EUROPEAN
COMMISSION

Community Research

RAPHAEL

Contract Number: 516508 (FI6O)

DELIVERABLE (D-CT1.1)

Components specifications for IHX, isolation valves and coolers

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Reporting period: 15/04/2005– 15/10/2006

Date of issue of this report: 03/05/2006

Start date of project: **15/04/2005** Duration: **48 Months**

Project co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Sixth Framework Programme (2002-2006)		
Dissemination Level		
PU	Public	
RE	Restricted to the partners of the RAPHAEL project	X
CO	Confidential, only for specific distribution list defined on this document	

RAPHAEL ***(ReActor for Process heat, Hydrogen And ELectricity generation)***

ReActor for Process heat, Hydrogen And ELectricity generation (RAPHAEL)		
Sub-project: SP-CT **Work package:** 1	**RAPHAEL document no:** RAPHAEL-0604-D-CT1-1	**Document type:** D=Deliverable / M=Minute / P=Progress report / S=Support
Issued by: AREVA NP **Internal no.:** NFPVE DC 1075 A + NESS-G/2006/en/0037 A		**Document status:** Review

Document title

Deliverable D-CT1-1 Components specificationsfor IHX, isolation valves and coolers

Abstract

The aim of this document is to specify the operating conditions and design requirements for the IHX, isolation valves and coolers.

This Deliverable gathers two reports:
The first one issued by AREVA NP France, establishes the RAPHAEL requirements and the typical steady state and transient operating conditions for the IHX based on VHTR ANTARES input data. The helium/water coolers requirements concerning the reactor **S**hutdown **C**ooling **S**ystem and the **M**otor **C**ooling of the main blower are presented and a potential heat application like desalinization or district heating using the energy extracted by the water circuit, have to be evaluated.

The second one issued by AREVA NP Germany, establishes the RAPHAEL requirements and the typical normal and abnormal conditions for closing the Secondary Separation Valves (SSVs).

The requirements for the Secondary Hot Gas Separation Valve (SSV-H) and for the Secondary Cold Gas Separation Valve (SSV-C) based on the requirement that these valves are not highly safety graded.

Revisions

Rev.	Date	Short description	Author	WP Leader	SP Leader	Coordinator
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01						

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A	2006-02-28	MAUGET Christian	FRECON Christophe	PREL	First issue	SERPANTIE Jean-Pol
REV.	**DATE**	**AUTHOR**	**CHECKED BY**	**STATUS**	**MODIFICATIONS / OBSERVATIONS**	**APPROVED BY**

AREVA

CONSORTIUM : **AREVA** Project Code ANTARES	**ANTARES**	**WORK PACKAGE Number**
		ECS Number

ECCN: N

AL: N

TITLE:

RAPHAEL IP - Contract 516508 (FI60)
Deliverable D-CT1.1
Components specifications for IHX and Coolers

DOCUMENT KIND :	**DCC :**	**CONFIDENTIALITY :**
FUNCTIONAL REQUIREMENTS	AJ	RESTRICTED

Framatome ANP		NFPVE DC 1075
Name of the issuing company	**COMPANY CODE**	**DOCUMENT NUMBER**

	Document type
AREVA	FUNCTIONAL REQUIREMENTS
	Confidentiality: RESTRICTED
	Number of pages: 25
	Number of appendices: 0

Document Title

RAPHAEL IP - Contract 516508 (FI60)
Deliverable D-CT1.1
Components specifications for IHX and Coolers

Short Title

RAPHAEL IP - Deliverable D-CT1.1
Specifications IHX and Coolers

Rev	Date	Author	Checked by	Modifications / Observations	Status	Approved by
A	2006-02-28	MAUGET Christian	FRECON Christophe	First issue	PREL	SERPANTIE Jean-Pol

AL: N ECCN: N

Customer Contract Number: Contract 516508	Project ANTARES	NFPVE DC 1075
FANP Contract Number: 40T.3060103 Export Classification : AL=N, ECCN=N	ECS code WBS code	INTERNAL IDENTIFICATION NUMBER

2005.12 ANP 2288

REVISIONS

IND REV	STATUS DATE	PARAGRAPH	SCOPE OF THE REVISION
A	2006-02-28		First issue

SUMMARY

This preliminary document establishes the RAPHAEL requirements and the typical steady state and transient operating conditions for the IHX based on VHTR ANTARES input data.

It could be necessary to re-examine these data by taking into account the HYTHEC process application**.**

The helium/water coolers requirements concerning the reactor **S**hutdown **C**ooling **S**ystem and the **M**otor **C**ooling of the main blower are presented and a potential heat applications like desalinization or district heating using the energy extracted by the water circuit, have to be evaluated.

KEY WORDS

RAPHAEL ANTARES INTERMEDIATE HEAT EXCHANGERS COOLERS FUNCTIONAL REQUIREMENTS

ABBREVIATIONS

IHX	Intermediate Heat Exchangers
PCHE	Printed Circuit Heat Exchanger
PFHE	Plate Fin Heat Exchanger
VHTR	Very High Temperature Reactor

ECCN: N
AL: N

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0. REFERENCES

[1] HTR – E 02/08 D-2-1-0 /B (11/01/2003) HTR-E Recuperator – Specifications of typical operating conditions for HTR

[2] Minutes (M-CT02) SP – CT – RAPHAEL /HYTHEC interfaces meeting July 28TH? 2005 AREVA Tower

[3] D-CT1.0-6-1 (3/08/2005) – Work plan RAPHAEL IP ST-CT-Component Development Heat Exchangers, valves and vessel Work plan of the work package WP-CT-1 – Deliverable n°1

[4] Minutes (M-CT4) SP – CT – Component Development – Second Progress meeting October 20 and 21th, 2005 AREVA Tower

[5] RAPHAEL IP Contract n° 516508 (FI60) Annex I “Description of work”

[6] NFPVE DC 1074/A – WP CT2 – Deliverable D-CT2.1 Specification for helium circulator

[7] Minutes (M-SI0.3) – Second meeting with HYTHEC December 7TH,2005 – AREVA Tower

1. INTRODUCTION

The purpose of this document is to establish the typical steady state and transient operating conditions for the components (IHX and coolers) based on VHTR ANTARES.

The key issues for these components, IHX and Coolers are their compactness and their integrity under the applied loads.

The organisation of this document is as follows :

- function and general description of the component,
- thermal and hydraulic steady state conditions,
- typical transient conditions,
- environment and the quality of fluid,
- the life time,
- the safety requirements,
- inspection requirements during manufacturing and operation,
- space requirements,
- loss of efficiency accepted,
- design rules.

This specification will be defined in accordance with the recommendations issued from Design Safety, Materials, System Integration, Hydrogen Production and High Performance Helium turbine sub-projects.

2. GENERAL DESCRIPTION

2.1. ANTARES program

ANTARES is the **A**REVA **N**ew **T**echnology based on **A**dvanced gas cooled **R**eactor for **E**nergy **S**upply program.

ANTARES has been designed from the start with the flexibility of meeting not only electricity production but also process heat generation, able to produce process heat at above 800°C and co-generate electricity (**Figure2**). Its indirect cycle configuration allows such a possibility without affecting the nuclear heat source.

The competitiveness of a modern HTR indirect cycle is directly linked to the reliability of the **I**ntermediate **H**eat e**X**changers. The integration of the IHX modules inside the component vessel should be achievable without major difficulties and without penalty on the vessel size requirement.

3. RAPHAEL PROJECT

RAPHAEL is the **R**e**A**ctor for **P**rocess heat, **H**ydrogen **A**nd **EL**ectricity generation project.

RAPHAEL aims at developing the HTR/VHTR technologies mainly in the fields of materials and components. The incentive is to integrate the results of the R&D effort in order to provide preliminary assessments of concepts of VHTR plants, coupled with hydrogen production processes.

It was decided during the RAPHAEL/HYTHEC interfaces meeting (**Ref.2**), to adopt the general features of **RAPHAEL** **I**ntegrated **P**roject which are as follows (issued from ANTARES Program):

- indirect cycle arrangement,
- reactor thermal power of 600MWth,
- primary loop arrangement with 2 variants (one loop with plate type IHX and two loops (or more if needed) with tubular IHXs),
- core inlet temperature in the range 390°C to 440°C and core outlet temperature in the range 850°C to 1000°C.

The key design parameters that will affect the choice of materials and, therefore, the needed R&D include the reactor coolant system pressure, the reactor coolant inlet and outlet temperatures, and, in the case of the indirect cycle plants, the choice of the secondary-side coolant and the associated temperatures and pressures of the secondary coolant. According to the major specifications of the VHTR system, the core outlet temperature will be greater than 900°C with a final objective of 1 000°C.

The high-temperature heat from the VHTR will be coupled to the power conversion (in the case of an indirect cycle design with an **IHX** (**I**ntermediate **H**eat e**X**changers)) and hydrogen production (or other process heat application) systems through an intermediate heat transport loop. The intermediate heat transport loop working fluid could be pressurized helium or helium/nitrogen mixture, and molten salt are also envisioned.

A full range of materials test data, including extensive creep, fatigue, and environmental effects data, will be required for qualification of the heat exchanger materials and joining processes. Nevertheless, if the heat exchanger is encapsulated in a secondary pressure vessel, Section III ASME code work may be avoidable and the heat transfer portion of the IHX can be qualified under ASME Section VIII.

3.1. Description

This preliminary document defines the operating conditions with an IHX used to transfer heat from primary circuit to secondary circuit of a **V**ery **H**igh **T**emperature **R**eactor with **indirect cycle**. The functions and requirements has been established for the pre-conceptual design of the ANTARES program.

In this pre-conceptual design (**Figure 3**), the IHX are located into the component vessel to the side of the reactor vessel, the communication between the component vessel and the reactor vessel is provided by the concentric cross duct. Depending on the IHX design mainly, the number of components and component vessels could be different (with IHX compact designs or tubular type design).

For information, the document in **Ref.1**, defines the typical operating conditions and functional requirements for an HTR with **direct cycle** (GT-MHR type, PBMR type).

3.2. RAPHAEL/HYTHEC interfaces

The **HYTHEC** (**HY**drogen **THE**rmochemical **C**ycles) is a long term massive hydrogen production route application, two cycles are envisaged: **S-I cycle** and Hybrid-Sulfur cycle.

To get this objective, HYTHEC is interested in using a nuclear energy source. The IHX requirements related to the coupling of a RAPHAEL/HYTHEC have to be defined. In particular, the main thermal characteristics in normal operating conditions and in accidental events will have to be elaborated.

The preliminary HYTHEC/RAPHAEL interfaces have been presented during the last meeting, December 7^{th}, 2005 AREVA Tower (**Ref.7**) and are given in the **Figure 3**.

4. INTERMEDIATE HEAT EXCHANGERS

The **IHX** must be a highly reliable boundary between the primary and the secondary coolants, compact, and thermally efficient. **PCHE** (**P**rinted **C**ircuit **H**eat **E**xchangers) or **PFHE** (**P**late-**F**in type compact **H**eat **E**xchangers) are favoured because of their size and high efficiency. Shell and tube heat exchangers can be a back-up option.

