Proceedings HTR2006:
3rd International Topical Meeting on High Temperature Reactor Technology
October 1-4, 2006, Johannesburg, South Africa

E00000027

TECHNOLOGICAL LOOPS FOR HIGH TEMPERATURE HEAT EXCHANGERS DEVELOPMENTS AND QUALIFICATION

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ABSTRACT

In France, a comprehensive research and development program is in progress, that relates to several fields (design studies, fuel, materials, codes, high temperature helium technology), for Helium GCR projects with both direct and indirect cycles.

In this framework, High Temperature Heat Exchangers, such as the helium/helium recuperator or the Intermediate Heat Exchanger, are considered as key components for the overall efficiency of the system. Within a Brayton cycle, the Heat Exchangers (HE) have to work under very severe conditions (temperature, pressure, pressure differences between the circuits). Thus, no directly available compact technologies exist in the market. However some potential technologies (tubes, plate fin, printed circuit HE) have to be investigated.

The main purpose of this paper is to present the methodology for the heat exchangers developments and qualifications. In addition, the main experimental test rigs are described as follows:

- Analytical benches, at channel scale, for providing reliable data of thermal hydraulic correlations.
- Small air loops, CLAIRE loop (~ 100 kW), at the mock-up scale, for testing different technologies and selecting the most promising one. Both thermal hydraulics and thermal mechanical (thermal cycling) aspects are concerned.
- Technological validation (endurance tests), of the most promising technology under representative conditions of temperature, pressure and helium velocity, on a multi-purpose technological loop, HELITE loop (~ 1 MW).
- Large helium facility (10 MW) for component qualification on model at scale 1.

I. INTRODUCTION

In previous years, CEA together with EDF (Electricité de France) and AREVA-NP has launched feasibility studies of future nuclear advanced systems in a consistent series of gas-cooled reactors ranging from thermal reactors such as the High Temperature Reactor (HTR) to be operative by 2025, the Very High Temperature Reactor (VHTR) for the mid term and the gas fast reactor (GFR) for the long term.

For the common HTR-GFR helium technology development at a temperature up to 850°C, R&D program is supported by AREVA-NP ANTARES Project (600 MW_{th}). The objectives for the reactor are electricity generation and a heat supply for high temperature applications such as hydrogen production. The final design might be finished in 2012. A particular characteristic of the concept is the choice of an indirect combined Brayton and Rankine cycle with a plate type intermediate heat exchanger (IHX). The IHX therefore becomes the key component that has to be developed and validated, as a part of the primary circuit and secondary circuit, as well as a part of the efficiency of the HTR concept. The IHXs have to work under very severe conditions (temperature, pressure, pressure difference between the circuits).

On the other hand, for the direct Brayton cycle, the helium/helium recuperator, is considered a key component for the overall efficiency of the system.

The purpose of this paper is to present the methodology for the heat exchangers developments and qualifications. Thus, no directly available compact technologies exist in the market. However some potential technologies (tubes, plate fin, printed circuit HE) have to be investigated. This important R&D program involves research in several fields: design, high temperature materials, plate fabrication and welding, mounting, integration in the vessel, thermo hydraulics and thermo mechanical behavior calculations in steady state and transient conditions.

II. ANTARES IHX R&D NEEDS AND DESIGN

The reference data set for the electricity production option with indirect cycle VHTR is summarized in the following Table 1:

Global thermal power (MWth)		610
PRIMARY SYSTEM	IHX inlet temperature (°C)	850
	IHX outlet temperature (°C)	392
	Pressure (MPa)	6
	Flow rate (kg/s)	255.6
	Maximum pressure loss (75% for IHX & 25% for ducting)	2% (75% for IHX 25% for ducting)
SECONDARY SYSTEM	IHX inlet temperature (°C)	350
	IHX outlet temperature (°C)	800
	Pressure (MPa)	5.5
	Flow rate (kg/s)	695.5
	Maximum pressure loss (75% for IHX & 25% for ducting)	4% (75% for IHX 25% for ducting)

The indirect Brayton and Rankine combined cycle is illustrated in the figure 1 here under:

