THE COPERNIC/CYCLOP COMPUTER TOOL: PRE-CONCEPTUAL DESIGN OF GENERATION 4 NUCLEAR SYSTEMS

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0. INTRODUCTION

The French Atomic Energy Commission (CEA) has launched a significant R&D program in support to the Generation 4 initiative. Among the six selected concepts, CEA has focused its program on the gas cooled reactor concepts : the VHTR (Very High Temperature Reactor) and the GFR (Gas cooled Fast Reactor).

In a first step, the viability of these concepts must be established and pre-conceptual designs proposed. This latter objective requires to consider numerous constraints, specifications and to involve quite different technical areas : core physics, thermal-hydraulics, materials, mechanical design, energy conversion, … In order to better take into account this context and to manage it fruitfully, a dedicated computer tool has been developed by CEA : COPERNIC/CYCLOP.

In more details, the COPERNIC/CYCLOP code has the following main purposes :

- to make pre-sizing of main reactor components (core, coolant circuits, heat exchangers, pumps, vessels, containments, etc),
- to describe the energy conversion system associated with the reactor and to run thermodynamic cycle efficiency calculations and optimizations,
- to quickly evaluate the consequences of the modification of the operation setpoint or of the geometrical data on the general reactor design,
- to build a database of reactors parameters which provides the data necessary to the computer codes used for more detailed studies: thermal-hydraulics, core physics, etc,
- to contribute to select and to optimize design options for innovative reactor concepts, then to evaluate these design options.

The COPERNIC/CYCLOP code is developed on the basis of Microsoft EXCEL software using spreadsheets and the VBA language. These sheets contain essential reactor data values, gathered per main components (core, vessel, pump,…) and used as input or output in the pre-sizing computation. These sheets use COPERNIC low level VBA function library to calculate all the necessary physical data [1]. After some preliminary parametrical explorations, the EXCEL solver is used to optimize a first set of parameters.

In this paper, we will present in details the COPERNIC/CYCLOP capabilities especially for gas cooled nuclear reactors. In particular, we will discuss the first results obtained by comparing several existing direct cycles, in term of thermodynamic efficiency and pre-sizing of some components. These cycles have been normalized for a better accuracy. This study has confirmed the interest to have such a global approach at the preliminary stages of the pre-conceptual design.

1. THE COPERNIC TOOL

COPERNIC is a tool which is implemented under EXCEL and has two main components :

- a library of functions (EXCEL complementary macro) providing physical data for several fluids and materials (enthalpy, entropy, specific heat, conductivity, ...), and a set of functions (simplified models, correlations) relative to specific physical problems (e.g. heat conduction, pressure loss, component dimensioning) used to evaluate other physical parameters like core power density, flow rate, size and mass of different reactor components,

- a set of spreadsheets describing several existing or innovative reactors, with their essential data values, gathered by components (core, vessel, pump, ...) used as input or output in the dimensioning computation. The approach ensures that each reactor concept (and each main component of the concept) is described by a consistent set of parameter values.

In short, the objectives of COPERNIC are the following :

- to contribute to select design options for new reactor concepts,
- to quickly evaluate the consequences of the modification of the operation setpoint or of the geometrical data on the general reactor design and its cost,
- to give the first sets of data necessary to the codes used for detailed studies : thermohydraulics, neutronics, etc.
- to build a database of reactors parameters,
- to evaluate design options of innovative reactors concepts proposed out of the CEA,
- to provide data entries for economical evaluations.

The EXCEL solver is used to optimize a set of pre-defined parameters to which dimensioning constraints are imposed, for example the maximum value of the fuel temperature for a given reactor thermal power.

The optimization procedure is assisted by a graphical interface displaying the most critical parameters: maximum cladding and fuel temperature, critical heat flux, pressure drop in the core,...

This dimensioning method has been assessed against available data on the French PWR series and BWR reactors.

COPERNIC makes it possible to quickly get results and therefore to perform parametric studies on a given concept, or comparative studies between various concepts. To date, several COPERNIC sheets have been developed for ALWRs and Gas Cooled Reactors.

2. THE CYCLOP TOOL

2.1. Objectives of CYCLOP

The COPERNIC spreadsheets describe and calculate reactors with an already fixed configuration. But a tool was lacking to easily describe, study and optimize any power conversion cycle, and to compare several cycles based on the same core.

Therefore the CYCLOP tool was implemented under EXCEL, based on the COPERNIC functions library. It allows a user to model a power conversion system in its globality and to study the respective influence of any components characteristics or cycle thermodynamical points on the global net efficiency of the cycle (or any other global parameter that should be optimized).

