets more requirements of closed-cycle GT are the diffusion bonded Plate Fin Heat Exchanger (PFHE) and the Printed Circuit Heat Exchanger (PCHE). In spite of a more important pressure drop and other limitations, this concept is best rated compared to the other concepts in particular in terms of reliability, mechanical resistance, compactness and simultaneous operation at high pressure and high temperature. For high pressure applications, the pressure drop is not a constraint, but for low or moderate pressure applications, it will be the main barrier to the use of such heat exchangers (Li et al., 2011).

Table 3 Features of compact heat exchangers

Type	Maximum Pressure (bar)	Maximum Temperature (˚C)	Compactness (m^2/m^3)	Hydraulic diameter (mm)	Comment
Spiral heat exchanger	25	200-540	200	10-50	Temperature limit depends on gasket material. Easy to clean.
Plate heat exchanger	2-40	200-400	120-660	2 - 10	Operating limits determined by the technology (gasketed, brazed or welded). Generally restricted to low temperature and pressure application.
Brazed PFHE	80-120	200-550	800-1500	1-2	Selected for GT-MHR recuperator [78]. Operating limits depend on the materials (aluminium, stainless steel)
Diffusion bonded PFHE	620	800	700-800	1-2	Can tolerate higher pressures than other PFHE
PCHE	500-1000	900	2500	0.5-2	Selected for Sandia S-CO_2 loop [40]. No gaskets or brazing material, hence reduce risk of leakage, fluid incompatibility and temperature limitations.
Marbond	400	900	10000	<PCHE	Novel with little information on its application.
Ceramic heat exchanger	10	1300	-	-	Novel heat exchanger primarily constructed by replacing parts of existing CHEs with ceramic.

3.4 Physical layout/configuration

The arrangement of the closed-cycle GT components, usually the heat exchangers and the turbomachinery, gives the physical layout and configuration of the system. Modification of the simple cycle layout in an effort to improve the cycle efficiency can leads to cycle with recuperation, intercooling and reheating as well as other unique configurations for supercritical CO_2 cycle. Also the design choice can be classified based on the plant orientation as either vertical or horizontal layout; based on the number of rotor shaft as either single shaft or multi-shaft configuration; and based on the interconnection of the components as either integrated or distributed layout.

3.4.1 Recuperated, intercooled and reheated cycle

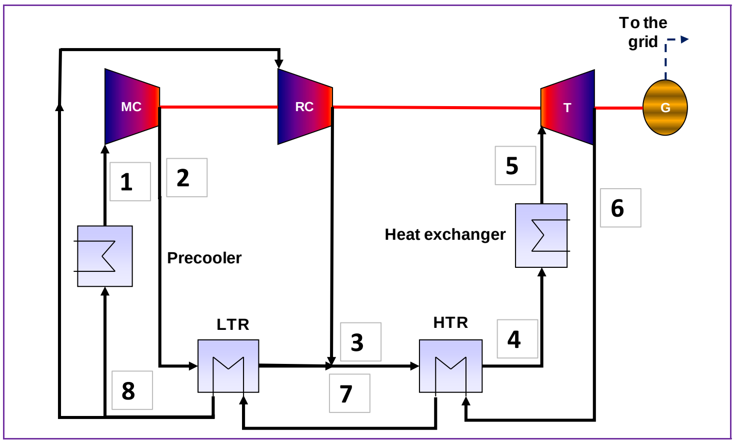
A fundamental design choice for improving the efficiency of closed-cycle GT is the addition of recuperative/regenerative heat exchanger in which heat is transferred from the turbine hot exhaust gas to the compressor discharge stream. Addition of the usually large regenerator will increase the cost of the plant. However almost all design of closed-cycle GT employs regeneration because the loss of efficiency in a non-regenerative cycle is prohibitive [79]. Alternatively, a heat recovery steam generator (HRSG) can be place in the turbine exhaust instead of the recuperator for increased utilisation of the heat input. The HRSG then produces steam for either cogeneration of heat or for a steam turbine bottoming cycle in a combined cycle arrangement.

For intercooled cycles, efficiency is improved by reducing the average temperature of heat rejection from the cycle. On the other hand, reheating increases cycle efficiency by increasing the average temperature of heat addition to the cycle. The optimal number of inter-cooling and reheating is selected by the trade-off between a merit of cycle efficiency increase and a demerit of capital cost increase [80]. Some HTGRs like the HTR-10GT and the GT-MHR include inter-cooling in their configurations while others like the GTHTR300 ruled out the use of inter-cooler despite the 2% efficiency gain because of the added complexity to the turbomachinery [81].

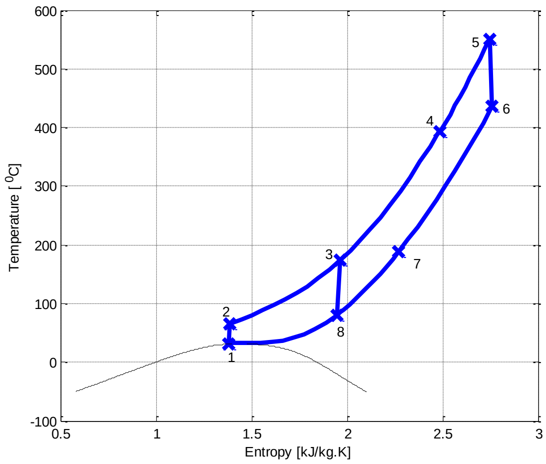
3.4.2 S-CO_2 cycle layouts

In order to take advantage of the reduced compression work around the critical point, the selection of cycle conditions for S-CO_2 is radically different compared to other fluids. For S-CO_2 cycles, the compressor inlet conditions is selected to be around the critical point (30.978 ºC, 73.773 bar) and a turbine inlet pressure (TIP) much higher than other Brayton cycle is chosen. Also, it is difficult to achieve high efficiency with the usual simple cycle and cycle with intercooling and reheating because heat transfer is not effective in the recuperators due to pinch point problem.

Therefore, several other configurations have been proposed for CO_2 power cycle in an attempts to achieve higher efficiency [4,34,35,82]. Such alternative layouts include the recompression, the precompression, the split expansion and the partial cooling layout. The recompression layout shown in **Figure *7*** seems to be the most promising. The drawback to a recompression cycle configuration is the addition of a compressor and separate recuperator, adding more complexity and capital cost to the system [56].



(a) Recompression S-CO_2 Brayton cycle layout



(b) T-S diagram

Figure 7 The recompression cycle

[83] compared the use of helium in conventional configurations and CO_2 in recompression layouts. It was found that whereas the He-Brayton cycle needs to get to rather complex layouts in order to achieve good performances, plain configurations of the recompression cycles already reach those good performances. SNL is already at demonstration phase of supercritical CO_2 closed-cycle GT for power generation. The results obtained in this project demonstrated stable and controllable operation near the critical point over a range of conditions and confirmed the performance potential of these cycle [84].

3.4.3 Horizontal versus vertical configuration

A primary reason for the choice of horizontal orientation of GT is the ease of maintenance as both ends of the plant will be accessible. Also in the event of bearing failure, the weight of the rotor is shared by two or more radial auxiliary bearings in horizontal machines. In contrast, the weight is usually concentrated on a single axial auxiliary bearing in vertical machines [85]. The auxiliary bearing must be able to withstand the initial impact and the heat generated [85]. Using horizontal bearing, the years of experience with combined cycle gas turbine (CCGT) and steam turbine system can be applied to the closed-cycle GT system [86].

One benefit of vertical system is that the turbine thrust, which poses a problem in horizontal machines, can be balanced by gravitational force. Also in horizontal system, the turbomachine shaft is bent by few millimetres because of gravitational force causing loss of efficiency. This problem is not present in vertical configuration because there is no bowing of the shaft under gravity [28]. Both PBMR and GT-MHR turbomachines adopted the vertical orientation. These machines are large in size and therefore the design of the auxiliary bearings is challenging as there is only a limited experience with vertical turbomachines [85].

3.4.4 Integrated versus distributed configuration

Design choice selected for the GT-MHR is the integral configuration in which all the components of the power conversion unit (PCU) are bundled into a single pressure vessel. This eliminates complicated ductworks, minimise pressure losses and saves cost [28]. On the down side, it is difficult to accommodate valves inside an integral vessel, and access for inspection and maintenance could be difficult [86,87]. Also, integral PCU in a conventional steel pressure vessel put a limit on the power rating due to differential and transient temperature gradient in the vessel.

In contrast, distributed (multi-module or fully-dispersed) configuration is the most common design choice for CBC [87]. In this case, the PCU components are dispersed and individual components connected by ducts. Distributed configuration requires larger volume for the ductworks than integral design because of the distances between the components [88].

3.4.5 Single shaft versus multi-shaft configuration

Decision to employ either a single shaft or a multi-shaft turbomachinery train is also a fundamental design consideration. In single shaft arrangement, the turbines, compressors and generator are mounted on a single rotor shaft. In multi-shaft, two or more independent turbomachinery-generator rotor shafts are employed. The GT-MHR and the GTHTR300 employ single shaft arrangement while the PBMR employs three shafts. Single shaft is inherently easier to control in the event of loss of load and usually have smaller footprint than multi shaft configuration [88]. Problems of single shaft include the difficulty with isolating different pressure zones and the problem associated with the dynamics of the long rotor shaft [88].

Adopting a multi shaft turbomachine provides the benefit of improved performances in the plant compared to one-shaft option [48]. For instance, the augmented shaft stiffness as a result of the smaller length of the shafts will improve the dynamic performance of the rotating shaft. Also multi shaft arrangement provides more flexibility for part-load operation and the rotational speed of the turbomachinery can be optimised independently [87,89,90]. However there are problems of control and protection of the turbomachine during loss of load [91].

[92] compared single and three-shaft closed-cycle GT configurations based on steady state and transient simulations. The cycle efficiency and specific power of the two configuration were found to be similar at full power operation. However, their transient performance differs, with the single shaft requiring ten times more power for start-up than the three-shaft configuration.