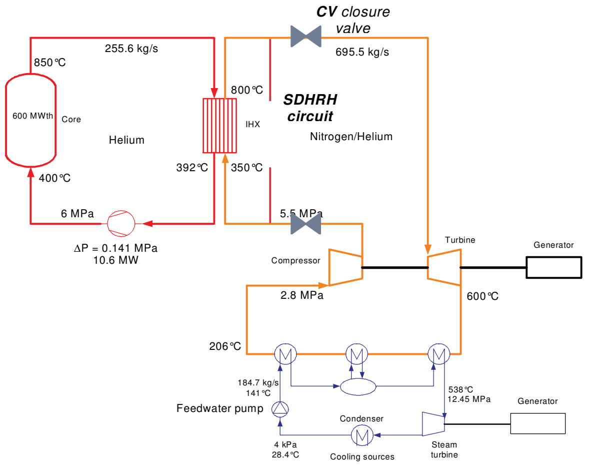

Figure 1: ANTARES combined cycle

The temperature range is envisaged (up to 950°C) for heat production.

The plate IHX modules are set in a pressure vessel. Due to the limited possibility for In Service Inspection of the plate IHX the leak tightness is not strictly required but some closure valves, installed very close to the primary circuit, are implemented on the secondary inlet and outlet piping.

A leak is detected at a very low mass flow rate using gas activity and thanks to the pressure difference between primary helium (6 MPa) and secondary mixed gas (Helium 20 % Nitrogen 80%) at pressure 5.5 MPa.

The plate IHX Safety class is therefore 3 but for investment protection and availability the component quality level would be 2. The plate IHX modules must be easily removable and their lifetime is planned for 20 years compare to 60 years for the plant.

Transient scenarios have to be considered under incidental and accidental conditions. Due to an indirect cycle, the secondary circuit is depressurized in case of a reactor trip. Some dispositions are proposed to limit the time duration of the depressurized state which occurs at high temperature level.

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Five representative transients have been retained in the pre-conceptual phase:

- Reactor trip with grid disconnection and turbo machine trip,
- Primary blower trip,
- Loss of Load with turbo machine trip,
- Loss of load to house load,
- Primary break (Loss Of Coolant Accident – accidental situation).

For the LOCA the requirement is to maintain the IHX integrity to prevent (or to limit) air or water ingress from secondary side.

Heat Exchanger integration in IHX pressure vessel is to be achieved considering:

- Overall compactness,
- Good organization of flow distribution,
- Cooling of containment pressure vessel and piping,
- Limitation of thermal mechanical loading in nominal and transient conditions.

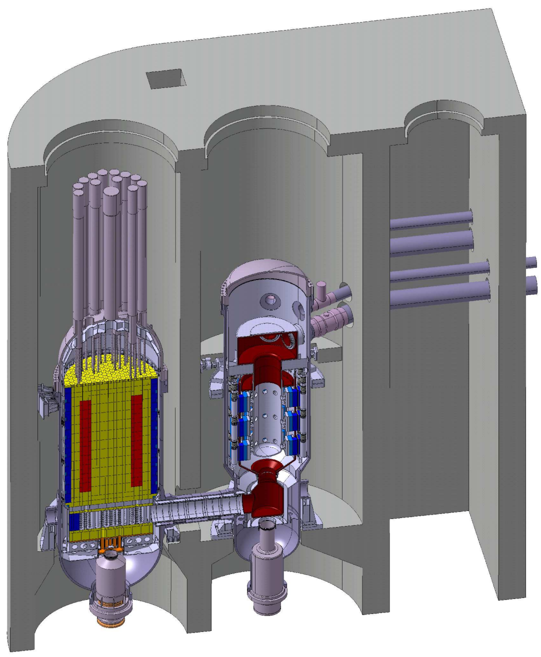

Figure 2: ANTARES primary circuit

III. R&D DEVELOPMENT PLAN

In the framework of a development plan, the EDF (Electricité de France), AREVA-NP, and CEA partnership develops a set of several out-of-pile helium experimental facilities for strengthening theoretical studies, qualifying components mock-up, and models. The objective is to study, to select, to validate and finally to qualify the technological concepts and components:

- Analytical benches, at channel scale, for providing reliable data of thermal hydraulic correlations.
- Small air loops (~ 100 kW), with scale 1 channel geometry mock-up, for testing different technologies (~ 5) and selecting the most promising ones. Both thermal hydraulics and thermal mechanical (thermal cycling) aspects are concerned.
- Existing helium facility (~ 450 kW), for tests in the temperature range 500°C-200°C, in order to verify heat transfer and friction correlations (European Community program – RAPAHEL-FP6).
- Large air loop (~ 1.3 kg/s) for validating the general arrangement of headers and IHX modules, and checking the homogeneity of flow distribution at scale 0.2.
- Technological qualifications (endurance tests) of the most promising technology in representative conditions of temperature, pressure, helium velocity and gas chemistry on a multi-purpose technological loop (~ 1 MW).