CYCLOP (for CYCLe OPtimization) is a computer tool implementing an automatic resolution of mass and energy balances of any reactor (first law of thermodynamics). A reactor is designed as a set of fluid loops built out of energetic components connected together by thermodynamical points and exchanging energy through calorific, mechanical or electrical transfers.

Several fluids are available : gas like helium and nitrogen, but also two-phase fluids like water or carbon dioxide (from liquid to supercritical domains). Gas mixtures are also possible.

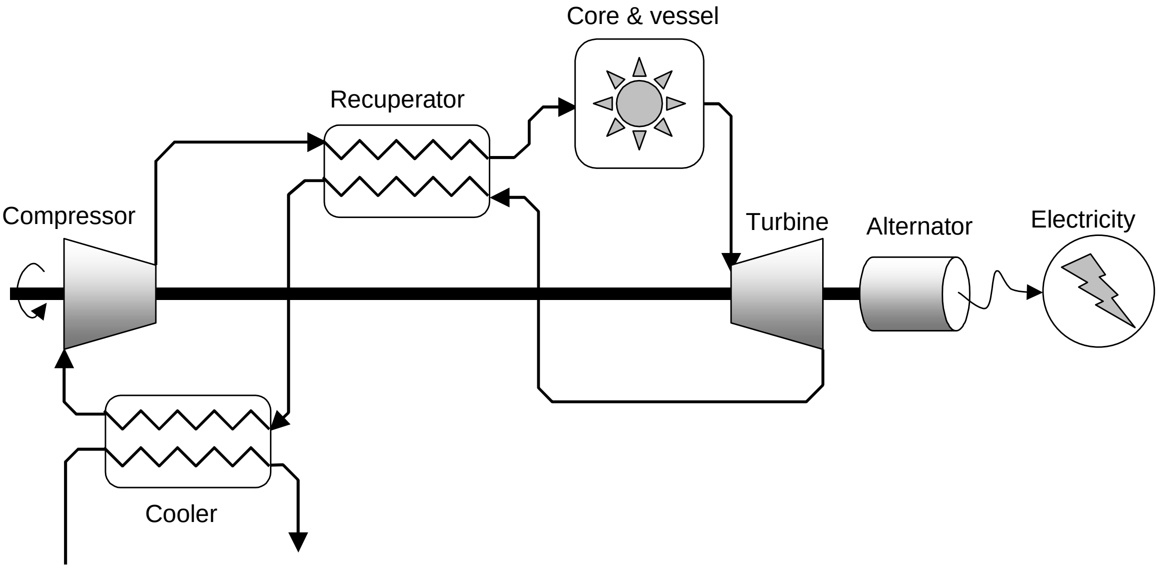
Various components are available, like reactor cores, turbines, pumps, compressors, heat exchangers, alternators, steam generators, water condensers, dryers, etc... Each component is described by macroscopic parameters like isentropic efficiency, pressure loss, calorific loss, mechanical or energetic efficiency, that implements the second principle of thermodynamics. At this stage of the modeling, no more precise physical pre sizing data are used.

This highly flexible model allows to study various solutions. The user just has to describe the configuration of the cycle and to set a necessary and sufficient number of input data for the whole system to be automatically solved. Then data can easily be modified to study and optimize the cycle.

2.2. CYCLOP interface

Like COPERNIC, CYCLOP is a library of functions (EXCEL complementary macro), integrated into EXCEL sheets describing a power conversion cycle.

As a leading example, in the rest of this article we will consider a simple Brayton cycle with a recuperator.

