Supercritical CO2 heat removal system - integration into European PWR fleet

Hájek, Petr; Vojacek, Ales; Hakl, Vaclav

In: 2nd European sCO2 Conference 2018

DOI: https://doi.org/10.17185/duepublico/46083

URN: urn:nbn:de:hbz:464-20180827-130410-5

Link: https://duepublico.uni-duisburg-essen.de:443/servlets/DocumentServlet?id=46083

2nd European supercritical CO2 Conference
August 30-31, 2018, Essen, Germany

2018-sCO2.eu-109

SUPERCRITICAL CO_2 HEAT REMOVAL SYSTEM - INTEGRATION INTO EUROPEAN PWR FLEET

Petr Hajek
ÚJV Řež, a. s.
Hlavni 130, Řež,
250 68 Husinec, Czech Republic
petr.hajek@ujv.cz

Ales Vojacek
ÚJV Řež, a. s.
Hlavni 130, Řež,
250 68 Husinec, Czech Republic

Vaclav Hakl
ÚJV Řež, a. s.
Hlavni 130, Řež,
250 68 Husinec, Czech Republic

ABSTRACT

This technical report describes the basic principles for integration of possible sCO2-HeRo loops in to the European PWR reactors fleet. This technical report is focused on integration to the VVER 1000 reactor design on existing operational units. The integration of sCO2-HeRo loops is described to level of detail in conceptual study. In this technical report there is specified initial information for design and design basis. There are summarized safety and reliability requirements, safety assurance principles, safety classification together with thermodynamic analyses supporting the selected technical solution.

INTRODUCTION

In the report the basic information is given about the possibility of integrating sCO2-HeRo loop into PWR design as well as information about the selected design for this integration and thermodynamic analyses supporting the selected technical solution.

The basic idea is to use the steam from the reactor in BWR or from the SG (Steam Generator) in PWR design as source of heat in heat exchanger of sCO2-HeRo loop and to return the condensed water back to the reactor or SG. This idea ensures the cooling of the reactor core and there is no need for feed water supply, no loss of coolant inventory, use of saturated steam allowing using evaporation heat and the use of small and compact heat exchangers.

The potential of sCO2-HeRo design is significant. The utilization of sCO2-HeRo exceeds SBO (Station BlackOut) accidents. It is expected that this system has a capability to be employed as a system for removal of heat from containment of NPP's. In case of LOCA (Loss Of Coolant Accident) or SA (Severe Accident) the containment vessel will contain a huge amount of mixed air and saturated water vapor. In emergency state as LOCA there are installed sprays systems for removing of this heat and for handling SA there are no systems available in current NPP's design. The only way on current NPP's, how to remove heat from containment to prevent its damage, is containment ventilation or cooling of containment inner wall. The heat exchangers of sCO2 HeRo loop can possibly act as heat removal device for containment cooling system.

In the process of developing integration of possible sCO2-HeRo loops in to the European PWR reactors fleet the two following concepts of sCO2-HeRo deployment have been worked out.

- Design of SBO-SG_HRS (Heat Removal System)
- Design of Containment_HRS

SBO-SG_HRS is a design in case of a SBO and the system draw steam from main steam line and condensed water is fed back to SG via normal feed line pipe. For more details see chapter 2 "Basic design".

Containment_HRS design is based on the installation of additional heat exchangers inside the containment, which will be condensing vapor from containment atmosphere on its outer surface. Condensed water can be used in case of LOCA in containment sump for emergency cooling systems and in case of SA according the used strategy for reactor vessel cooling (IVR) or corium cooling (ExVR).

