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Recommendations for code development and validation

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

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Recommendations for code development and validation

Executive summary

One of the objectives of the Sub-project Safety is to have qualified tools for performing safety analyses. This document is a starting point for the WP1 dedicated to the comparison between global system transient analysis codes (code-to-experiment comparisons and code-to-code benchmarks).

This deliverable includes a list of candidate transient analysis codes, with a detailed description of each code. A series of transient situations to be analysed have been identified as well as the physical phenomena to be modelled and the required functionalities for the codes. A first point on the codes' capabilities to describe all the circuits of a Gas Cooled Reactor is drawn up, concerning different aspects such as reactor physics model, TH model (core, primary/secondary systems, vessel TH modelling), number of fluids in a model, physical correlations, heat transfer modelling, fuel modelling, existing coupling.

The need of validation of these system codes is underlined with a first description of few existing system experiments.

Revisions

Rev.	Date	Short description	Author	WP Leader	SP Leader	Coordinator
00	01/12/2005	First issue	Geneviève GEFFRAYE (CEA)	Walter VAN HOVE (TRACTEBEL Engineering)	Jacques PIRSON (TRACTEBEL Engineering)	
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1. Context of this document

One of the objectives of the Sub-project Safety is to have qualified tools for performing safety analyses and supporting the safety approach and demonstration. The validation of the thermo-fluid dynamics codes needed for the system transient analysis in VHTR should be performed. This validation will be carried out against experimental data when available and by comparing simulation results given by several codes.
Nine organizations have chosen to participate to the WP1 dedicated to the comparison between the global system transient analysis codes (code-to-experiment comparisons and code-to-code benchmarks). In front of each involved organization, the transient code chosen by the participant is mentioned in the list below:

- CEA (France) - Cathare
- VUJE (Slovak Republic) - Cathare
- ANSALDO Nuclear (Italy) - Relap
- NRG (Netherlands) - Spectra
- IRSN (France) - Icare-Cathare
- IKE der Universität Stuttgart (Germany) -Flownex
- FRA-ANP (France). - Manta
- AMEC NNC Limited (UK) - Relap5/Mod3 with WIMS9
- NRI (Czech Republic) - Relap5/Mod3.3
- TRACTEBEL (Belgium) - Melcor

This document is a starting point on the accident analysis specific to HTGR. The purpose is to contribute to recommendations for code development and validation. The aim is to have simulation tools capable to describe all the circuits of a Gas Cooled Reactor under nominal and accident conditions. The reactor core may be prismatic or pebble bed. The power conversion system may be direct or indirect cycle.

2. Main features of HTGRs

The introduction of HTGR is not only to achieve the industrial purposes such as high efficiency and low construction costs, but also because of its capability to produce high-temperature process heat and its inherent safety.
The main HTGR specific design characteristics and inherent safety features are:

- High quality ceramic coated-particle fuel of proven design, which adequately retains its ability to contain radioactive fission products over the full range of operating and accident conditions;
- A single-phase inert coolant (helium), with no heat transfer limits that would be associated with phase change;
- Post shutdown decay heat removal achievable through conduction, natural convection and radiation heat transfer, limiting maximum temperatures to values consistent with coated fuel particle and structural design limits;
- Combination of low core power density, large reactor core and internal heat capacity, high core thermal conductivity and large fuel thermal margins, resulting in very long times (days) for evolution of response to loss of normal shutdown functions without protective actions;
- Fuel temperature margins and negative temperature-reactivity coefficients sufficient to accommodate any foreseeable reactivity insertions during start-up and power operation without damage to the fuel.

So far, various options for the design of modular HTGRs have been evaluated, while the basic design features shown above are the same. These include:

- The use of pebble fuel or block fuel;
- The use of various fuel forms;
- The use of steam cycle or gas-turbine cycle;
- The use of direct cycle or indirect cycle gas turbines.

3. List of transients to be simulated

The system analysis specific to HTGR should include **normal conditions,** such as

- Start-up
- Stop
- Load following (fast and low transients)

A series of **transient situations** should be analysed corresponding to the following list **of initiating events.** The consequences of initiating events are mitigated if needed by the operational/safety systems, performing the reactivity control, decay heat removal and confinement functions.

- Reactor trip
- Control rod drop
- Inadvertent control rod withdrawal
- Control rod ejection
- Malfunction of the IHX cooling systems leading to overcooling (indirect cycle):
    - Increase of secondary gas circulation
    - Increase of steam generator cooling
- Malfunction of the primary coolers cooling circuits leading to overcooling (direct cycle):
    - Increase of water circulation
    - Increase of water cooling
- Malfunction of the primary blower leading to overcooling (indirect cycle)
- Malfunction of the turbomachine leading to overcooling (direct cycle)
- Inadvertent closure of bypass line (direct cycle)
- Inadvertent operation of the Shutdown Cooling System at power
- Partial or complete loss of heat sink (indirect cycle):
    - Failure of secondary gas circulation: gas turbine failure or IHX isolation valve spurious actuation
    - Failure of steam generator cooling: failure of water circulator, failure of condenser cooling, steam/water leakage, increase of heat sink temperature

- Partial or complete loss of heat sink (direct cycle):
    - Failure of water circulation: pump failure or heat exchanger isolation valve spurious actuation
    - Failure of water cooling: failure of water circulator, water leakage, increase of heat sink temperature
- Steam Generator leak leading to steam inlet to the secondary gas system (indirect cycle)
- Leak on the secondary gas circuit (indirect cycle)
- Inadvertent secondary gas safety valve opening
- Primary blower malfunction leading to decrease of flowrate (indirect cycle)
- Turbo machine malfunction leading to decrease of flowrate (direct cycle)
- Inadvertent opening of by-pass line (direct cycle)
- Malfunction of Shutdown Cooling System when operating
- Malfunction of Secondary Heat Removal System when operating (indirect cycle)
- Loss Of Off-site Power (short/long duration)
- Primary helium system (primary pressure control) malfunction
- Secondary gas system (primary pressure control) malfunction (indirect cycle)
- Flow blockage in Intermediate Heat eXchanger
- Primary helium leakage/pipe break (pipes connected to the vessels, excluding cross vessel)
- Primary helium leak within the Pressure Boundary (e.g., through the hot duct)
- Inadvertent Pressure Boundary safety valve opening
- Primary helium leakage through the Intermediate Heat eXchanger (indirect cycle)
- Auxiliary (e.g., SCS, primary blower) heat exchanger leak
- Primary heat exchanger leak (direct cycle)