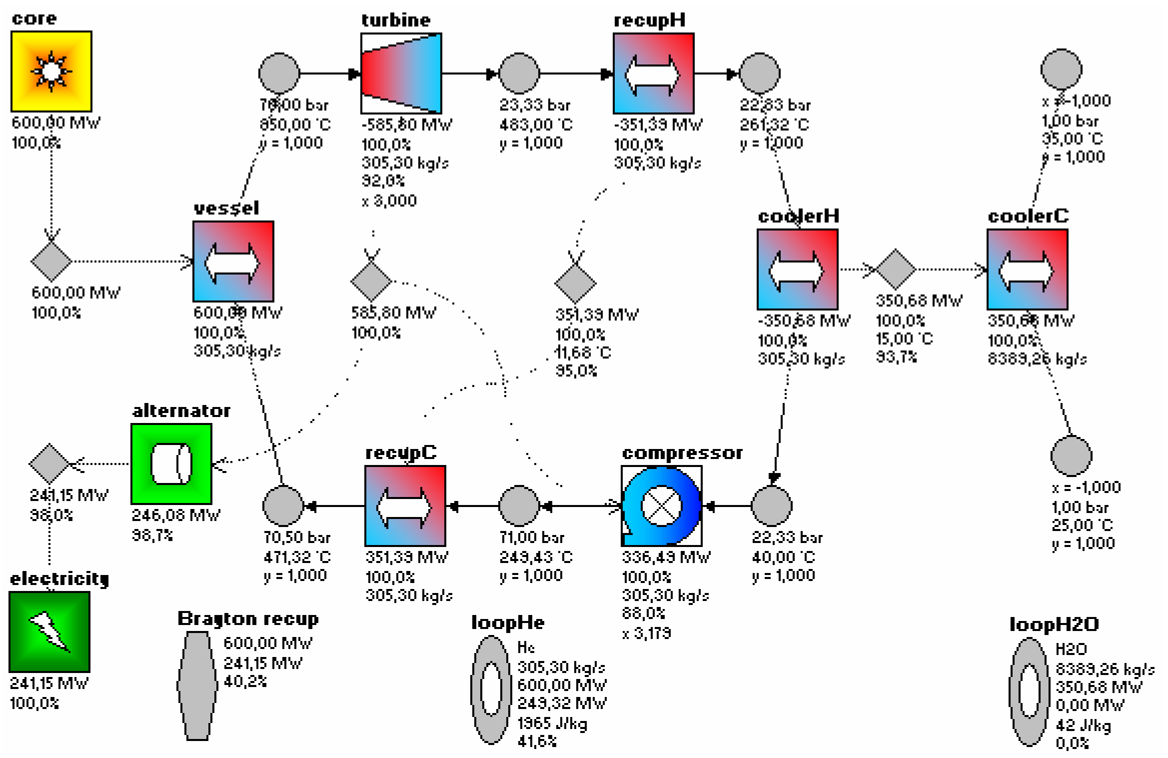


The main sheet is a standard spreadsheet divided in two parts :

- an input part describing the configuration and setting some numerical values,
- an output part which is almost a mirror of the input part, but with every missing value calculated when it is possible. If there is not enough input data, some cells are highlighted, pointing the fact that some calculation cannot be completed. If there are too many input data, some cells are highlighted, indicating some contradictions in the calculation.

Let say one want to study and optimize such a cycle, fixing a vessel outlet of 850°C / 70bar a recuperator efficiency of 95%, a turbine isentropic efficiency of 92%, a compressor isentropic efficiency of 88%, and a cooler outlet temperature of 40°C. Some reasonable pressure loss are also set on the pressure vessel and on heat exchangers. At a first glance, one will set the turbine pressure ratio to 3.0.

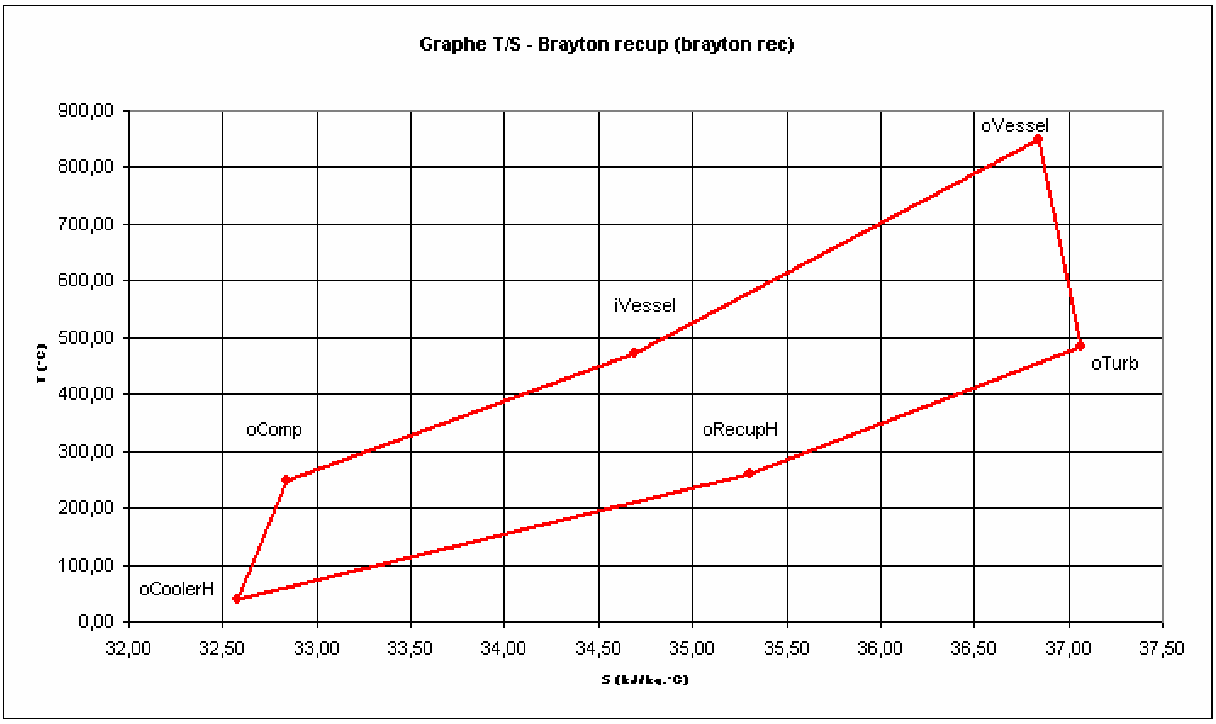
We will not present here the main CYCLOP spreadsheet, but the tool can semi-automatically generate interactive schematics of the resulting cycle :



