Technical document: Data set about ASTRID design and operating conditions to be simulated

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Summary

In the frame of the European project TRANSAT (TRANSversal Actions for Tritium), a code benchmarking activity must be performed between calculation tools developed either for the fission reactors or for the fusion machines, in order to evaluate tritium inventory, transfers and potential releases in the different circuits. This study is supposed to be applied to the conditions and characteristics of the ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) sodium fast reactor concept. Two calculation tools will be used for this benchmarking activity: ECOSIM PRO code developed at CIEMAT for the assessment of tritium inventory and migration in fusion systems and the KUTIM code developed at CEA for the assessment of hydrogen and tritium transfers in sodium fast reactors. As a first step of the study, a data set of the circuit and components characteristics as well as operating conditions must be described. In addition to a general presentation of the different transfers to be considered to simulate tritium and hydrogen behavior in Sodium Fast Reactors, this document aims to give the list and the description of data and information necessary for the preparation of calculations applied to ASTRID reactor. Because of confidentiality concerns related to ASTRID design, the numerical values of all data and parameters are communicated separately and under restricted diffusion only to persons in charge of calculations to be performed for this task.

Approval

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Abbreviations

EC DG RTD	European Commission – Directorate General for Research and Innovation
DoA	Description of Action
ECCP	Electronic Collaborative Content Platform
ExCom	Executive Committee
GB	Governing Board
PMO	Project Management Office
PQP	Project Quality Plan
PR	Periodic report
QA	Quality assurance
WP	Work package
WPL	Work package leader
DEN	Nuclear Energy Sector
CEA	French Alternative Energies and Atomic Energy Commission
CAD	CADarache Center
DTN	Department of Nuclear Technology
SMTA	Measurements and modeling of Transfers and Severe Accidents Section
SFR	Sodium Fast Reactor
ASTRID	Advanced Sodium Technological Reactor for Industrial Demonstration
IHX	Intermediate Heat Exchanger
PCS	Power Conversion System
EPuR	Alternative system of residual heat removal
EPX1	Heat exchanger number 1 for residual heat removal
EPX2	Heat exchanger number 2 for residual heat removal
RRA	Residual heat removal system with forced convection
RRB	Residual heat removal system with natural convection

Summary

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1. Introduction

In the frame of the European project TRANSAT (TRANSversal Actions for Tritium) started in September 2017, a 4-year multidisciplinary project was built to contribute to Research and Innovation on "cross-cutting activities" needed to "improve knowledge on tritium management in fission and fusion facilities" [1]. The second work package (WP2) is devoted to "Tritium inventory management and modelling" and is managed by CIEMAT (work package leader) with the collaboration of different european partners, and especially CEA. The objective of task 2.2 "Database development and modelling of tritium migration in fission & fusion processes" is to improve knowledge of tritium inventories in the circuits and to proceed to a code benchmarking activity between calculation tools developed either for the fission reactors or for the fusion machines.

This code benchmarking activity will lead to the improvement of the level of confidence in the tritium inventory estimated by such codes. It was also decided that this benchmarking activity would be conducted on the ASTRID sodium fast reactor concept.

1.1 Subject

The two calculation tools that will be used for this benchmarking activity will be on the one hand the ECOSIM PRO code developed at CIEMAT for the assessment of tritium inventory and migration in fusion systems and on the other hand the KUTIM code developed at CEA for the assessment of hydrogen and tritium transfers in sodium fast reactors.

The first action of task 2.2 consists in the "Description of the circuit and components to be introduced in the simulation" for which CEA will be the major contributor in order to provide a description of the circuits and components of ASTRID reactor, at the level required for the simulation of the tritium mass transfer.

This document aims to give data and information necessary for the preparation of calculations applied to ASTRID reactor:

- a global description of the different transfers and physico-chemical mechanisms involving tritium and hydrogen in the different circuits and components,

- the description of the physical models to be implemented in calculation tools and the numerical values of the required physical parameters (especially for sodium behavior),

- the list and description of characteristics and operating conditions of ASTRID to be implemented in the benchmarking calculations.

Because of confidentiality concerns related to ASTRID design, the numerical values of all data and parameters are not presented in this document but communicated separately and under restricted diffusion only to persons in charge of calculations to be performed for this task. On the base of this data set, the next step actions scheduled in the frame of this task will be the adaptation of the library of ECOSIM PRO (CIEMAT), and then the simulation of tritium mass transfer with ECOSIM PRO and KUTIM and comparison of the results and analysis of the potential differences.

1.2 References

[1] European Commission – Directorate General Research & Innovation - project TRANSAT number 754586 (identification: NFRP-14) – Annex 1 – Part A

[2] FORCEY, ROSS, SIMPSON, EVANS – "Hydrogen transport and solubility in 316L and 1.4914 steels for fusion reactor application" – J. Nucl. Mat. (December 1988) **160**, p. 117-124

[3] TANABE T., IMITO S. – « Hydrogen permeation through Incoloy 800" J. Nucl. Science and Tech. (April 1979) **16**, p. 301-302

1 Models of chemical behavior and transfers of tritium and hydrogen implemented in calculation tools

Since it was decided to apply the benchmarking activity of task 2.2 to the case of ASTRID sodium fast reactor concept, this chapter gives a brief description of the different transfer and equilibrium phenomena to be considered for the evaluation of tritium and hydrogen material balance. It gives also explicit formulation of main physical models and associated parameters to be used in both calculation tools ECOSIMPRO and KUTIM codes.