4. Physical phenomena and required functionalities

The system codes must be able to deal with a wide range of components such as compressors, turbines, pipes, diffusers, valves, heat exchangers and reactor cores, to connect them into a network and to model both steady-state and transient flows.
Many accident analyses to show the inherent safe nature of HTGRs have been performed and published corresponding to each design of HTGRs. The increased capacity of new computer technology has made it possible to switch to new generation of computer codes, which are capable of representing physical phenomena in more detail and including more precise consideration of interactions of multiple phenomena (thermal hydraulics, neutronics, chemical reactions, etc.)

The table 1 below tries to list in front of some transients, the physical phenomena occurring during the transient and the required functions for the system code. This list is established from the experience acquired by CEA in the frame of studies performed on GCR (direct and indirect cycles).

Transient	« Physical » phenomena	Specific needs
Start-up	• Fitting pressure and temperature of the circuit • Starting Turbo-machine rotation • Connection of the Turbo-Machine • Actuation of the regulations (core outlet temperature and mass)	• Modelling of TM performances • Coupling of TM to a shaft /generator/grid
Load Following	• Load variation controlling the mass inventory	• Modelling of non active volumes actuated by regulation
Primary depressurisation (break) with/without TM trip	• Depressurisation • Decay Heat removal by forced convection , then by conduction/radiation	• Local sonic flow models (break, valves) • Allowance for thermal inertia of structures • Heat transfer by forced convection, conduction, radiation
Loss of load without TM trip	• Regulation of the Turbine bypass line valve to avoid TM over-speed • Increase of the Core temperature • Increase of the	• Local sonic flow models (valve) • Allowance for thermal inertia of structures • Modelling of TM dynamics characteristics

	Primary/secondary exchange: water boiling on the 2ary side?	• Disconnection generator/shaft
Total blackout on indirect cycle	• SCRAM occurs • Stop of the primary blower/2ndary TM/ 3ry pump	• Control rod position modelling / residual power decay law • Modelling of Turbomachinery and blower when stopped (Ex :DP) • Allowance for thermal inertia of structures (core and IHX) • Modelling of the 3ry circuit
SCRAM for indirect cycle	• Residual Power decay calculation / imposed law • System effects : core power transfered through IHX to the TM and generator	• Control rod position modelling / residual power decay law • Modelling of the IHX and TM dynamics characteristics
water ingress	• tube rupture of a cooling exchanger	• Two-phase flow modelling
Turbine deblading	• turbine deblading with and without reactor trip (all turbine blades break off) • total flow blockage: the flow area is entirely blocked by the turbine blades • partial flow blockage	• Acoustic waves propagation • Need of coupling : fluid structure interaction • Degradation in TM performances

***Table 1**: physical phenomena and required functions for the system code*

<u>Other required functionalities due to the possible presence of a 3ry water circuit</u>

- Need to model vapour turbine
- Need to couple vapour turbine, gas turbine, compressor and generator possibly coupled to a same shaft
- High level o control command to manage the three circuits
- In case of a break on the 2nd Intermediary Heat Exchanger, water and ingress in the 2ndary circuit

5. Specific need of coupling

The transient analysis tool has to be coupled with the modelling of specific phenomena within the reactor i.e. graphite oxidation in case of air ingress, transport of passive substances (small quantities of dust, FPs…). The inclusion of such effects can have significant influence on the results.

In the table 2, a first list is established considering some accident situations, the physical phenomena associated and the specific needs regarding the coupling:

Situations	**« Physical » phenomena**	**Specific needs**
Air ingress after depressurisation.	• Calculation of (forced or natural) air flow rate in the reactor block • Calculation of mass/thickness of oxidized graphite	• Coupling TH and graphite corrosion code and/or mockups
Primary gas/water exchanger tube rupture (SCS, precooler, intercooler)	• Calculation of steam flow rate in the reactor block • Reactivity increase due to steam water • Calculation of mass of oxidized graphite	• Coupling TH/neutronics • Coupling TH and graphite corrosion code and/or mockups
Situations using DHR by RCCS: ➢ Pressurized or depressurized circuit, with or without SCRAM ➢ Reactivity insertion with or without SCRAM	• Thermal transfer by conduction, natural or forced convection and radiation • Core neutronics	• Coupling TH/system code • Coupling TH/neutronics
Core, IHX behavior in degraded situations	• Increase of temperature • Weighty particles tearing, transport and deposit	• Need of a global model • Coupling porous medium/CFD • +Specific data

Table2*: specific need of coupling*

6. Evaluation of the capability to analyse VHTR transients

A questionnaire has been established by Mr Coddington (PSI) in the frame of the CCFR STREP to evaluate the capability of different system codes to analyse Gas Cooled Fast Reactor Transient. The same questionnaire has been used and filled by all the participants of the WP1 listed in the introduction. The questionnaire deals these main items:

- Reactor physics model
- TH model (core, primary/secondary sytems, vessel TH modelling)
- Number of fluids in a model
- Physical correlations
- Heat transfer modelling
- Fuel modelling
- Existing coupling

The full results of the questionnaire, including the response from all partners is given in Annex, while a synopsis of the results is presented below in table 3.

The following comments can be made:

- Reactor physics model: all the codes can run point kinetics/thermalhydraulic calculations, except ICARE and MELCOR. Two codes (MANTA and RELAP) can perform coupled system and 3D neutronic analyses.
- Reactor core TH modelling: there is no limitation for the reactor core geometry which can be cylindrical or hexagonal. All the code proposes a multiple parallel channel modelling.
- Vessel TH modelling: A 1D modelling is possible for all the codes. Five of them (Cathare, Relap, Icare, Flownex, Melcor) can model the vessel in 3D. Only Flownex can use a CFD approach to model the vessel.
- Primary/secondary system modelling: All the codes, except Melcor, have specific modules for pump, valve, compressor, heat exchanger, turbine.
- Number of fluids in a model: All the codes can model any type of needed coolant for the modelling of experiments.
- Fuel modelling: Only Relap can deal with all types of fuel.

