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Specification for helium circulator

Author: **Alain GERBER AREVA NP**

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Deliverable D-CT2-1 Specification for helium circulator

Abstract

The aim of this document is to specify the operating conditions and design requirements for the Main Primary Gas Circulator(s) of the primary circuit of RAPHAEL Integrated Project.

In the RAPHAEL project configurations envisaged so far, the electricity and/or the process heat productions (including hydrogen production) are decoupled from the primary helium circuit via an indirect cycle arrangement. In the case of a VHTR configuration such as developed in the ANTARES program of FRAMATOME-ANP, the circulation of this primary fluid is consequently ensured by a Main Primary Gas Circulator(s).

These requirements are given in the present document with the aim of carrying out functional pre-sizing studies and assess the feasibility and cost of such a component.

Several potential cases must be considered in the design study, depending on whether one or several primary loops are used, and on the gas circulator pressure head.

This document only lays claim to provide preliminary requirements which are more objectives than definite requirements

This component specification will be revised at the end of DIP-2 (Detailed Implementation Plan) phase when comments from SP-ST and designers will be available.

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SUMMARY

The aim of this document is to specify the operating conditions and design requirements for the Main Primary Gas Circulator(s) of the primary circuit of a Very High Temperature Reactor such as developed in the frame of the RAPHAEL Integrated Project. This document is elaborated in the frame of the WP CT2 sub-task and corresponds to the deliverable D-CT2.1, see refs. [1] and [2].

In the RAPHAEL project configurations envisaged so far, the electricity and/or the process heat productions (including hydrogen production) are decoupled from the primary helium circuit via an indirect cycle arrangement. In the case of a VHTR configuration such as developed in the ANTARES program of FRAMATOME-ANP, the circulation of this primary fluid is consequently ensured by a Main Primary Gas Circulator(s).

These requirements are given in the present document with the aim of carrying out functional pre-sizing studies and assess the feasibility and cost of such a component.

Several potential cases must be considered in the design study, depending on whether one or several primary loops are used, and on the gas circulator pressure head. Table 1 summarizes the cases to be considered.

This document only lays claim to provide preliminary requirements which are more objectives than definite requirements.

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KEY WORDS

GAS CIRCULATOR – FUNCTIONAL SPECIFICATIONS

ABBREVIATIONS

ANTARES	AREVA New Technology based on Advanced Reactor for Energy Supply
AMB	Active Magnetic Bearings
CB	Catcher Bearings
DHR	Decay Heat Removal
G1	Primary mass flow-rate
HSS	Helium Services System
HTR	High Temperature Reactor
IHX	Intermediate Heat eXchanger
LOHS	Loss Of Heat Sink
LWR	Light Water Reactor
MPGC	Main Primary Gas Circulator
NHS	Nuclear Heat Source
PGA	Peak Ground Acceleration (used for seism considerations)
Q1	Primary volumetric flow-rate
RCCS	Reactor Cavity Cooling System
SCS	reactor Shutdown Cooling System
SGU	Steam Generator Unit
VHTR-IP	Very High Temperature Reactor – Integrated Project (also called RAPHAEL)

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REFERENCES

[1] RAPHAEL – Contract Number 516508 (FI60) – ANNEX I – Description of work.

[2] RAPHAEL IP – FP6 – SP CT – Component Development – Gas Circulator – Work-plan of work-package WP-CT-2 – Issued by JT: 6GA20190/A, dated July 08, 2005.

[3] RAPHAEL – Contract Number 516508 (FI60) – MINUTES (M-CT04) Second progress meeting – October 20-21, 2005.

0. INTRODUCTION

The aim of this document is to specify the operating conditions and design requirements for the Main Primary Gas Circulator(s), also called MPGC(s), of the VHTR-IP - RAPHAEL.

Main objective of RAPHAEL is process heat production (including hydrogen production) with potential very high levels of temperatures (1000°C of core outlet average temperature is a long-term objective). The possibility to partly produce electricity for external and/or internal needs is not excluded so far. The potentiality to combine both process heat and electricity production is also retained.

The RAPHAEL Nuclear Heat Source (NHS) is based on the physical separation between nuclear reactor and the downstream use (process heat, hydrogen, electricity). This entails in all cases the presence of at least one intermediate gas loop. The heat generated by the nuclear reactor is transferred to this intermediate gas loop through an intermediate heat exchanger (IHX) which is a separate component housed in a pressure vessel. In the case of a VHTR configuration such as developed in the ANTARES program of FRAMATOME-ANP, the circulation of the primary fluid is consequently ensured by the MPGC(s), topic of the present specification.