4 Important R&D programmes and experimental/pilot plants, and commercially operated plants

This section gives a brief review of some important research programmes and pilot/demonstration plants worldwide for closed-cycle GT. Also, an overview of some of the early commercially operated plants will be provided.

4.1 R&D programmes and experimental/pilot facilities worldwide

Over the years and particularly in the last two decades, R&D efforts have being growing in the USA (DOE, SNL, ANL, INL, MIT), China, Japan, Korea and Europe. This has led to the construction of some experimental/pilot plants for investigating thermal performance, component testing and to demonstrate the feasibility of closed-cycle GT. Table 4 gives some technical data of these programmes and facilities.

4.1.1 The AK-36 test plant

4.1.1.1 Participants and purpose

In 1939, Escher Wyss in Zurich, Switzerland built this first closed-cycle GT installation [20,25]. The plant was used to test the operation of closed-cycle GT and hence opened the door for the construction of commercial fossil-fired closed-cycle GT with air as working fluid in Europe.

4.1.1.2 Description of facilities

The recuperated closed cycle with air as working fluid was externally fired by light oil and the TIT was 650 °C. The plant adopted two shaft configuration with three compressors and two intercoolers. The high-pressure turbine and the compressors were on one shaft rotating at 8000 rpm while the low-pressure turbine and the generator were on the second shaft rotating at 3000 rpm. The two shaft were connected with gears to improve dynamic performance and to mitigate shaft over speed during load shedding [23]. **Figure *8*** shows a picture of the AK-36 plant.

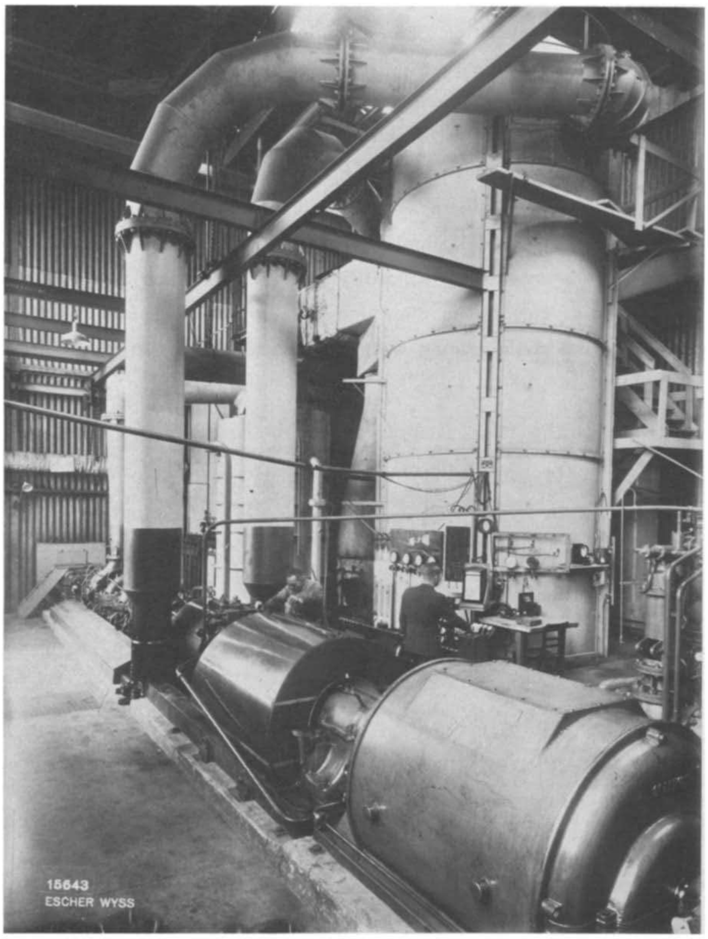


Figure 8 The Escher Wyss AK-36 test plant [20]

Table 4 Research programmes and test facilities technical information

Programme/Plant	Country	Developer	Development Phase/Status	Rating	Working fluid	Fuel/Heat source	TIT (°C)	TIP (bar)	Description	Efficiency	Reference
AK-36	Switzerland	Escher Wyss	Test plant	2 MWe	Air	Light oil	650	24	2 shaft, 2 speed connected by gears	31.6 % at 700 °C	[23]
ML-1	USA	US Army	Test plant	350 kWe	Nitrogen	Nuclear	650	-	Mobile trailer mounted	-	[23]
La Fleur	USA	La Fleur Enterprises	Test plant	2 MW	Helium	Natural gas	650	18	Closed cycle GT cryogenic process for air liquefaction	-	[23,25]
Feher Module	USA	John R. Hoffmann and Ernest G. Feher	Design	150 kWe	CO_2	Helium-cooled reactor	732	114	Indirect cycle, two-shaft PCS	-	[37]
HHV	Germany	KFA Juelich	Test facility	-	Helium	-	850	51	No external heat, compressor, turbine & motor on one shaft	-	[93]
Garrett CCGT 5000	USA	Garrett Corporation	Demonstration	9 MWe (5 MWe + 4 MWe)	Air	Petroleum coke	788	41	Combined cycle & non-recuperated closed cycle GT fired with AFBC	24%	[22,94]
SBL-30	USA	SNL/BNI	Test facility	30 kWe	N_2, Air, CO_2, He, Mixtures	Electric	-	-	Uses a modified Capstone C-30 gas-micro-turbine	-	[95]
MHTGR-IGT	China	INET	Concept design	200 MWth	Nitrogen	Helium HTGR	850	60	Indirect cycle, three compressor, two intercooler	48%	[96]
ACACIA	The Netherlands	Nuclear Research and consultancy Group (NRG)	Concept design	40 MWth	Helium	HTGR	800	22.8	Cogeneration, recuperated CBC	-	[97]
BPCU (Brayton Power Conversion Unit)	USA	NASA	Test facility	2 kWe	Helium-Xenon	Electric heater	723	-	Integrated PCS Turbine/Alternator/Compressor, recuperators, and gas cooler)	-	[98]
Sandia S-CO_2 loop	USA	SNL/BNI	Test plant	260 kWth, 780 kWth	CO_2	Electric heater	-	-	Modular & reconfigurable hardware unit	-	[84,99]
GTHTR300	Japan	JAERI	Design	600MWth	Helium	HTGR	850	70	Direct cycle, horizontal single shaft	45.8%	[100]
PBMR	South Africa	PBMR Pty (Ltd)	Conceptual design	400 MWth/165 MWe	Helium	HTGR	900	70	Direct cycle	42.7% (net)	[101]
MPBR	USA	MIT & INEEL	Concept design	250 MWth/120 MWe	Helium	HTGR	879	78	Indirect cycle, modular components, three shaft arrangement	48%	[15]
GT-MHR	USA & Russia	GA & MINATOM	Design	600MWth/286 MWe	Helium	HTGR	850	70	Intercooled and recuperated direct cycle; integrated, vertical and single shaft configuration	> 47%	[102]

GT-HTGR	USA	GA	Concept design	2000 MWth/800MWe	Helium	HTGR	850	81.6	Direct cycle with two heat transport loops, single-shaft turbomachinery	40%	[103]
BG Demonstrator	UK	British Gas	Test facility	1 MWth	Nitrogen/Oxygen mixture	Natural gas	900	-	Two turbocharger arrangement, no generator	-	[25]
HTR-10GT	China	INET	Test facility	10MWth/2.2MWe	Helium	HTGR	750	-	Intercooled & recuperated single shaft direct cycle	22%	[104]
NR IST	USA	Naval Reactors (NR), KAPL & Bettis Lab	Test facility	779kWth/100 kWe	S-CO_2	Electric heater	300	160	Simple recuperated CBC, two shaft arrangement	-	[105]
ANTARES	France	AREVA	Concept design	600 MWth	Nitrogen/Helium mixture	VHTR	950	70	Indirect cycle cogeneration combined cycle	-	[31]
JAEA S-CO_2 loop	Japan	JAEA	Test loop	30 kWth	S-CO_2	Electric heater	-	130	No electric output	-	[106]
ASTRID	France	CEA	Concept design	1500 MWth	Nitrogen	SFR	515	180	Indirect intercooled & recuperated CBC, single shaft turbomachine	37.8 %	[107]
STAR-LM	USA	ANL	Concept design	400 MWth/181 MWe	S-CO_2	LFR	560	200	Single shaft split flow recompression cycle	45%	[108]

4.1.1.3 Activities

The 2 MWe plant was operated for about 6000 hours during the Second World War for supplying electricity to the Escher Wyss factory in Zurich [20]. Initial test results confirmed the need to change the turbomachinery design. Hence all compressors stages were changed into axial type instead of the previous design with radial end stages. An efficiency of 31.6 % was recorded in test conducted at a higher TIT of 700 °C in 1944 by Prof Quiby of ETH Zurich [23].

4.1.2 Feher (supercritical CO_2) cycle test module

4.1.2.1 Participants and purpose

Ernest G. Feher patented the supercritical cycle heat engine in 1966 and later reported on a fully supercritical CO_2 power cycle [35,109]. In 1970, Hoffmann and Feher designed a 150 kWe S-CO_2 test module [37]. The purpose was to investigate the possibility of using S-CO_2 cycle for advance ground nuclear reactors for the US Army.