BASIC DESIGN

1. SBO-SG_HRS

<u>Progress of typical SBO event on VVER1000 units:</u>

After a SBO on VVER 1000 unit there is an automatic reactor shut down by falling regulating rods. Meanwhile, in the active zone residual heat is produced. By nature, natural circulation is established in the primary circuits, which transfers

DOI: 10.17185/duepublico/46083

this heat to the SG and evaporates its water content. Generated steam is released by battery operated Atmospheric Exhaust Station (PSV) or by SG Pilot Operated Pressure Relief Valve (PRV). During a SBO accident without sources of electric energy, it is not possible to feed water to SG, so the level on SG secondary side steadily decreases. Parameters in primary loops are steady till the moment when the tube bundle in the SG starts to be uncovered by water (and only by vapor). After that the temperature and pressure in the primary loop starts to rise. According to analyses it takes about 50 – 60 minutes, till the tube bundle in the SG will be totally uncovered and cooling primarily coolant by evaporation SG water content is severely limit. The temperature in primary circuit starts to rise dramatically and primary coolant is released to the containment by pressure relieve valves. Eventually, it leads to SA.

The impact of SBO-SG_HRS on SBO progress:

The SBO-SG_HRS extracts the heat from the evaporated SG water and the generated condensate is fed back (driven by natural draft) to the SG secondary side. This process prevents the reduction of water content on the secondary side of the SG and enables the removal of the residual heat for a long period of time. The heat is conveyed to UHS (Ultimate Heat Sink - air).

An important role in the design of the SBO-SG_HRS system plays the balance between generated heat and SBO-SG_HRS heat removal capacity. The design of the SBO-SG_HRS system is based on basic requirements of heat removal capacity systems. The basic design of the nominal capacity of the heat removal system design was selected for 5 MW for one unit and on one NPP. It is planned to install 4 units in total.

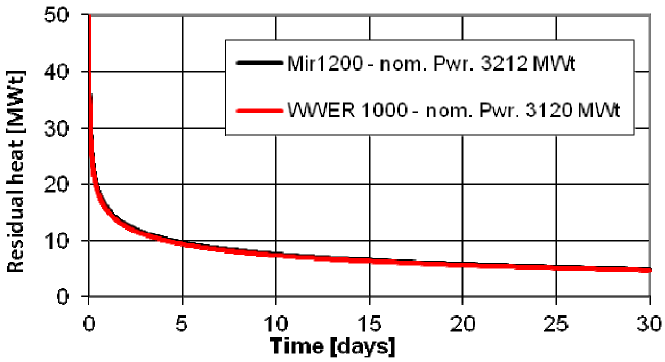

Figure 1-1 Residual heat for MIR 1200 and VVER 1000 types of reactors.

Figure 1-1 shows a graph of residual heat dependence on time. According to this graph it is possible to find out, that the proposed basic heat removal capacity of 20 MW is adequate of reactor core residual heat production after **8 hours** after reactor shut down (VVER 1000 unit).

The capacity of one system unit with regulation of the bypass over the turbine is 4.2 – 8.4 MW. The total possible capacity of 33.6 MW (4 times 8.4 MW) is sufficient for heat removal after **1 hour** after the reactor shut down. Within this period of time the water level in SG decreases below the tube bundle; however, the water deposit in primary circuit stays intact yet. The inventory of coolant on secondary site of the SG without emergency feeding corresponds to cooling reactor core for 1 hour by evaporation. From this mass and energy balance follows the requirement to start these systems at latest in **45 minutes** from SBO and reactor trip.

The water content from the SG which was released to the atmosphere till the SBO-SG_HRS starts to operate, can be restored to nominal SG water level by special SBO feed water pumps (Emergency supply pump to SG), which are already installed on units as result of Stress test procedures solution. Power for their operation can be produced by SBO-SG_HRS.

The requirements on the proposed systems are to enable a long term heat removal for at least 72 hours according the requested capability of the unit withstand all possible emergency situations without assistance from outside of the plant site. On top of that the design of the sCO2-HeRo aims for long term of residual heat removal systems in terms of weeks or month. This is possible due to the modular distribution of the system to 4 units, capable of independent operation and regulation of removed residual heat as in.

1.1. System description

As you can see in Fig. 1.1-1 and Fig. 1.1-2**Chyba! Nenalezen zdroj odkazů.** the SBO-SG_HRS (Station BlackOut heat Removal System from Steam Generators) is composed of three parts.