1.1 Main tritium transfers in SFR reactors

The main transfer fluxes of both isotopes (hydrogen and tritium) to be considered in a SFR (Sodium Fast Reactor) are represented by different arrows (green for hydrogen, yellow for tritium) on Figure 1.
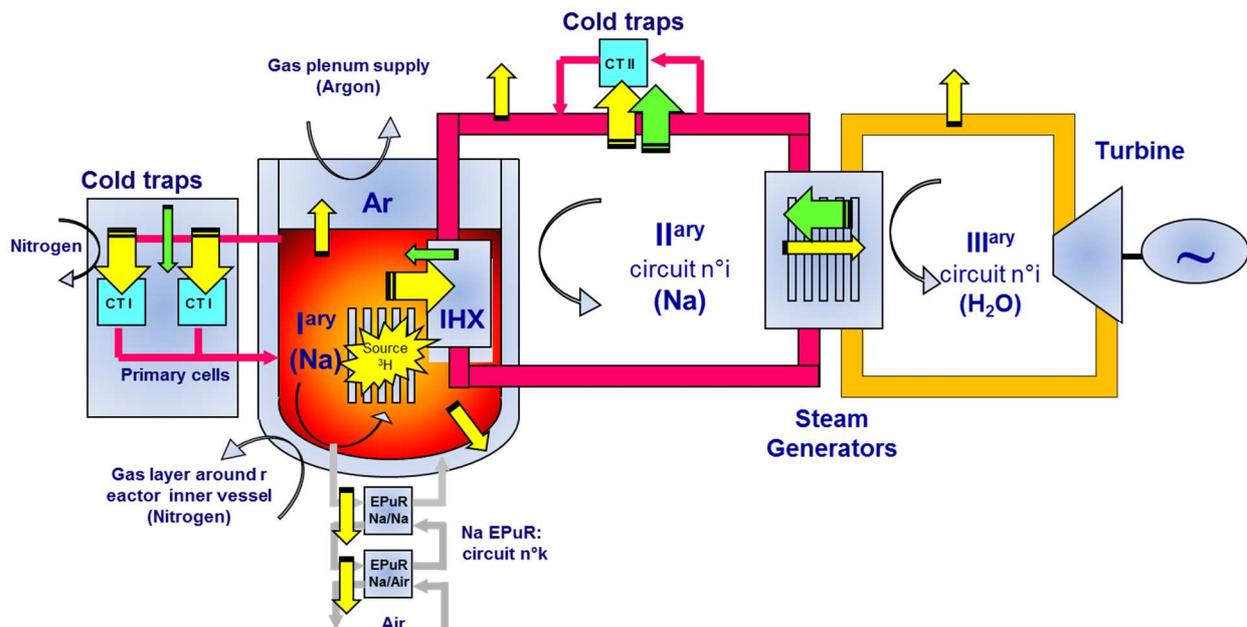

Figure 1 : Main tritium and hydrogen transfers in a SFR

Tritium is produced in the core (both in the fuel pins and in control rods made of boron carbide) and a large proportion is transferred and dissolved in primary sodium. Due to gradients of concentrations in different circuits, a major contribution to tritium transfers is related to permeation phenomena through metallic walls (enhanced by higher temperatures) especially through heat exchanger tubes (Intermediate Heat Exchanger "IHX", Steam Generator) but also through circuits piping more generally. In cover gas (argon) above primary sodium, a concentration equilibrium at interface between liquid sodium phase and argon gas phase controls the tritium transfer into the cover gas. Moreover, a major part of the tritium amount transferred into primary sodium is trapped in purification systems (cold traps) integrated in primary and secondary circuits.

In the case of a water/steam power conversion system (PCS), hydrogen is produced in tertiary circuit due to water corrosion of circuits and is engaged in the same kind of transfers as tritium, mainly permeation through metallic walls (but in reverse direction from tertiary to primary circuits due to reverse concentration gradients). Due to its higher (more than 1000 times) source term (expressed in atoms / time unit) and its higher concentration in secondary sodium, hydrogen crystallization in cold traps (as sodium hydride) enhance the recovery and trapping of tritium in these components, thanks to co-crystallization mechanism. A much smaller hydrogen source term transferred into primary sodium is also taken into account in calculations of hydrogen material balance.

1.2 Tritium and hydrogen source terms

First of all, the source terms of both isotopes (tritium and hydrogen) must be specified.

1.2.1 Tritium source term

In the SFR core, tritium is produced due to 2 main mechanisms :

- ternary fissions within the fuel pins,
- neutronic reactions with ^{10}B of boron carbide (B_4C) in control rods.

A third potential mechanism due to neutronic reactions with impurities is also possible but with negligible contribution which is not taken into consideration.

1.2.1.1 Tritium production from ternary fissions

The fission of fissile radioisotopes (^{239}Pu; ^{235}U) may generate a ternary fragment which is a light nucleus such as an alpha particle or a tritium nucleus, in addition to the formation of other fragments. The probability of a tritium nucleus formation is estimated by the value of a rate of ternary fission " y_T^i " for a given fissile nucleus i.

The tritium production rate for a SFR operated at a thermal power P_{th}, is theoretically given by the following expression:

$$S_T^{fuel}(atoms/s) = \alpha \cdot P_{th} \cdot y_T \qquad \textbf{Eq. 1}$$

Where: α = typical value (α) of the number of fissions per thermal energy unit (fissions / J)

P_{th} = thermal power (W) of SFR reactor

y_T = mean rate of ternary fission (atoms T / fission) calculated from the contributions of each fissile nucleus (weighed by its proportion of fission events).

For easier estimation, it is commonly considered that the mean rate of ternary fission is determined by the characteristic value of ^{239}Pu which is envelope in comparison with ^{235}U. It is also considered that the retention of tritium within the fuel material and its cladding is negligible ($\tau_r^{fuel} = 0$) in the case of usual stainless steel used as cladding material and that the whole tritium production in the fuel is released in primary sodium.