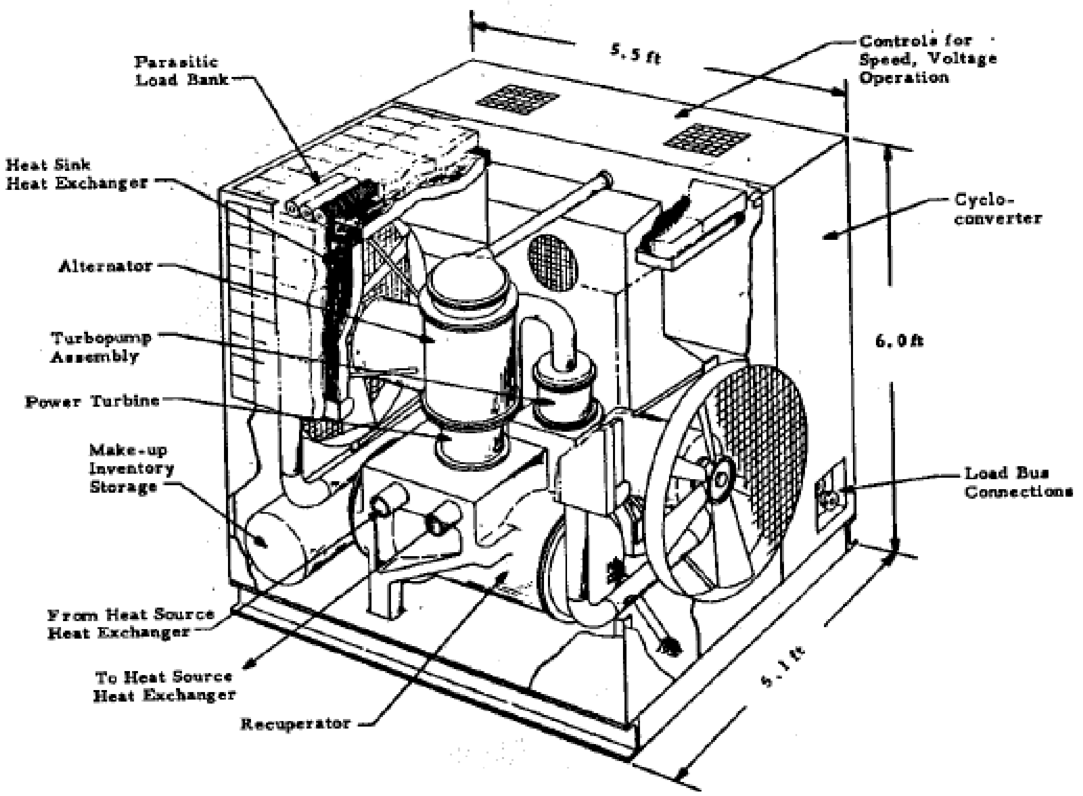


Figure 9 Sketch of the Feher 150 kWe S-CO_2 power cycle [37]

4.1.2.2 Description

A helium HTGR with core outlet of 760 °C and 350 bar was proposed as the heat source for the cycle. In order to independently optimise the rotational speed of the pump and turbine, a two-shaft arrangement was adopted. The generator shaft rotational speed was optimised as 40,000 rpm. CO_2 was chosen as the working fluid due to its many favourable properties. The working fluid in this recuperative cycle was maintained above the critical pressure throughout the cycle but temperature in the compression process was below the critical temperature. Hence cooling the CO_2 to liquid phase will require a year-round supply of cold water between 10 – 15 °C which might be difficult to obtain [4]. The schematic of the module is shown in Figure 9.

4.1.2.3 Activities

The cycle components such as pump, turbine and recuperators were designed. The pump, the turbine driving the pump and the power turbine were designed with efficiency of 75%, 88% and 85% respectively. Also, the start-up and control strategies for the plant were suggested. Parasitic load bank was suggested for part-load operation instead of turbine bypass valve control because of demanding requirements on bypass valve.

4.1.3 HHV

4.1.3.1 Participants and purpose

The HHV helium test system was built in 1981 at Research Centre Juelich (KFA) in Germany as part of the HHT project in an international cooperation between Germany, Switzerland and the United States [93].

The purpose of the HHV test rig was to carry out a 1:1 scale test of helium turbomachinery, pipes, heat exchangers and valves at extreme temperatures similar to HTGR-coupled closed-cycle GT plant [23].

4.1.3.2 Description of facility

The turbine, compressor and electric motor are on a single shaft rotating at 3000rpm (Figure 10). Helium is circulated around the system by the turbomachinery at about 200 kg/s. The 90 MW compressor power is jointly supplied by the electric motor (45 MW) and the turbine. The compression process was able to raise the temperature of the helium gas up to 850 °C and hence no external heater was employed. The hot gas leaving the compressor then passed through a test bed section after which it is cooled to about 829 °C and expanded in the turbine.

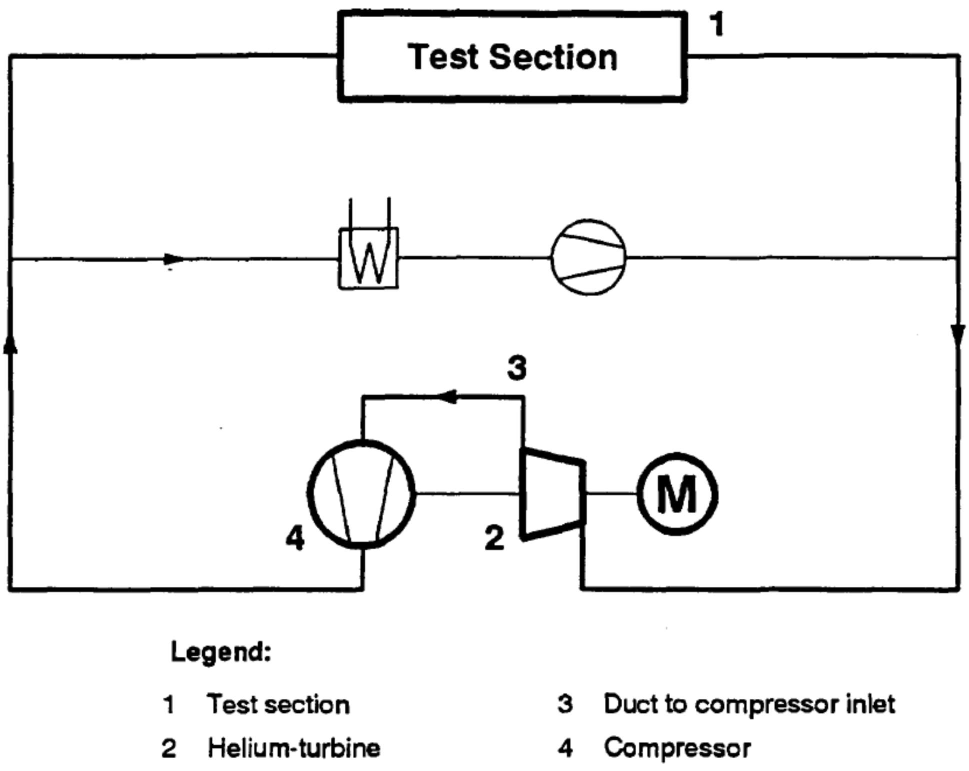


Figure 10 Schematic of HHV test circuit [93]

4.1.3.3 Activities

Initial issues encountered during commissioning are oil ingress into the helium circuit and leakage of helium at the operating temperature of 850 °C. These problems were resolved by redesigning the labyrinth seal, and the buffer and helium cooling system [25]. The facility was operated for about 1100 hour and test results indicated that the turbomachinery have better efficiency than the design value. Important test data were obtained for validation of blade performance, rotor cooling, seal system, controls and rotor dynamic stability [110]. In late 1981, the HHT project was stopped and the test facility was shutdown.

4.1.4 GT-MHR

4.1.4.1 Participants and purpose

In 1995, GA (USA) and MINNATOM (Russia) jointly signed an agreement to develop and design the GT-MHR [102]. The facility is to be constructed in Russia at the Siberian Chemical Combine in Seversk. FRAMATONE (France) and Fuji Electric (Japan) later joined the project in 1997 [49].

The goal of the programme was to construct a facility for the destruction of Russian weapons-grade plutonium and use the heat generated to produce electricity in a direct cycle gas turbine and with the future prospect of serving as commercial nuclear plant burning uranium fuel.

4.1.4.2 Description

The GT-MHR consist of a 600 MWth helium-cooled reactor with a core outlet temperature of 860 °C directly coupled to a closed-cycle gas turbine PCS (Figure 11). The reactor and the PCS are enclosed in two separate vertical steel vessels connected with a horizontal vessel. The PCS has a single-shaft turbomachine that is oriented vertically and supported by electromagnetic and protective bearings. The generator, turbine, and two compressors are connected to the turbomachine shaft rotating at 3000 rpm. Also included in the surrounding annulus of the PCS vessel are the recuperators, intercooler and precooler. The whole facility is contained in an enclosure with an internal pressure of 30 – 40 bar [102].

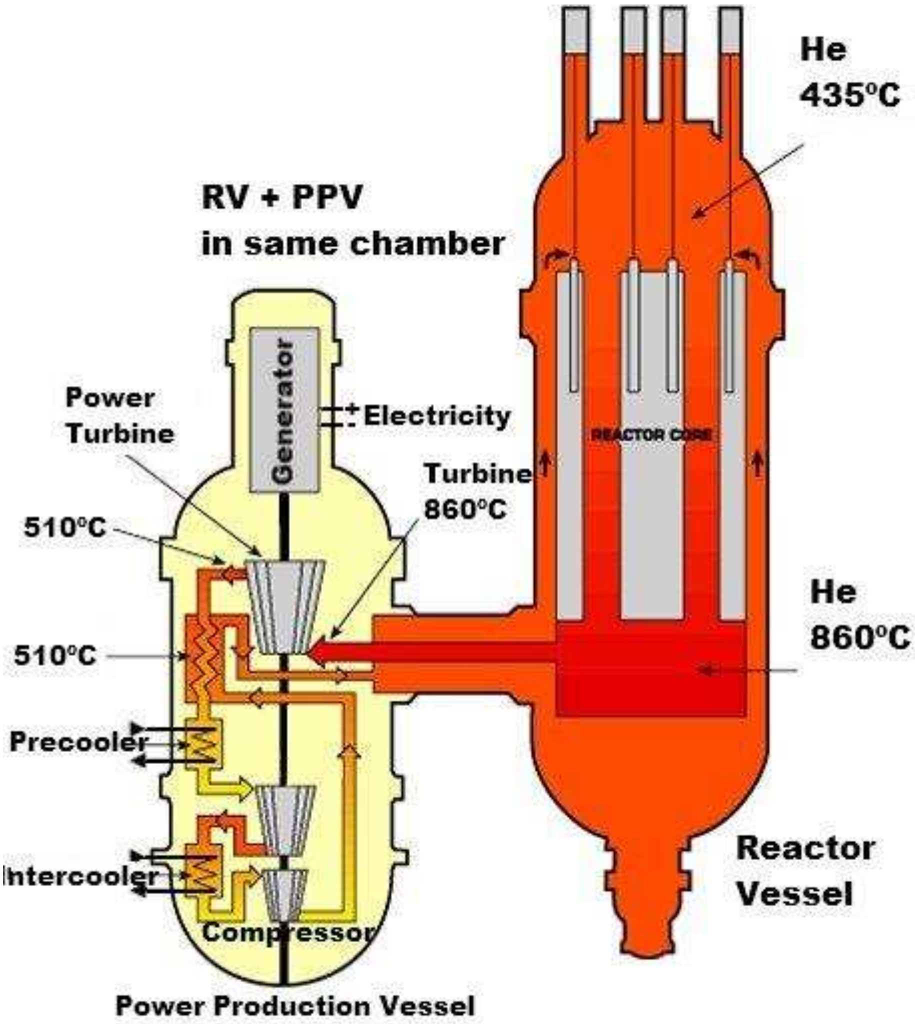


Figure 11 GT-MHR layout [111]