Rated power of the MPGC(s) will depend on the necessary number of IHXs this last parameter being largely linked to the IHX design type. In the present document two possibilities are examined, the first with two tube-type IHXs, the second with only one plate-type IHX. In the present document, the hypothesis of one MPGC per IHX is retained.

For abbreviations, see page 4.

1. MAIN PRIMARY GAS CIRCULATOR(S) DESCRIPTION

1.1. Situation and environment

The MPGC(s) belongs to the primary pressure boundary system. Its situation within the primary helium loop can be seen on the example of cycle arrangement presented in the figure 1 related to a combined production of electricity (power generation) and hydrogen. Within the primary pressure boundary it is located on the top head of the gas/gas Intermediate Heat Exchanger (IHX) vessel as presented in figure 2; this is the basic configuration for the present specification. This is applicable to both IHX designs, the plate-type and the tube-type IHX. But the option of locating this MPGC(s) at the bottom of the IHX vessel remains in order to favor access and dismounting facilities of the IHX vessel internals through the IHX vessel head if this is further required. For each requirement of the present specification, the supplier shall provide any information which could lead to impossibility / advantages / drawbacks of such a bottom disposal.

The electrical motor shall be submerged in helium in the system and form an integral part with the compressor rotor. This is preferred because this avoids any rotating seal between primary helium and ambient air. A small diameter and limited length machine would be preferred in order to optimize the compactness coping with the primary circuit general layout.

The MPGC(s) interfaces with the IHX vessel basically at the top or bottom of the IHX component. It shall include a shutoff valve to isolate the heat transport system from the reactor vessel when the MPGC(s) is not operational and the Shutdown Cooling System (SCS) is cooling the core.

The rotor of the MPGC(s) shall be supported by Active Magnetic Bearings (AMB) and by Catcher Bearings (CB) for emergency cases (AMBs failure). Permanent Magnetic Bearings are also developed as part of this work package SP-CT WP2.

1.2. General functions

The MPGC(s) is used to control the helium flow to match the heat generation with the heat removal. One possibility to control the helium flow-rate is the modulation of the rotational speed of the MPGC(s) electric motor drive. This allows operating at constant primary helium inventory. This possibility is retained in the frame of the present study.

Helium is pumped by the MPGC(s) to the top of the core through the outer annulus of the concentric cross-duct, then downward through the core and back to the circulator through the IHX, see figure 2.

The MPGC(s) shall ensure the forced primary helium circulation during normal reactor operation. Depending on the kind of transients the MPGC(s) should be required in forced convection or stopped. The primary helium circulation must be stopped in case of loss of secondary power extraction in order to limit the temperature increase of structures which have been designed for “cold” conditions (MPGC(s), vessels, cold internal structures). The failure of the MPGC trip system is considered as a severe accident on the plant and may provide safety concerns, see next section 1.3.

1.3. Safety considerations

MPGC(s) is basically not a safety-related component. From the safety point of view its envelope only participates to the primary pressure boundary.

Because of the reactor design philosophy the primary gas circulation is not needed for achieving the Decay Heat Removal (DHR) function. The DHR safety function is ensured by the Reactor Core Cooling System (RCCS) without need of primary circuit helium circulation.

In normal operation, the decay heat removal function is provided by the Shutdown Cooling System (SCS) and limits the thermal loading on the core, the internal structures, and the reactor vessel. Specified delivery heads and flow-rates have to be ensured by SCS in pressurized as well as in depressurized conditions of the reactor but these functions are not safety-related.

The current assessment for using the MPGC for DHR is the following: in order that SCS can operate the MPGC must be stopped. The MPGC can be used for DHR only in the case of secondary power extraction availability. It could also be useful in case of unavailability of the SCS if bottoming cycles operate. In any case the philosophy for DHR in normal operation is preferably stated on the SCS use if this system exists. As a preliminary assessment there is no requirement on the MPGC during the shutdown states.

In case of a Loss Of Heat Sink (LOHS) due to failure or malfunction of the indirect cycle system, the heat transport by the primary gas circulation has to be broken off in particular in order to limit the increase of the reactor vessel temperature. A reduction of the primary gas circulation is then required. This has to be done by a MPGC trip. This entails the shutt-off valve closing (passive event). In addition, a rapid decrease of the primary circuit mass flow could also be done by depressurization of the primary circuit.