1.2.1.2 Tritium production from neutronic reaction with ^{10}B

In control rods and in neutron shielding made of boron carbide (B_4C), tritium is mainly produced from neutronic reactions with boron isotope ^{10}B due to the following predominant reaction:

$$^{10}B + {}^1n \rightarrow {}^3H + 2\ {}^4He + 0{,}23\ MeV$$
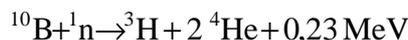
The tritium production rate S_T^{B4C} due to this reaction with ^{10}B isotopes contained in control rods made of B_4C material, is defined by different parameters:

- N = number of ^{10}B atoms present in the whole group of control rods,
- σ = absorption cross section of the reaction $^{10}B(n,2\alpha)^3H$, (cm^2/atom ^{10}B)
- ϕ = neutronic flux density (neutrons/cm^2/s)

Depending on thermal and neutron flux profiles in the core, a retention factor τ_r^{B4C} must be taken into account (reduction factor) to estimate the effective tritium transfer in sodium. Consequently, the contribution of B_4C for the evaluation of tritium production and effective transfer into sodium can be estimated by the following expression:

$$S_T^{B4C}(atoms/s) = (1 - \tau_r^{B4C}) \cdot N \cdot \sigma \cdot \phi \qquad \textbf{Eq. 2}$$

In the case of ASTRID project, an updating of the global tritium source was carried out in 2016 on the base the core design CFV BD 16-10 and last estimation of associated retention factor and using the JEFF3.1/A nuclear data library.

1.2.2   Hydrogen source terms

In primary circuit, hydrogen atoms are produced in the fuel elements due to (n,p) type neutronic reactions and also fission reactions, and diffuse trough the cladding similarly as tritium. When new assemblies are introduced in the core, the presence of adsorbed humidity on surfaces also contributes to hydrogen production but with a decreasing impact.

In secondary circuits, the major source of pollution in liquid sodium comes from hydrogen diffusion through the tubes of steam generators after production in water/steam tertiary circuit due to:

- water corrosion at the surface of steam generator tubes,

- thermal decomposition of hydrazine (N_2H_4), if this additive is used to reduce oxygen content in hot water/steam circuit in order to limit corrosion behavior.

The hydrogen source term also depends on the formation of a metal oxide layer (magnetite Fe_3O_4) which behaves as a diffusion barrier for hydrogen isotopes. On the base of experimental feedback from reactors and from expert analysis, this hydrogen source term was estimated for each ASTRID secondary circuit.

1.3   Permeation transfers

One major phenomenon involved in tritium transfers is the permeation of hydrogen isotopes through the various metallic walls of circuits and components. Depending on the metallic walls considered, different configurations are encountered and permeation occurs sometimes:

- from a liquid sodium circuit (or capacity) to another liquid sodium circuit (IHX tubes between primary and secondary sodium, EPuR heat exchangers used as Alternative system of residual heat removal),
- from a liquid sodium circuit (or capacity) to a gas phase (pipings of all sodium circuits immersed in air environment, inner reactor vessel protected by an outer security vessel and a nitrogen gas phase between the two vessels, EPuR circuits cooled down by air in aerothermal coolers),
- from a gas phase to another gas phase (parts of cover gas circuits in contact with air atmosphere).

The permeation of hydrogen isotopes (H or T) through a metallic wall is defined by the 1st Fick's law:

$$\varphi = -D \cdot \frac{\partial C}{\partial x} \qquad \textbf{Eq. 3}$$

where φ = density of diffusion flux ,(atoms/s/m²)

D = diffusivity of H or T in the metallic wall (m²/s)

C = concentration of H or T in the metal (atoms/ m³)

x = length unit in the diffusion flux direction (m)

In stationary mode, the global diffusion through a plate with thickness "e" and surface area "A" is expressed as:

$$\Omega = D \cdot \frac{A}{e} \cdot (C_1 - C_2) \qquad \textbf{Eq. 4}$$

Where Ω = diffusion flux of H or T through the metallic wall (atoms/s)

C_1, C_2 = concentrations of H or T on both sides surfaces of the metallic wall (atoms/m³)

For the resolution of the equation system built with the different material balances and equilibrium, it is convenient to use concentrations of hydrogen isotopes within the circulating fluids instead of concentrations within metallic wall. This is why it is interesting to consider the concentrations $[H]_i$ or $[T]_i$ within the fluid circulating on each side (liquid or gas), and to express them relatively to the mass of fluid (in atoms/kg).

The Sieverts relation defines the equilibrium between partial pressure of hydrogen or tritium (isotope X) in gas phase and concentration in liquid sodium or in metal at the interface number "i" :

$$C_{X,i}^{met} = K_{SX}^{met} \cdot \sqrt{P_i} \quad ; \quad C_{X,i}^{Na} = K_{SX}^{Na} \cdot \sqrt{P_i} \qquad \textbf{Eq. 5}$$

In this relation, P_i represents the partial pressure of diatomic molecules of hydrogen or tritium in gas phase and in equilibrium with its dissolution under monoatomic form within the metal (liquid or solid).

Considering the Sieverts relation defining equilibrium between partial pressure of hydrogen (or tritium) in gas phase and concentration in liquid sodium or in metal, a relation exists between these concentrations, which involves the Sieverts constants in liquid sodium and in metal K_{SH}^{Na} and K_{SH}^{met}:

$$C_1^{met} = \frac{K_{SH}^{met}}{K_{SH}^{Na}} \cdot C_1^{Na} \quad \textbf{and} \quad C_2^{met} = \frac{K_{SH}^{met}}{K_{SH}^{Na}} \cdot C_2^{Na} \qquad \textbf{Eq. 6}$$

The concentrations in sodium can be converted in (atoms/kg) using the density of sodium ρ^{Na} (kg/m³):

$$[X]_i = C_i \cdot \rho^{Na} \qquad \textbf{Eq. 7}$$

Where X = H or T, and i = 1 or 2.

