Resumen

El siguiente proyecto ha sido realizado en el departamento STEP (Simulation and information technologies for power generation systems) de la división R&D (investigación y desarrollo) en la empresa EDF (Electricité de France). Este proyecto estudia nuevas metodologías de seguimiento del funcionamiento de una central nuclear mediante el programa CEF (Contrôle Economique du Fonctionnement), utilizado por las centrales para controlar el funcionamiento termodinámico del circuito secundario. El objetivo principal es incrementar el rendimiento del circuito. Esta memoria comienza con una presentación detallada del funcionamiento del circuito secundario y terciario, de la actividad concreta de STEP y del programa CEF para facilitar la comprensión del estudio.

Después de un amplio estudio bibliográfico y de reuniones con expertos en centrales nucleares del departamento STEP, se ha creado un documento con la descripción de los principales problemas de cada uno de los componentes pertenecientes al circuito secundario y terciario y los métodos de EDF de control de funcionamiento y detección de problemas. Gracias a dicho documento puede encontrarse degradaciones actualmente no detectables y analizar si podría automatizarse la detección utilizando el CEF.

El análisis de este documento ha permitido el estudio de dos casos susceptibles de ser mejorados mediante un método de detección termodinámico. El primero es la erosión de las turbinas de alta presión debido a la humedad del vapor. En el segundo se trata de un incidente creado por la ruptura de la tubería de acceso al condensador del circuito de refrigeración. Ambos estudios contienen un planteamiento teórico donde varios parámetros son propuestos con la intención de poder anticipar la aparición de ambos sucesos. Después se realiza una aplicación práctica con datos reales de las centrales francesas para comprobar la validez y la utilidad de los parámetros propuestos.

Este estudio ha permitido identificar algunos indicadores bastante esperanzadores y, por tanto, será necesario que la investigación prosiga para confirmar su validez y estudiar las modalidades prácticas de utilización en las centrales nucleares del parque de producción de EDF.

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1. Glossary

At next there are defined some of the terms that are repeated throughout the document and which are useful to explain.

CEF: Economic monitoring of plant performance (Contrôle Economique de Fonctionnement)

CITER: Interpretation and processing code for the commissioning tests (Code d'Interpretation et de Traitement des Essais de Reception)

CNEPE: Engineering support branch (Centre National d'Equipement de Production d'Electricité)

CNPE: Nuclear centre of electricity generation (Centre Nucléaire de Production d'Electricité)

EDF: Electricité de France

Fouling: progressive sealing of solid or liquid particle deposits

HP: High-pressure

LP: Low-pressure

MRI: Department of industrial risk management (Departement Management des Risques Industriels)

MSR: Moisture separator reheater

PWR: Pressurised Water Reactor

R&D: Research and Development

STEP: Simulation and information technologies for power generation systems (Simulation et Traitement de l'information pour l'Exploitation des systèmes de Production)

Throttle: The turbine inlet steam

The following terms correspond to the remarkable abbreviations used in the equations:

P_{COND}: Vacuum pressure of the condenser (mbar)

Q_{COND}: Condenser flow (kg/s)

Q_{CP}: Circulation pump flow (kg/s)

T_{CCW}: Cold cooling water temperature (°C)

T_{WCW}: Warm cooling water temperature (°C)

$\dot{W}_{COND}$ **:** Condenser power (kW)

$\eta_{THERMAL}$ **:** Thermal efficiency

2. Preface

2.1. Origin of the project

Since 2000, on the beginning of the privatisation of EDF, the opening of the electric market in France has given place to the competition. Therefore, the necessity of improving the performance of the power stations in order to produce cheaper MW largely augmented. In 2007, EDF will be in wide open market. Thus, the enhancing of the efficiency in the nuclear stations is especially important.

The origin of this project appears from a proposal of the group STEP within the Research and Development division of EDF. Its main function is to help the plant operators of the power plant to improve the monitoring and the maintenance in a thermal and an environmental way, and it has created several material and software systems in order to improve the efficiency of the stations.

New projects are related to the development of new material and software systems, to the enhancement of the existent systems and to the proposal of new methods of performance monitoring. This project is included in these two last points.

2.2. Motivation of the project

On the secondary and the tertiary system of the French PWR nuclear stations there are several methods of performance monitoring. Nevertheless, the feedback of the plant operators shows that it is possible to enhance the performance. Therefore, the main motivation is to improve these methods, because the enhancement of the units will signify:

- An economical gain for EDF by improving the produced kWh.
- An environmental stake, because the research for an optimal efficiency means also a better use of the nuclear fuel and less waste.

3. Introduction

3.1. Aim of the project

The aim of the project is to study the feasibility of the thermodynamic follow-up of some components and its respective degradations in order to enhance the performance in the secondary and tertiary systems of the French nuclear units. To reach this objective, this will be divided in four steps, which are:

- To identify the components where the performance monitoring can be enhanced.
- To set up new techniques in order to improve the monitoring.
- To test these new techniques on real cases.
- To conclude from the results about the feasibility of implementing these techniques.

3.2. Scope of the project

This project includes the system of the 58 units of the PWR nuclear stations, and initially all the components of the secondary and the tertiary system, which are the fields where the STEP department is working on. Afterwards the study will isolate those components with the most improvable performance monitoring and the greatest potential.

The data used for this project are data of thermodynamic performance, because these are the ones that are used by the group in STEP where the project is taking place. Moreover, it is very difficult to accede to other kind of data. These data proceed from the commissioning tests made always under a performance of the unit in a stationary status between 80% and 100% of nominal power. Therefore, the study will not experiment with other data belonging to a different status than the stationary one.

Finally, the main trade of STEP is the monitoring of the performance and the degradations of the components. Thus, this project will especially concern the maintenance of the power stations.

4. PRESENTATION OF EDF

Electricité de France (EDF) is one of the European leaders in energy. In 2005 it has realized a turnover of 51 billion Euros (of which 23% out of France) thanks to his great capacity of energetic production. It has a capacity of 130 GWe through the world, which is divided up into hydraulic, thermal, nuclear, wind, solar and geothermal energies. "The research and analysis of new performance monitoring methods in PWR Nuclear stations" is made in the Research and Development division.

4.1. The Research and Development section

The research and development section (R&D) is composed of approximately 2650 researchers and technicians with a budget in the order of 400 million Euros. It works on four different work areas:

- The production: The R&D carries out the design studies of the way of production and provides the tools for the installation checking. In this way it reduces the maintenance costs by ensuring the installation safety.
- The network: It carries out the specification and the design of the network, studies its maintenance and working problems and expects the possible network evolutions.
- The use: This area treats the consumption and energetic use problems in industry, the tertiary sector and the buildings.
- The environment: It develops the analyse methods of the environmental impacts, studies the cleaning up techniques and develops the new renewable energy sources.

This division is composed in 16 technical departments that manage the projects distributed in the different work areas. This project is done in the STEP department of Chatou (Paris), which is presented in the next section.

4.2. The STEP department

STEP is the abbreviation of “Simulation and information technologies for power generation systems”. It is a new department deriving from the departments “Optimisation of the process performances” and “Generation and environmental systems”. The global mission of STEP is:

- To help the plant operators of the power plant to improve control, monitoring and maintenance of the plant for enhanced thermal and environmental performance.
- To specify, design and develop material and software systems to improve the operation performance of the generation processes, the tests and data management on site, and the analysis and expertise of the experimental data.