The trip of the primary gas circulation must be reliably provided (preferably including passive means). The MPGC(s) trip should be initiated by detection, in particular, of an abnormal increase of the helium temperature at the IHX outlet (i.e. the MPGC(s) inlet), for instance +50K as a preliminary value. Specific studies are necessary to conclude that this trip is a safety function or not. If a safety function, it must be ensured by passive means.

In any case, the detection of failures in the primary circuit or the intermediate circuit shall lead to, at least, the reactor shutdown, the bottoming cycle trip, the MPGC(s) trip and the consequently closure of its shutoff valve. These actions shall be performed by equipment having a high reliability.

1.4. Number of Main Primary Gas Circulators

This number of MPGCs strongly depends on the IHX technology.

In the next section 2.1, it is explained that two cases are to be considered: one MPGC for the plate-type IHX, and two MPGCs for the two tube-type IHXs (one per IHX).

2. MAIN PRIMARY GAS CIRCULATOR(S) OPERATING CONDITIONS

2.1. Normal steady state conditions

Temperature and pressure conditions at the MPGC(s) inlet are imposed by the IHX outlet conditions.

Total helium flow-rate in the reactor is the sum of individual flow-rates of the implemented MPGCs.

The core thermal power level to retain for the present specification is 600 MWth.

Within a possible range of data, the nominal performance data to be considered for the present specification have been preliminary defined in ref. [3] and are recalled in Table 1:

TABLE 1:
RAPHAEL – NOMINAL DATA RANGE

	Option 1	**Option 2**
Reactor power	600 MWth	600 MWth
Primary fluid	Helium	Helium
Core outlet temperature	950°C	950°C
Core inlet temperature (= T at MPGC outlet)	400°C	400°C
MPGC inlet temperature(*)	≈ 390°C	≈ 390°C
Primary pressure (at MPGC outlet)	5.0 MPa	5.5 MPa
Primary mass flow rate	210 kg/s (105 kg/s per IHX)	210 kg/s
MPGC pressure head(**)	0.15 – 0.2 MPa	0.15 – 0.2 MPa
Number of MPGCs	2 (one per IHX)	1
Type of IHX	Tube-type	Plate-type
Number of IHXs	2	1
Reactor vessel material	9 Cr	9 Cr
Secondary fluid (for information)	He	He

(*) The temperature at MPGC inlet is slightly lower than core inlet temperature in order to take into account of helium heating by the MPGC(s) itself; preliminary value 10K under core inlet temperature.

(**) In each case of this table, the margins are requested to be identified: in particular for the highest value of pressure head (0.2 MPa) which is the most challenging design. The WP-CT leader shall inform the SP leader and the coordinator of the items (cliff edge effect) which could lead to prevent the capability of designing such an “extreme” MPGC.

Other useful data for MPGC(s) sizing at nominal operating conditions of the primary circuit are the following :

- The order of magnitude of the primary He volume is: 1000 m^3.
- Maximal temperature increase through the MPGC(s) : 20 K (preliminary value)
- Helium flow-rate variation preliminary values (mini - max): 30 % (10% if possible) - 110 %

If those parameters are very limiting for the present sizing the supplier will inform the Sub-Project Component Development WP-CT leader for a possible updating of those data.

2.2. Transient operating conditions

The general approach for transients shall be considered:

- In case of normal transient condition, the MPGC shall follow the variations by the appropriate plant control.
- In case of abnormal transient, most of the cases should induce a reactor trip. In that case it is required to stop the MPGC in a few dozens of seconds (preliminary value = 60 s). This avoids any significant hot spot on the normally cold part of primary circuit structures. The normal DHR is ensured by the SCS gas circulator and in case of failure the RCCS should ensure the DHR safety function. As a preliminary conclusion there is no significant transient on the MPGC(s).
- In order to favor availability of the plant:
  - During short time grid loss (< 10 s, realistic value 2 to 3 seconds) the MPGC(s) operability shall allow avoiding to stop the reactor. Active Magnetic Bearings (AMBs), see 3.1.1, must be emergency-supplied by specific means.
  - During short time grid loss, the MPGC shall get some inertia in order to keep a given rotation speed, preliminary value of 80% of nominal speed after 2 s following the grid loss. This is requested to allow the plant not being shutdown and so favoring the overall availability.
  - During long time grid loss (> 10 s, at least > 3 s) the reactor is tripped. The MPGC(s) must be emergency-supplied by specific means. Falling on the Catcher Bearings (CBs) before the reactor trip end shall be considered as an exceptional case. The number of occurrences of such falls is limited to 1 per 10 years (preliminary value). The catcher bearing can be replaced after such an event.
- In case of accident (out of the MPGC), no requirement is asked to the MPGC.
- The safety approach according to earthquake is not yet completely defined for RAPHAEL but for this specification following considerations will be taken into account.
  - The seism level below which the MPGC must be safeguarded remains to be defined. As a first assessment, in order to cover further considerations on seism within future VHTR projects whatever and wherever they are, the seismic level for design is 0.25 g PGA (Peak Ground Acceleration). Horizontal and vertical accelerations are supposed to be the same for this specification.
    - First option to be assessed: the AMBs are able to sustain these loadings. The MPGC shall be able to re-start after examination and limited repair.

- Second option to be examined: the MPGC(s) falls on the CBs, these last can be changed but the MPGC shall be reusable after examination and limited repair.
- In case of a higher scale seism the MPGC(s) may fail but it is required that it does not entail any significant aggression (no significant missile effect) on core (due to blades for instance) or on vessel system (no drill) and on IHX vessel internals.

3. MAIN PRIMARY GAS CIRCULATOR(S) DESIGN REQUIREMENTS

3.1. Design characteristics

3.1.1. Main Primary Gas Circulator(s) support

Active Magnetic Bearings (AMBs) technology will be used to avoid any lubricating product ingress into the primary circuit. Design of the bearings will ensure no interaction problem between electric motor power supply and magnetic bearing supply and control system.

Dynamic performances of the rotor with consideration of gyrostatic effects will be taken into account for the design of the AMBs. The AMBs control system shall be able to compensate the dynamic effects of imbalances. Damping performances will allow operating over the required speed range without being influenced by resonance.

As far as possible auxiliary mechanical catcher bearings (CBs) shall support loads from the MPGC(s) rotor during maintenance operation or at standby conditions or when AMBs fail. It is specifically required that the CBs allow the trip of the MPGC(s) with electrical braking and cold helium injection. Just before end of MPGC(s) braking phase, the AMBs are de-energized for MPGC(s) setting on the CBs; CBs will be accelerated to the MPGC(s) speed over a short time when AMBs are de-energized. Dry lubrication systems available in pure helium will be used for CBs.

3.1.2. Driving motors

The MPGC(s) will be driven by electrical motor(s) capable of rated and variable speeds.

The design is required to favor easy accessibility to internal parts in case of need. In addition a compact design is asked for layout reasons.

Startup when connected to the supply system and re-startup after any system interruption (except if protection) and switchover shall be possible.

3.1.3. Main Primary Gas Circulator(s) thermal insulation and cooling systems

Thermal insulation is required to protect the electrical components (motor, bearings, etc.) by reducing heat migration due to the primary system temperatures within the range [400 - 450°C] in order to cover possible future variations of core inlet temperature in the choice of reference nominal data.

A specific internal cooling circuit is required to maintain a low temperature according to RCC-E requirements or equivalent code for electrical equipments. The requirements for this circuit are as followed:

- The number and size of nozzles on the MPGC(s) casing should be limited at the minimum necessary.
- The nozzles are equipped with isolating valves.
- The casing gas is pure helium, maintained through specific bottles at a slight overpressure above primary circuit helium pressure (preliminary value of overpressure: 0.01 MPa). The helium circulation within the MPGC casing shall be ensured by fans. The requirement is to get as far as achievable a leak-tight connection between helium casing and primary circuit helium in order to get a controlled leakage. The leaky helium should be mixed with primary circuit helium and

the equivalent mass removed to the Helium Services System (HSS) for purification and pressure fitting.