Metallic materials for the IHX and reactor outlet pipe will be exposed to a reactor outlet coolant temperature of up to 900°C with a final goal of 1 000 °C. For a near term application, advanced Nickel base alloys grades such as: Inconel 617, Haynes 230 and Hastelloy XR are being investigated.

Materials for very high temperature are not currently approved for use by ASME Code Section III. Development of metallic super-alloys and ceramic materials (SiC) and coatings are expected as longer term materials for temperature higher than 900°C. Notably, oxide dispersion-strengthened (ODS) alloys based on Iron or Nickel, could provide a class of materials capable of operating at very high temperature.

The characteristics of the recommended steel will be produced by the sub-project SP-ML through the Deliverable D-ML2.2.

4.1. Thermal and hydraulic steady state conditions

The VHTR ANTARES selected cycle is presented into **Figure 2**.

In steady state, the ANTARES IHX nominal operating conditions are provided in the **tables 3** and **4** respectively for electricity supply and for process heat supply. It is postulated that the IHX has to remove a conservative value of 610MWth power including the core power and the main primary gas circulator power.

The main input data are related to pressure, temperature for both design (**tubular or plate type**) into **table 4** are proposed for RAPHAEL application (**Ref.4**).

4.2. Typical operating conditions

4.2.1. Design normal and incidental transients conditions

The incidental transient conditions are issued from the ANTARES IHX nominal operating conditions given in the **table 3**.and are to be used at this stage of the project as "**working" values**.

The expected transients to be considered for the design, in first and 2nd category events are mainly:

- Reactor trip,
- Primary blower trip,
- Loss of secondary flow-rate.

The results of the transients are respectively presented into the **Figures 4, 5** and **6.**

The **reactor trip** transient with grid disconnection and turbo machine trip (**Figure 4**) is a cold shock, the primary inlet temperature is decreasing from 850°C to approximately 450°C in 400 seconds, the maximum pressure difference value is 4 MPa between primary and secondary side.

The **primary blower trip** transient (**Figure 5**) is also a cold shock in the secondary side, the secondary outlet temperature is decreasing from 800°C to approximately 400°C in 40 seconds, the maximum pressure difference maximum value is 3 MPa between primary and secondary side, the primary mass flow-rate is around 0 in 40 seconds.

The **loss of secondary flow-rate** transient (**Figure 6**) is a hot shock, the primary outlet temperature is increasing from 390°C to approximately 500°C in 80 seconds, the maximum pressure difference value is around 4 MPa between primary and secondary side at 80 seconds of the beginning of the transient.

The occurrence number for each event is **100** ("working" values) during the lifetime of **20 years**.

These preliminary design conditions could be updated by taking into account the input data proposed for RAPHAEL application (**Figure3**), if agreed.

4.2.2. Design accidental transients conditions

In case of primary break (one occurrence), classified in accidental transients conditions, the primary pressure drops from the nominal value (6MPa) to atmospheric pressure (0.1 MPa) with an average pressure variation of 0.1 MPa/s. All the other parameters are kept constant.

4.3. Environment and quality of fluid

Due to environmental degradation processes from exposure to high-temperature helium with contaminants such as CO, CO_2, H_2, H_2O, and CH_4, the concentration for each impurity has to be clearly specified.

The tritium permeation rate through IHX without permeation barrier has to be evaluated (input data could be: P tritium $=10^{-8}$ bar, value measured in AVR, Peach Bottom, Fort St Vrain and used for HTTR).

4.4. Life time

The expected RAPHAEL Reactor service life is 60 years.

It shall be designed for a 60 years lifetime. For components that cannot be designed for 60-year operation, provisions shall be foreseen in the design for economic replacement of the part or component.

The equipments should be optimized by using replaceable and non replaceable parts in order to allow plant operation during the same lifetime.

The foreseen lifetime at high temperature of the IHX plate type concept is **preliminary stated as 20 years**. For the tubular concept, the foreseen lifetime could be 20 to 30 years.

Concerning the IHX plate type concept, replacing at minimum a failed module by a spare unit should be an objective.

4.5. Safety requirements

The first step for determining the safety classification of this equipment is to identify the safety function.

4.5.1. Safety classification

The safety classification of the equipment is based on the functions performed by the equipment, the consequences of the failure of the equipment to perform its safety functions, the probability that the equipment has to perform its safety function, the failure of the equipment.

The functions of the IHX are:

- to transfer heat from primary system to secondary system,
- to confine radionuclides of the primary helium
- and to separate primary and secondary fluids.

The IHX is not the pressure boundary, this function is ensured by the component vessel.

The IHX is not high safety graded because the helium activity is expected to be low. The consequences of the failure of this safety function are judged with regard to the radiological risks in the environment : if the consequences lead to potentially exceed the design basis radiological limits, the equipment performing the safety function has the highest safety classification ; if the radiological consequences don't exceed the radiological releases accepted for normal operating conditions, the equipment is not safety classified ; Intermediate safety classifications are defined for intermediate radiological consequences.

Nevertheless, the IHX module is “over-class” to Class 2 components due to high reliability level envisaged for plant availability and investment protection reasons.

The IHX module structural integrity has to be maintained to avoid “missile effect” and to damage safety classified equipment or the containment of the primary helium, like component vessel example.

4.5.2. Conclusion of the analysis

The IHX is not high safety classified because the cooling function of the core and the structures, in normal and shutdown conditions should not be a safety function and because the helium activity is expected to be low.

Nevertheless, the features assuring the support could be safety classified and the structural integrity of the IHX required, if their failures could lead to damage safety classified equipment or the containment of the primary helium.

4.6. Inspection requirements during manufacturing and operation

4.6.1. Manufacturing

The requirements from ASME rules (if applicable) concerning the elementary steps of manufacture and associated non-destructive examination are applicable. If the ASME code is not applicable (like diffusion bonding for **PCHE** concept,.….), based on its experience, the manufacturer has to propose complementary tests (bursting tests in severe conditions (to be defined) for example,..) to compensate the lack of rules applicable.

A choice of leak testing method (preferably helium test), has to be checked and a procedure defined in order to get the sensitivity required 5.10^{-8} Pa.m^3/s. Global test criteria in factory: $1.33.10^{-7}$ Pa.m3/s is specified to be performed after complete fabrication in factory of the IHX module.

The pressure test required by ASME Code will be defined regarding design conditions.

A manufacturing record book including engineering drawings (as built), conformity certificates and statements of conformance, design document, material certification and procurements documents, welding documentation, visual, dimensional and non-destructive testing records, pressure testing records and quality records, has to be established.

An installation manual providing the information necessary for the handling, unpacking and installation on site has to be established.

4.6.2. In-service Inspection and repair

Design recommendations have to be issued in accordance with the past experience (Magnox, AGRs,..) on the main components, like heat exchangers for our application. The needed inspections for these components have to be specified, may be developed and certainly qualified.

The IHX is not free from risk of mechanical damage, particularly because of high temperature and the severe pressure and thermal transients.

Its location inside the component vessel, which makes the IHX inaccessible to hand in operation requires high reliability, which must be ensured by design backed up, by in-service monitoring of mechanical and process parameters in order to timely detect any symptom of deviation and to take corrective actions.

There are two different candidate types of IHX, namely the helical tube bundle and the plate-type concept with different potential failures and hence different ISI requirements.

4.6.2.1. Plate-type IHX design concept

Even if industrial experience exists for the plate-type exchangers, the operating conditions which combine high temperature, high pressure and thermal loads in transients are new.

The component surveillance should include monitoring of the process parameters temperature and pressure loss.

Thus continuous surveillance of the helium gas purity is a stringent requirement for this component.

Support vibration will be monitored and acoustic surveillance will detect any collector leakage.

The thermal stresses occur between the thick and the thin structures of the IHX modules, which may lead to local progressive deformation with consequent modification of the component outline dimensions. Strain gauges could be used first for ensuring that local stresses remain within the calculated levels and then surveillance will be pursued forward to ensure that permanent deformations remain within allowable limits over the lifetime of the component.

4.6.2.2. Helical tube IHX design concepts

Helical-tube IHX are proven-technology components and can withstand the operating conditions within the RAPHAEL Project. Tubes can sustain pressure difference and thermal displacements can be accommodated by the flexibility of the helical tube in normal operation and transient conditions.

Monitoring of the thermal cycle will give evidence of no significant fouling, Thus continuous surveillance of the helium gas purity is not a stringent requirement for this type.

Support vibration will be monitored and acoustic surveillance will detect any tube rupture or collector leakage.

The need of repair or component replacement will depend on the amount of associated degradation of the reactor performance or on the excessive level of component vibration.

4.7. Space requirements

The RAPHAEL reactor arrangement proposal is the same as VHTR ANTARES (**Figure 3)**.

The IHX are located inside the component vessel, the preferable maximum vessel diameter is 6 meters, in particular for transportation constraints, and with an objective value of 26 meters height, including primary blower at the bottom side.

The tubular IHX, due to higher heat transfer surface, need more than one component vessel to transfer the thermal power 610MWth (may be four).

4.8. Loss of efficiency accepted

Loss of efficiency accepted has to be defined and will be defined later by the customer.

4.9. Design rules

The IHX design will be based on ASME Code applicable (if possible) for the design and the construction rules of this mechanical equipment. Other potential candidates are RCC-M, RCC-MR and KTA, but it is preferable that finally a single code shall be used.

The adaptation of current industry codes and standards to the RAPHAEL project is an open issue. The development and/or extension of design codes and standards for metallic materials at higher operating temperatures, in “impure” helium environment, and for ceramic materials and ODS alloys could be required.

For fabrication techniques not covered by the code, it could be admitted that licensing will be resolved in the design process of the first of the kind demonstrator.

5. COOLERS

The helium/water heat exchangers used as coolers are to be studied for VHTR ANTARES, in particular for the Reactor **SCS (S**hutdown **C**ooling **S**ystem, figure2, **Ref.6**) application.

The requirements of the operating conditions attached to this component are in table here-under.

		Depressurized Shutdown	**Pressurized Shutdown**
	Transferred Thermal Power (MW)	**5.1**	**5.1**
Helium side	Pressure (MPa)	**0.18**	**6**
	Mass flow rate (kg/s)	**8.2**	**43.0**
	Inlet temperature	**253**	**113**

	(°C)		
	Outlet temperature (°C)	**118**	**88**
Water side	Pressure (MPa)	**5**	**5**
	Mass flow rate (kg/s)	**150**	**150**
	Inlet temperature (°C)	**29**	**29**
	Outlet temperature (°C)	**39**	**39**

The water side outlet temperature seems too low for a potential utilization.

And also:

For the conservation of the low temperature (lower than 80°C) of the motor of the **main blower** (Figure2, **Ref.6**) thus imposes that this one is equipped with heat exchangers. These equipment have to be capable of extracting the losses generated by the motor and the heat fluxes resulting from the surrounding walls of the intermediate heat exchangers.
Helium water exchangers are used, the heat flux to evacuate is approximately **1.2 MW**, the water outlet temperature reaches **64°C**.
The cooler design is a tubular concept, which could also be compatible with potential heat applications like desalination or district heating using the energy extracted by the water circuit.