First part – the steam/water part is used to remove the heat from the secondary side of the steam generators. It is connected to the main steam line pipe in front of the fast acting valves (FAV, these valves are pneumatically operated valves with the purpose to separate the loop from the steam generator in case of a main steam pipe rupture) on the side, which is permanently connected to the SG. Next to it are the loop isolation valve and compact heat exchanger (CHX) for steam condensation. The Condensate leaves the CHX in the pipeline which is connected through the containment localization group of valves to the main feedwater line. The circuit is driven by the natural convection force. The position of the heat exchangers is selected in such manner (higher than the steam generators) so that the natural circulation works.

Second part – the CO2 loop extracts the heat from the compact heat exchanger through the sCO2-HeRo turbo machinery to the air cooled sink heat exchanger. The sCO2 loop is a simple Brayton cycle with a compressor, a turbine, a CHX and a sink HX. The positive energy balance of this cycle enables to extract electric energy which can be used for energy supply to essential instrumentation and control system or to

DOI: 10.17185/duepublico/46083

emergency supply pump for the SG feed water to recover water level inside the SG.

Third part – the air cooling loop serves as heat sink for the whole system and dissipates heat to the atmosphere. The fan is used for forced air flow through the sink heat exchanger to increase the heat transfer efficiency and is powered by the electric energy produced by turbine.

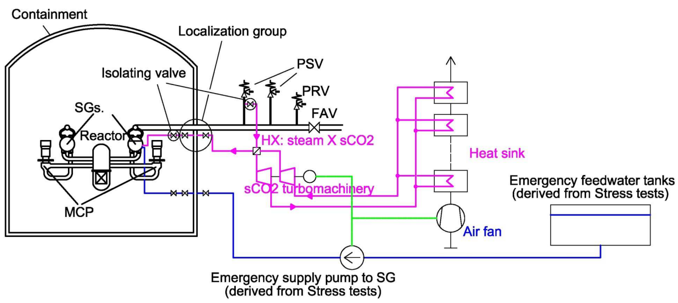

Figure 1.1-1 SBO-SG_HRS (Station Blackout heat Removal System from Steam Generators) – one unit structure.

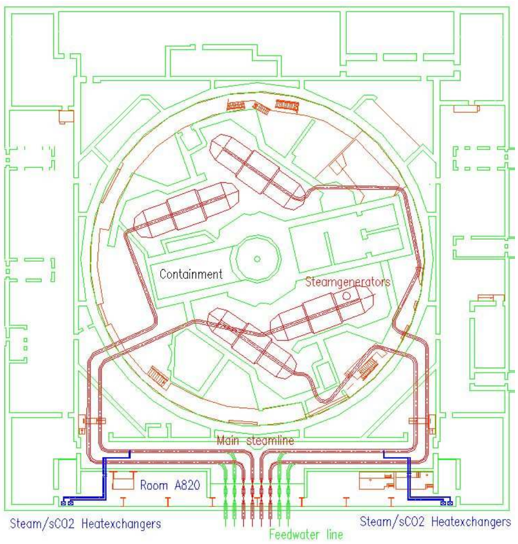

Figure 1.1-2 SBO-SG_HRS – Arrangement of four units on SG and main pipe lines

Arrangement of four units in containment

The System of heat removal in conditions of SBO consists of two independent systems. The description of the individual system is stated above. The system is divided to this “sub systems” to cope with all range of residual heat of a shutdown of the reactor. With a gradual cooling down of the core, the amount of residual heat is obviously decreasing so it is gradually coming to the point when only one sub-system is sufficient. Hence, the other sub system is from this moment further disconnected.

Each sub-system is connected to the main steam line of one steam generator. The heat which is generated in the core is equally distributed into the steam generators, so there is no need to connect the system to all main steam pipelines (steam generators).

For a further operability of the system, each sub system has 2 heat exchangers steam/sCO2, which can be in operation both or just one of them, depending on the situation. Each heat exchangers steam/sCO2 is then connected with its 1 unit of the sCO2 turbomachinery 5 MWth and with the sink HXs (altogether 6 for each 5 MWth unit).

This is the main part of the SBO-SG_HRS which takes care about the CO_2 circulation and the production of electric energy.