It is composed of five groups:

- P1A: Command control and safety
- P1B: Dynamic systems and data processing
- **P1C: Operation and control**
- P1D: Information and monitoring systems
- P1E: Physical measurements, instrumentation and radiological protection

This project is being realised in the P1C group.

5. General characteristics

5.1. Description of the PWR nuclear power plants

A nuclear power plant differs from a conventional power plant by the way the heat is generated. In a conventional thermal power plant, steam is produced in a combustion process in a steam boiler. In a nuclear power plant, the heat source is the fission process of the uranium atoms 235 contained in the reactor.

The first reactors, built between 1958 and 1966, featured GCR (Graphite-Moderated Gas-Cooled Reactor) technology. These reactors are now being decommissioned. EDF subsequently adopted a more efficient and less costly technology, which is the pressurised water reactor.

Pressurised water reactors (PWR) are a type of light-water reactors. In these reactors, ordinary light water (H_2O) serves as neutron moderator and as coolant, which absorbs and transfers the heat produced in the fission zone by nuclear fission. The fission zone is composed by fuel elements and control rods and is contained in a reactor pressure vessel, which is under a pressure of 150 to 160 bars. Due to this, the water cannot begin to boil even at the temperature of the coolant (325 °C approximately). That is why it becomes the name of "pressurized water reactor".

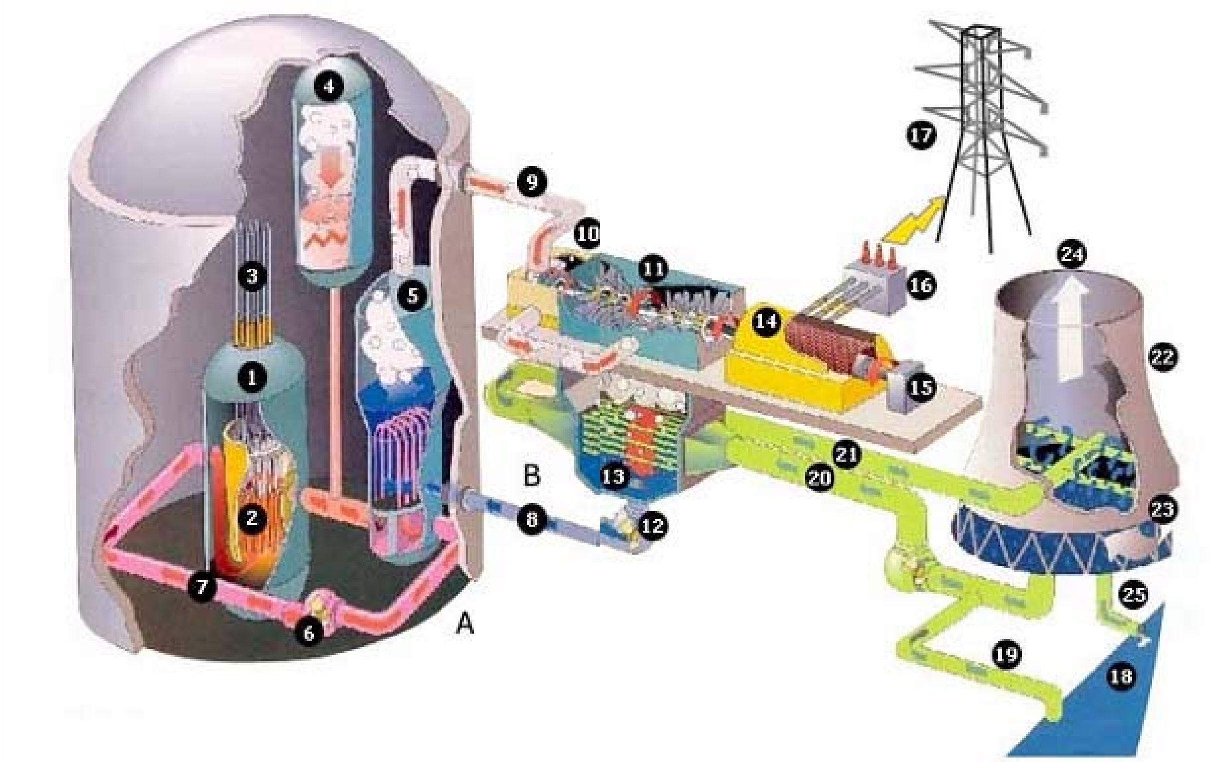
The production of steam in a pressurised water reactor (PWR) is achieved in three separate circuits:

1. The primary circuit containing hot water, which routes the heat from the reactor to the secondary circuit via a heat exchanger, the steam generator. After the hot water has transferred its energy, a primary pump pumps it back to the reactor.

2. The secondary circuit or water-steam circuit has a lower pressure than the primary circuit. The water is converted into steam and is then used to drive a turbine connected to a generator to produce electricity.

3. Finally, the steam leaving the turbine is converted back into water by cooling it. This cooling process occurs in the condenser via a separate tertiary cooling circuit, using water from an external source.

The research and the analysis of new performance functions will be done in the secondary and in the tertiary circuit, which are more specified in the next two sections.



A. Primary circuit	5. Steam generator	12. Condenser	19. Intake cooling water
B. Secondary circuit	6. Primary pump	13. Feedwater pump	20. Cold cooling water
C. Tertiary circuit	7. Feedwater primary circuit	14. Generator	21. Warm cooling water
1. Reactor	8. Feedwater secondary circuit	15. Exciter	22. Cooling water
2. Fuel assemblies	9. Steam secondary circuit	16. Transformer	23. Upward airflow
3. Control rods	10. High- pressure turbine	17. High voltage line	24. Steam
4. Pressurizer	11. Low-pressure turbine	18. River	25. Outlet cooling water

Fig. 5.1. Performance of a PWR nuclear station (Source: Association vinçotte nuclear)

5.2. The secondary circuit

The secondary circuit or water-steam circuit receives the heat from the reactor coolant water and employs it for the production of energy. It carries out two main functions. On the one hand it produces the steam, and on the other hand this circuit makes the insulation from the power reactor to avoid the radioactive contamination. The water-steam circuit is composed by the following elements:

- The steam generator
- The turbine and the moisture separator reheater
- The condenser with the degasification device
- The water reheaters
- The feedwater distribution for the steam generator
- The bypassing circuit

The simplified schema of the secondary system of the distribution of these elements can be observed in appendix A.

5.2.1. The steam generator

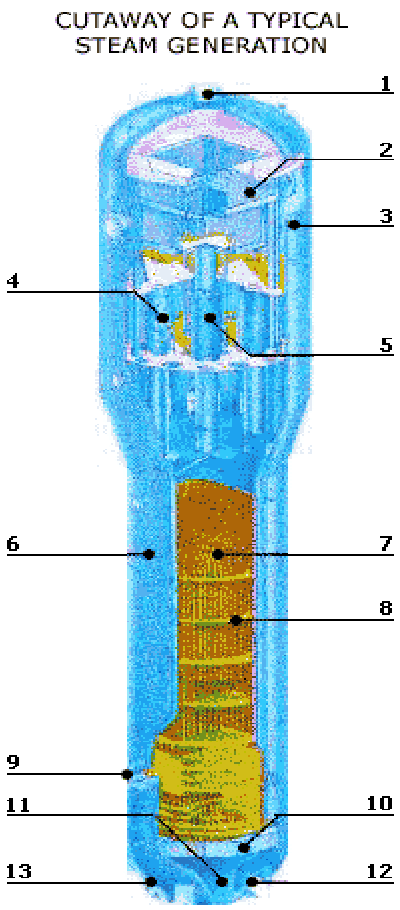
In a nuclear power plant, a steam generator replaces the conventional steam boiler. The steam generator is a tubular heat exchanger with a mechanical drying device of the produced steam that releases saturated steam. It has the following composition:

- A shell that resists the pressure from the secondary circuit
- A tube bundle with the water of the primary circuit
- The inlet and the outlet of the reactor coolant
- The moisture separators

The hot water in the primary circuit, coming from the reactor, circulates through the steam generator pipes. The feedwater arrives in crown through the admission ring of the generator and flows along the outside of the tube bundle. Due to a lower pressure in this circuit, when the secondary circuit water comes into contact with the heated pipes, it starts boiling and is converted in steam. Therefore, the water and steam in the secondary circuit do not come into contact with the primary water from the reactor, which absorbs the heat from the fuel rods. In this manner the steam generator acts as an additional safety barrier between the nuclear reactor and the outside world.