6. CONCLUSION

This preliminary document establishes the RAPHAEL requirements and the typical steady state and transient operating conditions for the IHX based on VHTR ANTARES input data.

It could be necessary to re-examine these data by taking into the HYTHEC process application**.**

The helium/water coolers requirements concerning the reactor **S**hutdown **C**ooling **S**ystem and the **M**otor **C**ooling of the main blower are presented and a potential heat applications like desalinization or district heating using the energy extracted by the water circuit have to be evaluated.

TABLE 1
ANTARES GENERAL DATA (VHTR FOR ELECTRICITY PRODUCTION)

For tubular concept (with 2 primary loops)

IHX specifications at condition of core outlet Temperature 850°C		
	Primary (hot side)	Secondary (cold side)
Fluid	Helium	Mix 80 % N2 20 % He in mass
Flow rate (kg/s)	**255.0**	**680.4**
Inlet Temperature (°C)	**850**	**339**
Outlet Temperature (°C)	**390**	**799**
Inlet Pressure (MPa)	**5.5**	**5.0**
Effectiveness Maximum Primary Pressure Loss Maximum Secondary Pressure loss	**90 %** **2 %** **4 %**	

ECCN: N

For plate-type concept reference (with one primary loop)

AL: N

IHX specifications at condition of core outlet Temperature 850°C		
	Primary (hot side)	Secondary (cold side)
Fluid	Helium	Mix 80 % N2 20 % He in mass
Flow rate (kg/s)	**255.0**	**680**
Inlet Temperature (°C)	**850**	**339**
Outlet Temperature (°C)	**390**	**799**
Inlet Pressure (MPa)	**6**	**5.5**
Effectiveness Maximum Primary Pressure Loss Maximum Secondary Pressure loss	**90 %** **2 % (1.5 % core IHX)** **4 % (3 % core IHX)**	

TABLE 2
ANTARES GENERAL DATA (VHTR FOR PROCESS HEAT PRODUCTION)

For tubular concept (with 2 primary loops)

IHX specifications at condition of core outlet Temperature 950°C		
	Primary (hot side)	Secondary (cold side)
Fluid	Helium	Helium
Flow rate (kg/s)	**210**	**210**
Inlet Temperature (°C)	**950**	**340**
Outlet Temperature (°C)	**390**	**900**
Inlet Pressure (MPa)	**5.0**	**4.5**
Effectiveness Maximum Primary Pressure Loss Maximum Secondary Pressure loss	**90 %** **2 %** **2 %**	

For plate-type concept (with one primary loop)

IHX specifications at condition of core outlet Temperature 950°C		
	Primary (hot side)	Secondary (cold side)
Fluid	Helium	Helium
Flow rate (kg/s)	**210**	**210**
Inlet Temperature (°C)	**950**	**340**
Outlet Temperature (°C)	**390**	**900**
Inlet Pressure (MPa)	**5.5**	**5.0**
Effectiveness Maximum Primary Pressure Loss Maximum Secondary Pressure loss	**90 %** **2 %** (1.5 % core IHX) **2 %** (1.5 % core IHX)	

FIGURE 1
VHTR SELECTED CYCLE

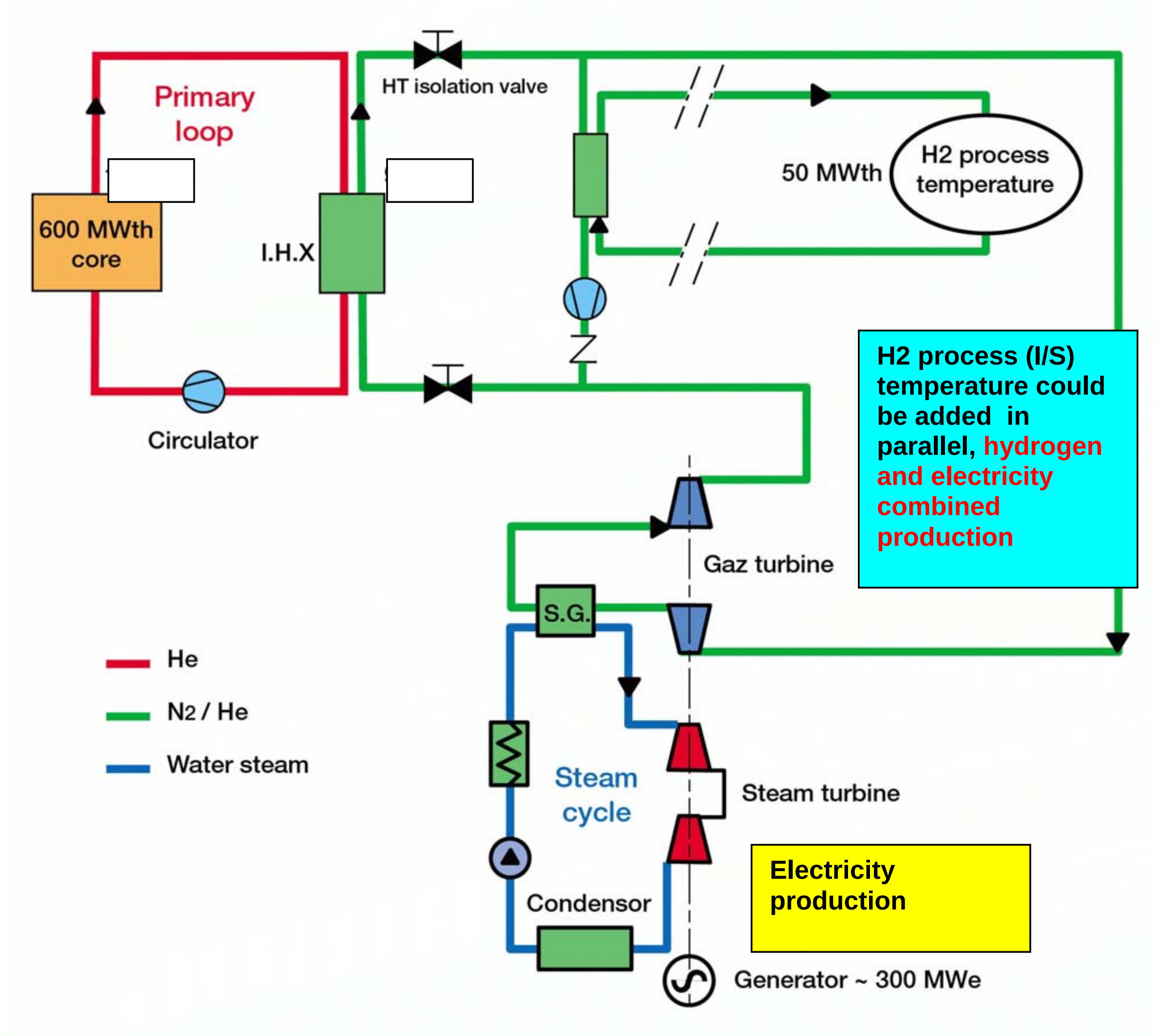


FIGURE 2
ANTARES PROGRAM – REFERENCE CONCEPT

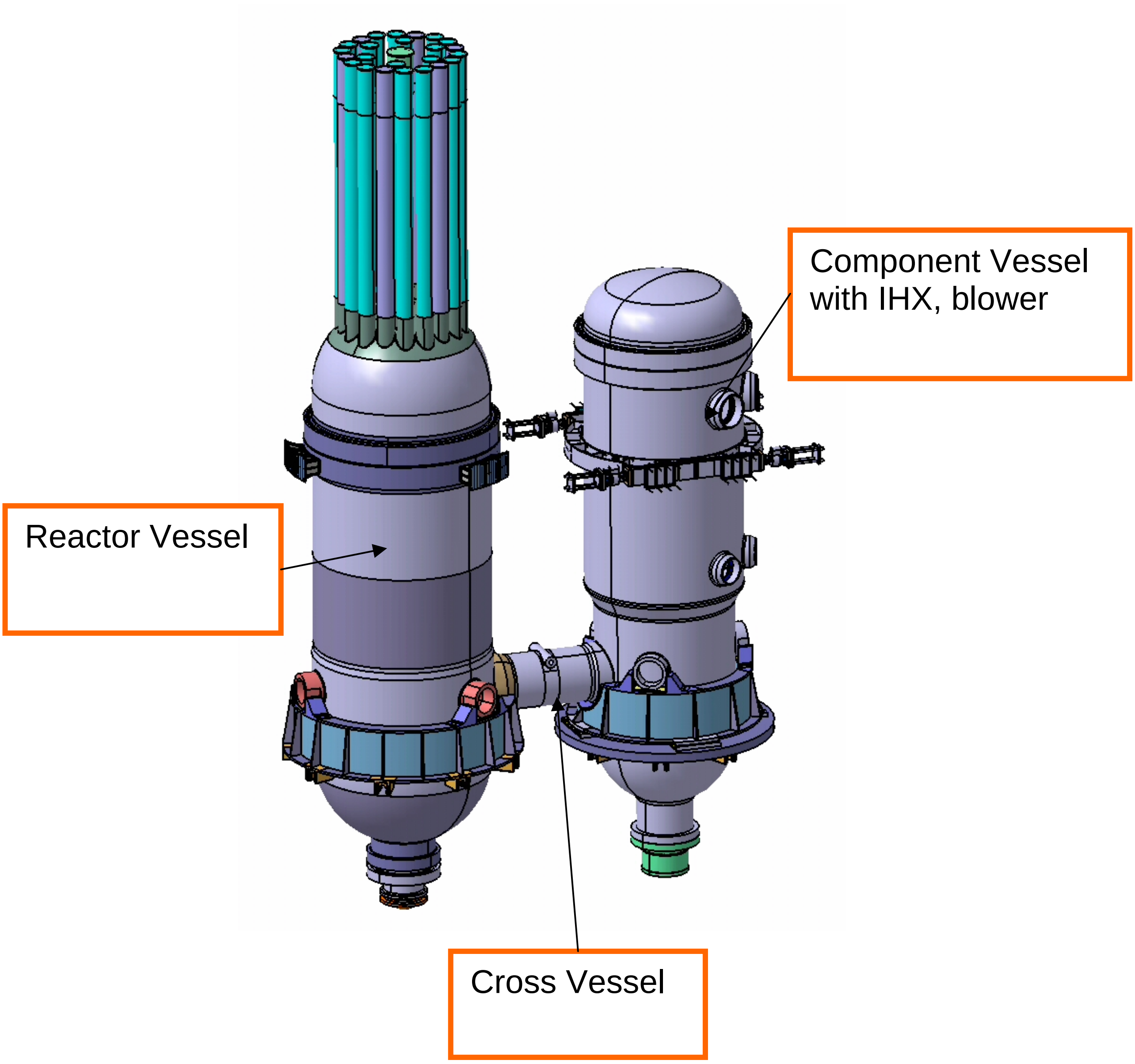
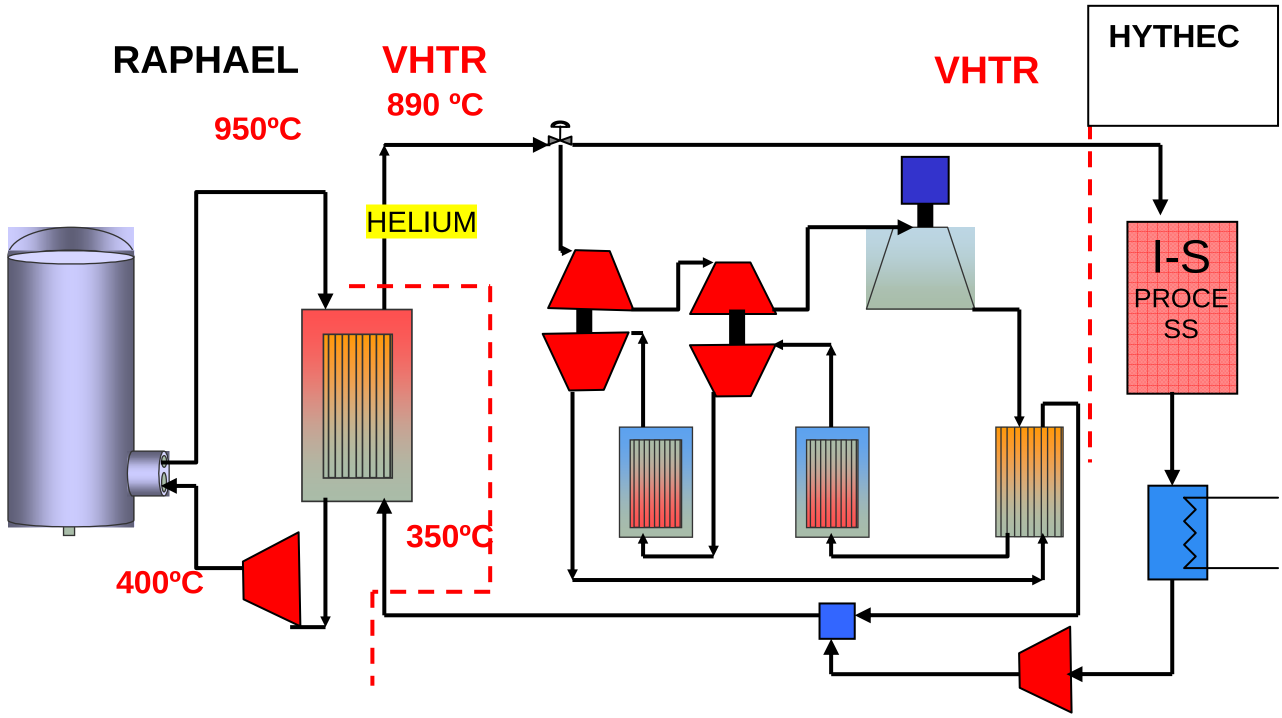