Consequently, in the case of liquid sodium circuits on both sides of the metallic wall, the permeation flux is described by a correlation introducing the permeability of metal relatively to hydrogen isotopes. For example, in the case of H isotope we consider the following expression:

$$\Omega_H = D_H \cdot \frac{A}{e} \cdot \left(C_{H,1}^{met} - C_{H,2}^{met}\right) = D_H \cdot \frac{K_{SH}^{met}}{K_{SH}^{Na}} \cdot \frac{A}{e} \cdot \left(C_{H,1}^{Na} - C_{H,2}^{Na}\right) = D_H \cdot \frac{K_{SH}^{met}}{K_{SH}^{Na}} \cdot \rho^{Na} \cdot \frac{A}{e} \cdot ([H]_1 - [H]_2) \qquad \textbf{Eq. 8}$$

For the simplification of formulations, we can introduce the definition of a permeation coefficient expressed in ($kg_{Na}.s^{-1}$) as follows:

$$PE_X = D_X \cdot \frac{K_{SX}^{met}}{K_{SX}^{Na}} \cdot \rho^{Na} \cdot \frac{A}{e} = pe_X \cdot \frac{\rho^{Na}}{K_{SX}^{Na}} \cdot \frac{A}{e} \qquad \textbf{Eq. 9}$$

In this expression, the first part is independent of wall dimensions and involves the permeability pe_X of hydrogen isotope (X) through the metallic wall which is expressed in ($atoms.m^{-1}.s^{-1}.Pa^{-1/2}$) and is

defined by the product of the diffusivity D_X (m².s⁻¹) and the Sieverts constant in the metal K_{SX}^{met} (atoms.m⁻³.Pa⁻¹ᐟ²).

$$pe_X = D_X \cdot K_{SX}^{met} \qquad \text{Eq. 10}$$

For the characterization of the permeation properties, data concerning metals used in sodium circuits are generally presented, in the form of a parameter Pe_X (named "permeability coefficient") expressed in (kg$_{Na}$.m⁻¹.s⁻¹) as follows:

$$Pe_X = D_X \cdot \frac{K_{SX}^{met}}{K_{SX}^{Na}} \cdot \rho^{Na} = pe_X \cdot \frac{\rho^{Na}}{K_{SX}^{Na}} \qquad \text{Eq. 11}$$

Consequently, we have the relation:

$$PE_X = Pe_X \cdot \frac{A}{e} \qquad \text{Eq. 12}$$

Then we can use the simplified expression of permeation flux :

$$\Omega_X = PE_X \cdot \frac{A}{e} \cdot ([X]_1 - [X]_2) \qquad \text{Eq. 13}$$

In the case of a gas phase in contact with the wall, because of the Sieverts relation $C_{X,i}^{met} = K_{SX}^{met} \cdot \sqrt{P_i}$ between the concentration (in atoms/m³) and the partial pressure in Pa, we need to introduce a conversion factor KU_i and to replace the concentration [X]$_i$ by the corrected term $KU_i \cdot \sqrt{[X]_i}$. The correction factor KU_i depends in particular on the total pressure P$_{t,I}$, on the global molar weight M$_{t,i}$ of gas phase and on the Avogadro number N$_A$:

$$KU_i = \frac{K_{SX}^{Na}}{\rho^{Na}} \cdot \sqrt{\frac{M_{t,i} \cdot P_{t,i}}{2 \cdot N_A}} \qquad \text{Eq. 14}$$

1.4 *Hydrogen – tritium equilibrium in gas phase*

In gas phase, diatomic molecules of hydrogen and tritium are not independent and react together to form HT molecules. Both isotopes are involved in a reaction equilibrium:

$$H_2 + T_2 \leftrightarrow 2\,HT$$
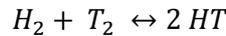
The thermodynamical constant of this equilibrium is function of temperature and can be expressed from the partial pressures of gaseous species by the following correlation.

$$K_{eq}(T) = \frac{p_{HT}^2}{p_{T_2} \cdot p_{T_2}} = e^{\left(-\frac{133}{T} + 1.4966\right)} \qquad \text{Eq. 15}$$

1.5 *Equilibrium between liquid phase and gas phase*

In the primary vessel, at the sodium surface in contact with the cover gas (argon), the transfer of hydrogen isotopes can be evaluated considering the simplification assumption of a concentration equilibrium (Sieverts law) between both phases. Moreover, the chemical equilibrium between different forms of hydrogen isotopes molecules has to be taken into account in the gas phase, with the equilibrium constant K$_{eq}$ defined previously in function of temperature (T/K)

The transfer flux of hydrogen isotopes from liquid sodium into the gas phase can be expressed as below in function of cover gas flowrate Q_{cg}:

$$\Omega_H = \frac{2 \cdot N_A \cdot Q_{cg} \cdot [H]^{Na}}{R \cdot T \cdot \left(K_{SH}^{Na}\right)^2} \cdot \left([H]^{Na} + \frac{\sqrt{K_{eq}}}{2} \cdot \frac{K_{SH}^{Na}}{K_{ST}^{Na}} \cdot [T]^{Na} \right) \qquad \textbf{Eq. 16}$$

1.6 Transfers in the cold traps

The purification of liquid sodium operated in cold traps is based on crystallization of sodium hydride on cold walls and sodium oxide or hydride on wire mesh packing. A major proportion of tritium is deposited in cold traps thanks to a co-crystallization mechanism with hydrogen impurities. This phenomenon is governed by the solubility of hydrogen in sodium and its dependence with temperature.