Item	VUJE/CEA CATHARE	ANSALDO/ NRI RELAP	NRG SPECTRA	IRSN ICARE-CATHARE	IKE FLOWNEX	FRA-ANP MANTA	AMEC NNC RELAP + WIMS9	TRACTEBEL MELCOR
Reactor physics model								
Point kinetics (application to critical/sub-critical systems)	Y	Y	Y	N	Y	Y	Y	N
3D spatial kinetics (application to critical/sub-critical systems)	N	Y	N	N	N	Y	N	N
Source of cross-sections (code used for cross-sections generation)	N		N	N	N	N	N	N
Cross-section parameterization (look-up table, polynomials, etc.); reactivity feedbacks available	Y	Y		N	N	Y		N
Power deposited in fuel	Y	Y	Y	Y	Y	Y	Y	Y
Power deposited in cladding	Y	Y	Y	Y	N	N	Y	N
Power deposited in coolant	Y	Y	Y	N	N	N	N	N
Core depletion analysis	N	N	Y	N	N	N	Y	N
Thermal Hydraulics: Reactor core modelling								

Item	VUJE/CEA CATHARE	ANSALDO/ NRI RELAP	NRG SPECTRA	IRSN ICARE-CATHARE	IKE FLOWNEX	FRA-ANP MANTA	AMEC NNC RELAP + WIMS9	TRACTEBEL MELCOR
Geometry: cylindrical, hexagonal, etc.	Y	Y	Y	Y	Y	Y	Y	Y
Modelling by a single TH channel	Y	Y	Y	Y	Y	Y	Y	N
Modelling using multiple parallel channels (their number)	Y	Y	Y	Y	Y	Y	Y	Y
Thermal Hydraulics: Vessel TH modelling								
1D	Y	Y	Y	Y	Y	Y	Y	Y
3D	Y	Y	N	Y	Y	N	N	Y
Computational fluid dynamics (CFD)	N	N	N	N	Y	N	N	N
Total number of control volumes	Around 1000	No limitation	Computer memory dependent	Around 1000	Any number	As many as necessary	Arbitrary	No practical limitation
Primary/secondary system modelling:								
Thermal-dynamic modelling of a pump (what types)	Y	Y	Y	Y	Y	Y	Y	Y
Thermal-dynamic modelling of a compressor	Y	Y	Y	Y	Y	Y	Y	Y
Thermal-dynamic modelling of a valve (what types)	Y	Y	Y	Y	Y	Y	Y	N
Thermal-dynamic modelling of a heat exchanger	Y	Y	Y	Y	Y	Y	Y	N
Thermal-dynamic modelling of a turbine	Y	Y	Y	Y	Y	Y	Y	N

Item	VUJE/CEA CATHARE	ANSALDO/ NRI RELAP	NRG SPECTRA	IRSN ICARE-CATHARE	IKE FLOWNEX	FRA-ANP MANTA	AMEC NNC RELAP + WIMS9	TRACTEBEL MELCOR
Flow regime models as codes	Y	Y	Y	Y	Y	Y	Y	Y
Number of fluid in a model								
Liquids: water, super-critical CO_2, Na, lead, lead-bismuth-eutectic (LBE), etc.	4	8	1	1	1	1	3	3
Gases: He, Air, N_2, CO_2, etc.	6	8	6	6	4	7	9	14
Two-phase fluids: number of equations solved	6	6	Y	6	6	5	6	Y
Heat transfer models used	Y	Y	Y	Y	Y	Y	Y	Y
Friction models used	Y	Y	Y	Y	Y	Y	Y	Y
Fuel modelling								
Pin fuel	Y	Y	Y	Y	N	Y	Y	Y
Plate fuel	Y	Y	Y	N	N	N	Y	N
Dispersed fuel	Y	Y	Y	N	N	Y	Y	N
Coated particles	N	Y	N	Y	Y	N	Y	N
Types of fuel available: oxide (U/PuO_2), carbide, nitride, etc.	Any	Any	Any	Any	1	Any	Any	1
Clad materials available: stainless steel, zircaloy, silicon carbide, etc.	Any	Any	Any	Any	N	Any	Any	Any
Heat transfer modelling								
Radial	Y	Y	Y	Y	Y	Y	Y	Y
Linear (axial)	Y	Y	Y	Y	Y	N	N	Y

***Table 3**: synopsis of the questionnaire on code's capability to analyse Gas Cooled Fast Reactor Transient*

7. Validation of system codes

The development of simulation tools is based on different main steps:

- The validation of the physical models (heat transfer coefficient, pressure drops)
- The validation of the 1D modelling of complex geometry such as Heat Exchanger, Turbine…
- The improvement and the development of new models: improvement of existing potentialities, validation feedbacks, specific models of the different studied models.

The validation process is to identify the deficiencies and the needs for improvements in the codes and the associated models. At the end of the project, possible needs for code development and for additional safety experiments for code validation will be defined.

The validation should be carried out on three different levels:

- Separate-effect tests for a validation on a *fundamental level*, with refined measurements to establish heat transfer and friction correlations for helium as well as gas mixtures, in all relevant flow regimes (laminar/turbulent, forced/natural convection).
- Validation on a *component level*, usually motivated by the geometrical complexity of certain components (core elements, heat exchangers), or because of their complex dynamical characteristics (turbomachines).
- Validation on the *system level*, to account for the dynamic interaction between components during transients, and for exploring the impact of various control strategies.

8. Experimental data available

All the European partners participating to the benchmark exercise prefer a comparison against experimental data rather than a benchmark code-to-code. In this frame, two possible experimental data sets have been identified. They correspond to data from the German utility Oberhausen II and from the Italian facility HE-FUS3. Hereafter, a brief description of those two facilities is given.