FIGURE 3
EXAMPLE OF CYCLE ARRANGEMENT FOR HYDROGEN AND ELECTRICITY COMBINED PRODUCTION

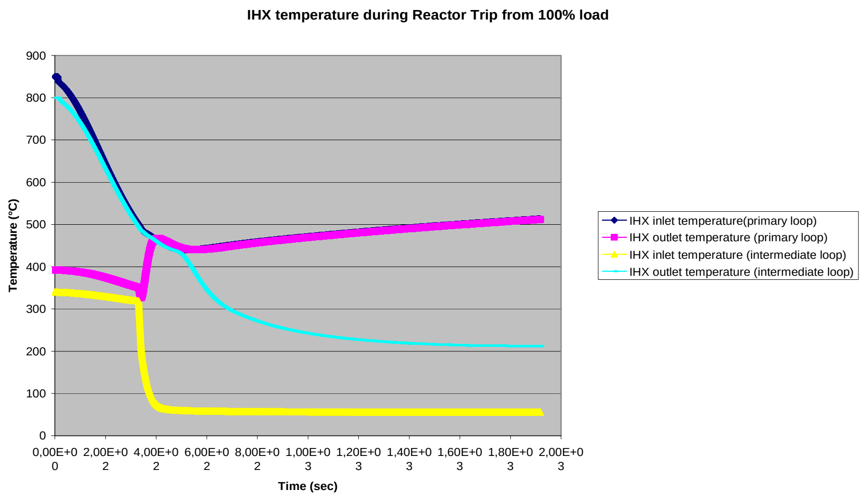


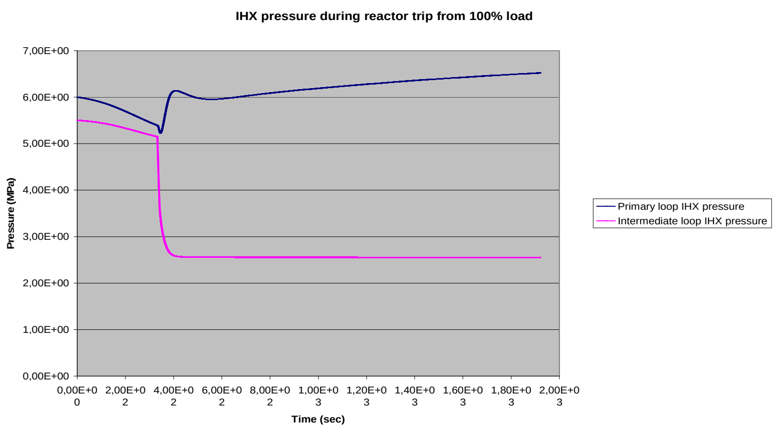
IHX duty (MWth)		613
Primary Loop	Tin/Tout IHX primary (°C)	**950*** / 387
	m IHX primary (kg/s)	209,95*
	Pin IHX primary (MPa)	5,5*
	Pout IHX primary (MPa)	5,4
	Tin/Tout IHX secondary (°C)	350 / 890
	m IHX secondary (kg/s)	218,93
	Pin IHX secondary (MPa)	5*

(*) REFERENCE VHTR PLANT DESIGN DATA (RAPHAEL-HYTHEC MEETING : DECEMBER 7TH, 2005 AREVA TOWER, REF.7

AL: N ECCN: N

FIGURE 4
REACTOR TRIP





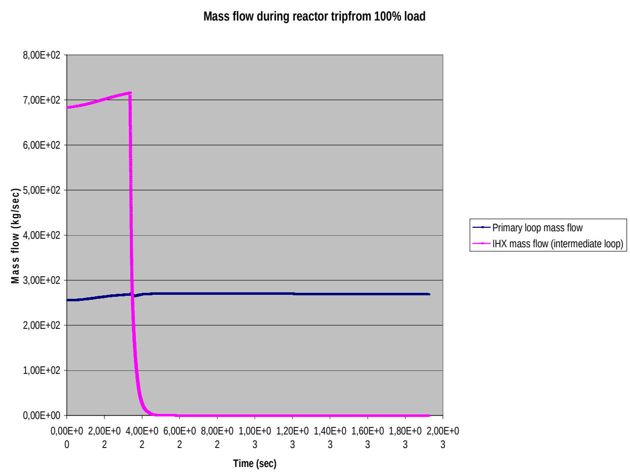
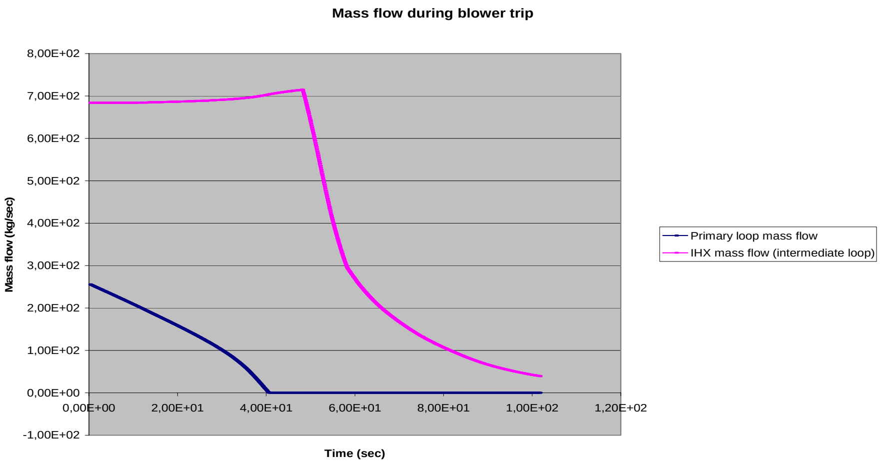
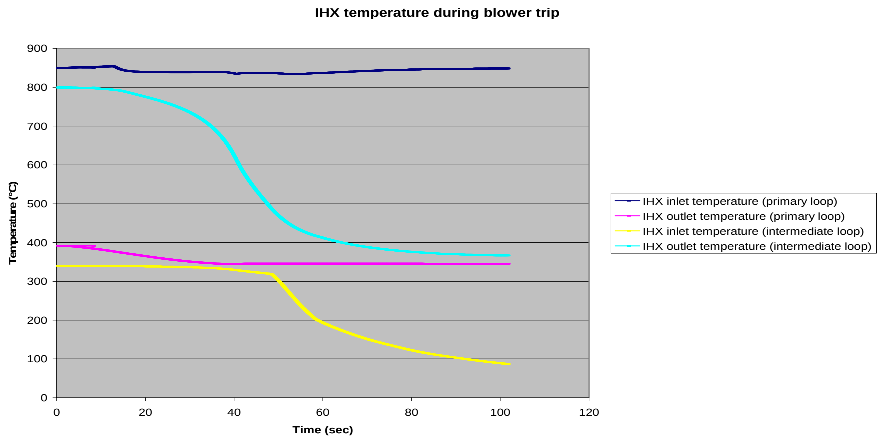