$$Na_{\text{liquid}} + H_{\text{dissolved}} \Rightarrow NaH_{\text{solid}}$$

The solubility of hydrogen in liquid sodium is given by the Whittingham correlation:

$$log_{10}\left(C_{H,sat}^{Na}\right) = 6.467 - \frac{3023}{T} \qquad \textbf{Eq. 17}$$

With: $C_{H,sat}^{Na}$ = hydrogen concentration in sodium at saturation (mass ppm)

            T = temperature of liquid sodium (K)

The solubility of tritium in liquid sodium is supposed to be the same as hydrogen. In fact, in the usual operating conditions of SFR, the tritium concentrations in sodium circuits are too small to reach the saturation value, and consequently its deposition in cold traps is due to co-crystallization with sodium hydride (as a mixture of crystals NaT + NaH).

The isotopic exchange of tritium atoms with hydrogen atoms present in sodium hydride crystals is another possible mechanism that can be cited about tritium behavior in cold traps. But the main parameters of this mechanism (efficiency and equilibrium concentration) are not known and this contribution is usually neglected in comparison with co-cristallization with hydrogen.

Consequently the flux of tritium deposition in cold traps is defined by the following correlation:

$$\Omega_T^{PF} = \frac{[T]}{[H]} \cdot Q_{Na}^{PF} \cdot \varepsilon \cdot \left([H] - [H]_{sat}\right) \qquad \textbf{Eq. 18}$$

1.7 Radioactive decay

The half-life of tritium is 12.3 years, which corresponds to a radioactive decay constant $K_D = 1.7857 \times 10^{-9}$ s^{-1}. The rate of radioactive decay considered in the tritium material balance is expressed in (atoms/s) by the following expression:

$$\Omega_T^{rad} = K_D \cdot m_{Na} \cdot [T] \qquad \textbf{Eq. 19}$$

Where: m_{Na} = mass of the media (liquid sodium, water, gas…) containing tritium (kg)

             [T] = tritium concentration in the media (atoms/kg)

2 Data set of characteristics and parameters to be implemented

The different models of transfer and equilibrium phenomena presented in the above section require the use of different characteristics and parameters to describe the design and the operating conditions of the circuits and components involved in tritium and hydrogen transfers in the reactor. The data set corresponding to the design of ASTRID considered in the last CEA calculations carried out in 2015 will be used for the present study and is presented in the following sections. Because of confidentiality concerns related to ASTRID design, the numerical values of data and parameters are not presented in this document but communicated separately and under restricted diffusion. Nevertheless, this section presents the list and the description of all these data by giving their nomenclature, their technical description and their physical units in different tables for each part and circuit of the reactor. Independently from numerical values, this information is useful to prepare the adaptation of calculation tools by implementing the physical models and related input data interface.

2.1 Reactor characteristics

Table 1 : Reactor characteristics

Symbol	Description	Unit
	Number of circuits and main components	
N	Number of secondary (and tertiary circuits also in this design)	
NG	Number of Intermediate Heat Exchangers (IHX) for each secondary circuit	
ngv	Number of steam generators for each tertiary circuit (Total: 4 steam generators, 1 for each secondary circuit)	
nrur	Number of alternative cooling circuits (EPuR circuits) (2 RRA circuits + 3 RRB circuits)	
	Pollution sources	
SH	Hydrogen source into primary sodium (neutronic reactions in the core)	(atom/s)
SH_i	Hydrogen source into secondary sodium for each secondary circuit "i"	(atom/s)
	Mass and volumes of coolants	
M	Mass of primary sodium	(kg)
Mi	Mass of sodium in each secondary circuit	(kg)
MRk	Mass of sodium in each EPuR circuit	(kg)
MO	Mass of water/steam in all tertiary circuits (Mass of water/steam in each tertiary circuit: MOi = MO/N)	(kg)
MQ	Mass of nitrogen gas in inter-vessel gap[1]	(kg)

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[1] The confinement function of primary vessel is protected by an outer vessel, and the gap between this double envelope is filled with nitrogen. In first assumption it is considered that this gas is not circulating (DQ = 0 kg/s)

	Conditions of gas phase in	
$Pt_{N2\text{-}IV}$	Total pressure of nitrogen in inter-vessel gap	(Pa)
$T_{N2\text{-}IV}$	Temperature of nitrogen in inter-vessel gap	(°C)
$Pt_{Ar\text{-}CG}$	Total pressure of argon in cover gas	(Pa)
$T_{Ar\text{-}CG}$	Temperature of argon in cover gas	(°C)
	Coolant flowrates	
DS1	Global circulation flowrate of primary sodium (total of flowrates in all IHX)	(kg/s)
DS2i	Circulation flowrate of secondary sodium in each secondary circuit i	(kg/s)
	Leakage flowrates (compensated by renewal supply) of gas and steam circuits	
DO	Global leakage flowrate of water/steam tertiary circuits	(kg/s)
DOi	Leakage flowrate of each water/steam tertiary circuit	(kg/s)
DG	Leakage flowrate of argon circuit in cover gas	(m³/s)

2.2 Design of main components and circuits

2.2.1 Main primary vessel

The main primary vessel in contact with primary sodium is protected by an outer vessel and the gap between the walls of both vessels is filled with argon. A permeation flux of hydrogen isotopes is considered through the wall of main primary vessel and the characteristics of this permeation wall are given in the following table.