On this schematic the full cycle is represented as components (squared shapes) connected together by thermodynamical points (round shapes) and exchanging mechanical, calorific or electrical energy though transfers (rhombus shapes). Each objects is described by its main characteristics and the whole cycle can be overviewed this way. More precisely here, the core gives its heat to the vessel. Then the helium flows trough the turbine, that provides works, losing pressure ; then helium flows through the hot part of the recuperator that exchanges heat with the cold part of the recuperator ; then the gas flows through a cooler, that exchanges heat with a water circuit which temperature increases from 25°C to 35°C ; then the helium is compressed before entering the cold part of the recuperator, gaining temperature before entering the vessel. The turbine (included on a single axis in a turbo machinery) transfers its mechanical energy to the compressor and the alternator, that converts a part of its energy into electricity. On every energy exchanges, energy losses can be represented, either in relative or absolute terms.

On the bottom of the schematics, global informations are gathered on the loops and system objects, providing for example the net efficiency of the cycle (40.2% in this case) but also the power density of the helium cycle (1965 J/kg).

CYCLOP also provides automatic generation of interactive thermodynamical diagrams (T/S) that eases the comprehension of the thermodynamical cycle :



We recognize on this diagram both almost vertical parts describing the non-isentropic compression and turbine pressure drops, but also almost pressure-constant parts concerning core heating, cooling and recuperator function. The area of the diagram represents the average power density of the cycle and could be maximized to get a relatively smaller plant. But on the other hand, we also want to maximize the overall cycle efficiency, which is a distinct and sometimes contradictory goal.

2.3. Parametrical studies and optimization

An objective of CYCLOP is to make parametrical studies of several cycles to evaluate the respective and eventually correlated influences of every local parameters of the cycle on the overall result.

The user can manually changes each value of the cycle, but CYCLOP also integrates a tool that automates such parametrical studies. The user just has to point the values that have to vary and to provides the range and incremental step of the variation. He also has to point the output values that must be checked and the tool can then calculate every intermediate cycles and creates synthetic diagrams, summarizing the study.

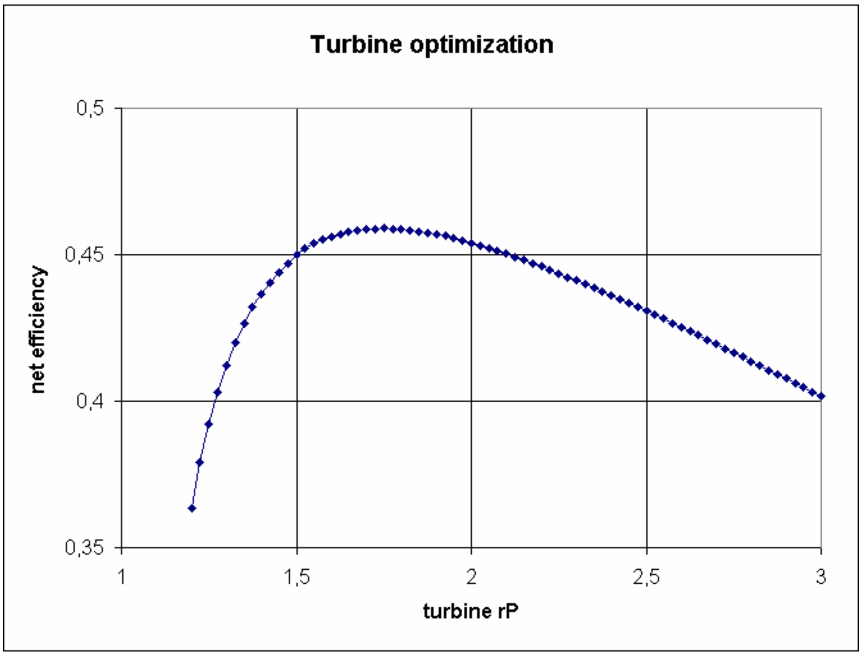
For example, in the simple case of the previous Brayton cycle, we can study the effect of the turbine pressure ratio on the net efficiency of the cycle and also on the vessel inlet temperature.