The development plan (Table 2) considers the R&D needs in terms of demonstration for the innovative technology, and improvement of the knowledge and experience, linked with the reactor project phases, and in agreement with the general schedule of the construction of the reactor:

Need and Objective	**Reactor Project Phases**		
	Pre-conceptual and conceptual design	**Preliminary design**	**Detailed design**
Analytical benches	Improve data and knowledge		
Small helium loops (< 1 MW)	Technological tests in representative conditions of T, P, V: select the most promising technology among those available Heat transfer and friction correlations in representative geometry	Technological tests in representative conditions of T, P, V: qualification of the chosen technology	
Air loops	Small loops: Technological tests in similitude for selection of the most promising technology	Large loops: Large flow rate tests in similitude and in representative geometry at scale 1, for validating the characteristics of the design	Large loops : idem
Large helium loops (10 MW)			Technological tests in representative conditions of T, P, V, and geometry: qualification of the chosen technology

Table 2 : Tests facilities development plan

IV. HEAT EXCHANGER VALIDATION METHODOLOGY

The problems to be solved are multiple:

a) First of all, the preliminary sizing of the IHX is made with significant uncertainties due to:

- the non-cylindrical geometry of the micro channels (half-cylinder),
- the hydraulic mode of flow in the transitional zone, between laminar and turbulent (Reynolds number range, roughness on the boundary),
- the nature of gas : helium, mixed gas.

Elementary tests on single channel with wall fixed temperature will allow us to measure parameters' influence, and tests in helium at 500°C will be performed in order to validate the friction and heat transfer (Nusselt number) gas correlations and reduce most of the uncertainties.

b) Secondly, the integration of the component in the primary circuit IHX vessel requires association of the design and the mechanical behavior calculations under normal and off-normal reactor operating transients. Some additional tests with representative headers as regards flow distribution will be achieved on a large air loop (PAT - EDF Chatou facility) operated at ambient temperature and atmospheric pressure. The purpose is to verify the gas velocity field, upstream from? the micro channels, in order to detect any distortion effect.

c) Then, and after the choice of the materials between two Nickel base alloys: Inconel 617 and Haynes 230, several industrial compact models should be fabricated in order to be tested, in severe conditions, on air loop CLAIRE (100 kW, 850°C) in Grenoble. The fabrication will require that we master the machining of the plates, the plate welding (diffusion bounding, other…), the headers/plates welding and quality controls.

The objectives are to select one or two promising technologies for the exchange cell, following endurance tests in representative helium operating conditions, on HELITE loop (1 MW, 850°C) at Cadarache.

V. ANATYCAL BENCHES

To accurately design a heat exchanger, it is necessary to get suitable thermal and hydraulic correlations. Using laws from literature generally leads to important uncertainties which may generate significant effects on the size of the heat exchanger when high effectiveness is required. For example, with a semi cylindrical channel, the aim is to verify the applicability of the Petukov-Gnielinski correlation,

$$Nu = \frac{(f/8)(\mathrm{Re}-1000)\,\mathrm{Pr}}{1.07+(900/\mathrm{Re})-\left[0.63/(1+10\,\mathrm{Pr})\right]+12.7\times(f/8)^{0.5}(\mathrm{Pr}^{2/3}-1)}\left(1+\left(\frac{D}{L}\right)^{2/3}\right)\left(\frac{T_b}{T_w}\right)^{n}$$

which is more penalizing than the Colburn one.