- The circuit devoted to cool the casing helium is flowing inside tubes of an independent circuit:
  - ❖ There is no precise specification so far on the nature of the coolant. Water, air, nitrogen, helium… should be used at this stage of the project. The requirement is that water, air or nitrogen ingress within the primary circuit helium is to be avoided. This can be made through several means: pressure of water or air or nitrogen lower than casing helium, or no use of water, air or nitrogen for coolant.
    - ✓ In case of water or nitrogen use, the circuit shall be a closed one with a reduced volume (0.1 m^3 preliminary value).
    - ✓ In case of air, this circuit should economically be an open circuit.
    - ✓ In case of water, air or nitrogen use, the heat exchanger shall get a robust design to fit with the primary circuit or MPGC casing break: the primary depressurization should not entail the break of the tubes and so the potential water or air or nitrogen ingress within the casing (potentially towards the primary circuit helium after that).
    - ✓ In case of helium used in a closed circuit, the requirement of robustness of the helium/helium exchanger is less severe than for the water, air or nitrogen cases.
    - ✓ The supplier should consider the two extreme cases of water in closed circuit and helium in closed circuit in the frame of the present study.
  - ❖ The internal motor cooling system will be effective when the MPGC(s) runs. In case of failure of this cooling circuit the consequences should be important in terms of investment saving and of availability (not required by the safety): the MPGC should be thermally stressed and probably not be able to correctly operate after that. This is the reason why two redundant (100% thermal exchange capacity each) cooling systems are required.
  - ❖ The internal motor cooling system will be effective when the MPGC(s) are at shutdown states (no rotation) with helium temperatures of the primary pressure boundary up to the nominal values.
  - ❖ This cooling circuit is within the scope of the present specification and the supplier shall consider the interfaces and provide the cooling operational conditions. As preliminary information, the reactor ambient air temperature will not exceed 30°C (preliminary value).

3.1.4. In-service inspection and maintenance

The MPGC(s) ISI and maintenance works should be minimized as far as possible because they decrease the availability of the plant. Possible repair of particular pieces of the MPGC (mainly rotating ones) or replacement by spare unit(s) shall be foreseen. Anyway a 10 years minimum lifetime (preliminary value) shall be ensured for the overall MPGC. The MPGC shall be replaced by a new one during one main outage of the plant. The lifetime will be revised by the supplier according to the research of the economical optimum considering a VHTR plant total lifetime of 60 years.

Access to the upper bearing (basic case of the MPGC positioned at IHX vessel top) and all electrical and coolant connections will be provided for possible maintenance work.

In case of serious repair work, the whole unit shall be withdrawn from the pressure vessel, decontaminated as far as needed, to be repaired outside of the reactor.

The design shall make the MPGC(s) repairable by allowing easy decontamination with simple assembly tools. Any replacement of parts will have to be possible at the site of installation, in the controlled area of the VHTR plant.

3.1.5. Hydraulic characteristics

Hydraulic characteristic shall be as stable as possible over the required speed range without distinctive reversal points and without a pronounced peak.

A one stage machine is preferable, if possible.

Impellers will preferably have a high degree of reaction. They will have to withstand high circumferential speed.

The MPGC(s) shutoff valve shall have only opening and closing functions. The valve mechanism shall move from one end position to the other within a few dozens of seconds (preliminary maximum value for sizing: 30 s). It must begin its closing in a passive mode when the MPGC speed reaches the rotation speed 10%↓ and must open at a relative pressure of 0.01 MPa maximum (preliminary values), it shall open at lower relative pressures if possible in the design.

3.1.6. Materials

Without any specific code applicable for the RAPHAEL, the ASME requirements for material shall preliminary be applied for the MPGC(s). This can be preliminary made because of the low temperatures of the MPGC(s) within the primary helium loop in normal operating conditions. The ASME code shall be applied but it is recommended that the supplier should verify the adequacy of designs choices with other national codes as for instance RCC-M and KTA.

For electrical parts of the MPGC(s), the RCC-E code or equivalent code for electrical equipments shall preliminary be used.

3.1.7. Availability

To achieve high reactor power availability, the MPGC(s) shall have itself a high availability. Well proven components technology shall be first used for design, with easy accessibility for maintenance.

As preliminary values the probability of failure shall not exceed 10^{-1} per year and the cumulated duration of repairs two weeks.

See also §2.2 for the case of short duration grid loss.

3.1.8. Qualification program, prototype and acceptance tests

To be proposed by the supplier.

4. CONCLUSION

The present note only lays claim to provide preliminary operating conditions and design requirements on the MPGC(s). Anyway these are more objectives than definite requirements at the current stage of the RAPHAEL Integrated Project. Table 1 gathers the feasibility cases to consider. Most of precise data provided in this specification are to be considered as preliminary.