Oberhausen II

Oberhausen II, operated also by the utility EVO, is a 50 MW(e) direct-cycle Helium turbine plant (see Bammert & Deuster, 1974 and Bammert et al., 1983). The facility was part of a large German research and development program initiated in 1968 to demonstrate the feasibility of a Brayton-cycle power conversion system with helium turbo-machines. The power source is a gas burner rather than a nuclear reactor core, but the power conversion system resembles those of direct-cycle GCR concepts. Oberhausen II was operated for more than 25000 hours between 1974 and 1988.

Design specifications, drawings and experimental data have been obtained through the European HTR-E project, offering a unique opportunity to validate system codes on a large-scale helium Brayton cycle. However some data are missing, such as precise transient measurements and regulation parameters, turbo-machine parameters (performance maps, rotor inertia, gearbox parameters, shaft friction parameters, generator friction parameter) and piping and valves characteristics. It is planned in the frame of RAPHAEL to gather additional data.

HE-FUS3

The HE-FUS3 facility is located at the ENEA Brasimone Laboratories in Italy, firstly developed in the frame of the International Thermonuclear Experimental Reactor. Its eightshaped loop configuration supplies the helium flow rate to an experimental Test Section. The purpose of the figure-eight-shaped closed loop arrangement is to separate two zones at different temperatures, the cold one including the compressor and the hot one the Test Section. An economizer, that is a high efficiency, tube-shell geometry, counter-current helium/helium exchanger, is placed at the crossover point, in order to recover the gas enthalpy before recirculating the helium through the compressor. The facility is adequately instrumented for mass flow rate, temperature, pressure measurements. The range of the parameters is: Pressure 25-50bar, Helium maximum temperature 530°C, Helium flow rate up to 0.35kg/s. A certain number of tests should be available in the frame of RAPHAEL.

Annex:

Detailed answer of the Questionnaire "Thermal Hydraulic codes and applicability to VHTR safety analysis"

Table 4 – Detailed answer of the Questionnaire
"Thermal Hydraulic codes and applicability to VHTR safety analysis"

Item	**VUJE/CEA CATHARE & IRSN CATHARE/ICARE**	**ANSALDO/NRI RELAP**	**IKE FLOWNEX**	**FRA-ANP MANTA**
		REACTOR PHYSICS MODEL		
Point kinetics (application to critical/sub-critical systems)	Each wall structure can have its own temperature-dependant reactivity coefficient, contributing to the total core reactivity. Walls can have several radial material layers. (for example one layer acting as moderator, and another layer representing a fuel pellet with a negative reactivity coefficient, due to the Doppler effect). All walls may receive a specified fraction of the fission or residual power, and the axial power distribution can be modified during a transient simulation. An external reactivity can be introduced in the input deck, to model the action of the control rods or effects of Xenon poisoning.	Point kinetics model is available. Limited to critical systems it takes into account all feedbacks contributing to the total reactivity.	The global reactor behavior can be simulated dynamically using the point kinetics model which calculates the power based on reactivity feedback equations taking into account the average fuel and moderator temperatures, xenon concentration and the control rod settings.	Each solid structure (e.g. fuel, moderator, reflectors …) can have its own temperature-dependant reactivity coefficient, contributing to the total core reactivity. The reactivity due to the control rods can be added. Reactivity is then an input for the neutronic density calculation by a model allowing 6 groups of delayed neutrons. The nuclear power is the sum of the neutronic power and the residual power.

Item	**VUJE/CEA CATHARE & IRSN CATHARE/ICARE**	**ANSALDO/NRI RELAP**	**IKE FLOWNEX**	**FRA-ANP MANTA**
3D spatial kinetics (application to critical/sub-critical systems)		Relap5 can be coupled to PARCS code. Originally developed for critical systems this code has been modified also to take into account sub-critical conditions by ENEA		1-D or 3-D neutronic calculations can be done by coupling SMART neutronic code with MANTA code.
Source of cross-sections (code used for cross-sections generation)		User input. Any deterministic code can be used to generate the information required		
Cross-section parameterization (look-up table, polynomials, etc.); reactivity feedbacks available	• Doppler feedback effect • Void feedback effect (fluid effect) • Structure feedback effect • Feedback coefficients must be supplied by the user by the means of finer neutronics computation	Look-up table - linear or quadratic interpolation. Reactivity feedbacks available.		• Doppler feedback effect • Structures feedback effects • Feedback coefficients must be supplied by the user.
Power deposited in fuel	Fission power and residual power With possible axial profile		With axial profile and normalized radial power distribution profiles within the axial layers in the core.	With possible axial profile.
Power deposited in cladding	With possible axial profile			A specified fraction of the nuclear power can be deposited

Item	**VUJE/CEA CATHARE & IRSN CATHARE/ICARE**	**ANSALDO/NRI RELAP**	**IKE FLOWNEX**	**FRA-ANP MANTA**
				in the moderator or any solid structure in the core.
Power deposited in coolant	With possible axial profile			
THERMAL HYDRAULICS MODEL				
Reactor core modelling				
Geometry: cylindrical, hexagonal, etc.	• Any 1D geometry • Possibly 3D coarse meshing	1-D radial Geometry, axial noding	1-D elements can be used to construct a 2-D axi-symmetrical core geometry with a cylinder shape.	Any 1D-geometry: the TH channels are described by their cross section, wetted perimeter and length
Modelling using multiple parallel channels (their number)	• Two channels representative of coolant channels in the hottest assembly and in the "mean" core. • Or more for by-pass modelling…	No practical limitation, up to the number of assembly of the core	Any number	As many channels as necessary
Vessel TH modelling				
1D				There is no specific reactor vessel model, since MANTA is able to describe the different flows and associated nphenomena, such as the flows imperfect mixing.
3D	Coarse meshing	Simplified 3-D model using	Two separate flow path	