FIGURE 5
PRIMARY BLOWER TRIP





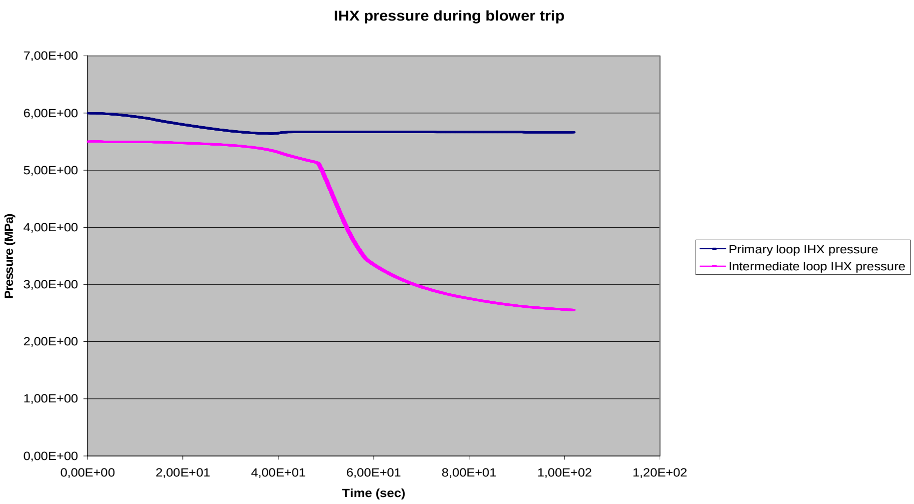


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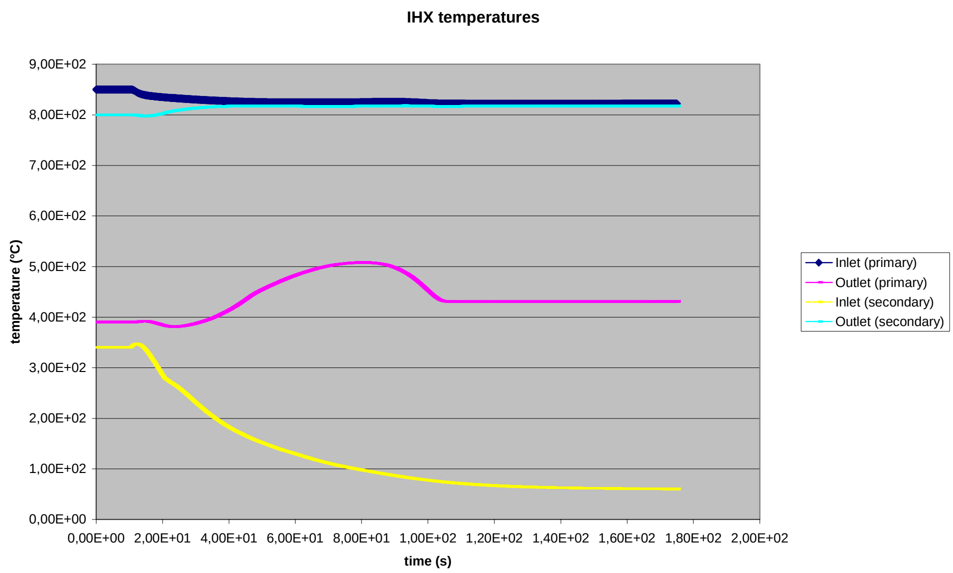
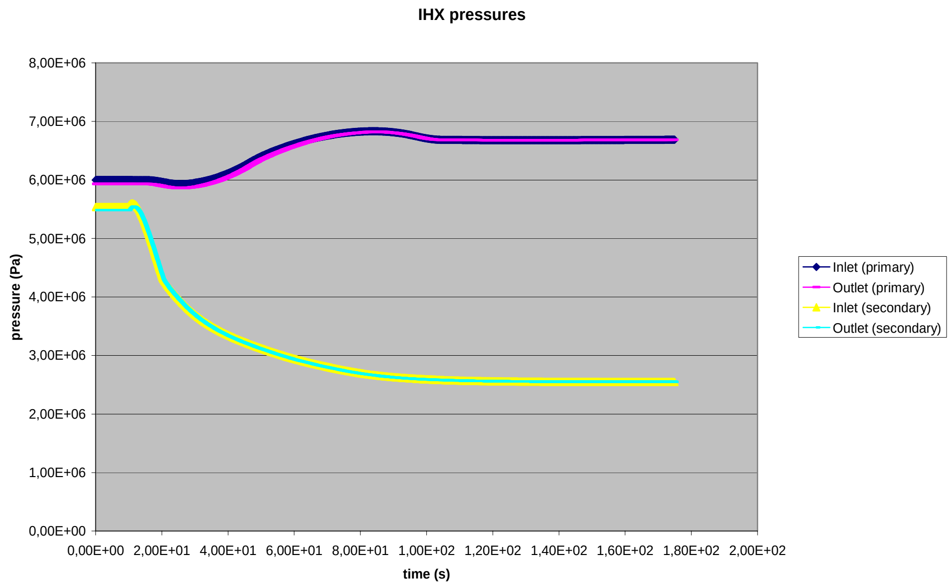
FIGURE 6
LOSS OF SECONDARY FLOW-RATE





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AL: N

AREVA

Work-Report

Ref. (Department/Year/Language/Serial No.)	Rev.
NESS-G/2006/en/0037	**A**

Subject/Title

RAPHAEL IP – Contract 5165508 (FI6O)
Deliverable D-CT1.1
Component specification for valves

Place	Date
Erlangen	30.04.2006

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ANTARES

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Handling Instructions

RESTRICTED

Export Classification (Reports with techn. content)

AL: N ECCN: N

Released by concerned department (content, handling, distribution)

released for external distribution

Proj.-Code	UA	DCC	Contents Code
ZFY116	BB	M BB	

Doc. Ident. No.

0600431310

Pages of Text: 26 Appendices -- Pages total: 26

Summary

This preliminary document establishes the RAPHAEL requirements and the typical normal and abnormal conditions for closing the Secondary Separation Valves (SSVs).

It could be necessary to reexamine these data by taking into account the HYTHEC process application.

The requirements for the Secondary Hot Gas Separation Valve (SSV-H) and for the Secondayr Cold Gas Separation Valve (SSV-C) based on the requirement that these valves are not highly safety graded.

Distribution

List of revisions

Rev.	Date	Scope of revision	Section/Page
A	30-04-2006	First issue	all

KEY WORDS

RAPHAEL ANTARRES SECONDARY SEPARATION VALVES FUNCTIONAL REQUIREMENTS

ABBREVIATIONS

IHX	Intermediate Heat Exchangers
PCHE	Printed Circuit Heat Exchanger
PFHE	Plate Fin Heat Exchanger
VHTR	Very High Temperature Reactor
PHGD	Primary Hot Gas Duct
SHGD	Secondary Hot Gas Duct (only the appendix between IHX and SSV-H)
SSV-H	Secondary Sepration Valve – Hor Gas Side
SSV-C	Secondary Separation Valve – Cold Gas Side
RPS	Reactor Protection System

TABLE OF CONTESTS

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REFERENCES

[1] HTR - E 02/08 D-2-1-0 /B (11/01/2003) HTR-E Recuperator - Specifications of typical operating conditions for HTR

[2] Minutes (M-CT02) SP - CT - RAPHAEL /HYTHEC interfaces meeting July 28TH , 2005, AREVA Tower

[3] Minutes (M-CT4) SP - CT - Component Development - Second Progress meeting October 20 and 21th, 2005 AREVA Tower

[4] Minutes (M-SI0.3) - Second meeting with HYTHEC December 7TH, 2005 - AREVA Tower

1. INTRODUCTION

The purpose of this document is to establish the typical steady state and transient operating conditions for the SSV-H and SSV-C based on VHTR ANTARES.

The key issues for these valves is to separate the nuclear plant from the conventional secondary loop by any abnormal condition inside the plant. This requirement is a main issue to protect the highly loaded IHX from too high pressure and temperature transients.

The organisation of this document is as follows:

- function and general description of the two valve types,
- thermal and hydraulic normal conditions,
- thermo and hydraulic conditions during closing,
- environment and the quality of fluid,
- the life time,
- the safety requirements,
- inspection requirements during manufacturing and operation,
- space requirements,
- pressure drop,
- design rules.

This specification will be defined in accordance with the recommendations issued from Design Safety, Materials, System Integration, Hydrogen Production and High Performance Helium turbine sub-projects.

2. GENERAL DESCRIPTION

2.1 ANTARES program

ANTARES is the **A**REVA **N**ew **T**echnology based on **A**dvanced gas cooled **R**eactor for **E**nergy **S**upply program.

ANTARES has been designed from the start with the flexibility of meeting not only electricity production but also process heat generation, able to produce process heat at above 800°C and co-generate electricity (Figure 1). Its indirect cycle configuration allows such a possibility without affecting the nuclear heat source.

The competitiveness of a modern HTR indirect cycle is directly linked to the reliability of the **I**ntermediate **H**eat e**X**changers (IHX) and to separate the nuclear plant from the conventional secondary loop by closing the SSVs. The integration of the IHX inside the component vessel or vessels should be achievable without major difficulties. The reference plant design is shown in figure 2.

3. RAPHAEL PROJECT

RAPHAEL is the **R**e**A**ctor for **P**rocess heat, **H**ydrogen **A**nd **EL**ectricity generation project.

RAPHAEL aims at developing the HTR/VHTR technologies mainly in the fields of materials and components. The incentive is to integrate the results of the R&D effort in order to provide preliminary assessments of concepts of VHTR plants, coupled with hydrogen production processes.

It was decided during the RAPHAEL/HYTHEC interfaces meeting (Ref.2), to adopt the general features of **RAPHAE**L **I**ntegrated **P**roject (IP) which are as follows (issued from ANTARES Program):

- indirect cycle arrangement,
- reactor thermal power of 600MWth (only core power),
- primary loop arrangement with 2 variants (one loop with plate type IHX and two loops (or more if needed) with tubular IHXs),
- core inlet temperature in the range 390°C to 440°C and core outlet temperature in the range 850°C to 1000°C.

The key design parameters that will affect the choice of materials and, therefore, the needed R&D include the reactor cooling system pressure, the reactor coolant inlet and outlet temperatures, and, in the case of the indirect cycle plants, the choice of the secondary-side coolant and the associated temperatures and pressures of the secondary coolant. According to the major specifications of the VHTR system, the core outlet temperature will be higher than 900°C with a final objective of 1 000°C.

The high-temperature heat from the VHTR will be coupled to the process heat application through an intermediate heat transport loop. The intermediate heat transport loop working fluid could be pressurized helium or helium/nitrogen mixture, and molten salt are also envisioned.

A full range of materials test data, including extensive creep, fatigue, and environmental effects data, will be required for qualification of the SSV-H materials and joining processes. Nevertheless the SSVs can't be built in general as a class 1 reactor component. They will be specified with a very high quality according to the pressure boundary (may be class 1), but with less quality for the internals, but high reliability.

3.1 Description

This preliminary document defines the operating conditions with an IHX used to transfer heat from the primary circuit to the secondary circuit of a **V**ery **H**igh **T**emperature **R**eactor (VHTR) with indirect cycle. The functions and requirements have been established for the pre-conceptual design of the ANTARES program.
In this pre-conceptual design (Figure 3), the IHX are located in the component vessel at the side of the reactor vessel, the connection between the component vessel and the reactor vessel is provided by the coaxial cross duct. Depending on the IHX design mainly, the number of components and component vessels could be different (with IHX compact designs or tubular type design).

The SSV-H connected directly to the IHX-pressure-Vessel nozzles and the reference concept is shown in figure 4. The connecting nozzles entering the IHX pressure vessel in the secondary part of the pressure vessel. This means the nozzles to the secondary loop are arranged only in the secondary envelope and not in the area with primary gas.

The design of the nozzles for the plant with tubular IHX is a little bit different. The secondary hot gas duct between the IHX-hot gas outlet and the SSV-H inlet is arranged in a coaxial design and this is important for the stress analysis because the secondary hot gas duct is classified as an internal and not as a pressure pipe (Figure 5).