Therefore, small test loops are used to validate or to determine laws. CLAIRETTE loop (Figure 3) is suitable for such application. It is an open air loop on which a 4 kW electrical heater can generate a temperature of 550°C for a mass flow rate of 6.5 g/s. If a single fluid is used, it is possible to apply a constant wall transfer rate using an electrical heater on the boundary of the geometry. If an open water loop is added, it is then possible to apply constant wall temperature on the geometry to be tested.

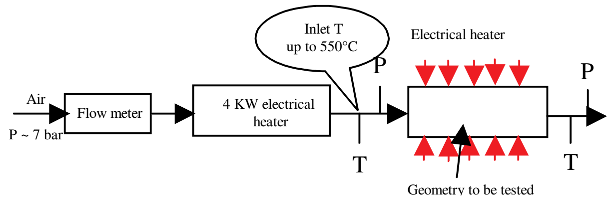

Figure 3: CLAIRETTE loop sketch

If necessary, the air flow rate can be increased up to around 20 g/s and an other heater is on the edge to be added to get higher specifications.
At the present time, the CLAIRETTE loop is used to build thermal hydraulic correlations for enhanced compact designs using metallic foams and mini channels under transitional flow regime (Figure 4). Coupling between local structure and global behavior is concerned. Figure 4 - Mini corrugated channels (courtesy of HEATRIC company).

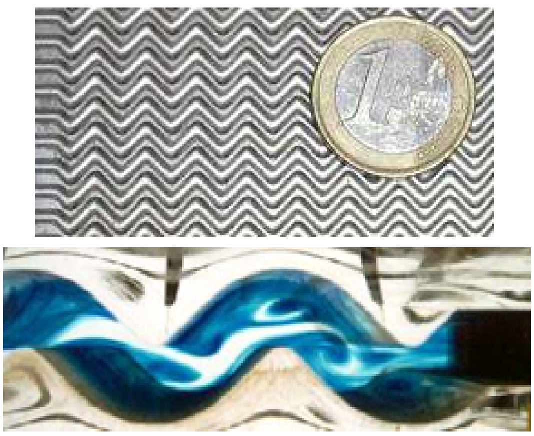

Figure 4 - Mini corrugated channels (with the courtesy of HEATRIC company).

VI. SMALL AIR LOOP FOR TECHNOLOGICAL DEVELOPMENT.

VI.A. Strategy for CLAIRE loop

A small air loop called CLAIRE loop, located at Grenoble, is an R&D tool for technological development of heat exchangers under high temperatures (now at about 550°C, and in 2008 at about 950°C). This loop is well suited for thermal hydraulic component tests (IHX, recuperator, coolers) with real elementary scale (actual plate but with a lesser number than a real heat exchanger), and thermo mechanical fatigue tests.

The main objectives of CLAIRE loop are:

- To validate overall thermal hydraulic performances on a representative scale (actual elementary scale) and under actual temperature.
- To test the strength of components under strong thermal transients.

Finally, the objective of this loop is to give enough information for the selection of technological components such as:

- Heat exchangers (recuperator, cooler) for direct cycle reactor (T < 550°C). They are usually made of stainless steel.
- Intermediate heat exchanger (IHX) for indirect cycle reactor (T > 800°C). They are expected to be made of nickel based alloy materials.

VI.B. Description of the loop

CLAIRE loop (Figure 5) is dedicated to test recuperator mocks-up in nearly actual working conditions.

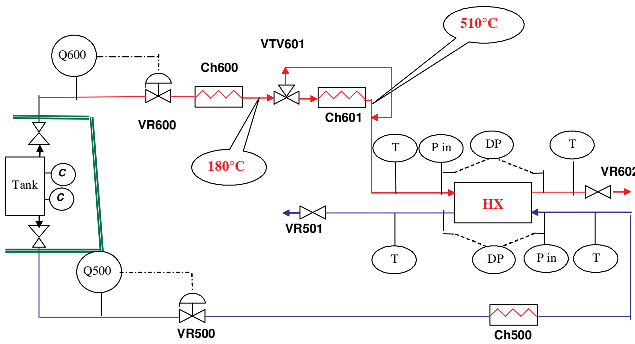

Figure 5: CLAIRE test loop

The loop is designed with the following specifications:

- Maximum mass flow rate on both sides: 0.2 kg/s,
- Maximum inlet pressure: 0.8 Mpa,
- 2 electrical heaters on hot side: 42 kW and 80 kW,
- 1 electrical heater on cold side: 24 kW,
- By commuting the valve VTV 601, it is possible to realize temperature transients by quickly bypassing the heater named Ch 601.