4.1.4.3 Activities

The conceptual design and the preliminary design of the plant were completed in 1997 and 2001 respectively [96,112]. The fuel technology (coated particle) were proven in various tests. Important activities included the fabrication of fuel kernels from weapon-grade plutonium. Development efforts were also directed at a full-scale facility for production of plutonium fuel at Siberian Chemical Combine [102]. Design work and calculation were carried out for the core, the compact heat exchangers and the turbomachinery.

Development challenges are vibration of the shaft, the requirement of large bearings, and the wide variations in pressure and temperature [24]. Beyond the preliminary design, the construction of the prototype plant in Russia did not materialise. In 2010, GA started the development of the Energy Multiplier Module (EM^2), a 500 MWt fast neutron reactor coupled to a gas turbine cycle [112]. This is a modified version of the GT-MHR.

4.1.5 PBMR

4.1.5.1 Participants and purpose

PBMR Pty (Ltd), a subsidiary of the South African power utility company, ESKOM started the design and construction of a prototype closed cycle helium GT plant using a Pebble Bed Modular Reactor (PBMR) as heat source [101]. Between 1999 and 2009, about US$ 1.3 billion was invested in the project by the South African government, ESKOM, Westinghouse, and the Industrial Development Corporation of South Africa. Local and international companies that participated in the project included Mitsubishi Heavy Industries of Japan (turbomachinery), Nukem of Germany (fuel technology), SGL of Germany (graphite), Heatric of UK (recuperator), IST Nuclear of South Africa (nuclear auxiliary system), Westinghouse of USA (instrumentation), ENSA of Spain (pressure boundary) and Sargent & Lundy of USA (Architect/Engineer services).

The purpose of the PBMR project is to build a commercial reference plant capable of meeting the requirements set for commercialisation such as being located at the centre of load growth in South Africa, capital and operation cost being within cost achieved by large coal-fired plants, reduced CO_2 emission, etc. [49].

4.1.5.2 Description

The PBMR is a direct cycle helium Brayton cycle with a core outlet temperature of 900 °C. The design was changed many times. The initial design consist of three rotating shaft – the LP turbo-compressor, the HP turbo-compressor and the power turbine-generator shaft (Figure 12). Other components include the recuperators, intercooler and a precooler. All the rotors were oriented vertically, housed in separate vessels and sustained on magnetic bearings due to the cold welding nature of helium preventing the use of mechanical bearing. The power turbine-generator shaft rotates at 3000 rpm synchronous speed while the LP turbo-compressor rotates at 15,000 rpm and the HP turbo-compressor at 18,000 rpm. The helium inventory tank will permit power control from 20 to 100% of full load. Below 20%, reactor bypass valve control are used [113].

In later designs, reactor thermal power was scaled up to 400 MWth and the configuration was changed to a single shaft horizontal arrangement. The shaft then rotates at 6000 rpm and a gear was used to reduce the speed to 3000 rpm for the generator [24].

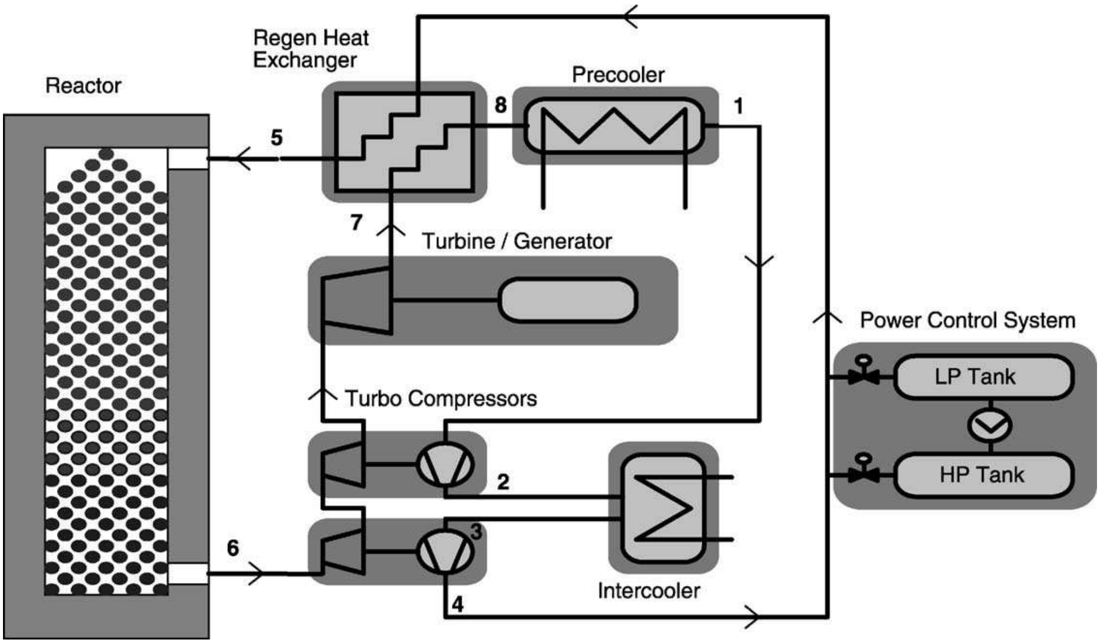


Figure 12 Simplified diagram of the PBMR Brayton cycle system [101]

4.1.5.3 Activities

Conceptual design of the plant was carried out and computational simulations were used to predict the performance of the GT plants [113-115]. Several experimental test were also conducted to support the design [116,117].

Challenges include limited experience with helium gas turbomachinery experience, rise in fuel temperature, economic competitiveness, development costs and funding, and the lack of customer to place order [118]. In 2009, the PCS was changed to an indirect Rankine steam cycle with cogeneration due to its less technical challenges. The project was terminated in 2010 due to financial difficulty.

4.1.6 GTHTR300

4.1.6.1 Participants and purpose

In 2001, the Gas Turbine High Temperature Reactor 300 (GTHTR300) programme was proposed by the JAERI to design and carried out R&D on a closed-cycle helium GT system [29,100,119].

The objective of the GTHTR300 is to establish the feasibility of a simple design that will significantly lower the technical requirement and cost for near-term deployment with a demonstration plant in the 2010s and commercial plant in the 2020s [96,100,119].

4.1.6.2 Description

The plant is designed with a reactor power of 600 MWth at 850 °C core outlet temperature and electrical output of 275 MWe. The key features of GTHTR300 are (Figure 13): inherently safe modular reactor design, non-intercooled Brayton cycle, horizontal single-shaft turbomachine with compressor, turbine and generator on magnetic bearings, and three separate steel vessels (reactor pressure vessel, power conversion vessel and heat exchanger vessel) connected by coaxial double pipes. The turbomachine shaft rotates at 3600 rpm. The disadvantage of this configuration is the need for a large building for the horizontal PCS [24].

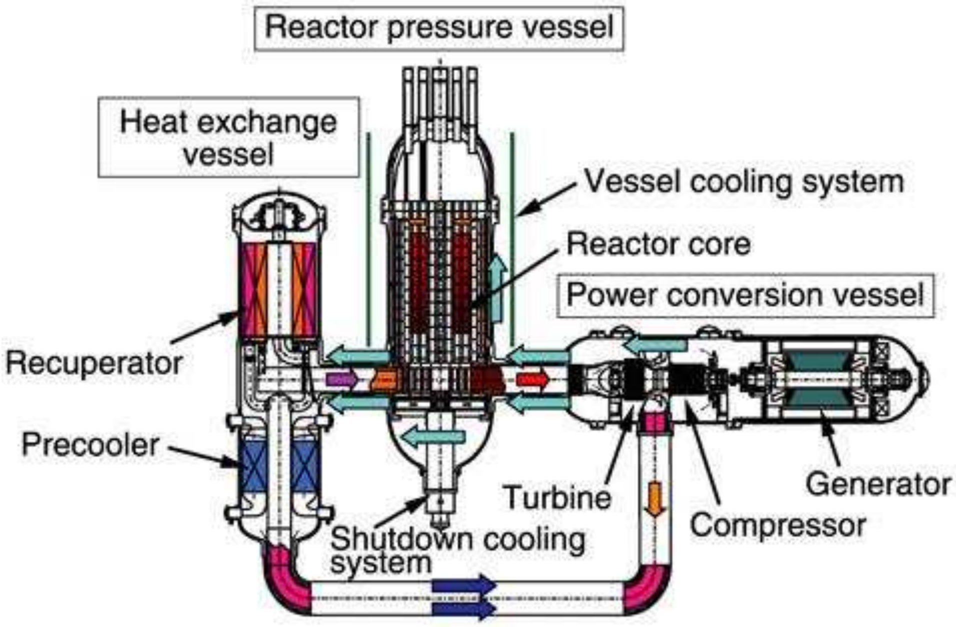


Figure 13 Layout of GTHTR300 (Courtesy of JAERI)

4.1.6.3 Activities

R&D activities include design of the helium turbomachinery, 1/3-scale model tests, aerodynamics performance test, magnetic bearing development test, and closed-cycle GT operation and control test [120-122].