For information, the document in Ref.1 defines the typical operating conditions and functional requirements for an HTR with direct cycle (GT-MHR type, PBMR type).

3.2 RAPHAEL/HYTHEC interfaces

The **HYTHEC** (**HY**drogen **THE**rmochemical **C**ycles) is a long term massive hydrogen production route application, two cycles are envisaged:

- S-I cycle,
- Hybrid-Sulfur cycle.

To get this objective, HYTHEC is interested in using a nuclear energy source. The SSVs requirements related to the coupling of RAPHAEL/HYTHEC have to be defined. In particular, the main thermal characteristics in normal operating conditions and in accidental events will have to be elaborated.

The preliminary HYTHEC/RAPHAEL interfaces have been presented during the last meeting, December 7th, 2005 AREVA Tower (Ref.7) and are given in Figure 3.

4. SECONDARY SEPARATION VALVES

The SSVs have to separate the nuclear power plant from the conventional secondary loop under normal and abnormal conditions. To minimize the loads to the SSVs the closing procedure will start always at the end of normal or abnormal transients.

For the SSV-H an axial valve based on the former GERMAN HTR-Program will be used because this valve has a small size and a very low pressure drop.

For the SSV-C it may be possible to use nuclear valves for pressure water reactors (e.g. EPR) with some special modifications. This has to be clarified with the manufactures.
As a back up option it is possible to use for the cold gas lines the same valve as for the hot gas lines with some modifications of the inside design (no inner insulation will be needed).

Metallic materials inside the SSV-H will be exposed to a secondary outlet coolant temperature of up to 800°C with a final goal of 900 °C (see Table 1 and 2). For a near term application, advanced Nickel base alloys grades such as: Inconel 617, Haynes 230 and Hastelloy XR are being investigated.

Materials for very high temperature are not currently approved for use inside possible regulation systems. Development of metallic super-alloys, fibre insulations and coatings for the valve seat are expected as longer term materials up to the temperature of 900°C.

The characteristics of the recommended steel will be produced by the sub-project SP-ML through the Deliverable D-ML2.2.

4.1 Thermal and hydraulic steady state conditions

The VHTR ANTARES selected cycle is presented into Figure 2.

In steady state, the ANTARES nominal secondary operating conditions are provided in the tables 1 and 2 respectively for electricity supply and for process heat supply.
The given data are calculated by the requirement that the IHX has to remove a conservative value of 610 MWth power including the core power and the main primary gas circulator power. With this thermal power level and the temperature difference between the IHX inlet and outlet the secondary mass flow is calculated.

The main input data related to pressure and temperature for both designs proposed for RAPHAEL are as follows (Ref.4).

4.1.1 Design conditions

The design conditions are:

	SSV-H	**SSV-C**
Inlet Temperature	800 °C up to 900 °C	300 °C up to 400 °C
Outlet Temperature	Max. 800 °C up to 900 °C	Max. 300 °C up to 400 °C
Inlet Pressure	6.0 MPa up to 7.0 MPa	6.0 MPa up to 7.0 MPa
Pressure Drop	Max. 0.1 bar	Max 0.2 bar
Temperature Drop	Max. 1K	Max. 1K
Closing time up to leakage rate 10^{-1} mbar*l/s	30 sec.	30 sec.
Closing time up to leakage rate 10^{-6} mbar*l/s	3 minutes	3 minutes

This design conditions covers all possible operation conditions and the SSVs can be used in all possible plant arrangements and possible variations.

4.1.2 Normal operating conditions

During normal operation conditions the normal temperatures and pressure levels don't change and the closing conditions are following:

Normal operating conditions	**SSV-H**	**SSV-C**
Start up conditions for Closing procedure		
Medium Temperature	800 °C up to 900 °C	300 °C up to 400 °C
Medium Pressure	Max 7.0 MPa	Max. 7.0 MPa
Mass Flow Medium	10% from normal mass flow	10% from normal mass flow

Conditions after closing		
Medium Temperature	800 °C up to 900 °C	300 °C up to 400 °C
Medium Pressure	Max 7.0 MPa	Max. 7.0 MPa
Pressure difference valve seat	Max. 5 bar	Max. 5 bar
Mass Flow Medium	0 kg/s	0 kg/s
Conditions for long time closing (after refilling IHX appendix)		
Medium Temperature	Max. 800°C up to 900 ^C	Max. 300 °C up to 400 °C
Medium Pressure	Max 7.0 MPa	Max 7.0 MPa
Pressure difference valve seat	Max. 6.9 MPa	Max. 6.9 MPa
Mass Flow Medium	0 kg/s	0 kg/s

During the long time closing conditions it is possible that the secondary loop behind the SSVs is depressurized for inspection or repair conditions. The appendix inside the IHX and between the SSVs is still under normal conditions to minimize the pressure loads to the IHX.

4.1.3 Abnormal operating conditions

The expected abnormal conditions to be considered for the design, in first and 2nd category events are mainly:

- Reactor trip,
- Primary blower trip,
- Loss of secondary flow.

The results of these calculations are not very important for the SSVs because it is assumed that the closing procedure will start at the end of the transient and there are nearly constant conditions inside the secondary loop.

With this requirement the closing conditions only for the VHTR for electrical production are the following:

Reactor Trip	**SSV-H**	**SSV-C**
Start up conditions for Closing procedure	**After 300 sec.**	
Medium Temperature	480 °C	320 °C
Medium Pressure	5.2 MPa	5.3 MPa
Pressure difference valve seat	Max. 2 bar	Max. 2 bar
Medium Mass Flow	Ca. 17 kg/s	Ca. 17 kg/s

	SSV-H	SSV-C
Conditions after closing	**After 400 seconds**	
Medium Temperature	460 °C	80 °C
Medium Pressure	2,8 MPa	2.8 MPa
Pressure difference valve seat	Max. 2 bar	Max. 2 bar
Medium Mass Flow	0 kg/s	0 kg/s

	SSV-H	SSV-C
Conditions for long time closing (after refilling IHX appendix)	**After 750 seconds**	
Medium Temperature	200 °C	80 °C
Medium Pressure	5.95 MPa	5.95 MPa
Pressure difference valve seat	Min. 31.5 bar Max. 58.5 bar	Min. 31.5 bar Max. 58.5 bar
Medium Mass Flow	0 kg/s	0 kg/s

After the SSVs are gas tight the appendix between the SSVs will be pressurised to nearly primary pressure to minimize the pressure loads to the IHX. The pressure behind the SSVs (inside the conventional secondary loop) can be the shut down pressure of the turbine (28 bars) or the secondary loop will be depressurized for repair.

Primary Blower Trip	SSV-H	SSV-C
Start up conditions for Closing procedure	**After 50 seconds**	
Medium Temperature	450 °C	320 °C
Medium Pressure	5.2 MPa	5,3 MPa
Pressure difference valve seat	Max. 2 bar	Max. 2 bar
Medium Mass Flow	Ca. 17 kg/s	Ca. 17 kg/s

	SSV-H	SSV-C
Conditions after closing	**After 350 seconds**	
Medium Temperature	350 °C	80 °C
Medium Pressure	2.8 MPa	2.8 MPa
Pressure difference valve seat	Max. 2 bar	Max. 2 bar
Medium Mass Flow	0 kg/s	0 kg/s

	SSV-H	SSV-C
Conditions for long time closing (after refilling IHX appendix)	**After 750 seconds**	
Medium Temperature	350 °C	80 °C
Medium Pressure	5.75 MPa	5.75 MPa
Pressure difference valve seat	Min. 29.5 bar Max. 56.5 bar	Min. 29.5 bar Max. 56.5 bar
Medium Mass Flow	0 kg/s	0 kg/s

After the SSVs are gas tight the appendix between the SSVs will be pressurized to nearly primary pressure to minimize the pressure loads to the IHX. The pressure behind the SSVs (inside the conventional secondary loop) can be the shut down pressure of the turbine (28 bars) or the secondary loop will be depressurized for repair.

Loss of Secondary flow	**SSV-H**	**SSV-C**
Start up conditions for Closing procedure	**After 80 seconds**	
Medium Temperature	820 °C	350 °C
Medium Pressure	5.3 MPa	5.3 MPa
Pressure difference valve seat	Max. 2 bar	Max. 2 bar
Medium Mass Flow	Ca. 17 kg/s	Ca. 17 kg/s

	SSV-H	SSV-C
Conditions after closing	**After 350 seconds**	
Medium Temperature	320 °C	180 °C
Medium Pressure	3.5 MPa	3.5 MPa
Pressure difference valve seat	Max. 2 bar	Max. 2 bar
Medium Mass Flow	0 kg/s	0 kg/s

	SSV-H	**SSV-C**
Conditions for long time closing (after refilling IHX appendix)	**After 750 seconds**	
Medium Temperature	800 °C	350 °C
Medium Pressure	5.3 MPa	5.5 MPa
Pressure difference valve seat	Min. 38.5 bar Max. 65.5 bar	Min. 38.5 bar Max. 65.5 bar
Medium Mass Flow	0 kg/s	0 kg/s

After the SSVs are gas tight the appendix between the SSVs will be pressurized to nearly primary pressure to minimize the pressure loads to the IHX. The primary pressure raises from 6.0 MPa to 6.7 MPa. Therefore the secondary pressure inside the appendix has to raise to 6.65 MPa. The pressure behind the SSVs (inside the conventional secondary loop) can be the shut down pressure of the turbine (28 bars) or the secondary loop will be depressurized for repair.

The occurrence number for each event is specified:

	60 years plant lifetime	**20 years compo-nent life time**
Reactor Trip	3.600	1.200
Blower Trip	600	200
Loss of Secondary Flow Rate (Loss of Offside Power)	300	100

These preliminary design conditions could be updated by taking into account the input data proposed for RAPHAEL application, if agreed.

4.1.4 Accidental transients conditions

In case of a primary break (one occurrence), classified in accidental transients conditions, the primary pressure drops from the nominal value (6 MPa) to atmospheric pressure (0.1 MPa) with an average pressure variation of 0.1 MPa/s. All the other parameters are kept constant. For the SSVs we can specify the following data:

Primary Break	**SSV-H**	**SSV-C**
Start up conditions for Closing procedure	**After 600 seconds**	
Medium Temperature	820 °C	350 °C
Medium Pressure	5.3 MPa	5.5 MPa
Pressure difference valve seat	Max. 2 bar	Max. 2 bar
Medium Mass Flow	Ca. 170 kg/s	Ca. 170 kg/s

	SSV-H	**SSV-C**
Conditions after closing	**After 900 seconds**	
Medium Temperature	820 °C	350 °C
Medium Pressure	Ca. 28 bar	Ca. 28 bar
Pressure difference valve seat	Max. 2 bar	Max. 2 bar
Medium Mass Flow	0 kg/s	0 kg/s

	SSV-H	**SSV-C**
Conditions for long time closing (after refilling IHX appendix)	**Time after 900 seconds**	
Medium Temperature	820 °C	350 °C
Medium Pressure	Ca. 28 bar	Ca. 28 bar
Pressure difference valve seat	Max. 27 bar Min 0 bar	Max 27 bar Min 0 bar
Medium Mass Flow	0 kg/s	0 kg/s

After the SSVs are gas tight the appendix between the SSVs will be depressurized to the primary pressure to minimize the pressure loads to the IHX. The primary loop is depressurized to 1 bar and also the appendix between the SSVs. The pressure behind the SSVs (inside the conventional secondary loop) can be the shut down pressure of the turbine (28 bars) or the secondary loop will be depressurized too.