1.2. System functions

The SBO-SG_HRS (Station BlackOut heat Removal System from Steam Generators) is designed for operation under design extension conditions (DEC).
Under design extension conditions, the SBO-SG_HRS shall perform the function of heat removal via the secondary circuit:

- residual heat removal and cooldown of the reactor plant under conditions of NPP blackout.
- residual heat removal and cooldown of the reactor plant under conditions of total feedwater loss.
- ensuring the reserve by the active safety systems

1.3. System requirements

This chapter summarizes the basic requirements on the designed systems from the point of view of safety assurance principles (passive/active, redundancy, diversity, separation, actuation, independence…), safety classification (safety functions, safety classes) and reliability requirements.

The SBO-SG_HRS (Station BlackOut heat Removal System from Steam Generators) is designed for operation under design extension conditions (DEC).
Under design extension conditions, the SBO-SG_HRS shall perform the function of heat removal via the secondary circuit:

- residual heat removal and cooldown of the reactor plant under conditions of NPP blackout.
- residual heat removal and cooldown of the reactor plant under conditions of total feedwater loss.
- ensuring the reserve by the active safety systems
-

1.4. Operational regimes and parameters

The system has four operational modes:

Normal operation

During the normal operation the SBO-SG_HRS is in a standby mode. The first part (steam/ water loop) is filled with

DOI: 10.17185/duepublico/46083

water on normal condition. The CO2 loop is filled with CO2 to stand-by pressure, which must be determined.
Isolation valves are closed.

Start up:

There is a possibility to start up by electricity from electric accumulators by converting the generator into an electromotor. Another possibility is to use pressure tanks with CO_2 and use this stored energy to start the initial circulation in loop. The solution which would be used in final design of loop will be done in further phase of this project.

Fulfilling of safety function:

In the first part of the loop the steam naturally circulates and condensates to water in the heat exchanger. The condensate is fed back to the SG. The CO_2 loop works as a Bryton cycle. Forced air circulation is powered by produced electricity by circulation fan.

In case external conditions will be changed, like for example the outside temperature, it is possible to add or disconnect sections of the heat exchanger CO_2 / air

Shut down:

It is possible to switch the system off by closing the isolation valve on line from the main steam pipeline to the heat exchanger.

1.5. Power supply

A battery source for the initial valves operation must be integrated into the system to control the system operation and for the system start.

The energy source for the start-up (electric energy in batteries or compressed gas in bottles) should be sufficient for 2-3 attempts to start the system.

During the operation of the systems there will be an adequate production of electric energy for self-consumption and for powering external appliances.

2. CONTAINMENT_HRS

As well as the SBO-SG_HRS the Containment_HRS is initially designed for the removal of 5 MW of residual heat for one modular unit and altogether it is planned to install it within four units. It well corresponds with the curve of active zone residual heat production.

The difference between the Containment_HRS and the SBO-SG_HRS is that in case of a SBO the inherent capacity of water in the SG, capable to withdraw residual heat by its evaporation, is adequate only for less than one hour. Hence, the SBO-SG_HRS must be started up very quickly.

On the other hand, in case of a LOCA or a SA inside the containment, there is a much higher heat capacity reserve in all internal materials (water, concrete, steel …). According to previously made analyses, the pressure in the containment rises to the level corresponding to the containment strength (5 bars) in about 15 hours.

On the other hand, parameters in the containment after a LOCA (like temperature, pressure, vapor content) are steadily rising after the primary circuit brake, but the first moments aren't sufficient for the Containment_HRS for a self-propellant, self-sustaining operation. The startup time of these systems must be adapted to the immediate situation inside the containment.

The requirement on the proposed systems is to enable a long term heat removal for at least 72 hours according the requested capability of the unit to withstand all possible emergency situations without assistance from outside of the plant site. On top of that the design of the sCO2-HeRo is aiming for long term of residual heat removal systems, in terms of weeks or month. This is possible due to the modular distribution of the system to four units, capable of independent operation and regulation of removed residual heat.