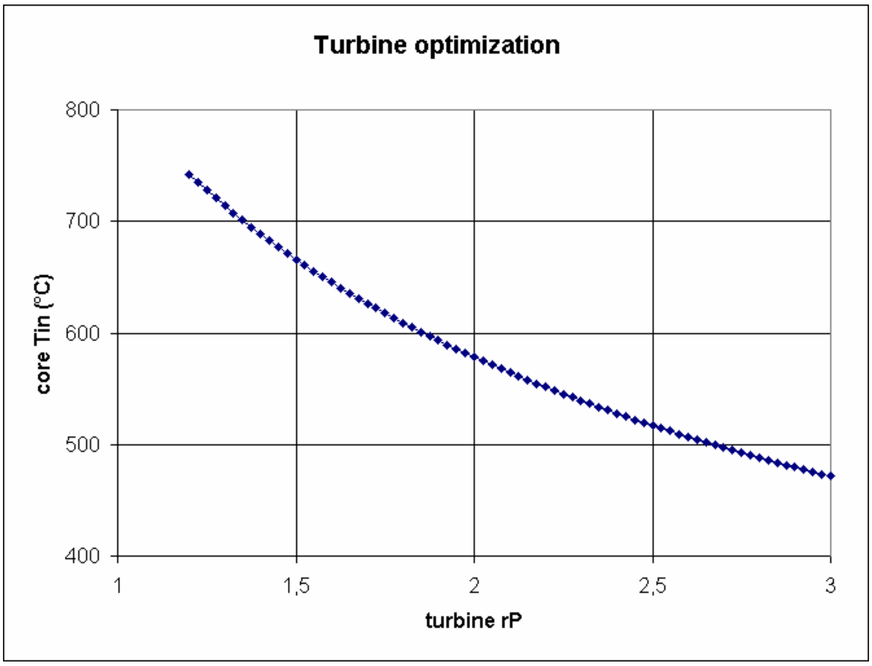
On this simple example, there is obviously an optimum of the turbine pressure ratio, regarding the net efficiency of the cycle.

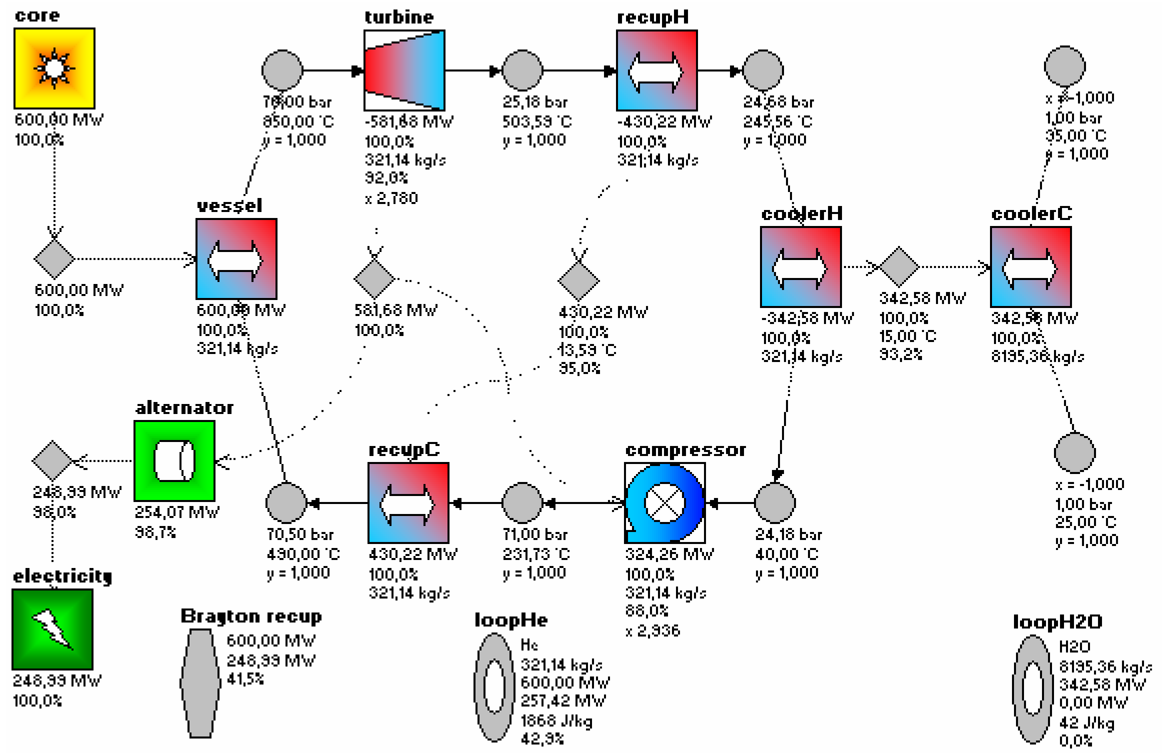
But we can also see that the lower is the turbine pressure ratio, the higher is the vessel inlet temperature, which can be a problem in term of mechanical constraints on the pressure vessel.