It appears a blend of water and steam that is going to be centrifuged with the moisture separators at the outside of the tube bundle. The water returns into the annular space and repeats the process while the steam elevates into upper structures of the steam generator.

The steam is going to dry in one or several stages until it becomes saturated steam. From that moment on, the steam pressure is directly bound at his temperature. There is a steam generator in each primary system loop. The steam generators are installed in the reactor building together with the reactor.



1 Steam outlet
2 Secondary moisture separator
3 Upper shell
4 Swirl
5 Primary moisture separator
6 Lower shell
7 Tube bundle
8 Support plates
9 Feedwater inlet
10 Tube plate
11 Partition
12 Reactor coolant outlet
13 Reactor coolant inlet

Fig. 5.2.1. Schema of a steam generator (Source: Association vinçotte nuclear)

5.2.2. The steam turbine and the moisture separator reheater

A steam turbine consists of a series of blades mounted on a shaft. As the steam jet is inflected, it puts pressure on these blades, making the shaft rotate. The pressure and heat content of the steam drops and part of the pressure and thermal energy is converted into kinetic energy and consequently mechanical energy.

The turbines are multicellular; they all contain one high-pressure and several low-pressure bodies (in a N4 reactor series they also have a medium-pressure body). They run at 1500 turns/min. Starting from 900 MW, the turbines need a big flow. That involves very high blades, especially in the low-pressure turbines, where the blades can reach 7 meters. These bad steam conditions cause blade erosion, which is the reason why the moisture rate must always stay below the level of 13-15%.

The vapour leaves the steam generators at a moisture rate of approximately 0,37% and passes in the high-pressure turbine, where it leaves expanded and cooled with moisture of 12-15%. Then it will be sent in the moisture separator reheater. These improve plant efficiency by first removing the moisture of the high-pressure turbine exhaust steam and then superheating this steam before it is sent to the LP -turbines. This means it no longer contains harmful water droplets and extra energy is supplied before the steam drives the low-pressure turbine. Thanks to the moisture separator reheater the blade erosion will be minimized.

The superheating is obtained from main steam, which circulates in a tube bundle. The global efficiency of the installation is better if the steam gets rid of its moisture before overheating it. The moisture separator reheater consists of a separating stage where the chevron vanes (narrow and tortuous paths) separate the water droplets under the centrifugal force.

There are also steam extractions throughout the expansions of the high-pressure and low-pressure, which take away a great part of moisture and feed at the same time the stations of reheating.

5.2.3. The condenser with the degasification device

The condenser is placed under the low-pressure turbines. It is a heat exchanger with thousands of tubes traversed by cooling water from the tertiary circuit. It fulfils several functions:

- The condensation of the expanded steam coming from the low pressure chambers, from the feed pumps, from the drain tanks and from the bypassing circuit. The condensate can then immediately be reused as feedwater for the secondary circuit.

- The water mass control of the circuit by considering the intake and the outlet cooling water (in case of leakages, expansions and drains).

- The degasification (this is a particular function of the secondary circuits of the PWR Alstom 900MW series). It consists in the extraction of incondensable gases dissolved in water, especially oxygen since it activates corrosion.

5.2.4. The water reheaters

To improve the efficiency of the power plant, the flow leaving the condenser is at first heated by the stations of reheating. These stations receive extracting steam from the turbine so that the feedwater going to the steam generator results in a higher temperature. The more reheaters are used, the greater is the improvement in overall plant thermal performance.

Other advantages are the diminution of thermal shocks and the turbine improvement by taking away part of moisture with the steam extractions routed to the reheaters.

The number and the situation of these water reheaters depend on the kind of reactor series (see appendix B).

5.2.5. The feedwater distribution for the steam generator

The pressure upgrading for the steam generator alimentation is carried out in the extraction pumps and in the feed pumps (turbo-pumps). The water is taken out from the condenser by the extraction pumps and afterwards recaptured by the turbo-pumps.

The feedwater setting is made by changing the opening of the feed valves situated at the exhaust of the turbo-pumps.

5.2.6. The bypassing circuit

The bypassing circuit allows to send steam to the condenser without going through the turbines. It ensures the vapour evacuation produced by the steam generators. It is used essentially in cases of important transients and for evacuating the residual heat in case of a shutdown of the installation. Other safety measures to avoid the fouling of the steam generator are:

- The relief valves to the atmosphere.
- The emergency feedwater system.

5.3. The tertiary cooling circuit

The nuclear power plants need as well as the other conventional power plants a cooling circuit in order to evacuate the residual heat. The water needed to condensate the steam in the condenser in the tertiary circuit is taken from the sea, from a river or from a lake (in France the power stations are on the sea or on the river coasts).

The tertiary cooling circuit can be opened or semi-closed. In the opened circuits, the cooling water at the outside of the condenser is returned to his source through a gallery. Sometimes it goes through quiet wells before being rejected, like in the Paluel power station. Opened circuits are situated at the sea and at some river coasts.

In the semi-closed circuits, the hot cooling water is pumped to the cooling towers. It is spread over a horizontal grid and pours down in a shower. Due to contact with an upward airflow (natural draught chimney effect), it cools off. A small fraction of the water (1,5% approximately) evaporates and escapes as a vapour plume above the tower. A minor part of the cold cooling water flows back into his origin. The majority is collected in a pool at the base of the tower to get mixed with fresh water. Once more it is going to be routed to the condenser and make a new cooling process. In the semi-closed circuits the volume of the pumping station is much more reduced than in the opened circuits. Power stations with this circuit are situated at some river coasts.

5.4. The description of the different nuclear power stations

At present, the nuclear energy production represents 88% of EDF in France. This production is distributed on 58 reactors among 19 sites. Located across the country, EDF's nuclear generating facilities include thirty-four 900 MW, twenty 1300MW and four 1450MW reactors.

EDF uses a certain terminology regarding its reactors, which are related with the term of nuclear power unit. Every power unit is equivalent to the association core, steam generator, turbines and cooling system. There are different units, and every model corresponds to a series. The main characteristics of the series in France and its respective units are presented in the appendix B.

Fig. 5.4. Distribution of the nuclear power stations in France (Source: EDF)

5.5. The software CEF

In a PWR unit, the primary circuit has a slightly variable thermal efficiency. The secondary system has to be monitored because of potential important variations, which are classified in two areas:

- The outside constraints (power level, weather conditions, intake cooling temperature) that cannot be acted upon;

- The status of the circuit (pipes, vessel, tanks, condenser…) that get old, and the adjustments (valves) that can be modified by the plant operators (maintenance decisions, re-settings…).