It is possible to use the CO_2 loop unit for regulation by the mean of turbine bypass, as in the SBO-SG_HRS. It is expected that the result in heat removal capacity range will be similar, which has to be shown in the future.

It is supposed that this active control is not necessary for the Containment_HRS, because of the containment high heat capacity, which enables regulation by the mean of switching of whole modular units of the Containment_HRS.

2.1. System description

The Containment_HRS (Containment heat Removal System) is composed of two parts. See **Chyba! Nenalezen zdroj odkazů.**.

First part – consists of a heat exchanger for the extraction of the heat from the air/steam atmosphere mixture inside the containment and the CO_2 loops transferring the heat, from this heat exchanger, due to turbo machinery to the air cooled heat exchanger. This loop is designed as a simple Brayton cycle with compressor, turbine and generator on one shaft. The slightly positive energy balance of this cycle enables to extract electric energy, which can be used for energy supply to systems essential measuring and control system and for the powering of the electric air fan.

On the CO_2 lines penetration through the containment wall will be grouped isolation valves. One of them, near by the

DOI: 10.17185/duepublico/46083

containment wall will be connected to the wall by double wall pipe to confine leakage in case of a tube rupture.

Second part – an open air cooling loop serves as a heat sink for the whole Containment_HRS and dissipates heat to the atmosphere. The fan is used for forced air flow true heat exchanger to increase the efficiency and it is powered by the electric energy produced by turbine.

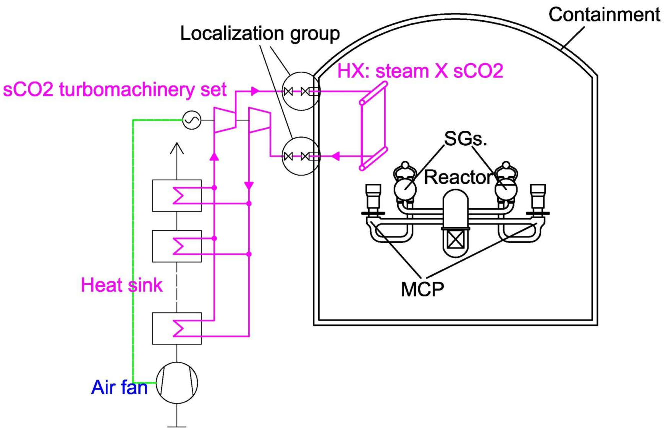

Figure 2.1-1 CONTAINMENT_HRS (Containment Heat Removal System) – one unit structure.

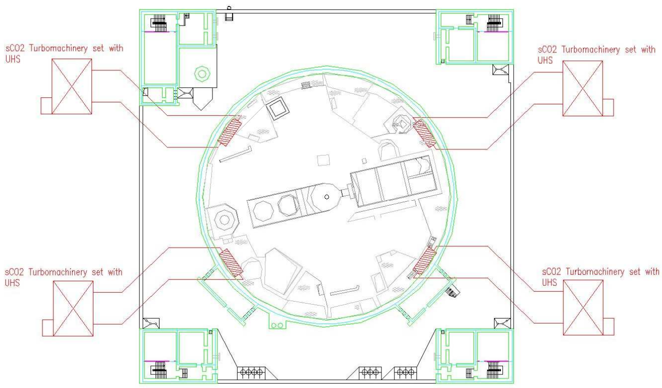

Figure 2.1-2 SBO-Containment_HRS – Arrangement of four units in containment.

<u>Arrangement of four units in containment</u>

The system consists of 4 individual trains. The description of an individual train is listed above. The containment heat exchangers (one for each 5 MWth unit) are placed at the top head of the containment at regular intervals around the circumference of the containment approximately at level +46m. The pipeline with supercritical CO_2 medium goes through the containment by new hermetic penetration to the rooftop of the surrounding building and then to the ground level. The situation is well displayed at **Chyba! Nenalezen zdroj odkazů.**. On the ground level the modular configuration of the sCO2 turbomachinery of 5 MWth are placed (one for each 5 MWth unit) together with the sink HXs (altogether 24 for each 5 MWth unit). The integration of the system into the civil part of an existing unit and the connection to the technology is described in the following chapter.