Item	**VUJE/CEA CATHARE & IRSN CATHARE/ICARE**	**ANSALDO/NRI RELAP**	**IKE FLOWNEX**	**FRA-ANP MANTA**
		cross flow terms perpendicular to main flow direction	networks constructed with a primitive one-dimensional flow element.	
Computational fluid dynamics (CFD)		If needed the possibility of a coupling with a CFD code can be analyzed and implemented. Alternatively specific computation can be made to tune the system modelling on CFD results.	The reactor is modelled as a sub-network, which is equivalent of a 2-D CFD model.	
Total number of control volumes	Around 1000	No practical limitation	Any number of control volumes in the axial and/or radial directions.	As many as necessary
Primary/secondary system modelling				
Thermal-dynamic modelling of a pump (what types)	Point pump module based on characteristic maps : - the pump head is added to the momentum equations $\Delta P_{pump}=\rho H(\Omega,Q)$ - the power exchanged is added to the energy equations $W=Ch(\Omega,Q,\rho)\,\Omega$	Pump centrifugal modelling based on pump head versus flow. Homologous curves used. Simulation of power dissipated to the fluid is included.	Pressure increase through a pump is interpolated from the pump curve ($\Delta p = Q$). Takes into account effect of energy transfer to the fluid on the temperature increase through the pump.	Point pump module The pump rotational speed can either be imposed externally or deduced from the momentum equation of the shaft, accounting for applied electrical, hydraulic, and friction torques. Hydraulic torque and pump head are then derived from homologous curves, using the rotation speed and the volumetric flow rate.

Item	**VUJE/CEA CATHARE & IRSN CATHARE/ICARE**	**ANSALDO/NRI RELAP**	**IKE FLOWNEX**	**FRA-ANP MANTA**
				The power dissipated to the fluid can be added externally.
Thermal-dynamic modelling of a compressor	• compressible subsonic model (see to the § turbine for more details) • the surge margin is modelled	An approximate solution has been already tested at ENEA using the centrifugal pump model. Alternatively simplified modelling based on performance data can be input by the user.	Models for axial, centrifugal and positive displacement compressors exist. Performance characteristics (pressure ration and efficiency) are provided. Compressor surge margin indication is featured.	Point compressible model A compressor is defined by its performance maps : - flow rate as a function of pressure ratio and rotational speed or pressure ratio as a function of flow rate and rotational speed - efficiency as a function of pressure ratio and rotational speed The surged margin is modelled.
Thermal-dynamic modelling of a valve (what types)	• Control valve, check-valve, flow limiter including sonic to subsonic transition • Valve capacity and critical pressure ratio are given by the user and depend on the valve technology	Trip valve, check valve, inertial valve, motor valve , servo valve, relief valve	Pressure regulating valve – performance characteristics give downstream total pressure as a function of upstream total pressure, mass flow and elevation ; Pressure relief valve; Control valve – modelled as an orifice in a pipe with a variable area ratio.	Definition of the valve coefficient (Cv) as a function of the valve opening Subsonic and sonic flows
Thermal-dynamic modelling of a	• Implicit wall to fluid coupling on each side of	Internal computation of heat exchange coefficients, user can	Gas-liquid heat exchanger; Shell-and tube; Recuperator;	Counter-courant and co-courant exchangers

Item	VUJE/CEA CATHARE & IRSN CATHARE/ICARE	ANSALDO/NRI RELAP	IKE FLOWNEX	FRA-ANP MANTA
heat exchanger	the HX • Semi implicit or implicit primary to secondary coupling	tune the performances on exp. data, any number of subdivision	Evaporator.Capable of handling compressible and incompressible flows. Pressure drop is calculated as a function of mass flow rate and fluid density. Heat exchangers are modelled as lumped systems with no thermal inertia in the case of transient flows. Heat transfer is calculated by using the effectiveness – NTU relations.	The heat transfer coefficient on each side can either be imposed externally or calculated with the convective heat transfer correlation
Thermal-dynamic modelling of a turbine	• Compressible subsonic model. • The data of the turbomachine performance maps can be entered either as fitted polynomial functions, or as tables of performance data. • Turbomachines can be run at a given speed, or coupled together on common shafts for which an equation of motion is solved. • Most operating parameters	Simplified modelling	Performance characteristics – see compressor. Ability to construct composite turbo machines of turbines, compressors and a generator connected on one shaft. At steady state power matching is available. During transient simulations the rotational speed can be calculated.	Point compressible model Different turbine models are available: - definition of the turbine by its performance maps (flow rate and efficiency as functions of pressure ratio and rotational speed) - Stodola model : the flow rate is a function of the pressure ratio only Turbomachines can be run at a given speed, or coupled

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	can be modified during the calculation			together (and eventually with an alternator) on a common shaft for which a dynamic equation is solved.
Etc.	• Mass and energy sources • Mass and energy sinks • Break modules • Boundary conditions • Point accumulator (for heavy gas injection for ex.) • Activity transport model			
Mechanistic models of components: 1D, 2D, etc.	• 1D Turbomachine module in progress	Pump, turbine		
Flow-regime models as coded	• Laminar and turbulent • Subsonic for gaz turbo-machinery • Sonic for BWR turbine ▪ Sonic-subsonic in valves • Predicted via fine meshing and small time step in 1D model	Two-phase flow regime maps based on empirical correlations (water)	Laminar and turbulent regimes, multi phase flows, buoyancy driven flows, compressible flows up to Mach 1.	laminar and turbulent regimes - sonic and sub-sonic regimes in valves
Number of fluids in amodel				
Liquids: water,	▪ Water	Water, heavy-water, lead, lead-	Water	Water

Item	**VUJE/CEA CATHARE & IRSN CATHARE/ICARE**	**ANSALDO/NRI RELAP**	**IKE FLOWNEX**	**FRA-ANP MANTA**
super-critical CO_2, Na, lead, lead-bismuth-eutectic (LBE), etc.	▪ Supercritical water ▪ Na (in progress) ▪ Freon • *Water for ICARE*	bismuth, lithium, lithium-lead, sodium, sodium-potassium (others can be implemented)		
Gases: He, Air, N_2, CO_2, etc.	- He, N2, H2, O2, air - Possibility to define easily any other non condensable gases. - Perfect gas with Cp(T) - 2 Mixing models for transport properties: Mason saxena and Wilke, average weighted by molar fractions	Argon, Helium, Air, Nitrogen, Hydrogen, Xenon, Krypton, SF6 (Others can be implemented)	He, O_2, N_2, air. Options: constant density, $\rho = \rho(T)$, rigid column theory or elastic theory, ideal and non-ideal gasses, gas mixtures.	- He, Ar, N_2, H_2, H_2O, NH_3, Na-Ar mixture - It is possible to define easily the properties of any other perfect gas - It is possible to define a mixture of two gases (mixing model available)
Number of fluids permitted in any control volume simultaneously (liquid/liquid, gas/gas, liquid/gas)	1 fluid liquid/vapor - + 4 Non condensable gases	One two-phase fluid with a non condensable added to the steam transport equation and one additional scalar traching in the liquid (for example boron in liquid water)	A liquid/vapor mixture or a mixture of two gasses.	1 fluid liquid/vapor 1 mixture of two gases
Two-phase fluids: number of equations solved	6 equations + 1 transport equation for each NC gas	6 equation + additional modelling for non condensable gas	Six conservation equations are implemented, namely mass, momentum and energy conservation equations for each	5 balance equations: - 2 mass balance equations - 2 energy balance equations - 1 momentum equation for