So we may want to optimize the efficiency of the cycle, changing the turbine pressure ratio, but keeping the vessel inlet temperature under a reasonable mechanical limit of 490°C for example.

We can then use the EXCEL solver to precisely determinate this constrained optimum. Here is the result :


Turbine optimization
net efficiency
0,5
0,45
0,4
0,35
1
1,5
2
2,5
3
turbine rP


Turbine optimization
core Tin (°C)
800
700
600
500
400
1
1,5
2
2,5
3
turbine rP



The gain in terms of net efficiency is 1.3%, while changing the turbine pressure ratio from 3.0 to 2.78.

Obviously what can be done on this simple example can be done on more complex ones. The parametrical tool should be used to study the whole range of variation of interesting parameters, while the solver optimization tool should be used to find a precise optimum in a restricted local area of possible solutions.

2.4. Validation

The CYCLOP tool has been validated on a wide range of existing or projected reactor cycles.

It has been first validated on cycle samples from the literature : various Brayton and Rankine cycles with irreversibilities, flow separations, reheat, superheat, regenerative feedwater heat, etc... (mostly found in [2]).

Then it has been validated on existing reactors like a French PWR (REP900 / CRUAS) but also a French fast breeder reactor (Superphénix).

Then it has also been validated on HTR reactor projects, when the cycle data were available : the HTGR (GTMHR) project (USA/Russia) [3], the PBMR project (South Africa) [6] and the GTHTR project (Japan) [7].

In each case, the cycles were recalculated with a very good precision, leading to the same net efficiency results.

2.5. Connection with pre-sizing tools

In CYCLOP, each component is described by non-dimensional macroscopic parameters. But optimizing the overall cycle net efficiency is valuable but not enough. We would like also to compare the feasibility of each cycle in terms of size (integration in buildings, containment), safety, operating capabilities and investment costs. That is why we are implementing pre-sizing algorithms to get a better idea of the real dimensions and mass of each component.

Some models are already available in the COPERNIC reactors spreadsheets (mostly on steam generators and heat exchangers), but significant works are still in progress on new components like gas turbines and compressors and other critical components.

Having size and weight characteristics will allow us to make preliminary assumptions on relative costs of each cycle. Therefore the CYCLOP tool has been designed to be connected to such pre sizing routines, and at the end we will be able to optimize a cycle not only on the net efficiency point of view but also on size and cost criteria. Such size and weight characteristics are also necessary to make normal operations and transient analyses.

2.6. Connection with external industrial processes

A nuclear reactor provides heat at different level of temperature, depending on its technology. As future high temperature reactor concepts could be directly connected to external industrial processes needing such high temperatures, CYCLOP was also designed to be connected to routines describing the behavior and energetic needs of such a process.

For example, we implemented such a routine describing an hydrogen production factory using high temperature water electrolysis. We will also implement a routine an hydrogen production sulfur-iodine process that also needs various heat contribution at different temperature levels. CYCLOP can be used to pre design, study and optimize the heat exchanging intermediary loop between the process and the reactor. And when the configuration is fixed, we can study the impact of such a process on the overall cycle and also on electricity production, but also the forecasted hydrogen production for a given reactor power.

3. FIRST CYCLOP APPLICATIONS

3.1. STUDY OF DIFFERENT CYCLE OPTIONS FOR THE GFR

As mentioned above, the Gas cooled Fast Reactor (GFR) is the CEA reference Generation 4 concept [4]. Two ranges of reactor power are considered : a medium power (about 600 MWth) close to the power of some ongoing HTR projects and a large power (about 2400 MWth).