Table 2 : Characteristics of main primary vessel

Symbol	Description	Unit
	Design characteristics of the wall of main primary vessel	
Tube wall material	Wall material of primary vessel	/
A_{PV}	Global surface area of primary vessel wall considered for permeation transfer	(m²)
t_{PV}	Wall thickness of primary vessel wall considered for permeation transfer	(m)
T_{PV}^{N2}	Mean temperature of nitrogen in inter-vessel gap	(°C)
T_{PV}^{Na1}	Mean temperature of primary sodium in contact with primary vessel wall	(°C)

2.2.2 Intermediate Heat Exchangers (IHX)

Table 3 : Characteristics of Intermediate Heat Echangers

Symbol	Description	Unit
Design characteristics of each IHX		
Tube wall material	Wall material of thermal exchange tubes	/
A_{IHX}	Global surface area of tubes considered for permeation transfer	(m²)
t_{IHX}	Wall thickness of tubes considered for permeation transfer	(m)
$T_{IHX}^{in\text{-}Na1}$ / $T_{IHX}^{out\text{-}Na1}$	Inlet/outlet temperatures of primary sodium	(°C)
$T_{IHX}^{in\text{-}Na2}$ / $T_{IHX}^{out\text{-}Na2}$	Inlet/outlet temperatures of secondary sodium	(°C)

2.2.3 Steam generators

Table 4 : Characteristics of Steam Generators

Symbol	Description	Unit
Design characteristics of each steam generator		
Tube wall material	Wall material of thermal exchange tubes	/
A_{IHX}	Global surface area of tubes considered for permeation transfer	(m²)
t_{IHX}	Wall thickness of tubes considered for permeation transfer	(m)
$T_{IHX}^{in\text{-}Na2}$ / $T_{IHX}^{out\text{-}Na2}$	Inlet/outlet temperatures of secondary sodium	(°C)
$T_{IHX}^{in\text{-}H2O}$ / $T_{IHX}^{out\text{-}H2O}$	Inlet/outlet temperatures of water/steam circuit	(°C)

2.3 System EPuR of alternative heat evacuation

The system EPuR consists in a group of additional sodium circuits and heat exchangers devoted to the evacuation of residual heat from primary sodium, as an alternative solution in case of dysfunction of nominal heat transfer through IHX (in case of primary pumps dysfunction for instance). The system EPuR includes 5 circuits, and each one is composed of the following parts represented simply on Figure 2:

- A branch circulating a fraction of primary sodium to evacuate residual heat through a heat exchanger and towards another sodium circuit called "EPuR sodium"

- A heat exchanger called "EPX1" (Heat exchanger number 1 for residual heat removal) between circuits of primary sodium and EPuR sodium

- A sodium circuit called "sodium EPuR" between this exchanger and another heat exchanger devoted to aerothermal cooling of the "sodium EPuR" circuit

- An aerothermal cooler called "EPX2" (Heat exchanger number 2 for residual heat removal) between sodium EPuR and a flux of outside atmospheric air circulated around the tubes of heat exchanger for heat evacuation
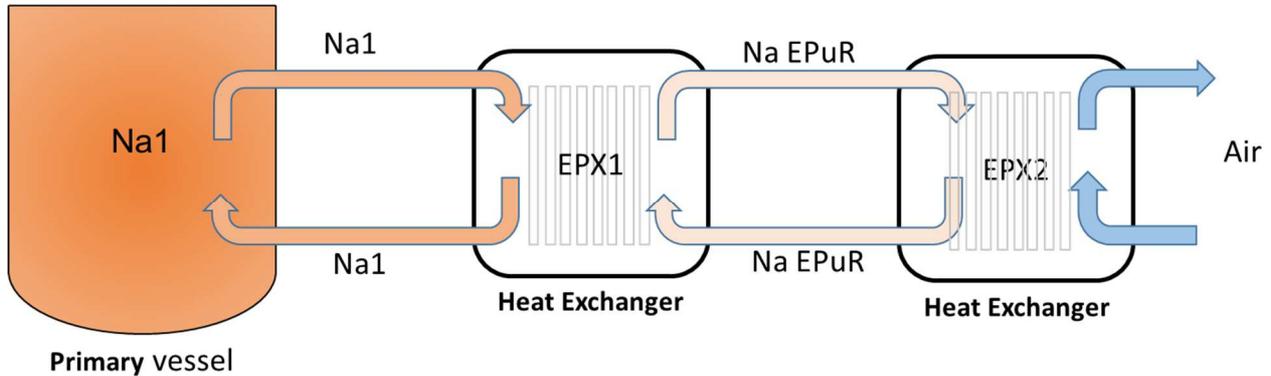

Figure 2 : Main elements of each system EPuR devoted to residual heat removal

Two types of circuits must be considered for the system EPuR with two different sets of characteristics:

- 2 circuits RRA type (Residual heat removal system with forced convection) operated by forced convection

- 3 circuits RRB type (Residual heat removal system with natural convection) operated by natural convection

2.3.1 Heat exchangers "EPX1" primary sodium / sodium EPuR

Table 5 : Characteristics of heat exchangers EPX1

Symbol	Description	Unit
Design characteristics of each (1/2) heat exchanger (EPX1) for RRA type circuits		
Tube wall material	Wall material of thermal exchange tubes	/
A_{EPX1}	Global surface area of tubes considered for permeation transfer	(m^2)
t_{EPX1}	Wall thickness of tubes considered for permeation transfer	(m)
T_{EPX1}^{Na1}	Mean temperature of primary sodium (no circulation of primary sodium in nominal condition)	(°C)
T_{EPX1}^{NaEPuR}	Mean temperature of sodium EPuR (no circulation of sodium EPuR in nominal condition)	(°C)