4.2 Environment and quality of fluid

Due to environmental degradation processes from exposure to high-temperature mixture (He and N) or helium the concentration for impurities has to be clearly specified.

4.3 Life time

The expected RAPHAEL Reactor service life is 60 years.

It shall be designed for a 60 years lifetime. For components that cannot be designed for 60-year operation, provisions shall be foreseen in the design for economic replacement of the component.

The equipment should be optimized by using replaceable components in order to allow plant operation during the same lifetime.

The foreseen lifetime at high temperature of the SSVs concept is preliminarily stated as 20 years. For the SSV-C it seams to be possible to start with a life time of 30 years because the design will be the same like the big primary valves of EPR.

4.4 Safety requirements

The SSVs have only plant protection requirements e.g. minimize the IHX loads or separate the conventional secondary loop from the nuclear power plant. Therefore only the functional requirement “to close” is a safety requirement.

4.4.1 Safety classification

The SSVs are not highly safety graded because the primary heat transfer medium activity is expected to be low. The classification of the SSVs is equal to or less than the class of the IHX.

Nevertheless due to the geometry of the valves to the IHX vessel for the boundary of the SSVs the quality class of the SSVs is linked to the vessel class.

4.5 Inspection requirements during manufacturing and operation

4.5.1 Manufacturing

The requirements from ASME rules (if applicable) concerning the elementary steps of manufacture and associated non-destructive examination are applicable. If the ASME code is not applicable based on its experience, the manufacturer has to propose complementary tests (bursting tests in severe conditions, to be defined, for example) to compensate the lack of rules applicable.

A choice of leak testing method (preferably helium test), has to be checked and a procedure defined in order to get the sensitivity required 5.10^{-8} Pa.m3/s. Global test criteria in factory: 10^{-6} Pa.m3/s is specified to be performed after complete fabrication in factory of the IHX module.

The pressure test required by ASME Code will be defined regarding design conditions.

A manufacturing record book including engineering drawings (as built), conformity certificates and statements of conformance, design document, material certification and procurements documents, welding documentation, visual, dimensional and non-destructive testing records, pressure testing records and quality records, has to be established.

An installation manual providing the information necessary for the handling, unpacking and installation on site has to be established.

4.5.2 In-service Inspection and repair

Design recommendations have to be issued in accordance with the past experience on the main components like heat seat, the sealing, the insulation system for our application. The needed inspections for these components have to be specified, may be developed and certainly qualified.

The SSH-H is not free from risk of mechanical damage, particularly because of high temperature and the severe pressure and thermal transients.

There are two different candidate types of SSVs namely the axial valve for the hot gas pipe and nuclear valves for EPR with special design for using gas.

4.6 Space requirements

The RAPHAEL reactor arrangement proposal is the same as VHTR ANTARES (Figure 3).

The SSVs are located directly to the IHX vessel appendix and build together a coaxial arrangement for the secondary hot gas duct between the IHX and the SSV-H.

For the building design it’s important to know, that the valves are located outside the IHX cavity and the IHX vessel appendix is located “in the cavity wall”.

4.7 Pressure drop

The pressure drop for the SSV-H is very small with the specified design of the past prototype built in GERMANY and the flow medium helium. For the design of the valve using mixture the maximum pressure drop is specified as 0.1 bar.

For the SSV-C the pressure drop will be bigger as the pressure drop of the SSV-H because the design is nearly a normal seat valve. The maximum pressure drop is specified as 0.2 bars.

4.8 Design rules

The SSVs design will be based on the ASME Code applicable (if possible) for the design and the construction rules of reactor internals. Other potential candidates are RCC-M, RCC-MR and KTA, but it is preferable that finally a single code shall be used.

The adaptation of current industry codes and standards to the RAPHAEL project is an open issue. The development and/or extension of design codes and standards for metallic materials at higher operating temperatures, in "impure" helium environment, could be required.

For fabrication techniques not covered by the code, it could be admitted that licensing will be resolved in the design process of the first of the kind demonstrator.

5. CONCLUSION

This preliminary document establishes the RAPHAEL requirements and the typical steady state and transient operating conditions for the SSVs based on VHTR ANTARES input data.

It could be necessary to re-examine these data by taking into account the HYTHEC process application.

TABLE 1
ANTARES GENERAL DATA: VHTR FOR ELECTRICITY PRODUCTION

For tubular concept (with 4 primary loops and 4 secondary pipe lines)

IHX specifications at condition of core outlet Temperature 850°C

	Primary loop	Secondary loop
Fluid	Helium	Mix 80 % N2 20 % He in
Flow rate (kg/s) in each loop	**4 x 63.75**	**4 x 170,1**
Inlet Temperature (°C)	**850**	**339**
Outlet Temperature (°C)	**390**	**799**
Inlet Pressure (MPa)	**5.5**	**5.0**

For plate-type concept reference (with one primary loop and 4 secondary pipe lines)

IHX specifications at condition of core outlet Temperature 850°C

	Primary loop	Secondary loop
Fluid	Helium	Mix 80 % N2 20 % He in
Flow rate (kg/s)	**255.0**	**4 x 170,1**
Inlet Temperature (°C)	**850**	**339**
Outlet Temperature (°C)	**390**	**799**
Inlet Pressure (MPa)	**6.0**	**5.5**

TABLE 2
ANTARES GENERAL DATA: VHTR FOR PROCESS HEAT PRODUCTION

For tubular concept (with 2 primary loops and 2 secondary pipe lines)

IHX specifications at condition of core outlet Temperature 950°C

	Primary loop	Secondary loop
Fluid	Helium	Helium
Flow rate (kg/s) in each loop	**2 x 105**	**2 x 105**
Inlet Temperature (°C)	**950**	**330**
Outlet Temperature (°C)	**390**	**900**
Inlet Pressure (MPa)	**5.0**	**4.5**

For plate-type concept reference (with one primary loop and 2 secondary pipe lines)

IHX specifications at condition of core outlet Temperature 950°C

	Primary loop	Secondary loop
Fluid	Helium	Helium
Flow rate (kg/s)	**210**	**2 x 105**
Inlet Temperature (°C)	**950**	**340**
Outlet Temperature (°C)	**390**	**900**
Inlet Pressure (MPa)	**5.5**	**5.0**