The loop is equipped with the following sensors:

- Mass flow meters on both circuits (Q500 and Q600),

- Differential pressure sensors between inlet and outlet of the two sides of the Heat Exchanger,
- Absolute pressure sensors at the inlet of the two sides of the Heat Exchanger,
- Thermocouples (K type) at the inlet and the outlet of the two sides of the heat exchanger and in several places on the loop for temperature heating regulation.

VI.C. Experimental test conditions

Tests could be carried out for recuperator or IHX in steady and transient conditions:

- For the steady state condition, the choice of the flow rate range is based on Reynolds similarity in order to be representative of helium conditions with air flow. Typically, for the CLAIRE loop, this means that the flow rate is changed from 0.05 kg/s up to 0.2 kg/s to determine thermal and hydraulic laws.
- In transient conditions, the mass flow is kept constant (classically 0.1 kg/s). Since it is not possible to generate all parameter variations (temperature, pressure, mass flow rate), the study focuses on temperature variation effects and to repeat these temperature variations as much as possible. As the hot side of the loop is equipped with 2 heaters (heater 600 and heater 601) it is possible to bypass the second one (heater 601) to quickly vary the inlet temperature of the heat exchanger (Figure 6). The outlet temperatures of heaters 600 and 601 are regulated at 180°C and at 510°C respectively. In the first configuration, the HX inlet temperature is equal to 510°C. If the VTV 601 valve is commutated in 2nd configuration, the HX inlet temperature decreases immediately from 510°C to 180°C, generating a cold shock. In the second way, the hot shock is generated by commutating the valve from the second configuration to the first one. The temperature variation is not immediate since it is the function of the performance of heater 601, so it requires around 4 minutes to reach 510°C at the inlet of the heat exchanger.

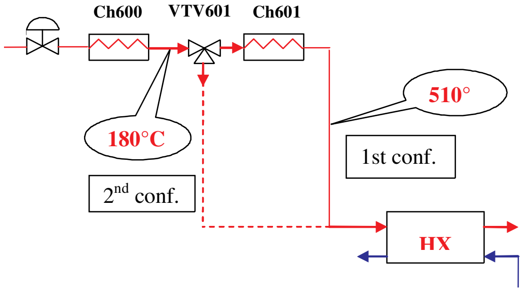

Figure 6: CLAIRE loop in transient configuration

The loop is also equipped with a robot which enables it to create a smoother transition by gradually modifying the heat duty on the electrical heaters. As an example, for HTGR recuperator testing, the following transients have been applied (Table 3):

Cold shock	From 510°C to 180°C within 5 seconds
Hot shock	From 180°C to 510°C within 120 seconds

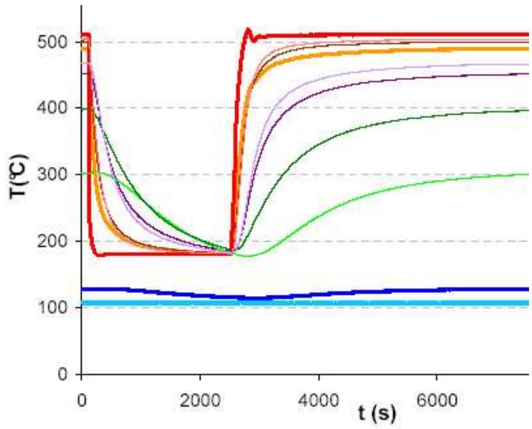

Figure 7: Typical thermal cycle on CLAIRE loop

VII. HELITE – 1 MW (HELIUM LOOP FOR INNOVATIVE TECHNOLOGY)

The main R&D tool, foreseen at Cadarache, will be a multi-purpose technological loop (~ 1 MW), called **HE**lium **L**oop for **I**nnovative **Te**chnology ; which will permit carrying out technological qualifications in representative reactor conditions of temperature, pressure and helium velocity. The HELITE Loop is especially well fitted for the qualification tests on exchangers (IHX, recuperator, coolers).