One of the main design options selected is the use of helium as the primary coolant. The interest of helium is quite obvious when we look for high temperatures in order to reach high net cycle efficiency. In addition, helium is almost transparent to neutron which simplifies the core design and the reactor safety (no voidage effect). As far as the energy conversion system is concerned, it has been decided to consider a direct Brayton cycle as a reference. For the 600 MWth unit, this direct cycle choice is consistent with the ongoing HTR projects and one has considered for our studies a Power Conversion System (PCS) similar to the HTGR (GT-MHR) PCS [3]. For this power level, we have focused our studies on the core design, the safety systems and the safety approach. For the 2400 MWth unit, there is no similar background for the conversion system, it is why one has decided to look at other energy conversion arrangements including indirect cycles.

In order to prepare the future design decisions for the GFR, we studied several alternatives to the direct HTGR-type cycle. These options are also direct cycles (one main loop of helium), but with other component arrangements. One is based on the PBMR South-African project [6] and the other on the Japanese GTHTR project [7]. For memory, here are the main characteristic of each of these cycles :

- HTGR : 1 turbine + 2 compressors on the same axis, 1 recuperator, 1 precooler, 1 intercooler. Core outlet at 850°C / 70 bar.
- PBMR : 1 power turbine coupled to the electricity network, 2 optimized turbine-compressor groups, 1 recuperator, 1 precooler, 1 intercooler, 1 bypass for pressure vessel cooling. Core outlet at 900°C / 70 bar.
- GTHTR : 1 turbine + 1 compressor on the same axis, 1 recuperator, 1 cooler. 2 bypasses for pressure vessel and turbine cooling. Core outlet at 850°C / 69 bar.

Each of these cycles uses specific tricks to insure a maximized core inlet temperature, while verifying vessel temperature constraints.

We modeled them into CYCLOP as precisely as possible, first using their original characteristics. These results were validated by a comparison to the published values.

But then, in order to establish a valid comparison of these three cycles, we had to adapt their characteristics to normalized values. We have to recalculate them with the same core outlet conditions (850°C / 70 bar), comparable recuperator, turbines, compressors and alternator quality and the same cold water temperature (25°C for French conditions, giving a cold gas point of 40°C and not 26°C like in some of these projects).

We have also calculated three theoretical cycles for comparison :

- a Brayton cycle with a recuperator, with a non-limited vessel inlet temperature,
- a Brayton cycle with a recuperator, with a vessel inlet temperature limited to 490°C,
- a Brayton cycle without recuperator.

The six cycles net efficiencies were then optimized, letting the turbine(s) pressures ratio(s) vary.

	HTGR	**PBMR**	**GTHTR**	**Brayt rec**	**Brayt rec**	**Brayton**
Published efficiency	46.3 %	43.7 %	45.6 %	-	-	-
Normalized efficiency	46.1 %	43.4%	44.0%	45.7%	41.0%	32.0%
Power density	1868 J/kg	1671 J/kg	1284 J/kg	1198 J/kg	1868 J/kg	2187 J/kg
Vessel inlet temp	490°C	530°C	**601°C**	**619°C**	490°C	**429°C**
Turbine(s) ratio	x 2.71	x 2.28	x 1.82	x 1.83	x 2.76	**x 5.74**

These results give an advantage to the HTGR cycle. The fact is that this cycle does not implement any bypass used in the other concepts to cool the core vessel wall in order to increase the inlet core temperature (like the GTHTR). On the other hand, the GTHTR design is much simpler and could lead to lower investment costs (only one cooler).

Another very significant point is that these different arrangements lead to very different constraints when we look at the overall reactor architecture (possibility to have or not the component inside the containment).

3. 2. STUDY OF DIFFERENT CYCLE OPTIONS FOR THE VHTR

CEA is also involved in the VHTR studies [5]. It actively participates to international collaborations. CEA has launched significant R&Ds on fuel, materials, high temperature helium technology and coupling of hydrogen processes to the reactor. As far as the latter issue is concerned, it appears that the cogeneration capabilities were not independent of the arrangement of the electricity conversion system. In a first approach, it has been decided to explore different options : direct, indirect, combined, in order to identify the most suitable solutions. The VHTR considered is very similar to the NGNP main specifications, in particular, the reactor power is 600 MWth.

In order to extract the power of the VHTR core, we studied several alternatives to the direct HTGR-type cycle. The final comparison includes these options :

- the basic direct HTGR-type cycle in helium,
- an indirect cycle with a simple primary loop in helium and a HTGR-type cycle in helium as a secondary loop.
- a combined cycle with a simple primary loop in helium, a secondary loop composed of a simple Brayton cycle in helium without recuperator and a simple water Rankine cycle as a tertiary loop (with superheat between two steam turbine stages, but no regenerative feedwater heat to keep a cold gas compressor inlet in the secondary loop).
- the same combined cycle with an helium-nitrogen gas mixture in the secondary loop.