Some items merit to be enhanced in this conclusion:

- Both arrangements: one MPGC and two MPGCs, are to be investigated.
- Basic position of the MPGC is at top of PHTS vessel. The supplier is requested to assess the main differences for a bottom disposal.
- The electrical motor shall be fully immersed in the primary helium within a dedicated cavity.
- The rotor of the MPGC shall be supported by AMBs and CBs.
- Compactness is required for layout reasons.
- The MPGC operation is not required by safety.
- The trip of the MPGC and the shutoff valve closing are not considered as safety-related (to be confirmed). At least, the MPGC trip must be reliably provided in case of LOHS. The shutoff valve should be a check valve for coping with a passive operation in case of safety further need.
- For abnormal conditions the current general trend is to systematically trip the MPGC(s) in order to avoid hot shocks on normally cold structures of the primary circuit. The trip of the MPGC must be achieved in a few dozens of seconds, preliminary value 60s. No significant transient on the MPGC is awaited.
- For normal and abnormal operating conditions the necessary cooling circuit of the driving system must remain in operation. Therefore a 100% redundancy is required and the cooling circuit shall be emergency-supplied. The cooling system shall be able to cool the MPGC(s) at their shutdown states (no rotation) with helium temperatures of the primary pressure boundary up to their nominal values. As a source of potential ingress of fluids within the primary system this cooling system is required to be designed against this risk.
- In case of grid loss, the MPGC must keep operating for at least 3 s following the loss (preliminary value). That means that the AMBs must be emergency-supplied in case of need. Some inertia is asked to the MPGC to maintain a sufficient rotation speed before restarting after a short term grid loss: a preliminary value is specified to 80% of nominal speed after 2 s following the grid loss.
- In case of a high level seism the MPGC may fail but without structural consequences on IHX vessel and on reactor vessel: no missile significant effect due the MPGC(s) is asked. As a first assessment, for this specification, a 0.25 g PGA seism level shall be considered for a possible re-use of the MPGC (after examination and a possible limited repair).