Symbol	Description	Unit
	Design characteristics of each (1/3) heat exchanger (EPX1) for RRB type circuits	
Tube wall material	Wall material of thermal exchange tubes	/
A_{EPX1}	Global surface area of tubes considered for permeation transfer	(m^2)
t_{EPX1}	Wall thickness of tubes considered for permeation transfer	(m)
T_{EPX1}^{Na1}	Mean temperature of primary sodium (no circulation of primary sodium in nominal condition)	$(°C)$
T_{EPX1}^{NaEPuR}	Mean temperature of sodium EPuR (no circulation of sodium EPuR in nominal condition)	$(°C)$

2.3.2 Heat exchangers "EPX2" sodium EPuR / Air

Table 6 : Characteristics of heat exchangers EPX2

Symbol	Description	Unit
	Design characteristics of each (1/2) heat exchanger (EPX2) for RRA type circuits	
Tube wall material	Wall material of thermal exchange tubes	/
A_{EPX2}	Global surface area of tubes considered for permeation transfer	(m^2)
t_{EPX2}	Wall thickness of tubes considered for permeation transfer	(m)
T_{EPX2}^{NaEPuR}	Mean temperature of sodium EPuR (no circulation of sodium EPuR in nominal condition)	$(°C)$
$T_{EPX2}^{in-Air}/T_{EPX2}^{out-Air}$	Inlet/outlet temperatures of Air	$(°C)$
	Design characteristics of each (1/3) heat exchanger (EPX2) for RRB type circuits	
Tube wall material	Wall material of thermal exchange tubes	/
A_{EPX2}	Global surface area of tubes considered for permeation transfer	(m^2)
t_{EPX2}	Wall thickness of tubes considered for permeation transfer	(m)
T_{EPX2}^{NaEPuR}	Mean temperature of sodium EPuR (no circulation of sodium EPuR in nominal condition)	$(°C)$
$T_{EPX2}^{in-Air}/T_{EPX2}^{out-Air}$	Inlet/outlet temperatures of Air	$(°C)$

The piping walls of the sodium EPuR circuits (RRA type and RRB type) between heat exchangers EPX1 and EPX2, must also be considered to evaluate tritium (and hydrogen) permeation and release into atmosphere. The characteristics of these sodium EPuR pipings are presented in the two following tables.

Table 7 : Characteristics of pipings for EPuR circuits

Symbol	Description	Unit
Pipings characteristics of each (1/2) sodium EPuR circuit walls for RRA type circuits		
Tube wall material	Wall material of pipings	/
$A_{EP\text{-}RRA}$	Global surface area of pipings considered for permeation transfer	(m^2)
$t_{EP\text{-}RRA}$	Wall thickness of pipings considered for permeation transfer	(m)
T_{RRA}^{NaEPuR}	Mean temperature of sodium EPuR (no circulation of sodium EPuR in nominal condition)	(°C)

Symbol	Description	Unit
Pipings characteristics of each (1/3) sodium EPuR circuit walls for RRB type circuits		
Tube wall material	Wall material of pipings	/
$A_{EP\text{-}RRB}$	Global surface area of pipings considered for permeation transfer	(m^2)
$t_{EP\text{-}RRB}$	Wall thickness of pipings considered for permeation transfer	(m)
T_{RRB}^{NaEPuR}	Mean temperature of sodium EPuR (no circulation of sodium EPuR in nominal condition)	(°C)

2.4 Secondary circuits

Each secondary circuit is divided into two sections: a cold section and a hot section. The piping characteristics of the two are presented in the two following tables.

Table 8 : Characteristics of pipings for secondary circuits

Symbol	Description	Unit
	Piping characteristics of cold section (CS) of secondary circuits	
Tube wall material	Wall material of pipings	/
A_{Na2-CS}	Global surface area of pipings considered for permeation transfer	(m^2)
t_{Na2-CS}	Wall thickness of pipings considered for permeation transfer	(m)
T_{CS}^{Na2}	Mean temperature of secondary sodium in cold section	(°C)
	Piping characteristics of hot section (HS) of secondary circuits	
Tube wall material	Wall material of pipings	/
A_{Na2-HS}	Global surface area of pipings considered for permeation transfer	(m^2)
t_{Na2-HS}	Wall thickness of pipings considered for permeation transfer	(m)
T_{HS}^{Na2}	Mean temperature of secondary sodium in hot section	(°C)

2.5 Cold traps systems

2.5.1 Purification of primary sodium

The purification of primary sodium is ensured by a cold trap, in which a fraction of primary sodium is circulating with a partial flowrate. The sodium temperature is cooled down in order to crystalize impurities in solid form (sodium hydride crystallization). The flux of tritium deposition in cold traps defined in § 1.6 can be calculated from the operating data presented in the following table.

Table 9 : Characteristics of primary cold traps

Symbol	Description	Unit
	Characteristics of primary cold trap	
N_{CT1}	Number of primary cold traps in operation	/
F_{NaCT1}	Flowrate of primary sodium in primary cold trap (kg/s)	(kg/s)
F_{NaCT1}	Flowrate of primary sodium in primary cold trap (m^3/h)	(m^3/h)
T_{cp}^{CT1}	Cold point temperature of primary cold trap	(°C)

2.5.2 Purification of secondary circuits

The purification of primary sodium is ensured by a cold trap, in which a fraction of primary sodium is circulating with a partial flowrate. The sodium temperature is cooled down in order to crystalize impurities in solid form (sodium hydride crystallization). The flux of tritium deposition in cold traps defined in § 1.6 can be calculated from the operating data presented in the following table.