In April 1993, in order to improve the thermal efficiency of EDF's PWR fleet, the software CEF (which means "Economic monitoring of plant performance") was created. At present this software is used in all the French units, and it allows the Test section of the CNPE (Nuclear centre of electricity generation) to control the thermodynamic performance of the secondary system. CEF is based on a numerical modelling: the model is fed with accurate data (plant commissioning test data) used to compute plant optimal available thermal efficiency ratio. It computes estimated power losses and sources of losses, and can be used to simulate consequences of modifications of settings. It is made up of:

- About 80 sensors that make accurate measurements of temperature, pressure, flow rate, enthalpy, and steam moisture content placed at the inlets and outlets of the different components in the secondary system.

- PATERN, which is the data acquisition and processing system of physical data.

- CITER (Interpretation and processing code for the commissioning tests), which is the heat balance model of secondary system, including accurate reference data. It allows calculating the values of the pressure, flow, temperature, enthalpy and moisture at the component terminals from the thermodynamic conditions of the cooling water and the steam generator. CITER gives the reference status of the unit. This model is also used by the CNEPE (Engineering support branch) for performance studies.

CEF processes the data after its acquisition by PATERN and analyses them by comparing the data with the performance model of CITER in order to find if there are any anomalies.

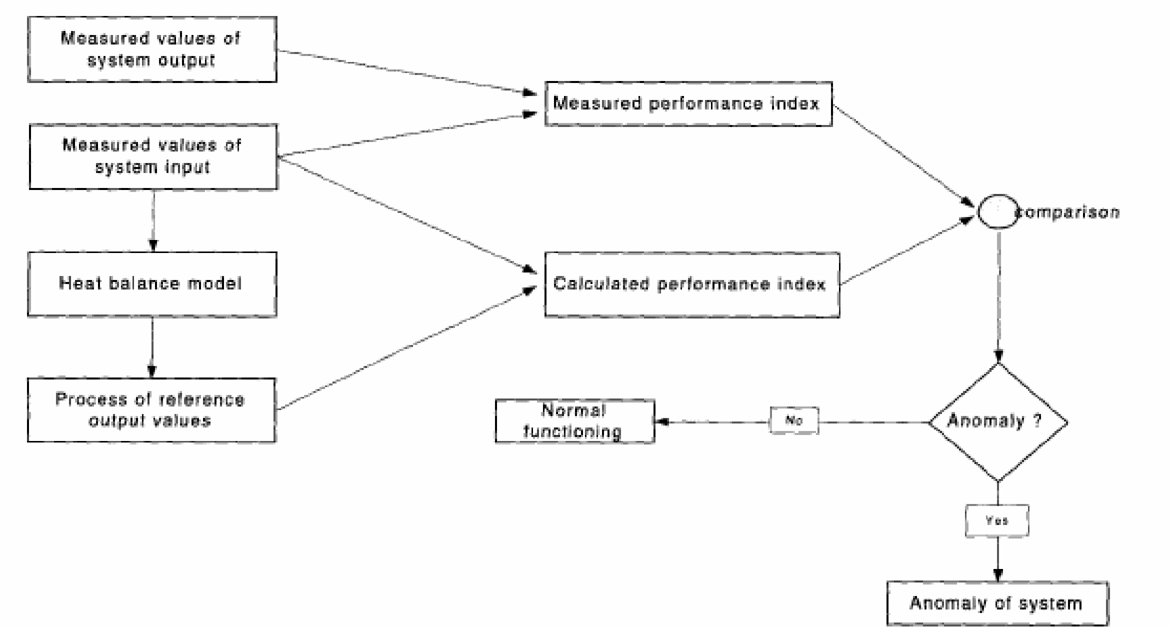


Fig. 5.5.1 General organization of CEF

Finally the expected uncertainties (that correspond to the approximation of a unit to a theoretical model) and the measured uncertainties (the tolerance of the sensors) have to be included.

CEF can only be used if the unit is performing in a stationary status between 80 and 100% of nominal power. The potential benefits of CEF are:

- An economic stake based on the improvement of the produced kWh (in the competition context).
- An organizational stake for the different services in the CNPE unit: this software is a powerful tool for an association and motivation of management, test section and maintenance services, because they have in common the objective of an economic performance research of the unit.

- A stake for the availability of the units: the follow-up of thermal performances of the circuit (identification of slow degradations) or the evidence of failures enable to anticipate or to better manage the maintenance operations by limiting the inavailabilities. It is also possible to make a diagnosis on plant components that are not CEF-instrumented (like for example the localization of possible leaks).

- A stake for the nuclear image in public opinion: the research for an optimal efficiency means also a better use of the nuclear fuel and less waste, thus supporting the standard ISO 14001.

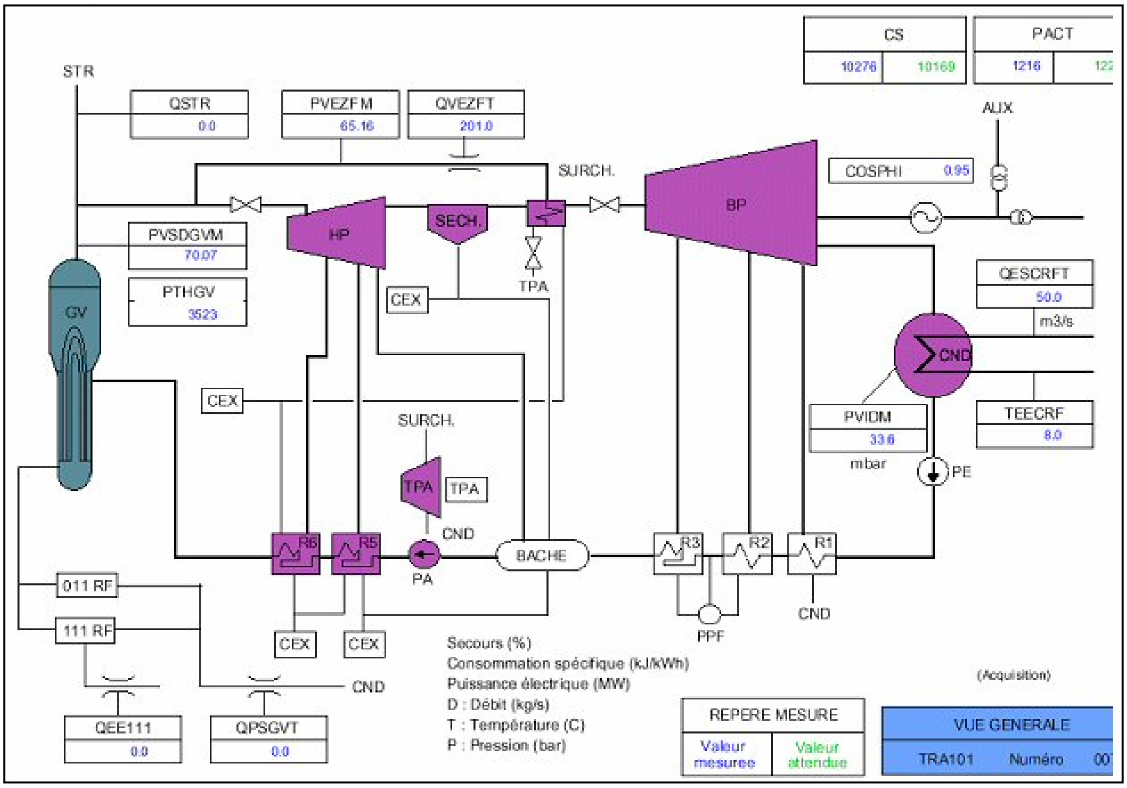


Fig. 5.5.2 Global schematics CEF of the secondary system

Finally, the test data recorded in the nuclear units by CEF is saved in the database called MOLENE. There are about 10 000 tests CEF in MOLENE and 800 000 data to exploit.