Although several R&D work has been done, the prototype demonstration plant is yet to be constructed.

4.1.7 JAEA S-CO_2 cycle test loop

4.1.7.1 Participants and purpose

The test loop was fabricated by JAEA (Japan Atomic Energy Agency) and its aims are to determine the performance of CO_2 compressor near the critical point, to confirm the thermal-hydraulic performance of PCHE recuperator and to determine the operational stability of S-CO_2 cycle coupled to sodium-cooled fast reactor (SFR) [106].

4.1.7.2 Description of facilities

A view of the S-CO_2 test loop is shown in Figure 14. The test loop consists of three compressors (LP, HP and bypass compressor), two PCHE recuperators, an expansion valve to simulate turbine, a 30 kWt electrical heater to represent sodium/CO_2 heat exchanger, a precooler, a cooler and an intercooler.

The electrical heater heats the CO_2 to 300 °C and the thermal power is only about 1/20000 of the actual IHX power. Reciprocating CO_2 compressors were employed because the CO_2 flow rate (about 200-400 kg/hr) is too low for centrifugal or axial compressor. The cooler is located before the expander because the expander cannot be used at temperature above room condition. The precooler and intercooler are used to condition the CO_2 temperature to the supercritical condition [106,123,124].

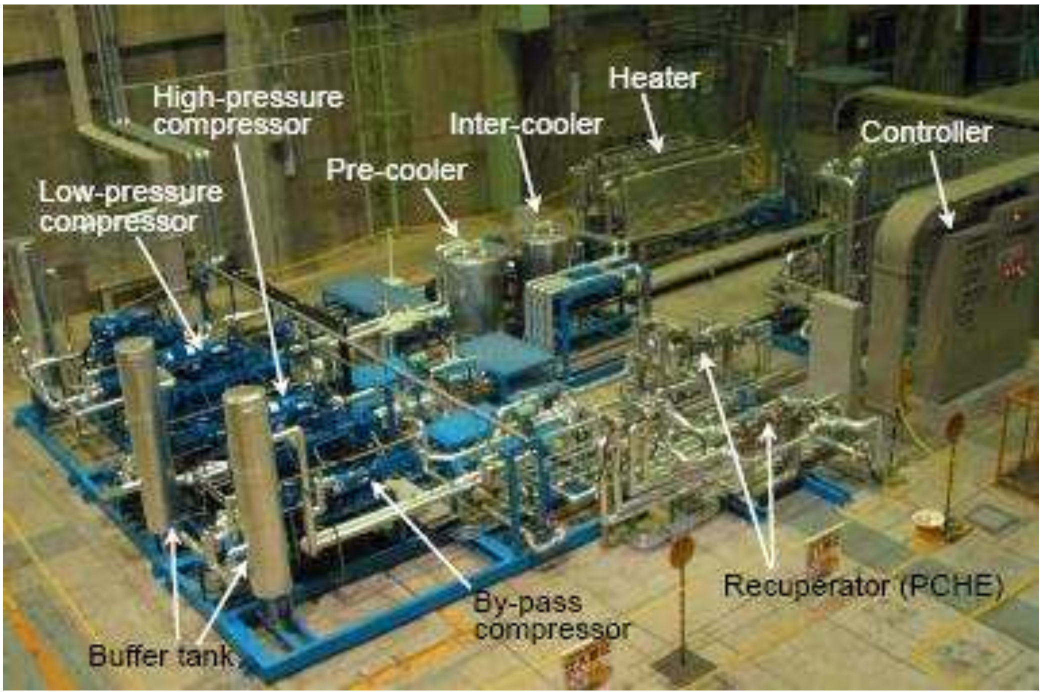


Figure 14 JAEA S-CO_2 cycle test loop [106]

4.1.7.3 Activities

Compressor efficiency tests were carried out with test data obtained at different conditions both further from the critical point and around the critical region. Test results confirmed that compressor efficiency increased significantly around the supercritical region. Recuperator thermal-hydraulic tests were conducted with two types of PCHE, one with zigzag fin and another with the new S-fin type. Thermal-hydraulic properties of the different fin is evaluated by means of CFD analysis. The two recuperator types showed similar thermal performance but the S-fin type is better in term of pressure drop which is about 1/6 of the zigzag type. Finally both transient and steady state operation stability tests were performed by changing the compressor condition from subcritical to supercritical and then maintained at steady state afterward. Test results showed no instability during the transient and steady state operations [106,123,124].

A full-scale test to simulate an actual cycle was suggested for a more precise investigation of S-CO_2 cycle [106].

4.1.8 Sandia S-CO_2 Brayton cycle loops

4.1.8.1 Participants and purpose

SNL constructed the S-CO_2 cycle loops with funding from the US DOE's Office of Nuclear Energy and the Laboratory Directed Research & Development (LDRD) programme [84]. Barber-Nichols Incorporated (BNI) was contracted to design, manufacture and assemble the loops. Modification of the initial compression loop to a heated un-recuperated Brayton loop was contracted by Knolls Atomic Power Laboratories (KAPL).

The purpose of the programme is to investigate S-CO_2 Brayton cycle that could be used with nuclear (and solar, fossil or geothermal) heat source by constructing small scale S-CO_2 Brayton cycle loops. The loops are for studying the important issue of operation and control near the critical point and to obtain test data for validating S-CO_2 cycle models and turbomachinery design tools [84].

4.1.8.2 Description of facilities

SNL fabricated two S-CO_2 cycle loops:

- An S-CO_2 compression loop with a centrifugal compressor driven by a 50 kWe motor/alternator at 75,000 rpm with a flow rate of 3.51 kg/s was constructed in 2008 [84]. This loop uses ball bearings and has no heat source and no turbine but uses orifice valve for reducing pressure instead. In 2009, the loop was modified to a heated but un-recuperated Brayton loop and the turbomachine reconfigured as a turbo-alternator-compressor unit with addition of gas-foil bearings. The CO_2 is heated by two Watlow electric heaters supplying 130 kW each. The turbine was included to assist the motor in supplying part of the compression power. However net output power can be produced if the TIT is sufficiently high [84].
- A power producing S-CO_2 split flow recompression CBC test assembly (Figure 15) started test operation at BNI site in Arvada, Colorado in 2010 with potential of generating up to 250 kWe [40,99]. The facility was later relocated to SNL in 2012 [99]. The loop uses gas-foil bearing, permanent magnet motor/generator and Heatric's PCHEs. The heaters supplied about 780 kW to the cycle at 538 °C [40].

Figure 15 S-CO_2 split flow recompression CBC test assembly at SNL (Courtesy of SNL)

4.1.8.3 Activities

The S-CO_2 compression loop was operated in the liquid region, vapour region and in the saturation curve, all around the critical point with over 80 tests. Tests included measuring leakage flow rates, windage losses, compressor performance and balancing thrust loads [84]. Also investigated are bearing type and sealing technologies. The loop was modelled with the SNL's RPCSIM (Reactor Power and Control SIMulation) Simulink code. Test data agrees with the design and model performance predictions. Results also showed stable and controllable operation in the region of the critical point [84].

The next phase is the development of a large industrial demonstration S-CO_2 GT plant capable of generating more than 10 MWe [84].

4.1.9 HTR-10GT

4.1.9.1 Participants and purpose

In China, INET of Tsinghua University started the construction of a 10 MWth pebble-bed high temperature reactor (HTR-10) test facility in 1995 under the China High Technology Programme. The reactor reached criticality in 2000 and full power was achieved in 2003[104]. In the second phase of the programme, the HTR-10GT project was started in 2002 to test the coupling of CBC to the HTR-10. In 2000, OKBM of Russia signed agreement with INET for the conceptual design of the GT power conversion system.

The purpose of the HTR-10GT project is to carry out R&D on HTR-coupled gas turbine power generation system and demonstrate the feasibility [125].

4.1.9.2 Description

The components of the direct closed-cycle GT system include the HTR-10 heat source, LP and HP compressors, turbine, recuperator, intercooler and precooler (Figure 16). The single shaft turbomachine rotor is supported by Active Magnetic Bearing (AMB) [30]. The reactor core outlet temperature is about 750 °C and the thermal effciency is about 22%.

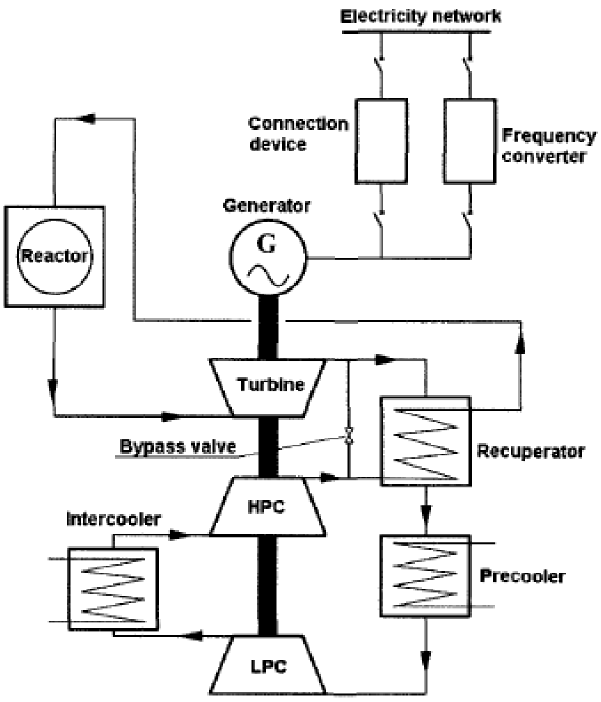


Figure 16 Schematic of HTR-10GT [30]

4.1.9.3 Activities

Safety demonstration tests of the HTR-10 reactor were completed. Studies were made on the design of the turbomachinery and heat exchangers and the conceptual design of the PCS by OKBM and INET was completed in 2002 [104,125]. Different test rigs were established to test the turbocompressor and the AMB [30,126,127]. The HTR-10GT project is still ongoing.