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			of the phases.	average mixture flow and a drift flux model providing differential velocities for both phases
Heat transfer models used	• Natural convection (turbulent and laminar) • Forced convection (turbulent and laminar) • Radiation Component specific laws (heat exchangers…)	Natural and forced convection, radiation	Natural and forced convection, conduction, radiation	• Natural convection (laminar and turbulent): Mac Adam correlation • Forced convection (laminar and turbulent), Dittus-Boelter correlation; in two-phase flow and boiling conditions, Chen formulation • Conduction • Radiation: only the radiative heat transfer between a wall and an ambient medium can be calculated (as a boundary condition)
Friction models used	• Wall friction correlations for laminar, transition and turbulent flow regime • Singular pressure losses may be introduced by the user • Component specific laws (heat exchangers…)	Wall friction, singularity pressure losses, specific losses Reynolds dependent	Friction coefficients for circular cross-sections are presented in terms of Reynolds number, Re, and relative roughness, k/D. Friction coefficients for non-circular cross-sections are obtained by applying a correction factor to	For friction pressure drops, friction coefficients are imposed or calculated by Colebrook formula. For two-phase flows, specific volume is calculated either in homogeneous conditions or by a separated phase model.

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			the circular cross-sections values.	- Singular pressure losses may be introduced by the user • - Calculations of pressure losses occurring in pipe tees
Fuel modelling				
Pin fuel				Two existing models: - a 0-D thermo-hydraulic model taking into account the fuel and the cladding - a 1-D model thermo-hydraulic model accounting for radial conduction in the fuel and in the gap.
Plate fuel				No existing model Development of a model possible with the existing MANTA objects
Dispersed fuel				Definition of the fuel fraction in the matrix
Coated particles	• No particular thermal conduction computation – • Possibility to adopt a modelling based on an equivalent fuel ? • *ICARE: Possibility to define*		The reactor core is made up of fuel spheres. Each sphere consists of an inner fuel region set inside a graphite matrix. The fuel region is covered by a fuel-free graphite layer.	

Item	**VUJE/CEA CATHARE & IRSN CATHARE/ICARE**	**ANSALDO/NRI RELAP**	**IKE FLOWNEX**	**FRA-ANP MANTA**
	fuel particles with any coating, diameter and porosity			
Etc.	•	Cylindrical, spherical, plate geometry are directly inputted to the code. For dispersed fuel and coated particle some rough approximation may be needed.		
Types of fuel available: oxide (U/PuO_2), carbide, nitride, etc.	• UO2 • Any other to be entered by the user	Any material easily defined by user input	UO2	UO2, MOX Any other type of fuel can be defined by the user
Clad materials available: stainless steel, zircaloy, silicon, carbide, etc.	• stainless steel, zircaloy, Inconel XXX, ceramic… • Possibility to define easily any other material.	Any material easily defined by user input		Any material can be defined by the user
Heat transfer modelling				
1D, 2D, 3D	• 1D radial Conduction • 2D radial and explicit axial conduction • Radiation *ICARE: 2D radiative heat transfer*	1D radial 2D radial and axial	1D, 2D radial convection and conduction; 1D, 2D axial convection and conduction; radiation	

Item	**VUJE/CEA CATHARE & IRSN CATHARE/ICARE**	**ANSALDO/NRI RELAP**	**IKE FLOWNEX**	**FRA-ANP MANTA**
Radial				Radial conductive heat transfer in a linear or cylindrical geometry
Linear (axial)				No axial conduction
Special models	ICARE: • Zircaloy oxidation (rods or particles) • Steel oxidation, Boron Carbide oxidation (control rods) • Mechanical creep and rupture of claddings • Collapse of fuel particles, and any other solid particles • Melting of particles • Relocation of molten materials • Material chemical interactions • U02 liquefaction by solid Zr • U02 and Zr02 dissolution by molten zircaloy • Dissolution of Zr by molten Ag • Interaction between solid			- I&C systems: existence of a library of elementary functions; I&C systems actuate automatic actions of reactor systems such as control rods, valves, pumps … - compressible or incompressible mode for the balance equations resolution - boundary conditions - mass and energy sources or sinks

Item	**VUJE/CEA CATHARE & IRSN CATHARE/ICARE**	**ANSALDO/NRI RELAP**	**IKE FLOWNEX**	**FRA-ANP MANTA**
	stainless steel and Zr • Interaction between B4C and solid -stainless steel • Reflooding of high temperature degraded geometry • 2D heat treansfers in particle beds			

Item	**NRG SPECTRA**	**TRACTEBEL MELCOR**	**AMEC NNC RELAP + WIMS9**
		Reactor physics model	
Point kinetics (application to critical/sub-critical systems)	Reactivity feedback from fuel temperature (Doppler effect), moderator density (alternatively moderator temperature and void fraction), and changes of nuclide concentrations (for example Xenon poisoning, fuel depletion, etc.) Calculation of average core parameters based on user-defined weighting factors, separate for fuel and moderator. Fuel and moderator materials can be defined as solids, liquids or gases. An external reactivity can be introduced as a Tabular or Control Function to model control rods, radial and axial expansions,		Modified by AMEC NNC to include xenon poisoning and better representation of moderator temperatures.