FIGURE 1:
EXAMPLE OF CYCLE ARRANGEMENT
FOR HYDROGEN AND ELECTRICITY COMBINED PRODUCTION

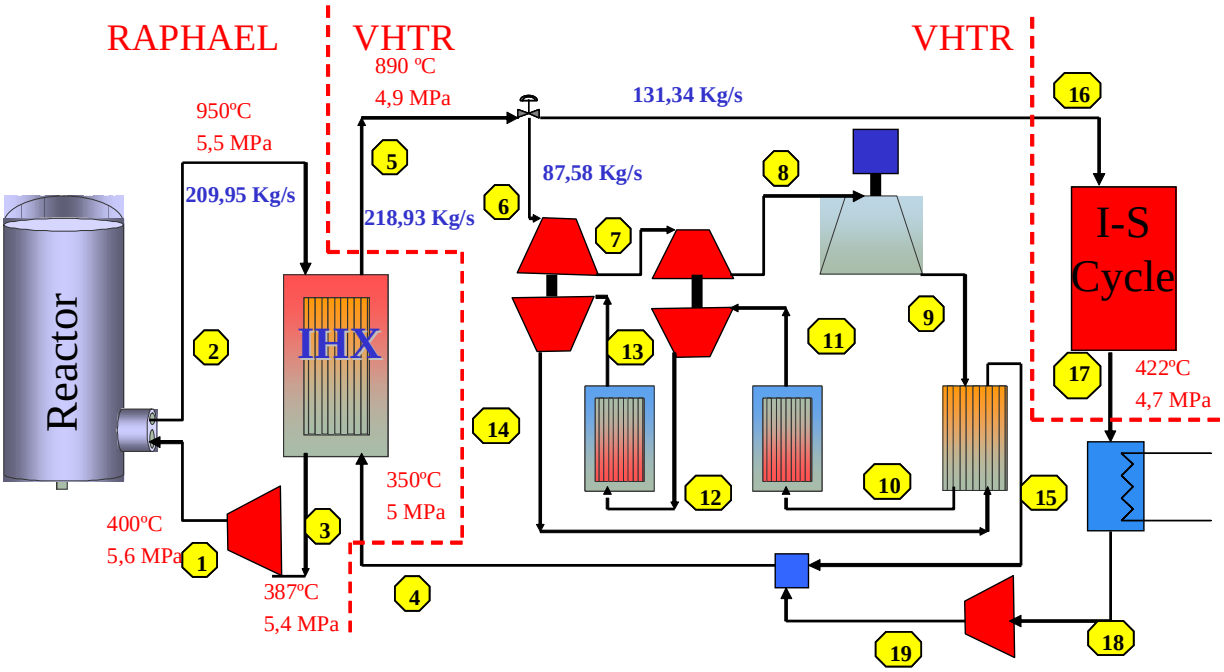

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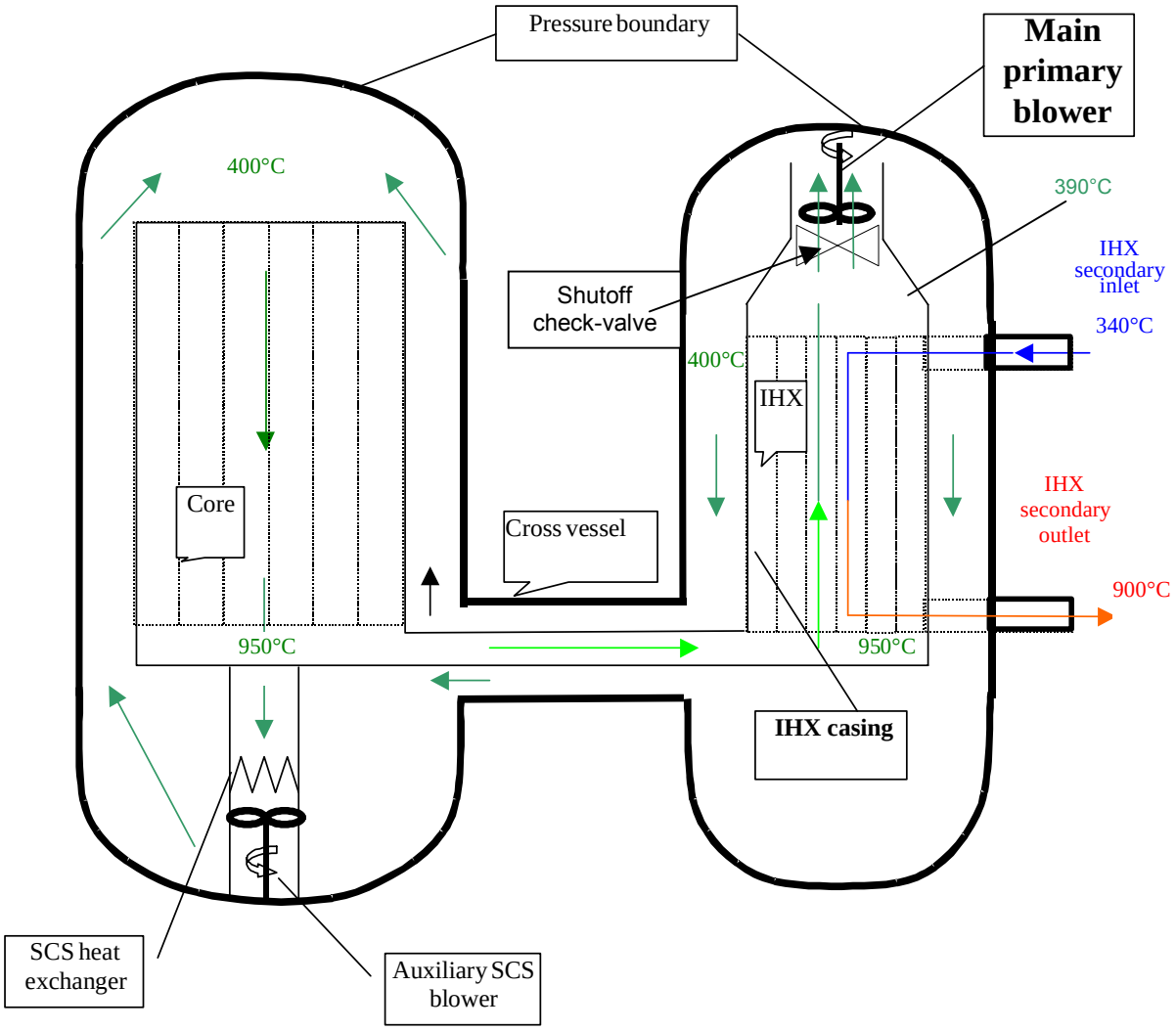
FIGURE 2:
PRIMARY PRESSURE BOUNDARY –
EXAMPLE OF ARRANGEMENT AND OF DATA



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