4.1.10 ANTARES

4.1.10.1 Participants and purpose

In France, Framatone ANP, a company jointly owned by AREVA and Siemens, developed the ANTARES concept for the production of hydrogen and generation of electricity.

The aim of the ANTARES programme is to create a commercially competitive advanced HTR to meet the future industrial requirement for carbon free electricity generation and fossil free process heat supply.

4.1.10.2 Description

The VHTR ANTARES plant employed an indirect cycle and distributed layout. It is design for cogeneration of high temperature process heat (for hydrogen production) and high efficiency electricity generation with combined cycle components (Figure 17). The reactor thermal power is 600 MWth and helium is circulated in the primary circuit at 1000 °C reactor outlet temperature [31]. Heat is transferred to the PCS through the IHX. The topping closed-cycle GT uses mixture of helium and nitrogen as working fluid to obtain fluid property similar to air for derivative GT design technology. The plant efficiency is improved with a bottoming steam turbine cycle facilitated with steam generator. The gas turbine turbomachine, the steam turbine and the generator rotate on a single shaft.

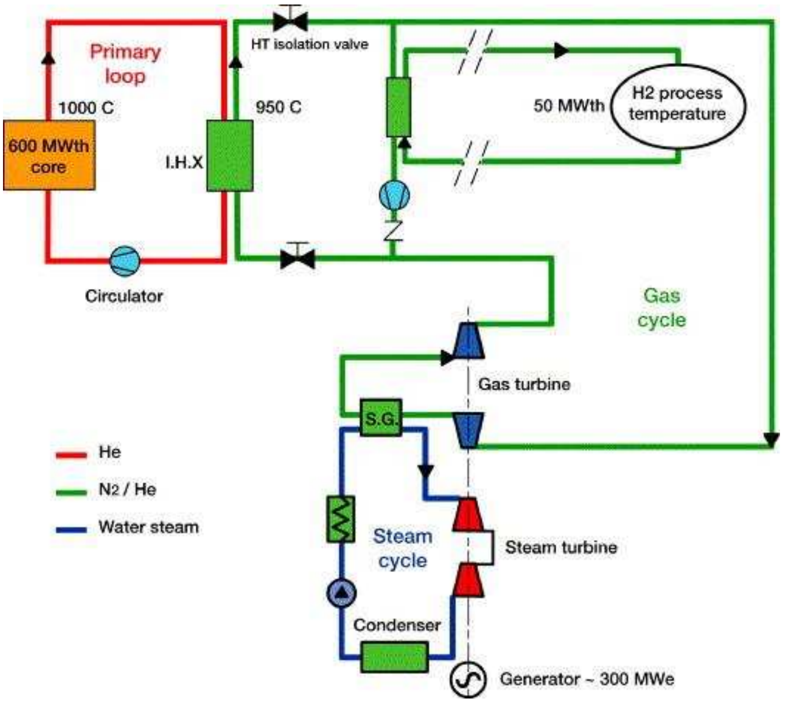


Figure 17 Schematic of the V/HTR ANTARES plant [31]

4.1.10.3 Activities

Manufacturing feasibility for the large components was established and in 2006 the conceptual design phase was completed [128].

4.1.11 BG demonstration plant

4.1.11.1 Participants and purpose

In the UK, British Gas (BG) developed a closed-cycle GT demonstration facility at Coleshill near Birmingham in 1995 [25]. The aim of the facility was to serve as test plant for larger closed-cycle GT power plant using helium as working fluid and higher TIT [11,25].

4.1.11.2 Description of facilities

The facility used mixture of nitrogen and 2% oxygen as working fluid. The cycle is fired with natural gas through advanced gas-fired heater rated at about 1 MWth. The advanced gas-fired heat exchanger is a major feature of the facility has it can raise the working fluid temperature to about 1000 °C, which is much higher than the temperature of previously operated fossil-fired closed-cycle GT plants [25].

4.1.11.3 Activities

The construction of the facility was completed (Figure 18). However demonstration activities could not progress beyond initial development phase as a result of changes in the company [25].

Figure 18 BG demonstration facility [25]

4.2 Commercially operated closed-cycle GT plants

Some fossil-fired closed-cycle GT plants were built and operated mostly in Europe in the 50s, 60s and 70s. A comprehensive description of these plants is given by [20,23,25]. A few of them is highlighted as follows:

- **Coventry plant:** As a result of encouraging test results from AK-36 installation, a 700 kWe closed-cycle GT was built in Coventry, UK in 1949. It used waste heat as heat source and air as working fluid. With about 25% efficiency, the power output doubles those obtained from conventional steam turbine plants of that era.
- **Paris plant:** In 1952, EDF (Electricite de France) contracted Escher Wyss to build the 12 MWe plant at St. Denis in Paris. The air working fluid is heated to about 660 °C by burning light or heavy oil. The plant adopted a rather complex layout with two shafts, four compressors, three intercoolers, and two turbines as well as the precooler, recuperator, intermediate gas heater and the primary side flue gas circulating equipment. However, stable and reliable operation was attained. The plant was replaced by a 250 MWe steam turbine plant after operating for about 7000 hours.
- **Toyotomi plant:** Fuji Electric under the license of Escher Wyss built a natural gas fired air closed-cycle GT plant at Toyotomi, Japan for the Hokkaido electricity company in 1957. It produced 2 MWe of electricity with a TIT of 660 °C and 26% efficiency. After operating successfully for about 125,000 hour, the plant was shut down due to non-availability of fuel [23].
- **Oberhausen I:** The cogeneration plant was built for the municipal works of Oberhausen, Germany in 1960 by GHH Sterkrade AG under the license of Escher Wyss. It was fired by bituminous coal and uses air as working fluid. The plant was operated for more than 100,000 hour with about 14 MWe electrical power output and 28 MWth district heating. It was later modified for coke oven gas firing in 1971 and stopped operation in 1982. Technical challenges included failures of compressor rotor and stator blades due to corrosion and vibration.
- **Kashira plant:** Escher Wyss of Zurich was contracted by the Institute of Thermal Engineering, Technical University of Moscow in 1961 to build a 12 MWe closed-

cycle GT at Kashira. The plant burned coal to generate electricity and produce heat energy for district heating with a TIT of 680 °C and 28% efficiency. Difficulties included un-solidified ash resulting in excessive slag formation and the high content of pyrite in the coal causing the plates of the coal crusher to wear out fast.

- **Gelsenkirchen plant:** Starting from 1967, the Gelsenkirchen plant was successfully operated for nearly 100,000 hour generating 17 MWe of electricity plus heat energy for district heating. The plant used blast furnace gas and light oil as fuel. It stopped operation due to a crack in the blast furnace. This was the last closed-cycle GT with air as working fluid to be commercially operated. It became obvious during this time that the fossil-fired closed-cycle GT could no longer compete with open cycle GT [25].
- **Oberhausen II:** In 1974, the second closed-cycle GT plant at Oberhausen was built for commercial production of electricity (50 MWe) and district heating (53.5 MWth). It also serve as a demonstration plant for the HHT nuclear project providing information on dynamic behaviour and integrity of components. It used helium as working fluid and was fired with coke oven gas. The plant was only able to produce 30 MWe instead of the rated 50 MWe due to poor turbomachinery design and excessive pressure losses [23]. Operation was terminated in 1988 due to non-availability of fuel. Problems encountered are axial movement of rotor leading to labyrinth seals damage, blade failure and vibrations causing bearing damage.

Other constructed fossil-fired closed-cycle GT reported in literature are: Clydebank test facilities, UK (1950 & 1951); Dundee plant, UK (1954); TUCO 52, Switzerland (1955); Ravensburg, Germany (1956); Altnabreac, UK (1959); Rothes, UK (1960); Coburg, Germany (1961); Nippon Kokan, Japan (1961); Haus Aden, Germany (1963); Phoenix helium turbine for nitrogen liquefaction, USA (1966) and Vienna, Austria (1972).

5 Summary of modelling and simulation studies, operation and control strategies

The steady state thermodynamic performance, dynamics and control of closed-cycle GT have been studied by a number of researchers through modelling and simulation. This section will provide an overview of literatures on steady state thermodynamic analysis and dynamic modelling as well as suggested operation and control schemes for closed-cycle GT. The section will also provide a highlight of modelling/simulation tools employed for closed-cycle GT.

5.1 Steady state thermodynamic performance studies

Various closed-cycle GT heat sources, working fluids and layouts have been studied in literature in order to determine their thermodynamic performances.

5.1.1 Performance comparison with conventional plants

[74] compared the performance of molten carbonate fuel cell (MCFC) hybrid system using S-CO_2 closed-cycle GT to a reference hybrid system using air in open cycle configuration. Results indicated that the MCFC-SCO_2 hybrid system yielded about 10% efficiency increase with respect to the reference system as a result of improved performance specifications of S-CO_2 components (turbine, compressor and heat exchanger). Technical-economic analysis of coal-fired S-CO_2 Brayton cycle with carbon capture by [46] showed promising results with net plant efficiency of 41.3% as well as reduction in levelized cost of electricity and reduction in cost of avoided CO_2 compared to superheated steam power cycle with carbon capture. Modelling results of biomass to PCSs based on cascaded S-CO_2 cycle showed a 10% efficiency increase above the convention biomass plant PCS based on Organic Rankine Cycles (ORC) or reciprocating internal combustion engines [64].

[80] examined steam Rankine cycle, helium and S-CO_2 closed-cycle GT for nuclear fusion reactor and recommended the S-CO_2 cycle based on its reasonable efficiency, reduced volume and the ease of permeated tritium separation. The coupling to small modular Light Water Reactor (LWR) to S-CO_2 Brayton cycle was investigated by [129]. Preliminary results showed comparable efficiency to the conventional steam cycle and potential for further reduction of capital cost of SMR plant due to the small size of S-CO_2 cycle components.