The main objectives of the HELITE Loop are to validate and qualify the materials, the generic technology (seals, thermal insulation, instrumentation), the helium purification systems, the safety cooling systems, and the technology of components such as :

- Heat exchangers (recuperator, cooler) for direct cycle reactor (T < 550°C).
- Intermediate heat exchanger (IHX) for indirect cycle reactor (T > 800°C).
- Experimental reactor fuel assembly mock-up.

VII.A. Description of the loop

a) Principles of design

The principles of design chosen are:

- to provide experimental conditions (temperature, pressure, velocity, quality of helium atmosphere) in medium (500°C) and high (< 1000°C) temperature test sections, which will be designed for receiving the mock-up and satisfying the experimental program requirements.
- to work at a pressure from 2 to 8 MPa,
- to have sufficient flow rate to be able to reproduce high helium velocity conditions, such as 60 m/s in the reactor hot duct : Helium flow rate chosen at a value of 0,4 kg/s at 5 MPa.
- to reach the high temperature in two stages : 850°C and then 950°C after the development of a second electric heater module intended to increase the power of the heater.
- therefore, the heat exchanged power is around 1 MW.

b) The primary helium circuit description

The primary circuit has a figure eight loop configuration [1]. The loop is filled with helium (Figure 8). Upstream of circulator is at room temperature and the loop pressure is maintained at about half of service pressure by Helium Pressure Circuit (HPC). The circulator provides the helium mass flow for circulation. The helium at 70°C to 150°C is heated first in an exchanger recuperator up to 450°C, and then is heated to the required value of 850°C, after passing through an electric heater. Helium is cooled first by means of a high temperature cooler to 500°C, and cooled again through the recuperator to 150°C. Finally, the helium passes through the low temperature cooler, and its temperature goes down to a temperature less than 50°C before going again through the circulator.

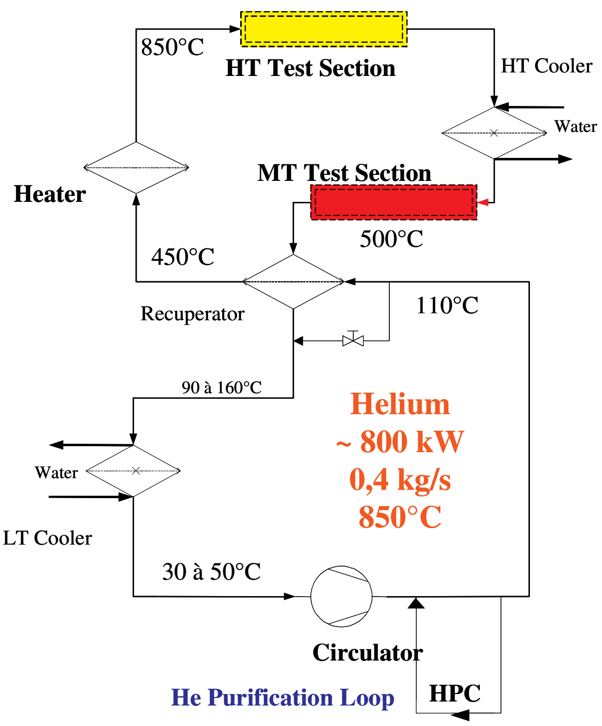

Figure 8: HELITE sketch

The loop will have attached all necessary ancillary systems such as gas purification systems. The principles of the control system are as follows :

- Helium flow rate control: The flow rate is controlled by varying the rotating speed of the circulator, in accordance with the value of the helium flow rate measured in the circuit. The circulator will be designed tocompensate for a pressure drop of 0.38 MPa (including 0.2 MPa in test sections) in the primary helium loop, at the nominal operating point (5.0 MPa, 0,4 kg/s).
- Pressure control: The pressure is controlled by the Helium Pressure and gas Control circuit (HPC), by means of two regulating valves located on the admission and discharge piping in function of the signal given by a pressure transducer.
- Gas chemical composition control (*i.e. § c*): The gas composition is controlled by an HPC circuit. A part of the helium flow is directed to the purification system downstream from the circulator and then back to the main flow path after passing through the purification system.
- Temperature control: The temperature in the HT test section is controlled by the thermal power of the electric heater. The temperature in the MT test section is controlled by the outlet temperature of the HT cooler, fitted by the water cooling flow rate. The inlet temperature of the circulator is controlled by the water cooling flow rate of the low temperature (LT) cooler.
- Transient configurations: HELITE facility is provided with a control system which allows for simulation of the thermal hydraulic transients (ie § VII-D).
- Safety System: Although the control process system monitors the loop continuously, both during normal and abnormal conditions, there is an additional redundant independent protection system. A passive safety system is also provided according to the safety requirements. The safety system is based on:
  - an emergency discharging pneumatic valve able to limit the pressure gradient value, in the loop, under 0.3 MPa/s,
  - a passive safety rupture disk, fitted at a pressure value higher than the depressurization value,
  - a series of isolating valves located on the boundaries of the loop.