Item	**NRG** **SPECTRA**	**TRACTEBEL** **MELCOR**	**AMEC NNC** **RELAP + WIMS9**
	etc.		
3D spatial kinetics (application to critical/sub-critical systems)	-		Yes in RELAP5-3D
Source of cross-sections (code used for cross-sections generation)	-		WIMS9
Cross-section parameterization (look-up table, polynomials, etc.); reactivity feedbacks available	Reactivity feedback entered either using a full reactivity table: $R = f(T_{fuel}, \rho_{mod})$, or: $R = f(T_{fuel}, T_{mod}, \alpha)$ alternatively separable reactivity tables: $R = f_1(T_{fuel}) \cdot f_2(\rho_{mod})$ or: $R = f_1(T_{fuel}) \cdot f_2(T_{mod}) \cdot f_3(\alpha)$ Feedback coefficients must be supplied by the user by the means of finer neutronics computation		Feedback coefficients given as input data, determined from WIMS models.
Power deposited in fuel	The power calculated by the point kinetics model can be distributed among the solid structures, liquids and gases, according to user-defined fractions.	Fission power and residual power. Axial profile is possible. ORIGEN calculations determine decay heat power.	Power level determined by point kinetics and power distribution obtained from WIMS9
Power	The power calculated by the point kinetics		Neutron and gamma heating could be

Item	NRG SPECTRA	TRACTEBEL MELCOR	AMEC NNC RELAP + WIMS9
deposited in cladding	model can be distributed among the solid structures, liquids and gases, according to user-defined fractions.		specified as input.
Power deposited in coolant	The power calculated by the point kinetics model can be distributed among the solid structures, liquids and gases, according to user-defined fractions.		Only by convective heat transfer, no nuclear heating of the coolant.
Core depletion analysis	Possible within the point kinetics model, using one group cross sections		Core states at different times through a cycle are determined by WIMS9.
		Thermal Hydraulics model	
Reactor core modelling			
Geometry: cylindrical, hexagonal, etc.	Any user-defined geometry. Description in terms of hydraulic diameter etc.	2D axi-symmetrical core geometry with a cylinder shape. The core consists of a user defined number of axi-symmetric core rings. Each of these rings can be split up in a user defined number of core levels.	Cartesian or Hex geometries in RELAP5-3D. Bespoke models developed for coupling to WIMS to determine feedback coefficients: 3D r-z-θ continuum model for pebble bed cores and multi-channel 1D flow with 3D hex-z thermal model for prismatic cores.
Modelling by a single TH channel			More likely to use multi-channel models including hot and nominal channels.
Modelling using multiple parallel channels (their number)		Each core ring has a TH channel with a user defined width. This width varies when the core degrades (candling - blocking).	Arbitrary

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Vessel TH modelling			
1D	1D Euler equation of motion, no momentum transfer between parallel channels due to viscosity and turbulence (no CFD)		
3D		The user can choose the number of control volumes in the core. By using a large number, eg. one for every core segment, a 3D flow model in the core can be obtained.	Yes in RELAP5-3D
Computational fluid dynamics (CFD)			RELAP5 has been linked to run in parallel with CFD models, but there is no intention to do that in this exercise.
Total number of control volumes	Depends on computer memory. In practical problems ~100.	No practical limitation	Arbitrary
Primary/secondary system modelling			
Thermal-dynamic modelling of a pump (what types)	Pump model based on characteristic maps. The maps specify reduced (dimensionless) head versus reduced flow and reduced speed. The reduced flow and speed are given by: $V_R = \left(\frac{V}{V_N}\right) \quad \omega_R = \left(\frac{\omega}{\omega_N}\right)$ The maps are defined using polynomial expressions, with user-defined coefficients. The pump head is added to the momentum	Two models exist: 1) Define pressure head vs. mass flow rate; 2) Parabolic relationship between the head (DP), developed by the pump and the volumetric flow through it.	All types for which characteristics can be supplied

Item	**NRG** **SPECTRA**	**TRACTEBEL** **MELCOR**	**AMEC NNC** **RELAP + WIMS9**
	equations. The power exchanged is added to the energy equations The speed is either user-defined or calculated from the rotor inertia equation $I\frac{d(2\pi\omega)}{dt} = T_m - T_{hydr} - T_{fric}$ The motor torque, T_m, may be specified by a Tabular or Control Function, or it may be linked to another machine, such as turbine, to obtain a turbine driven pump.		
Thermal-dynamic modelling of a compressor	Similar to the pump model The reduced flow and speed are given by $V_R = \frac{\left(\frac{V}{V_N}\right)}{\left(\frac{R}{R_N}\right)\sqrt{\frac{T}{T_N}}} \frac{\sqrt{\frac{1+v^2/2c_pT}{1+v_N^2/2c_pT_N}}}{\left(\frac{1+v^2/2RT}{1+v_N^2/2RT_N}\right)}$ $\omega_R = \frac{\left(\frac{\omega}{\omega_N}\right)}{\sqrt{\frac{T}{T_N}}}$ The surge margin is modelled.	Fan-cooler model	Model developed by AMEC NNC. Aero-engine industry standard approach based on pressure ratio, mass flow and efficiency maps.

Item	**NRG SPECTRA**	**TRACTEBEL MELCOR**	**AMEC NNC RELAP + WIMS9**
	The speed is either user-defined or calculated from the rotor inertia equation $I\frac{d(2\pi\omega)}{dt}=T_m-T_{hydr}-T_{fric}$ The motor torque, T_m, may be specified by a Tabular or Control Function, or it may be linked to another machine, such as turbine, to obtain a turbine driven compressor.		
Thermal-dynamic modelling of a valve (what types)	Motor valve with flow area controlled by a Tabular or Control Function. Check-valve with a user-defined opening and closing setpoints.	Specific valve types are not available. Valves can be simulated by controlling the open fraction and flow resistance of a flow path (junction).	Isolation, relief, static or actuator driven. Generally specified through prescribed loss coefficients and flow area~time histories .
Thermal-dynamic modelling of a heat exchanger	User-defined nodalisation with 1D or 2D Solid Heat Conductors transferring heat at the boundaries. Temperature averaging concept allows to model accurately HX with large inlet to outlet ΔT and small primary to secondary ΔT (such as recuperator) Implicit wall to fluid coupling on each side of the HX	There is no model for a steam generator. The primary side and secondary side of the SG have to be modelled with control volumes and interconnected heat structures	
Thermal-dynamic modelling of a	Similar to the compressor model The reduced flow and speed are given by		Model developed by AMEC NNC. Aero-engine industry standard approach based on pressure ratio, mass flow and efficiency