In [59], S-CO_2 cycles were investigated for concentrated solar power (CSP) plants as alternative to the conventional steam cycle. Performance results showed that S-CO_2 cycle has the potential to compete with the steam cycles based on efficiency and cost. Similarly, Sasol Technology of South Africa benchmarked three S-CO2 cycles layouts and a supercritical steam cycle against a superheated steam cycle for CSP plants with molten salt storage system [130]. In this instance, results showed that S-CO_2 cycles cannot compete with the current steam cycle technology in term of efficiency and cost. The conflict between the conclusions of the two studies can be attributed to the differences in assumed TITs, gear box and generator/motor efficiencies, and costs associated with material selection.

5.1.2 Studies based on working fluids

[131] analysed the performance of helium and its binary mixtures of helium-xenon and helium-nitrogen for VHTR plants with closed-cycle GT. It was found that while the cycle with pure helium has the highest efficiency, the cycles using the binary mixtures as working fluid have significantly fewer number of turbomachinery stages and hence shorter length of the rotating shaft. [57] studied He, N_2 and air Brayton cycles for a HTGR and results indicated comparable efficiencies for the gases and the He turbomachinery has more stages than those of N_2 and air while He and N_2 have shorter blade length than air.

For power generation in space, [132] analysed Ar, He, Xe, Ar-Xe, He-Xe, N_2 and H_2 closed-cycle GT and found that the diatomic gases (N_2 and H_2) gave higher efficiencies than the monoatomic gases. [10] compared the performance of closed-cycle GT using He, combustion gases, air and CO_2 as working fluid for heat recovery. Different helium and S-CO_2 cycle layouts for fusion reactors involving intercooling, recuperation, combined cycle and dual cycle with ORC and steam Rankine cycle were studied by [83]. Results indicated that higher efficiency can be obtained with helium, albeit with complex cycle layouts. However, S-CO_2 cycle achieved the improved performance with less complex layouts.

5.1.3 Studies based on cycle configuration

[81] investigated helium direct Brayton cycle with single and three-shaft configurations with emphasis on the effects of intercooling and reheating using the parameters and conditions of PBMR reactor. Thermodynamic and economic assessment indicated that intercooling produces substantial improvement in efficiency, reheating produces no remarkable improvement in performance other than allowing flexibility of operation and use of multi-shaft configuration tends to increase cost of plant without any efficiency improvement.

Dostal thesis at MIT provided a detailed steady state analysis of S-CO_2 cycles for next generation nuclear reactors based on thermodynamic performance and cost [2]. The study settled on the recompression S-CO_2 cycle layout as the preferred option for reactor core outlet temperature above 500 °C because of its simplicity, compactness, cost and thermal efficiency. [133] performed exergetic analysis of S-CO_2 recompression cycle and found the exergetic efficiency more sensitive to the isentropic efficiency of turbine and the effectiveness of the high temperature recuperator (HTR) than compressor efficiency and low temperature recuperator (LTR) effectiveness respectively.

5.2 Dynamic modelling and simulation studies

Closed-cycle GT plants are expected to experience transient/dynamic conditions like start-up, shutdown and load changes more frequently than base-load plants. Therefore, accurate prediction of the dynamic characteristics of the plant through modelling and simulation is required for stable operation, fault diagnosis and control system design. Hence, following the efforts to develop closed-cycle GT is the numerical modelling of its dynamic behaviour under various operating and accident conditions.

5.2.1 Modelling studies and computer codes for research programmes

Dynamic models of closed-cycle GT developed at the Institute for Turbomachinery, University of Hannover were validated with measured data from the Oberhausen I plant [134,135]. The Swiss Federal Institute for Reactor Research in collaboration with Brown Boveri-Sulzer Turbomachinery Ltd (BST) developed the TUGSIM-10 computer code for transient analysis of a large nuclear closed-cycle GT cycle and the code was validated with measurement data from a 30 MWe fossil-fired closed-cycle GT using air as working fluid [136]. In 1980, GA developed a FORTRAN transient analysis computer code, called REALY2, for the dynamic and control modelling of the GT-HTGR plant [137]. The REALY2 model was used for design of control and instrumentation, plant configuration studies, performance selection and design of plant components. The GTSim transient simulation program was developed by [9] to investigate the dynamic characteristics and for control system design for an advanced nuclear GT plant.

Dynamic simulation studies were also performed for most of the recent closed-cycle GT programmes. [138] used Panthermix (for reactor core) and RELAP5 (for PCS) code to model the ACACIA pebble bed HTR coupled directly to helium closed-cycle cogeneration plant and analysed transients related to Loss of Coolant Incident (LOCI) and Loss of Flow Incident (LOFI). The transient simulation indicated that a LOCI or LOFI was not the worse-case scenario for the maximum reactor temperature. Different control options and the effect of design choices on dynamic behaviour of the ACACIA plant was investigated with Aspen Custom Modeller (ACM) by [97]. Later, [139] compared RELAP5 and ACM modelling of load rejection and part-load transients of the ACACIA plant. Also RELAP5-3D was used for analysis of CBC coupled with gas-cooled reactor for spacecraft propulsion [140], and transient simulation of lead-cooled reactor coupled to S-CO_2 cycle [141] and fusion reactor coupled to S-CO_2 cycle [142]. At ANL, Vilim developed the Gas Plant Analyser and System Simulator for Hydrogen production (GAS-PASS/H) for dynamic modelling of gas cooled reactor cycles [143]. The code was later modified for modelling of S-CO_2 recompression cycle by Carstens at MIT [89].

Flownex network simulation code was developed as the primary simulation software for the South African PBMR project [144]. The code can be linked with Simulink for control system design [89]. Closed Cycle System Simulation (CCSS) code for transient simulation of CBC was validated with experimental data from the NASA BPCU [98]. CATHARE2 code [145], developed by CEA (French Atomic Energy Commission), EDF (Electricité de France), IRSN (Radio-protection and Nuclear Safety Institute) and AREVA-NP originally for French PWR, was adapted by researcher at CEA for transient analysis of the CEA Gas Fast Reactor (GFR) coupled to closed-cycle GT [146,147]. The code was validated for CBC with data from Oberhausen I and II plants [148]. TRACE, a code developed by the United States Nuclear Regulatory Commission (NRC), was modified and used for transient analysis and control system design of the S-CO_2 Brayton cycle IST facility at Bettis Atomic Power Laboratory [149,150]. Aimed at HTR-10GT project, INET at Tsinghua University developed HTR-GTsim transient analysis software [151]. More test data are needed to verify the accuracy of the code but good agreement exist between the code and simulation results from THERMIX code.

At ANL, the Plant Dynamics Code (PDC) was created specifically for transient analysis of S-CO_2 recompression cycle and the coupled reactors [152]. Previously, the code has been employed to investigate behaviour of S-CO_2 cycle coupled to Lead-cooled Fast Reactor (LFR) like SSTAR (Small Secure Transportable Autonomous Reactor) and STAR-LM (Secure Transportable Autonomous Reactor with Liquid Metal coolant) developed at ANL, and SFR like the ABR-1000 and the French ASTRID plant [108,153,154]. The PDC code is currently been validated with experimental data from the SNL S-CO_2 loop [155,156].

5.2.2 Non project specific modelling studies and codes

Modelling tools mentioned above are mostly developed for specific projects and applications. Modelling studies of closed-cycle GT with commonly available software have been reported in literature as well. [157] used SIMULINK to perform dynamic modelling and control of space reactor coupled to CBC. MATLAB model and simulation of transient behaviour of HTGR helium turbine plant was presented by [158]. Studies of dynamic behaviour and control of geothermal S-CO_2 Brayton cycle during startup, heat addition, changes in cooling medium temperature and mass flow, and changes in loop mass was implemented in DYMOLA simulation environment by [159]. Modelica non-proprietary modelling language was employed by [63] for dynamic modelling and control studies of solar S-CO_2 Brayton cycle plant. At Korea Atomic Energy Research Institute (KAERI), MMS (Modular Modelling System) was used for modelling KALIMER-600 SFR coupled with S-CO_2 closed-cycle PCS.

Part load analysis of MCFC-SCO_2 hybrid system by [160] showed good performance and efficient control system as well as highlighted the impact of heat exchanger effectiveness on system efficiency. [161] investigated a simple dynamic modelling approach and control strategies under load following operation for an advanced molten salt reactor coupled to CBC. [162] presented the transient response of S-CO_2 Brayton cycle to a reduction in solar heat input for short duration in CSP and found that the system could continue to operate effectively until thermal input is restored. The computer model was validated with data from the Sandia recompression S-CO_2 experimental loop.

5.2.3 1-D, 2-D and CFD modelling of closed-cycle GT

Models of closed-cycle GT are usually based on turbomachinery performance maps (a 0-dimensional quasi-steady state approach) to simulate the dynamic characteristics and control of the plant [163]. Use of performance maps is sufficient in most cases for simplified dynamic performance studies and control system designs. However, its implementation is prone to interpolation errors and usually limited to normal operating range as it cannot simulate very low speed, heat exchange with wall, surge, stall or reverse flow conditions [163]. More detailed analysis of extreme transients will sometimes requires either a 1-D, 2-D or even 3-D CFD model of system components.

A 1-D turbomachinery modelling approach was applied by [163] to gas cooled reactor GT to investigate transient behaviour during pipe rupture accident event. [164,165] simulated load transients in GTHTR300 with a 2-D turbomachinery model implemented into GAMMA-T code. [21] performed CFD simulation of S-CO_2 compressor with ANSYS Fluent taking into consideration the unique features S-CO_2 cycle such as rapid property variation near critical point and possibility of condensation in the compressor. Based on similar reason, [166] and [167] used data from Sandia S-CO_2 loop for CFD modelling of S-CO_2 radial compressor and for simulation of flow in the test loop respectively. Other CFD studies included the work of [168] for S-CO_2 centrifugal compressor and [169] for pressure drops and heat transfer in S-CO_2 PCHEs.