6. Summary of the main problems in the secondary and the tertiary circuit and his performance monitoring functions

In EDF there does not exist any summary with the entirety of the degradations and his respective performance functions of the secondary and the tertiary circuit in a PWR power station. The following chapter is a recap of the EDF documents that contain information about this subject. This is the first approach and it will help to see where does the performance monitoring needs to be improved.

6.1. Cycle deterioration

The greatest part of efficiency deterioration in a nuclear power plant is due to cycle losses. Leaky valves, control valves that are not set properly, and erosion of restricting orifices cause these cycle losses. Nevertheless these kinds of deteriorations are already followed in EDF. With the CEF tool EDF examines the thermodynamic aspects of the secondary and the tertiary circuit, which indicates the efficiency of the plant. If there is a performance problem, depending on the materials and on the problem, EDF uses different detection methods that will help to localize and specify the deterioration.

The main degradations and failures are specified for each component in the following sections, including his respective detection methods. Note that the steam generator and his feedwater distribution are not treated in the STEP department.

6.1.1. The moisture separator reheater

The principal problems that happen in the moisture separator reheaters are usually:

- Rupture of a heating pipe.
- Loss of leaktightness in the moisture separator reheater valves.
- Control problems on the balloons recovering the drains.

There is a method with the CEF tool found by the CNPE (Nuclear Centre of Electricity Production) in Cruas-Meysse station that helps to detect these three problems [1]. This method consists in a graphic follow-up of the evolution in the inlet and outlet heating steam flow in the moisture separator reheater.

This performance monitoring excludes the industrial risk of a total ruin of the tube bundle, which could happen if many tubes brake at the same time and would take to the plant shutdown. Moreover it will not be necessary to continue the helium test, which has a great economical and manpower cost. Finally, the maintenance of the valve will be scheduled during the next outage.

6.1.2. The HP reheaters

Basically the loss in reheater performance is because of tube leakages and control problems. The energy section of the CNEPE (National Centre of Electricity Production Equipment) has made up a method to anticipate the leakage of the tube bundle through the high-pressure reheaters (500 and 600) [2]. It is based on CEF weekly tests in order to supervise three variables according to the time, which are:

- The moisture percentage of the steam extractions.
- The flow of the condensates leaving the reheater.
- The ”terminal variation” (temperature difference between the feedwater inlet and the condensate outlet).

It is necessary to supervise several variables (especially the moisture percentage and the flow of the condensates, which are the best indicators) in order to confirm the real causes of the performance deterioration.

6.1.3. The condenser

The steam pressure at the condenser is very significant for its performance; the smaller it is, the greater will be its performance. The principal problems that carry out a pressure increase are:

- The condenser fouling (progressive sealing of solid or liquid particle deposits). When the tubes are stopped or clogged following escapes, the heat exchange decrease and so its effectiveness.

- An increase of the air intake level. In an ideal case there would not exist any air inside the condenser, but there is always a little part of air that makes the pressure increase because of the air partial pressure.

- An abnormal orientation of the emergency valves towards the condenser.

There are also other parameters, like the load of the power unit (which determines the steam flow quantity to get condensed) and the temperature of the cooling water, that have an influence on the pressure, but these are external parameters that can not be changed.

The Department of Fluid Dynamics and Heat Transfer of EDF R&D indicates how this pressure is controlled [3]. The CEF tool shows the difference between the measured and the attended pressure, this difference is normally positive. An abnormal variation shows a pressure increase.

Other problems that occur in the condenser are its abrasion and his erosion, which are more detailed in section 6.1.6.

6.1.4. The valves

The degradation affecting the most the performance of the valves contained in the circuit is the leaktightness loss, causing a leakage. The valves are situated all along the circuit. The greater is the steam quality passing through the valves, the worst are the consequences of the leakage on the electrical output. The best steam quality is the one at the steam generator output. Another important point is the location of the affected valve. If it is placed before the turbines, the leakage will decrease the flow through the turbine stage and less electrical output will be produced.

Valves that are a potential source of loss are for example bypass valves and moisture separator reheater valves. This degradation can be localised with the acoustic emissions or with the infrared thermography.

6.1.5. The steam turbines

In general there is no appreciable deterioration of the steam path in nuclear power plants. Throttle pressure and temperature is lower than in fossil plants, water purity is excellent, and deposits are not a serious problem. In addition, the turbine speed is lower than most fossil turbines and the sealing strips experience only minor rubs. The efficiency of its stages would be slightly higher than the best fossil units except for moisture loss.

At present the turbines are almost not instrumented in a thermodynamic sense. The only follow-up is a continuous vibratory monitoring, which detects the mechanical problems. It is the only constantly monitored component in the secondary circuit. The vibratory monitoring permits to detect the unbalance and the streaking in the turbines unit. The unbalance is an inequality between the gravitational and the geometrical centre. It exists always, but it increases for example in case of the loss of a blade. The streaking is a longitudinal irregularity of the surface, usually occurring in the rolling or extrusion direction.

There are also visits to the turbines that take place every X period (confidential data), where the turbines are opened and supervised, so that the affected materials can be repaired or replaced.

Although the degradations in the nuclear turbines are much smaller than in the fossil plants, there are also cases of erosion, loss of leaktightness and foreign objects, which are only seen during the overhaul of the turbine. The vibration monitoring can only detect them if these are enough significant to cause a mechanical problem, which means that the degradation has been transformed in a failure.

6.1.6. The tertiary cooling circuit

Since a few years the tertiary cooling circuit has some technical problems whose impact has required the installation of action plans within the framework of different businesses and working groups. This affects specially the semi-closed circuits at the river. These problems are described in a document containing a study for the performance improvement in the cooling circuit by EDF R&D [4] and are:

- The durability of the components of the cooling circuit, that specially depends on:

- The scaling (Solid deposit formation that adheres to the interior walls, it is formed basically by calcium salts and magnesium) and the fouling of the whole circuit.

- The abrasion and the corrosion of the condenser.

- The concretes degradation.

- The sanitary problematics due to the development of microorganisms like the amoebas and legionella. These quickly reproduce in the calm basins of the circuit.

- The environmental problematics, caused by:

    - The chemical rejection associated to the circuit treatments

    - The temperature of the drains

    - The drain management

- Thermal exchange loss basically due to the scaling and the fouling of the condenser and the cooling tower

The stakes associated to the resolution to these problems are multiple, because these affect the availability of the power units, the environment, the health, the performance, the life span of the components and the costs.

At present, the CEF is used to supervise the thermal exchange in the tertiary cooling circuit. Other actions besides the STEP department are performed to minimize the problems:

- The circuit cleaning during and out of its normal operation.

- The disinfections treatment and the anti-scaling treatment.

- Materials choice of the condenser for its tubes.

- Materials choice for the heat exchange of the cooling tower.