2.2. System functions

The Containment_HRS (Containment heat Removal System) is designed for the operation under design basis accidents conditions (DBA LOCA) and in Beyond design basis accidents (Severe accidents SA) conditions.
Under DBA an SA condition, the Containment_HRS shall perform the function:

- Heat removal from containment inner atmosphere.

2.3. Operational regimes and parameters

The system has four operational modes:

<u>Normal operation:</u>

During the normal operation, the Containment_HRS is in a standby mode. The CO_2 loop is filled with CO_2 to stand-by pressure, which must be determined. The isolation valves are closed.

<u>Start-up:</u>

The principle of the Containment_HRS power up isn't decided yet. It. There is a possibility to start up by electricity from electric accumulators by converting the generator into an electromotor. Another possibility is to use pressure tanks with CO_2 and to use this stored energy to start the initial circulation in the loop. The final solution which will be used in the final design of the loop will be found at a later time of this project.

<u>Fulfilling of safety function:</u>

The CO_2 loop works as a Brayton cycle. The heat from the containment is withdrawn by CO_2 and potential steam in the containment atmosphere is condensed. Forced air circulation is powered by produced electricity by a circulation fan.
In case external conditions are changing, e.g. the outside temperature, it is possible to add or disconnect sections of the heat exchanger CO_2 / air.

<u>Shut down:</u>

The system can be switched off by closing the valve on the CO_2 loop isolation group on the containment wall.

2.4. Power supply

A battery source for the initial valves operation must be integrated into the system for control system operation and for the startup of the system.

DOI: 10.17185/duepublico/46083

The energy source for the startup (electric energy in batteries or compressed gas in bottles) should be sufficient for 2-3 attempts to start the system.

During the systems operation, there will be an adequate production of electric energy for self-consumption and for powering external appliances.

3. POSSIBILITY OF SELF-LAUNCHING SYSTEM

This chapter evaluates the possibilities in order to design the SBO_HRS and the Containment_HRS scenarios to be self-launching.

Generally, it must be considered that either both the SBO_HRS and the Containment_HRS will be added to currently operating units or these systems will be designed for newly built VVER (PWR) units.

- Newly built VVER units - For a newly built NPP it is possible to integrate the SBO-SG_HRS and Containment_HRS to the DID logic sequence, because it will be newly developed in the design phase of a project. If these systems should be self-launching, the condition and limitation of a system start-up have to be exactly addressed.
- Currently operating units VVER units – There are challenges to determine whether the SBO-SG_HRS and Containment_HRS could be operated in a self-launching or in a manually operated mode. Originally, in the NPP design the DEC - Postulated multiple failure events, beyond design basis accidents and severe accident were not considered.
    - SBO-SG_HRS - As a result of the European Stress Test, severe accident mitigation measures have been implemented in VVER plant. All such measures dealing with SBO DG stations, SBO SG feed water pumps or SBO-accidents in general are actuated and operated manually by the operator from special control workplaces. The HeRo System operating under SBO conditions would have the same restraints. A challenge here is, e.g. defining procedures how to manually operate systems together with the sCO2-HeRo-system. Such investigations are on the agenda for the 3rd year of the project when improved ATHLET simulations will be carried out with improved models.
    - Containment_HRS – For currently operating VVER units, severe accident management strategies are currently being prepared. The design and operation conditions of a sCO2-HeRo-system will depend on the accident management strategy, i.e. In-Vessel or Ex-Vessel retention scenarios, resulting in different atmospheric conditions at different times of an accident. A definition of starting conditions will depend on the outcome of the analysis of the accident scenario.

<u>The possibility of a self-launching system is generally conditional upon solving problems:</u>

- Definition of groups of events for which the system will be designed. In the designs, specific events must be addressed in a logic sequence DID for which the system should be used. A list of symptoms which definitely and unmistakably distinguish these events has to be set up.
- Evaluation of failure of other possible resources intended for this project event. There can be another system designed for the same purpose. It has to be clear, that the new system only starts if it clearly demonstrates that the primary systems fail to fulfill their function.
- Evaluation of launching point. Some parameters and set points must be given, which result in system start up when exceeded.
- Transitions between the phases of self-launching procedure. The start-up procedure will consist of several phases and has to define conditions verifying the fulfillment of the previous phase and enabling the transition to the next phase.