c) Helium purification system "HPC"

The performance of the helium purification system impacts directly on the safety of the HELITE loop as it controls the level of impurities in the primary helium that involves potential corrosion phenomena. The helium purification, chemistry and pressure control loop (HPC) will be coupled with the HELITE loop in order to qualify some processes and components.

The impurities foreseen are essentially gaseous ones. The main impurities are N_2, CO, CO_2, H_2O, H_2, O_2, NO, NO_2.

Range of temperature: - 180 °C to 400 °C, Helium flow rate: 20 g/s, Purification level: < 1 ppmV.

The processes used are classical ones, based on filters, oxidation on CuO beds, adsorption on molecular sieves and on activated carbon. The main advantage of such adsorbing units is the regeneration.

VII.B Installation and safety

The explosion risk has been evaluated for the high temperature part of the loop (T helium > 500°C): electrical heater, HT piping, HT test section and HT cooler. The chosen scenario takes into account the explosion of the largest component of this zone, under pressure: the heater. The recommendation is to set the hot piping circuit in a containment (Figure 9) made of 400 mm thick concrete walls and a heavy roof (mass > 100 kg/m²). These safety barriers are to be designed in order to reduce the over pressure outside the hot building, and the risk of projection fragments.

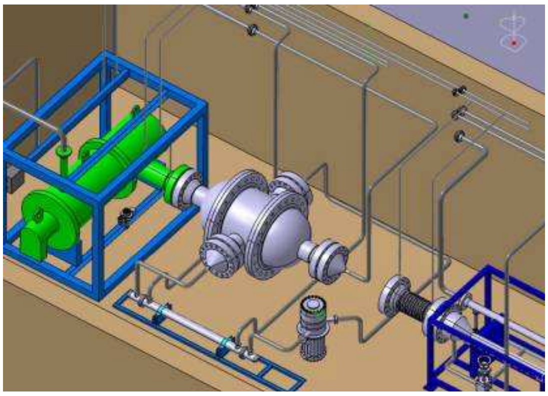

Figure 9: Hot circuit containment

VII.C Schedule

The main milestones of the project are as follows:

- 2005: end of HELITE and helium purification loop HPC detailed studies, and decision for HPC investment (Milestone 1).
- Beginning 2007: decision for HELITE investment (Milestone 2 : 30 months).
- 2007: At first, the HPC loop will work autonomously. Afterwards the loop will be connected to the HELITE in 2009.
- 2009: end of HELITE primary circuit realization, connection of HPC, tests at 850°C (generic technology, exchanger mock-up).

VII.D Experimental program

a) ANTARES model geometry (see § II)

The ANTARES IHX (600 MWth) is comprised of 8 modules (75 MWth each). Each module consists of eight 10 MW power elementary blocks.

b) Experimental limitations

The potential technologies investigated for compact IHX develop a volume power of 25 MW/m3 or more. This value is very important and means that the volume of the model to be tested will be small. For example, a 0.04 m^3 (40 litres) IHX model can be foreseen on a 1 MW heat exchanged loop, as HELITE.

The objective is to test the heat transfer cell at scale 1 (channel hydraulic diameter and length) with a sufficient number of plates for each primary or secondary circuit. Fifteen plates for each circuit are considered a minimum regarding the gas distribution requirements. The length at scale 1 required, the other dimensions are adjusted taking into account the number of plates. Thus, the model won't be fully representative of the feeding headers and distributors. The experimental objectives are the thermal-hydraulics (heat transfer and pressure drop coefficients), and thermal-mechanical behaviors of the model exchange cell in transients and endurance operating conditions.

c) Experimental configurations

Isobaric helium-helium conditions (Figures 10): In this configuration HELITE is fitted to qualify, in representative conditions of helium, temperature, pressure, gas velocity : exchanger recuperator model (T < 650°C) and IHX model (T < 850°C).