These actions also have negative side effects, because the problems are closely linked. For example the replacing of the brass pipes of the condenser by stainless steel, in order to avoid corrosion problems, has increased the amoebia development and the scaling. At present there is a study in charge of a multicriteria analyse optimisation of the tertiary cooling circuit (environmental, sanitary and economical actions together) in order to eliminate these side effects.

6.2. Decision about the susceptible issues to get improved by STEP

By analysing the previous components, most of them are already controlled in part by CEF. The valves are one of the exceptions, being supervised by the acoustic emissions or the infrared thermography. Nevertheless these are methods that work very good at the moment and it is not necessary to improve its control method. The other exception is the steam turbine, controlled by the vibratory monitoring. Because there are issues that are not detectable by this method, it has been decided to make a first study in order to observe if a thermodynamic follow-up could improve its performance.

The second study is a leakage problem occurred in the tertiary cooling system of Nogent station that has finished in a big failure and a big economical loss. This case has not been included in the tertiary circuit because it is the first time that it occurs. However, it is an issue that could arrive again. In the tertiary circuit there are not installed detection methods like the acoustic emissions or the infrared thermography, like in the secondary system. Both studies are detailed in the two following chapters respectively.

7. First study: research of a new monitoring method of the high-pressure turbine

As it has been seen in the previous section, the only follow-up existing at present in the steam turbines is the vibratory monitoring, which detects the mechanical problems. The other damage is detected during its overhauls, made once every long time (confidential data). It is not easy to make an overhaul since very delicate materials compose the turbine and these get easily damage. Because of this, not all the low-pressure turbines are opened during an overhaul. Even if these visits show smaller and uncommon degradations than in the fossil plants, they could develop to a failure causing big losses.

The aim of this study is to make up a thermodynamic follow-up avec the existing instrumentation of the circuit to detect the observable damage that is not supervised with the vibration monitoring. If there is sufficient information to enable proper interpretation of test data, there can be a corrective action as soon as possible in order to maintain optimum power plant efficiency. The potential benefit of this first study is to avoid the opening of the turbines by using a new method of external degradation detection. However, this new method will be adapted to the actual instrumentation of the turbine, which is very poor. That is due to the impossibility to instrument its inside, because it should be bored every time and this is technically not possible due to its delicate materials.

This study includes a theoretical part and a numerical part. The first phase before beginning with the theoretical part consisted in the research of the observable degradations in order to have the possibility of a data processing of several real cases. The Department of Industrial Risk Management (MRI) in R&D of EDF, which works on turbine performance among other subjects, was contacted. MRI conducted the experience feedback of the high and low-pressure nuclear steam turbines of the different power units in France. Among the different documents, the responsible person of MRI has recommended to work on the high-pressure turbines of the CP2 and 1300 units, because there are more interesting cases for the study than in the other documents and because it is the most updated experience feedback [5]. Furthermore, the CP2-1300 units have a database while the CP0-CP1 units do not. This database contains the degradations found in all the units of every nuclear power station up to the year 2001. There are several reasons that have led to make this first study with the high-pressure turbines instead of the low-pressure turbines. High-pressure turbines work from the steam inlet with a percentage of moisture while the low-pressure turbines begin with superheated steam and steam comes out at less moisture, having less moisture issues. Moreover, high-pressure turbines have a greater MW production and only a chamber (low-pressure have normally three). Studying these turbines become thus more attractive.

Among the possible degradations of the nuclear plant steam turbines, the ones that are likely to be detected in a thermodynamic way (according to common analyses with MRI) are the cases of erosion, loss of leaktightness and “foreign” deposits (not belonging to the turbine).

The second phase consisted in consulting the MOLENE database, which contains the data of all the thermodynamic tests performed on the different French units with the CEF tool. Unfortunately, there are many units where the information is not much updated. There are interesting degradations that appear in the CP2-1300 database but it has not been possible to find thermodynamic variables in MOLENE within the same timeframe. Therefore the study options were significantly reduced.

Finally the degradation mechanism where most information was found is erosion. This was detected in three EDF units, which are Cruas 4 (CP2 series), Chinon 3 (CP2 series) and Saint Alban 1 (H4 series). This first study is going to focus on the erosion case, which finally is the observable degradation. Furthermore, erosion is a degradation with a gradual influence on the affected component, which is not the case of “foreign” materials (sudden deterioration). Thus, due to its gradual evolution, it could be detected with more prevention than a foreign deposit.

7.1. High pressure turbine erosion

While the erosion in fossil steam turbines is generally due to magnetite-like oxide particles, the origin in the nuclear turbines is the steam moisture. In most nuclear power plants, the moisture of the throttle steam is close to zero and the high-pressure exhaust moisture is about 13%. There are two kinds of erosion:

- The “joint face” erosion: the steam tries to go through two joint faces and causes a little opening. This opening erodes and becomes greater with the time.

- Blade erosion: the waterdroplets going through the turbine cause the erosion at the blade tip. In fossil plants this erosion can lead to the loss of the blade tip, but in nuclear plants the erosion is not as strong. However, the turbine can degrade to a point where it is cost-effective to repair or upgrade it.

Both create internal leakages, which cannot be detected at present. In September 1999 it has been discovered a blade erosion in Cruas 4. This erosion has also affected the joint (dummies) between the blades and the steam chest and has induced internal leakage. In June 1998 an internal leakage in the steam chest has been discovered in Chinon 3. In July 2000 in Saint Alban 1 another erosion has been detected. This third case has caused a leakage between the steam extractions (five and six). These cases are supposed to have taken to a decrease of the performance. It is remarkable that the three cases have been repaired just after its discovery.

At next the study will be divided up into a theoretical and a practical part. Finally there is a section with the propositions according to the observed results in order to improve the high-pressure turbine performance.

7.1.1. Theoretical analysis of the erosion

The erosion, among other damage causes, was largely analysed by K. C. Cotton. He has been manager of turbine performance engineering within general Electric's and served as a member of ASME (American society of Mechanical Engineering). He was responsible for the design and implementation of development programs to improve turbine efficiency. The basis of this theoretical analysis is taken from one of his books, "Evaluating and improving steam turbine performance" [6]. It contains a systematic approach to diagnosing potential turbine problems, like increased steam-path clearances, blade deposits or solid particle erosion. Mr. Cotton got very good results for the solid particle erosion at the fossil plant steam turbines, but it has not been so far as much experimented on nuclear plant turbines. The aim of the theoretical analysis is to adapt the Cotton ideas to the nuclear configuration.

Afterwards several parameters are proposed in order to enable possible information about the high-pressure turbine performance and the presence of erosion. Not all the parameters will be used afterwards in section 7.1.2 because of the present lack of instrumentation. Nevertheless the theoretical part will include all the possibilities, then the data that is not observable now could become available in future.

1. The most important parameter for monitoring the performance of a nuclear power plant is thermal efficiency, whose calculation is:

$$\eta_{THERMAL} = \frac{ELECTRICAL\ MEGAWATTS}{THERMAL\ MEGAWATTS} \cdot 100 \quad \text{(Eq. 7.1)}$$

   This is a measure of the complete turbine-heater cycle. The thermal efficiency is also affected by the cycle leaks and performance of other cycle components such as condensers and moisture separator reheaters. Usually there is very little deterioration in turbine performance comparing to the affectation of leaky valves in the cycle, thus this parameter will be calculated to have a global information but it will probably not provide any concrete information about turbine performance.