FIGURE 1
VHTR SELECTED CYCLE

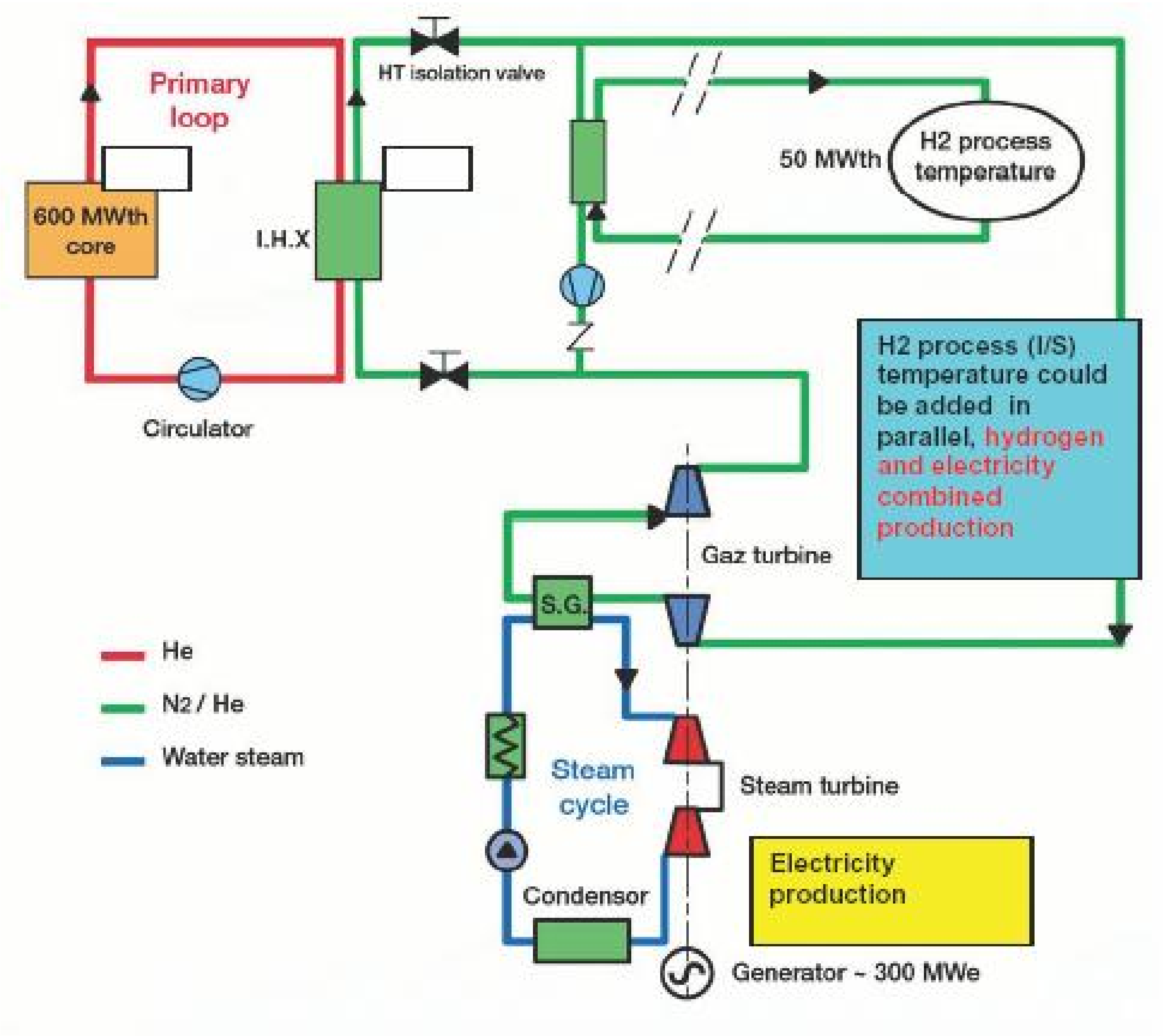


FIGURE 2
ANTARES PROGRAM – REFERENCE CONCEPT

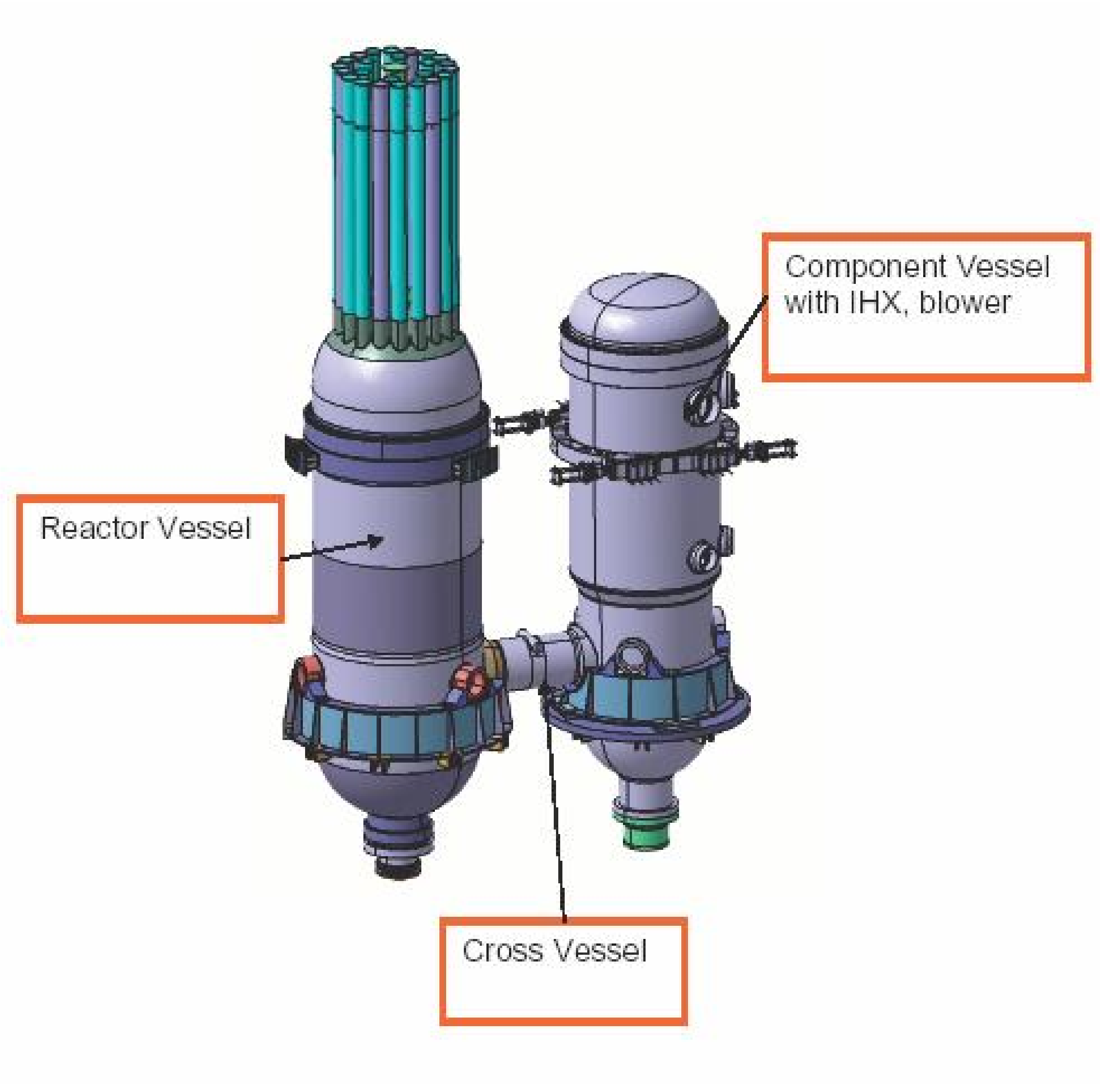
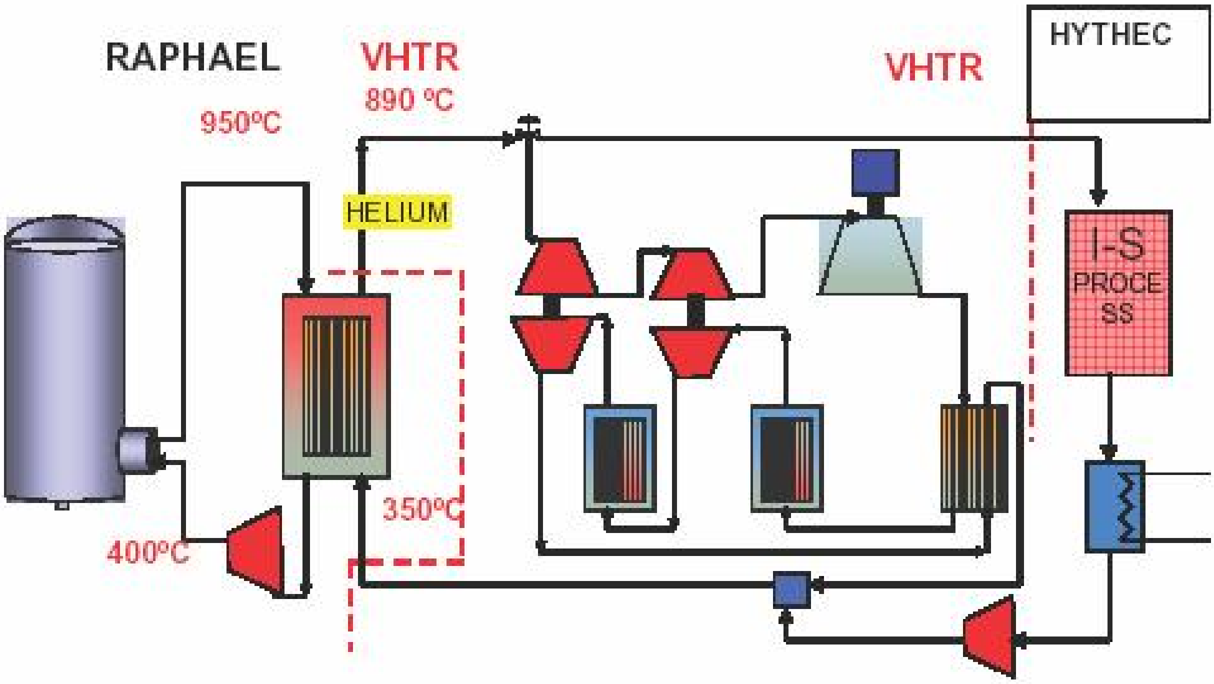


FIGURE 3
EXAMPLE OF CYCLE ARRANGEMENT FOR COMBINED HYDROGEN AND ELECTRICITY PRODUCTION



IHX duty (MWth)		613
Primary Loop	Tin/Tout IHX primary (ºC)	950* / 387
	m IHX primary (kg/s)	209,95*
	Pin IHX primary (MPa)	5,5*
	Pout IHX primary (MPa)	5,4
	Tin/Tout IHX secondary (ºC)	350 / 890
	m IHX secondary (kg/s)	218,93
	Pin IHX secondary (MPa)	5*

(*) REFERENCE VHTR PLANT DESIGN DATA (RAPHAEL-HYTHEC MEETING : DECEMBER 7TH, 2005 AREVA TOWER, REF.7

FIGURE 4
ANTARES VHTR with four secondary pipe lines

ELFD NT 06 0004 PHTS Preliminary Lay Out with PMHE Hot Center IHX

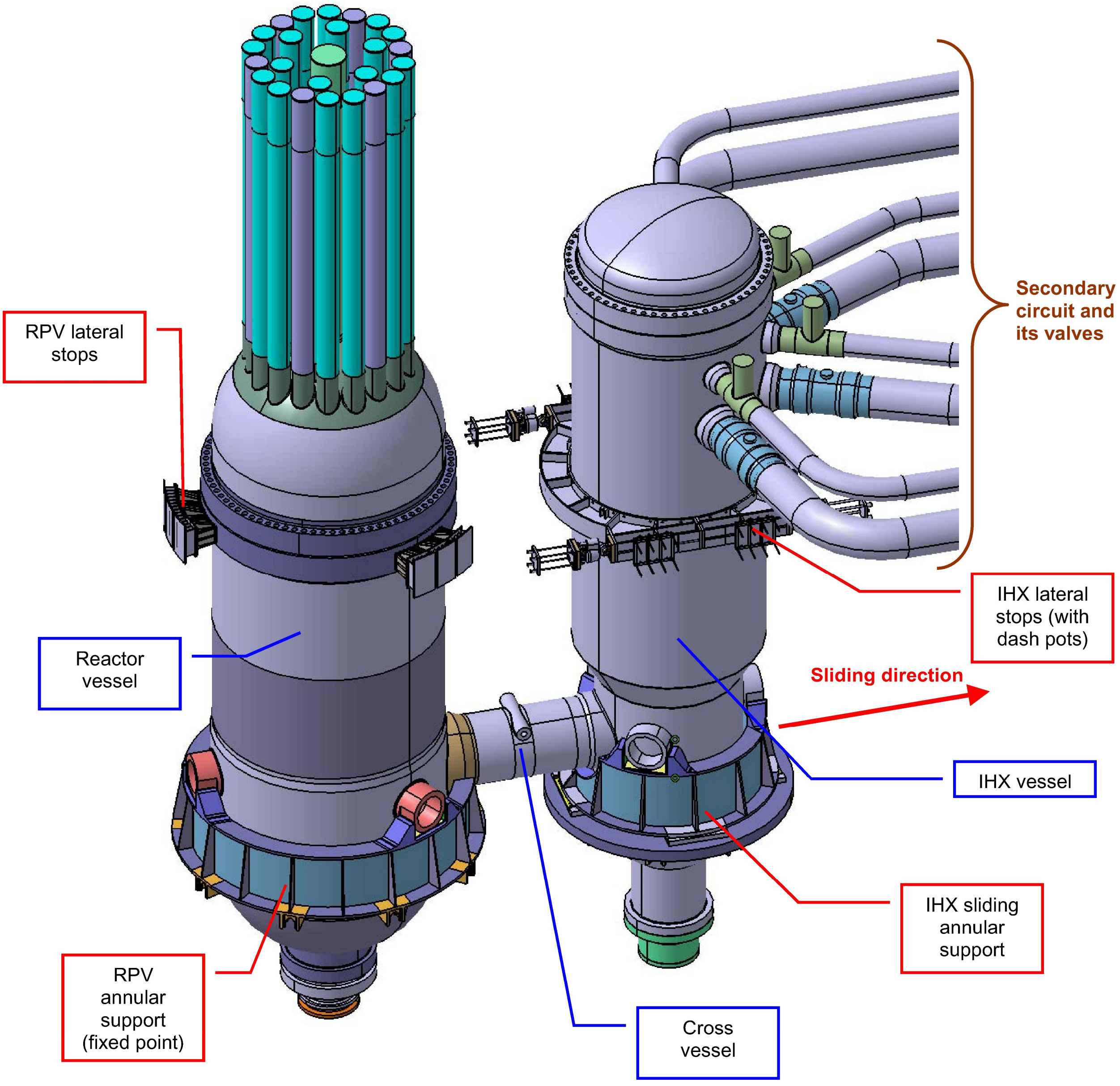


FIGURE 5
SSV arrangement with Tubular IHX