5.3 Operation and control options for closed-cycle gas turbines

An area that needs to be proven in order to determine the overall success of closed-cycle GT relates to its operation and control. Theoretically, the power output of closed-cycle GT is determined by the mass flow rate, the compressor inlet temperature, the TIT, the turbomachinery efficiencies and the pressure ratio [9]. Hence typical control options for modulating the power output of closed-cycle GT include inventory/pressure control, bypass control and temperature/thermal input control.

Changing the mass flow rate of the working fluid, usually called inventory or pressure control, is the most attractive option as power level can be varied without changing the plant efficiency [2]. This method uses inventory tanks to store the working fluid for power reduction, and releases working fluid into the cycle during power increase. Disadvantages of inventory control are that it requires an inventory tank whose size can be quite large depending on the power range to be controlled. Also the rate of change of power level is limited by the size of the control valves [2]. Hence while the 50 MWe Oberhausen II plant utilized multi-vessel inventory control, the large 800 MWe GT-HTGR project developed by GA did not use inventory control because of the large helium inventory that would be required and expected to be transferred between the tank and the power conversion circuit [9]. HTGR-GT adopted only bypass and TIT control.

In bypass control, the turbine pressure ratio is manipulated by controlling the mass flow rate through the heat source and turbine by regulating the bypass valve and hence a reduction in the power output. A significant advantage of bypass control over inventory control is its capability to deal with rapid power changes. For temperature control, the TIT is controlled by varying the amount of heat transferred in the IHX or reactor.

A typical control scheme for a plant is usually made up of a combination of the above control strategies. Bypass control is used for rapid changes in power demand, inventory control for the slower transients, while preserving cycle efficiency. Comparing their response time, bypass control has the fastest response time followed by inventory control while temperature control is the slowest. Shown in Figure 19 is a comparison of the cycle efficiency as a function of the percentage of rated power for the different control scheme. The main features of these control methods are shown in Table 5.

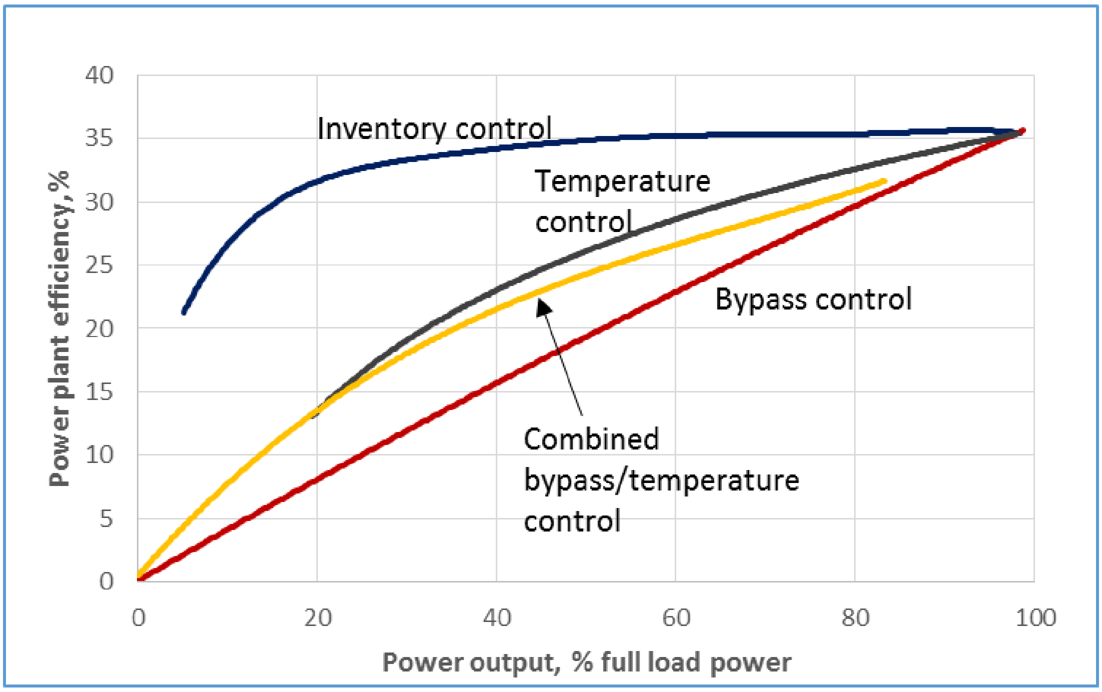


Figure 19 Effect of different control scheme on cycle efficiency

Table 5 Features of the control methods [160]

	Efficiency	Operating range	Response time
Inventory	Very good	Acceptable	Poor
Bypass	Poor	Good	Very good
Temperature	Poor	Acceptable	Poor

6 Challenges ahead and potential future breakthroughs

It has been identified that substantial benefits can be achieved with the use of closed-cycle GT for power generation. The closed-cycle GT provides promising alternatives to the conventional PCSs for nuclear, solar, geothermal, fossil and waste heat for terrestrial, space and marine power generation applications. However, there still remain technical bottlenecks in the areas of heat source technologies, heat exchangers, seals, bearings, materials and turbomachinery development which required further attention before full-scale commercial deployment can be realised.

6.1 Heat source technologies

Most of the high temperature heat sources proposed for closed-cycle GT application are still under development. Availability of heat energy at high temperature is one major way of improving the efficiency of closed-cycle GT. Hence, coupling of closed-cycle GT with high temperature heat sources is a key area of interest since closed-cycle GT mostly rely on improved thermal efficiency and reduced cost to compete with existing power plants.

For Gen IV and other HTRs, research is ongoing in the areas of reactor core design, design of pressure vessel, design of control rod, materials, IHXs, fuel and cladding design and nuclear fuel reprocessing [170,171]. Power generation from Gen IV reactor is projected to be available between the year 2030 and 2050. Hence full maturity of Gen IV nuclear reactor concepts and advanced concentrated solar receivers as well as future breakthrough in fusion reactor technology will contribute to application of closed-cycle GT for high temperature heat source.

6.2 Power conversion systems (PCSs)

Implementation of scaled-up size of PCS main components such as heat exchangers and turbomachinery running on magnetic bearing remain significant obstacles to the commercialisation of the plant.

The heat exchangers are usually complex, expensive and large in size and hence represent a significant driver in the capital cost and technical viability of closed-cycle GT. Meanwhile, further economic analysis is required to determine economic viability of closed-cycle GT. Development of highly reliable and cost effective compact heat exchangers remain an area of active research especially for high temperature applications. Long term effect of corrosion on heat exchanger materials, thermal stress under extreme operating conditions and thermal-hydraulic performance required further research and testing. The PCHE, which seems to be the preferred compact heat exchanger, is expensive and yet to be manufactured for large scale power generation application. Apart from the diffusion bonding process, breakthrough in other processes such as 3D printing manufacturing process, ceramic heat exchangers and novel Cast Metal Heat Exchangers (CMHEs) being developed at SNL [172] could offer a solution for high temperature heat exchanger for closed-cycle GT in the future.

Though aerodynamic design approach for air compressor and turbine can be applied, the use of a different working fluid will still affect the geometry and flow path of the turbomachinery. Nowadays, the turbomachinery design and analysis can be accomplished with the aid of sophisticated computer software. However, specific software tools might be required to handle the unique properties of working fluids like supercritical CO_2 because the existing turbomachinery design tools were intended for combustion gases or ideal gases.

Apart from the aerodynamic performance of the compressors and turbines, issues related to large magnetic bearings, seals, rotor dynamics and controls must be proven. The use of magnetic bearings in HTR application will remove the risk of oil ingress but it is yet to be tested for very heavy rotor weight likely to be encountered in some closed-cycle GT [25]. Closed-cycle GT presents new challenges for dry gas liftoff seals because the pressures, temperatures and rotating speeds could be higher than those in existing systems. Also working fluid with lighter molecular weight such as helium are difficult to contain. In some instances, to obtain synchronous operation, the generator will either be mated to high speed turbine with gearbox or a frequency converter is used. Both gearbox and frequency converter will lead to power loss and neither is currently available for large generator.

6.3 The need for closed-cycle GT demonstration plant

Before commercial deployment, a number of technologies remains to be proven and these will be largely addressed in a demonstration facility. A number of experimental and pilot test studies have been carried out for closed-cycle GT but they are usually too small to incorporate all the features and technologies typical of a commercial size plant. Also the newly developed enabling technologies for closed-cycle GT were never tested in the early operated fossil-fired closed-cycle GT power plants. Hence demonstration plants with scales of 10s of MWe will be required to evaluate the operation and performance of closed-cycle GT. [173] suggested a demonstration plant with power rating in the range 25-50 MWe for meaningful demonstration of helium closed-cycle GT plant. SNL is currently proposing a minimum size of 10 MWe for demonstration of commercial-scale S-CO_2 Brayton cycle plant [174].

The demonstration plant will permit the verification of the performance and integrity of turbomachinery and rotor assembly, heat exchangers, bearings, seals, and control systems under operating conditions identical to commercial plant. Similarly, the whole operating range (startup, shutdown, full load and part load operations) of the plant can be tested. The demonstration plant will be adequately instrumented to obtain data for validation of both steady state and dynamic models of the plant.

7 Conclusions

Closed-cycle GT has the potential for improved efficiency of electricity generation, compact and simple design, and reduced CO_2 emissions and therefore could complement conventional power generation plants. A state-of-the-art assessment of the plant and research work carried out so far is provided in this paper. These include its historical development, major concepts and features of the plant, important research programmes worldwide, experimental facilities, commercially operated plants, and studies through modelling and simulation. Based on past operation experiences, recent research studies and development, we tried to predict the challenges ahead and potential future breakthroughs. Finally, the need for closed-cycle GT demonstration plant was emphasized to establish the integrity, operation and performance of the plant before commercial deployment.

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