2. The high-pressure turbine enthalpy drop efficiency is another indicator that concretises more the performance of the high-pressure turbine. One of the main reasons erosion causes efficiency deterioration is increased surface roughness. This parameter is defined as the actual enthalpy drop from turbine inlet to turbine outlet divided by the ideal or isentropic enthalpy drop:

$$\eta = \frac{h_{hpi} - h_{hpo}}{h_{hpi} - h'_{hpo}} \cdot 100 \quad \text{(Eq. 7.2)}$$

   Where

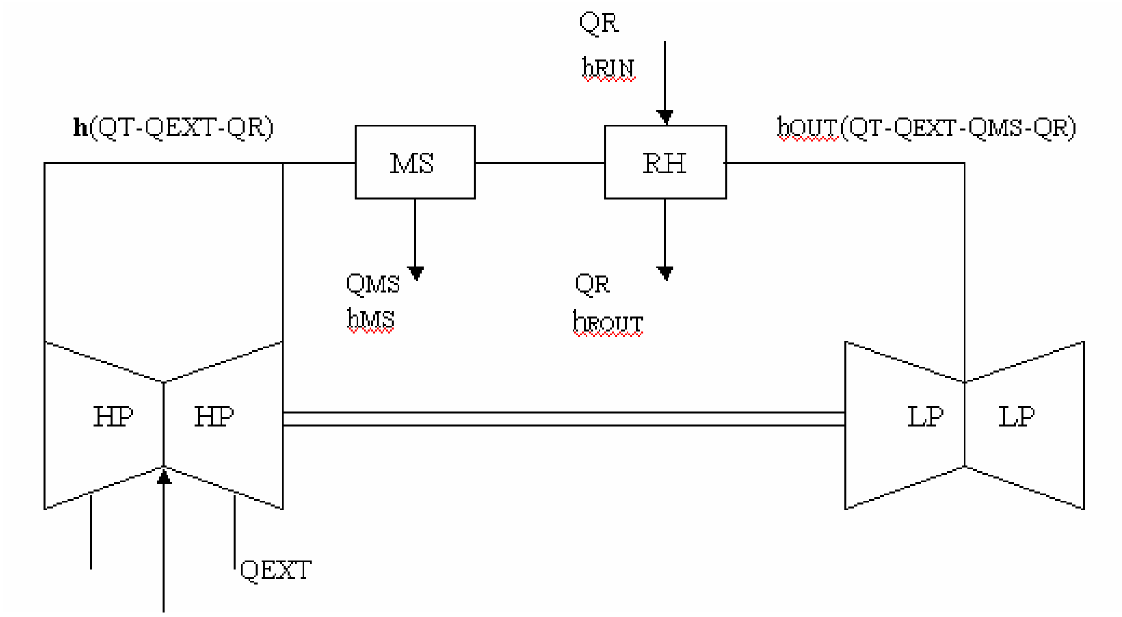
   h_{hpi}= specific enthalpy of the high-pressure turbine inlet steam

   h_{hpo}= specific enthalpy of the high-pressure turbine exhaust steam

   h'_{hpo}= ideal specific enthalpy of the high-pressure turbine exhaust steam

   The enthalpy drop efficiency test requires the measurement of enthalpy into and out of the high-pressure turbine. The enthalpy into the turbine is calculated from the steam leaving the steam generator, which is usually dry and saturated, So the throttle (the turbine inlet steam) moisture can be calculated with the pressure drop between the steam generator and the turbine, assuming a constant enthalpy process between them.

The enthalpy at the steam generator outlet corresponds to the saturation point where there is moisture of practically 0%. The enthalpy out the high-pressure turbine can be worked out by two ways. The first possibility is to calculate it directly from the data outside the turbine. It is necessary to know the steam moisture and the pressure (or the temperature) to find the enthalpy. Another possibility is to make an energy balance around the moisture separator reheater, since the steam leaving is superheated (there is not necessary to have the moisture data) and not wet like the exhaust high-pressure steam. For this efficiency there are several measurements required and the uncertainty of the results is larger. In this case, the repeatability of the calculation is better than the absolute accuracy, making the test results useful to indicate turbine degradation due to erosion and foreign deposits.



HP: high-pressure

LP: low-pressure

MS: moisture separator

RH: reheater

Q_{EXT}: Total extraction flow from the HP turbine to the feedwater heaters

Q_{MS}: Moisture separator drain flow

Q_R: Reheat steam flow

Q_T: Throttle flow

Fig. 7.1.2 Participating variables for the energy balance

This energy balance requires the following data:

- The steam flow through the moisture separator reheater, which is the throttle flow minus the extraction flow to the reheaters (Q_T-Q_R-Q_{EXT}).

- The moisture separator drain flow (Q_{MS}), and its pressure and temperature to calculate its enthalpy (h_{MS}).

- The reheat steam flow (Q_R), enthalpy (h_{RINL}, the same as the enthalpy at the steam generator outlet) and drain temperature to calculate its enthalpy (h_{ROUT}).

- The high-pressure turbine exhaust pressure and the temperature at the moisture separator reheater outlet to calculate its enthalpy (h_{OUT}).

$$h_{HP\,OUTLET} = \frac{h_{OUT}(Q_T - Q_{EXT} - Q_{MS} - Q_R) + h_{MS}Q_{MS} + (h_{ROUT} - h_{RIN})Q_R}{Q_T - Q_{EXT} - Q_R} \qquad \text{(Eq. 7.3)}$$

3. The section efficiency, by calculating turbine enthalpy drop efficiency over the load range. According to Mr. Cotton, the solid particle erosion deterioration in the control stage has a much smaller effect on high-pressure turbine efficiency at full load than at light load.

4. The performance model of CITER uses two laws for the simplified functioning of the turbines. The Bauman law is the equivalent of the enthalpy drop efficiency. The other law that characterizes the turbine performance is the Stodola law, which gives the flow according to the temperature and the pressure. The calculation of the Stodola number is the following:

$$Q_{INLET\,TURBINE} = St \cdot \sqrt{\frac{P_{INL}{}^2 - P_{OUT}{}^2}{T_{INL}}}$$

$$St = \frac{Q_{INLET\,TURBINE}}{\sqrt{\frac{P_{INL}{}^2 - P_{OUT}{}^2}{T_{INL}}}} \qquad \text{(T in K, P in bar)} \qquad \text{(Eq. 7.4)}$$

The better is the turbine performance; the greater is the difference between the pressure inlet and its outlet. Therefore, Stodola decreases with the performance improvement.

5. The throttle flow is affected by the changes in the first stage of the high-pressure turbine. If there is erosion in this stage, the blade area will reduce and the area of the passage will increase. As the throttle pressure and the temperature are held constant by the steam generator controls), the throttle flow is the only parameter in the turbine inlet affected by the area change and it should consequently increase. The throttle flow is calculated like the steam flow leaving the steam generator less the steam flow used for the reheating of the HP turbine exhaust flow.

6. The pressure at the high-turbine outlet also increases as a result of the throttle flow increase. Therefore, the pressure ratio between its outlet and its inlet should increase. Its expression is the following:

$$\text{Pressure ratio} = \frac{P_{OUT}}{P_{IN}} \cdot 100 \qquad \text{(Eq. 7.5)}$$

The smaller is the pressure ratio, the greater is the turbine performance. If this parameter increases, it could be also interesting to calculate the pressures at the different extractions and to compare them with the throttle pressure. That could help to see where the problem is localised.