For the same reason than in the GFR study, we had to adapt characteristics of each cycle to normalized values. We calculated them with the same core inlet and outlet conditions (490°C - 950°C / 70 bar), comparable recuperator, turbines, compressors and alternator quality, heat exchangers efficiency and pressure losses and the same cold water temperature of 25°C. Then we optimized their net efficiency.

	Direct He	**Indirect He/He**	**Combined He/He/H2O**	**Combined He/He-N2/H2O**
Cycle net efficiency	46.6%	43.4%	48.7%	48.6%
Gas turbine pressure ratio	3.6	3.9	5.6	7.1

Results show that we are losing 3.2% of efficiency when choosing an indirect cycle instead of a direct cycle. 2% are due to the temperature pinch between the primary and secondary loop (around 50°C) that makes the Brayton inlet and outlet temperature decrease. 1.2% are due to the power consumption of the primary blower.

On the contrary, using a combined cycle gives a better overall efficiency than the direct cycle. But at the price of a higher gas turbine pressure ratio, which is a consequence of the vanishing of the recuperator that becomes useless when you want to provide a good temperature to the Rankine cycle. This could be a sizing problem with an helium turbine. But using a He/N2 mixture shows that the efficiency is not really penalized by this introduction of nitrogen (the lost of efficiency in the secondary loop is quite absorbed by the Rankine cycle) : we can then use turbine components closer to standard air turbines.

4. PERSPECTIVES

In this paper, we have presented the COPERNIC/CYCLOP capabilities especially for the gas cooled nuclear reactors. The first results obtained, for the VHTR and GFR concepts, are very promising. These studies have confirmed the interest to have a global approach at the preliminary stages of the pre-conceptual design.

As far as the computer tools development is concerned, the next steps will be :

- to complete the development of all the required pre-sizing COPERNIC modules (turbines, compressors, recuperators, …) in order to be able to describe with more details the conversion cycle, then to undertake optimization with other criteria than the net efficiency (mass of components per MWe, for example)
- to develop pre-sizing modules dedicated to the hydrogen processes in order to study a cogeneration installation including electricity load following compensated by the hydrogen production,
- to develop links to economic evaluation methods.

As far as the GFR studies are concerned, our main objective is to propose two or three system arrangements for the 2400 MWth power. A special attention will be paid to the integration or not of some parts of the conversion system inside the containment building.

As far as the VHTR is concerned, one will keep studying the cogeneration for different power conversion arrangements in order to identify the most interesting configurations. Some limited economic evaluations are also foreseen.

REFERENCES

[1] Ph. Marsault, C. Renault, G. Rimpault, P. Dumaz, O. Antoni (CEA, France), Pre-design studies of SCWR in fast neutron spectrum : evaluation of operating conditions and

analysis of the behaviour in accidental situations, Proceedings of ICAPP ’04 Pittsburgh, PA USA, June 13-17, 2004 Paper 4078

[2] Fundamentals of Engineering Thermodynamics, Moran & Shapiro, 5th edition, Wiley & Sons 2004.

[3] A . I . Kiryushin, N.G. Kodochigov, N.G. Kouzavkov, N.N. Ponomarev-Stepnoi, E.S. Gloushkov, V.N. Grebennik, Project of the GT-MHR high-temperature helium reactor with gas turbine, Nuclear Engineering and Design, Volume 173, Issues 1-3, 2 October 1997, Pages 119-129

[4] C. Poette, JC. Garnier, A. Conti, JC. Bosq, B. Mathieu, JP. Gaillard, C. Bassi (CEA, France), Advanced gas cooled fast reactor preliminary design – 300 Mwe – Project status and trends for a higher unit power selection, Proceedings of ICAPP ’04 Pittsburgh, PA USA, June 13-17, 2004 Paper 4071

[5] P. Billot, D. Barbier (CEA, France), VHTR : very high temperature reactor, the French atomic energy commission (CEA) program, HTR ’04 Beijing, China, September 22-24, 2004

[6] A. Koster, HD. Matzner, DR. Nicholsi, PBMR design for the future, Nuclear Engineering and Design, Volume 222, Issues 2-3, June 2003, Pages 231-245

[7] X. Yan, K. Kunitomi, T. Nakata and S. Shiozawa, GTHTR300 design and development, Nuclear Engineering and Design, Volume 222, Issues 2-3, June 2003, Pages 247-262