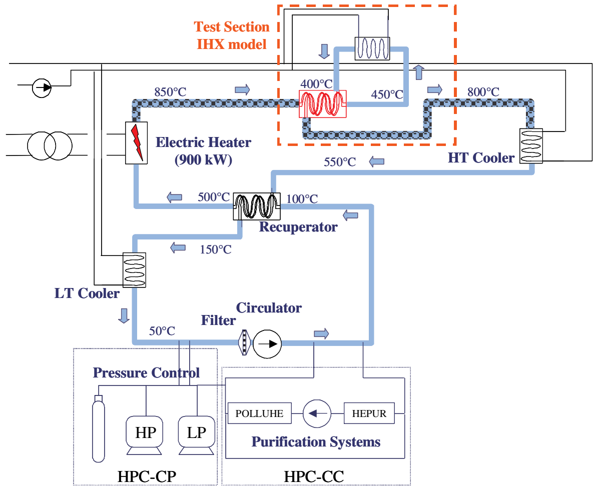

Figure 10: Isobaric helium-helium configuration sketch

Completed HELITE facility (Figure 11):

In this configuration, the HELITE loop is completed with a secondary mixed gas loop and a second electric heater module able to heat helium at a temperature up to 950°C. The loop will be able to test 1 MW Nickel base alloy IHX model in representative conditions of the reactor (950°C, Helium: 0.4 kg/s and mixed gas: 1.1 kg/s, pressure: 6.0 MPa).

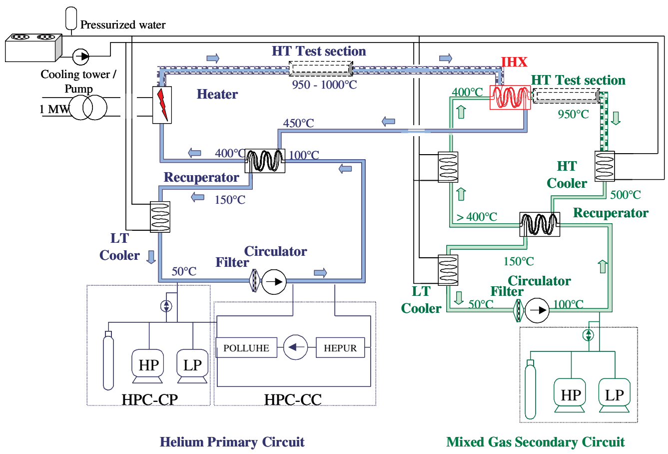

Figure 11: Configuration for IHX tests

Possible transients:

- Temperature ramps in HT test section: from 850°C to 480°C in 100 s (-220°C/min), then 480°C to 200°C in 15 min (-19°C/min), or 850 °C to 380°C in 5 min 30 s.
- Pressure : +0.9 MPa/min et –0.38 MPa/min in 80 s.
- Flow rate : +0,07 kg/s/s and -0,04 kg/s/s.

Component failures will also be simulated on the cooler water pump, on the circulator and on the IHX (channel choking, plugging …).

III. CONCLUSION

In the frame of the partnership between CEA, EDF and AREVA-NP, a strategy for the development of high temperature heat exchangers has been agreed on, covering the needs of all types of Gas Cooled Reactors Projects: HTR, VHTR, GFR, with direct and indirect cycle concepts.
The status and the milestones of the R&D program are the following:

- Medium temperature tests are already completed on CLAIRE facility for two recuperator concepts.
- Analytical tests will be finished at the end of 2006.
- In the framework of RAPHAEL project (European Community), tests should be performed in 2007, with helium at medium temperature range.
- CLAIRE loop enhancement up to 950°C and PAT modifications are planned to be operated in 2008.
- HELITE decision for investment is foreseen in 2007, to be in operation in 2009.

ACKNOWLEDGEMENTS

With acknowledgements to the HTR-E partners and the European Commission.

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