<u>Considered self-launching process phases:</u>

1. Filling of CO_2 to the system to the operational level.
2. Configuration of CO_2/Air heat exchanger for corresponding ambient temperature. Selection of needed sections and opening corresponding valves.
3. Start up by electricity from electric accumulators by converting the generator into an electromotor or usage of pressure tanks with CO_2 and use this stored energy to start initial circulation in loop.
4. Connection to the electric grid.
5. Optimization of operational parameters for CO_2 loops.

THERMODYNAMIC ANALYSIS

CYCLE CALCULATION – OPTIMIZATION PARAMETERS

The following chapter is devoted to the optimization of the thermodynamic cycles both for CONTAINMENT_HRS and SBO-SG_HRS systems. The optimization is based on searching a compressor inlet and compressor outlet pressure of the cycle to receive the highest efficiencies of the cycle. There were assumed expected isentropic efficiencies of the compressor and turbine as well as expected inlet temperature and pressure to the compressor and to the turbine. This optimization is extremely

DOI: 10.17185/duepublico/46083

important and determines whether the system will have a chance to be self-propellant or not.

The sCO2-HeRo cycle is designed as a simple Brayton cycle. At this preliminary state, neither the implementation of recuperation nor other improving elements such as modification of the cycle, e.g. recompression cycle (considered as the most promising conversion cycle for sCO2 with the highest efficiency) were considered, although there is an added value of these improvements in terms of higher electric power output since the efficiency of the cycle is increased. This would lead to rising up the mass flow rate in the system in order to keep the thermal power (decay heat removal) constant, thus increasing the power of the compressor and the turbine by the ratio of mass flow rates (simple Brayton cycle/enhanced cycle).

In no human endeavor, one can ever guarantee failure-free operation. The system and human failures are inevitable. The likelihood of any failure is higher for more complicated systems. Keeping this in mind, it leads to a rather small and safer simple Brayton sCO2 conversion cycle rather than more complicated enhanced cycles.

Table 1 gives the thermodynamic values of the CONTAINMENT_HRS and SBO-SG_HRS cycle which were considered.

The cycle calculation starts at the compressor inlet. The temperature and pressure are specified at that point. Both were parametric inputs. The compressor efficiency is an input variable parameter. It varies according to the common values depending on the sizes, rotation speed and pressure ratios. The compressor outlet pressure is specified also as a parameter.

Table 1 Thermodynamic values of the CONTAINMENT_HRS and SBO-SG_HRS cycle.

Variable	*Value*	*Unit*
inlet temperature sCO2 to the compressor	30, 40, 50	°C
inlet temperature sCO2 to the turbine CONTAIMENT_HRS/SBO-SG_HRS	114/280	°C
inlet pressure sCO2 to the compressor	75, 100, 125, 150	bar
inlet pressure sCO2 to the turbine	100, 150, 200, 300	bar
thermal power of heat source	5000	kW
isentropic efficiencies of the compressor	0.65, 0.75 and 0.8	-
isentropic efficiencies of the turbine	0.75, 0.85 and 0.9	-

CONCLUSION

This technical report describes the basic principles for integration of possible “supercritical CO_2 heat removal system” into the European PWR reactors fleet. This technical report is focused on integration to the VVER 1000 reactor design on existing operational units. The integration of sCO2-HeRo loops is described to a level of detail in a conceptual study. In this technical report, initial information is specified for design and beyond design basis. Safety and reliability requirements are summarized, safety assurance principles, safety classification together with thermodynamic analyses supporting the selected technical solution.

ACKNOWLEDGMENTS

This project has received funding from the European research and training programme 2014 – 2018 under grant agreement No 662116.

DOI: 10.17185/duepublico/46083