Table 10 : Characteristics of secondary cold traps

Symbol	Description	Unit
	Characteristics of primary cold trap	
N_{CT1}	Number of primary cold traps in operation	/
F_{NaCT1}	Flowrate of primary sodium in primary cold trap (kg/s)	(kg/s)
F_{NaCT1}	Flowrate of primary sodium in primary cold trap (m³/h)	(m³/h)
T_{cp}^{CT1}	Cold point temperature of primary cold trap	(℃)

2.6 Characteristics of permeation walls

As indicated in § 1.3 the permeation of hydrogen through metallic wall is generally characterized by a "permeability coefficient" Pe_X (kg$_{Na}$.m^{-1}.s^{-1}) that depends on temperature T (K) and can be evaluated by a correlation with the following form:

$$Pe_H(T) = D_H \cdot \frac{K_{SH}^{met}}{K_{SH}^{Na}} \cdot \rho^{Na} = e^{\left(-\frac{a}{T}-b\right)} \qquad \textbf{Eq. 20}$$

The exponential description of this dependence, involves the two parameters a and b which characterize the metallic permeation wall. The parameters usually used for permeation evaluation in SFR are given in Table 11 for the two materials to be considered for an application to ASTRID balance: stainless steel 316L used for almost all equipment in contact with sodium, while Incoloy 800 is selected for steam generators components.

Table 11 : Permeation parameters for the evaluation of temperature dependence

Material	a	b	Reference
SS 316 L	7701	7.79	Forcey [2]
Incoloy 800	6830	9.03	Tanabe [3]

On the base of these permeation characteristics and on the design data of the different components and circuits presented in section 2 (and in particular in paragraphs 2.2 to 2.4), the values of the permeation coefficients $\left(PE_X = Pe_X \cdot \frac{A}{e}\right)$ calculated for KUTIM calculations are reported in Appendix 1, as an information or a potential use for a direct implementation in ECOSIMPRO calculations.

2.7 Other data and parameters

2.7.1 Sodium physical properties

The Sieverts constants of hydrogen and tritium in liquid sodium can be considered as almost independent with temperature. The values commonly used for evaluations of tritium and hydrogen balances in reactor circuits are given hereunder in (atoms.kg$_{Na}$$^{-1}$.Pa$^{-1/2}$).

$$K_{SH}^{Na} = 2.6077 * 10^{20}\ atoms.kg_{Na}^{-1}.Pa^{-1/2}$$ **Eq. 21**

$$K_{ST}^{Na} = 8.6923 * 10^{19}\ atoms.kg_{Na}^{-1}.Pa^{-1/2}$$ **Eq. 22**

2.7.2 Operating conditions

Other data giving description of coolants operating conditions are also necessary for the evaluation of tritium and hydrogen transfers in the different circuits of the reactor. In particular, the flowrates of coolants may be necessary, but also the mean leak flowrates in order to evaluate the tritium releases in gas phase or in liquid phase:

- for gas phase releases, the two main sources should be considered, one from the cover gas (argon) circuit and one from the inter-vessel gap filled with nitrogen (but for the present ASTRID data set, it is considered a static nitrogen volume in the inter-vessel gap and no related gas leakage);

- for liquid phase releases, the only source to be considered is the global water leakage taking place in pressurized tertiary circuits.

Moreover, to calculate concentrations in gas phases (cover gas and inter-vessel gap), the conditions such as the gas composition, the temperature and the pressure, are necessary. These condition values are indicated for ASTRID (2015 data) in the following tables.

Table 12 : Other parameters and conditions for the description of ASTRID circuits

Symbol	Description	Unit
	Circulation flowrates in main circuits	
DS1	Circulation flowrate of primary sodium	(kg/s)
DS2i	Circulation flowrate of sodium in each secondary circuit "i"	(kg/s)
DW3	Global flowrate of water circulating in all tertiary circuits	(kg/s)
DW3i	Circulation flowrate of water in each tertiary circuit "i"	(kg/s)
DCG	Circulation flowrate of cover gas (argon)	(Nm^3/h)
	Estimated leak flowrates in circuits	
DO	Global leak flowrate of water in all tertiary circuits	(kg/s)
DOi	Leak flowrate of water in each tertiary circuit "i"	(kg/s)
DG	Leak flowrate of cover gas (argon)[2]	(Nm^3/h)
DQ	Leak flowrate of nitrogen in inter-vessel gap	(Nm^3/s)

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[2] It should be precised that the value of leak flowrate concerning the cover gas inventory was corrected in 2017 from previous value used for 2015 evaluation : a confusion was made in 2015 between the circulating flowrate (20 Nm^3/h) and the leak flowrate (3 Nm^3/h) to be considered for the evaluation of tritiated gas releases. It was decided to take this correction into consideration for this benchmark study.

	Operating conditions of gas phases	
T_Q	Nitrogen temperature in inter-vessel gap	(°C)
P_Q	Nitrogen pressure in inter-vessel gap	(bar)
T_{CG}	Argon temperature in cover gas	(°C)
P_{CG}	Argon pressure in cover gas	(bar)
	Impurities concentrations of hydrogen in gas phases	
KR	Hydrogen concentration (imputity level) in air	(atoms/kg)
KN	Hydrogen concentration (imputity level) in nitrogen	(atoms/kg)
KA	Hydrogen concentration (imputity level) in argon	(atoms/kg)

3 Appendix

Appendix 1 : Permeation coefficients evaluated for ASTRID metallic walls

Symbol	Description of permeation coefficient « PE » (kg/s)
PHX, PTX	through each IHX
PHVi, PTVi	through the steam generators of a single secondary loop
PHQ, PTQ	through the main primary vessel
PHRk, PTRk	through heat exchangers between primary sodium and EPuR sodium of all EPuR circuits (global value)
PHERk, PTERk	through heat exchangers between EPuR sodium and air of all EPuR circuits (global value)
PHKRk, PTKRk	through piping and tank walls of all EPuR circuits (global value)
PHK, PTK	through piping and tank walls of primary circuit
PHKi, PTKi	through piping and tank walls of each secondary circuit " i "