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turbine	$V_R = \dfrac{\left(\dfrac{V}{V_N}\right)}{\left(\dfrac{R}{R_N}\right)\sqrt{\dfrac{T}{T_N}}} \dfrac{\sqrt{\dfrac{1+v^2/2c_pT}{1+v_N^2/2c_pT_N}}}{\left(\dfrac{1+v^2/2RT}{1+v_N^2/2RT_N}\right)}$ $\omega_R = \dfrac{\left(\dfrac{\omega}{\omega_N}\right)}{\sqrt{\dfrac{T}{T_N}}}$ The speed is either user-defined or calculated from the rotor inertia equation $I\dfrac{d(2\pi\omega)}{dt} = T_m - T_{hydr} - T_{fric}$ The motor torque, T_m, may be specified by a Tabular or Control Function, or it may be linked to another machine, for example generator.		maps.
Etc.	Mass and energy sources (and sinks)	1) Mass and energy sources 2) Boundary conditions Activity transport model (deposition, filtering and washing of RN gases and aerosols)	Electrical generator, control systems, liquid accumulator, jet pump
Mechanistic			Lumped parameter models for all

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models of components: 1D, 2D, etc.			components except heat exchangers which are discretised using control volumes and heat structures.
Flow-regime models as coded	Non-homogeneous, non-equilibrium, two-phase, multi-component model. Laminar and turbulent flows. Bubbly, misty, stratified two-phase flow regimes. Counter-current two-phase flow	Full two-fluid treatment. Non-homogeneous, non-equilibrium, (stratified, bubbly, fog) two-phase, multi-component model. Counter-current two-phase flows. Laminar and turbulent regimes, buoyancy driven flows. Critical flow model.	Non-homogenous, non-equilibrium, two-phase, multi-component model. Laminar and turbulent flows. Bubbly, plug and stratified two-phase flow regimes. Counter-current two-phase flow.
Number of fluids in a model			
Liquids: water, super-critical CO_2, Na, lead, lead-bismuth-eutectic (LBE), etc.	Water	Water, heavy water	Water, water/boric acid mixture, S-CO2 (via ATHENA)
Gases: He, Air, N_2, CO_2, etc.	H_2, He, steam, N_2, O_2, CO_2	Air, steam, O_2, N_2, H_2, CO, CO_2, He, Ar, NO, N_2O, NH_3, CH_4 and UF_6	Ar, He, H_2, N_2, Xe, Kr, Air, SF_6, CO_2 via ATHENA
Number of fluids permitted in any control volume simultaneously (liquid/liquid, gas/gas,	• Atmosphere – continuous component consisting of a mixture of gases • Pool – continuous component consisting of water • Droplets – dispersed component consisting of water droplets suspended in the atmosphere	One two-phase fluid and no limitation regarding NC gas components.	Water + Steam + up to 5 non-condensable species

Item	**NRG SPECTRA**	**TRACTEBEL MELCOR**	**AMEC NNC RELAP + WIMS9**
liquid/gas)	Bubbles – dispersed component consisting of a mixture of gases in the pool		
Two-phase fluids: number of equations solved	• Mass conservation for each fluid (water + up to 6 gases) • Energy conservation for each component (2 continuous and 2 dispersed). • 1D Euler equation of motion for 2 continuous components. • Drift flux model for 2 dispersed components.	6 equation hydrodynamics: conservation of mass and energy for two fluids and change in flow velocity for two fluids. 1 transport equation for each gas.	• 2 phasic momentum equations, 2 phasic continuity equations, 2 phasic thermal energy equations, 1 boron concentration equation, 1 total non-condensable mass fraction equation and up to 4 non-condensable species mass fraction equations.
Heat transfer models used		Natural and forced convection, conduction, radiation, components and boiling.	• One-dimensional convective, conductive and radiative heat transfer. Convection and boiling heat transfer correlation built-into the code. These can be substituted for other correlations if those built-in are not adequate
Friction models used	•	Frictional pressure drops contain contributions from form loss (user input coefficients) and wall friction terms (MELCOR).	• Two phase friction, with wall and inter-phase friction modelled through correlations. Friction correlations can substituted for others if the built-in forms are not adequate.
Fuel modelling			
Pin fuel		1D model taking into account radiation between fuel pins, intra-cell conduction and fuel-cladding gap heat transfer.	
Plate fuel			• These different fuel forms are modelled

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			by changing the fuel surface area to volume ratios
Dispersed fuel			
Coated particles			
Types of fuel available: oxide (U/PuO_2), carbide, nitride, etc.		UO2	Fuel is defined by the properties provided.
Clad materials available: stainless steel, zircaloy, silicon, carbide, etc.	User-defined. A library of material properties exist that can be easily attached in the input decks using the ATTACH keyword	Stainless steel, Zircaloy, Inconel.	Cladding is defined by the properties provided.
Heat transfer modelling			
1D, 2D, 3D	• 1D thermal conduction for rectangular, cylindrical, and spherical geometries 2D thermal conduction for rectangular and cylindrical geometries	2D radial and axial conduction, convection and radiation	Multi-channel 1D axial + 1D transverse. 3D in WIMS9 core models.
Radial		Radial conduction	1D conduction/convection + gap radiation. Boiling heat transfer with critical heat flux calculation
Linear (axial)		Axial conduction	1D convection

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Special models	• Thermal and density stratification models • Critical flow • Hydrogen burn models • Metal oxidation • Radioactive particle transport (aerosols, fission product vapors).	• Thermal and density stratification; • Critical flow; • Hydrogen recombination (PAR) and burn model; • Metal oxidation; • Core concrete interactions; • Radioactive particle transport (gasses and aerosols) and deporsition; • Candling of core debris; Eutectic models in the core.	CANDU channel, PWR pressuriser

9. END of the DOCUMENT