7.1.2. Adaptation of the theoretical analysis to the real cases

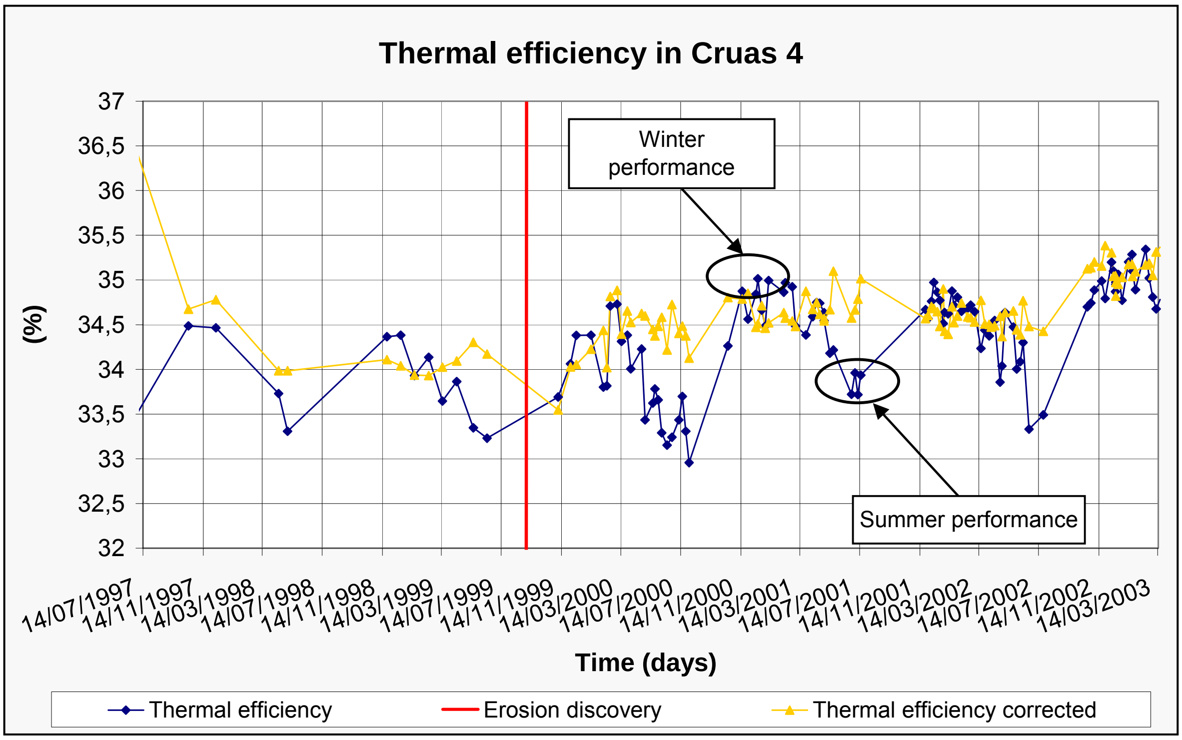
As it has been previously commented, the turbine has a very poor instrumentation. This section will try to extract the maximal information with the existent data.

Between the six proposed parameters in order to enable possible information about the high-pressure turbine performance and the presence of erosion, there are four parameters that can be exploited at present in STEP: The thermal efficiency, the Stodola number, the throttle flow and the pressure ratio between high-pressure turbine exhaust pressure and the throttle pressure. The section efficiency could not be calculated because the tests in the nuclear stations are always made under a performance of a stationary status between 80% and 100% of nominal power. There is no information about the turbine efficiency by light load.

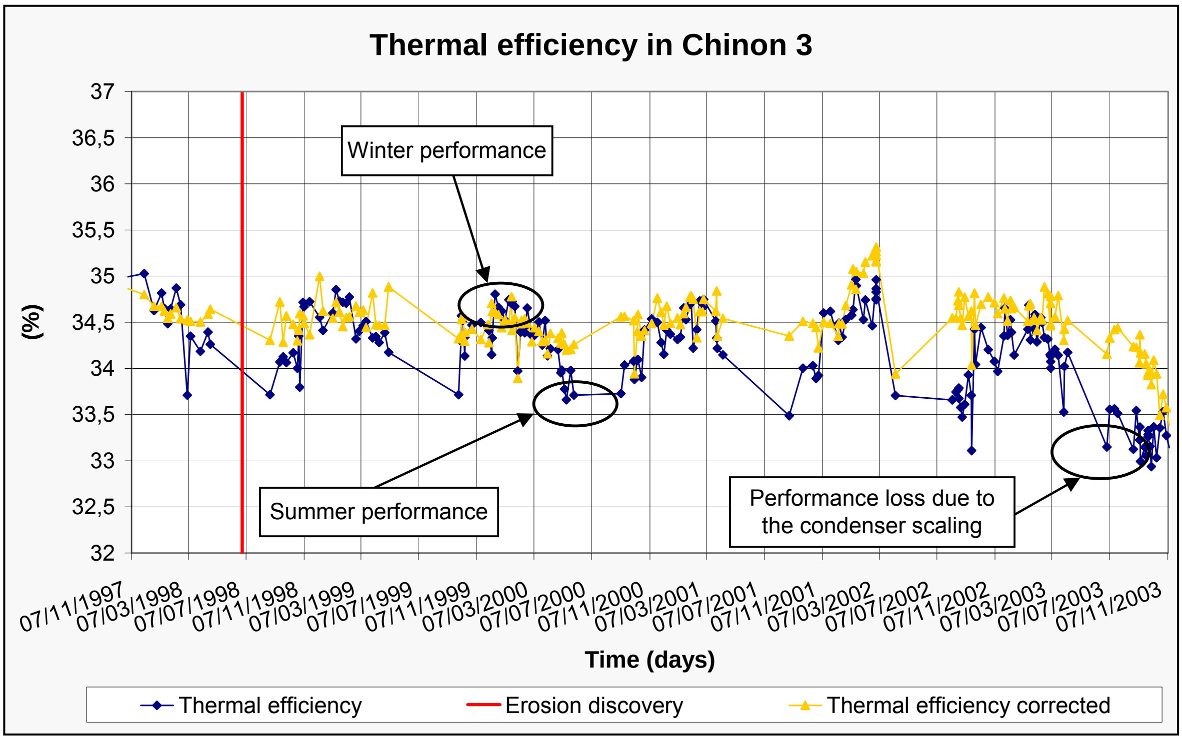
The turbine drop efficiency has neither been calculated. It is possible to calculate the enthalpy at the turbine inlet, because there are sufficient data in MOLENE: pressure and moisture (practically 0%) at the steam generator outlet to work out the steam generator outlet enthalpy, and throttle pressure for the moisture and inlet turbine enthalpy calculation. But unfortunately the only sensor installed at the turbine outlet is its pressure and enthalpy cannot be calculated directly. It is necessary to make the energy balance around the moisture separator reheater. This balance has been projected theoretically but there is a huge quantity of variables that are needed for the enthalpy calculation and the practical results are not yet displayed.

At next there are exposed the graphics of each parameter according to the time and corresponding to the three affected EDF units (Cruas 4, Chinon 3 and Saint Alban 1) and to Cattenom 3, where erosion has not been found. Cattenom has been chosen because of the high quality of its performance and the good precision of its data. The vertical line in the graphics indicates the date where the erosion has been discovered. Therefore, the four units will be used to analyse if erosion can be observable in a thermodynamic way.

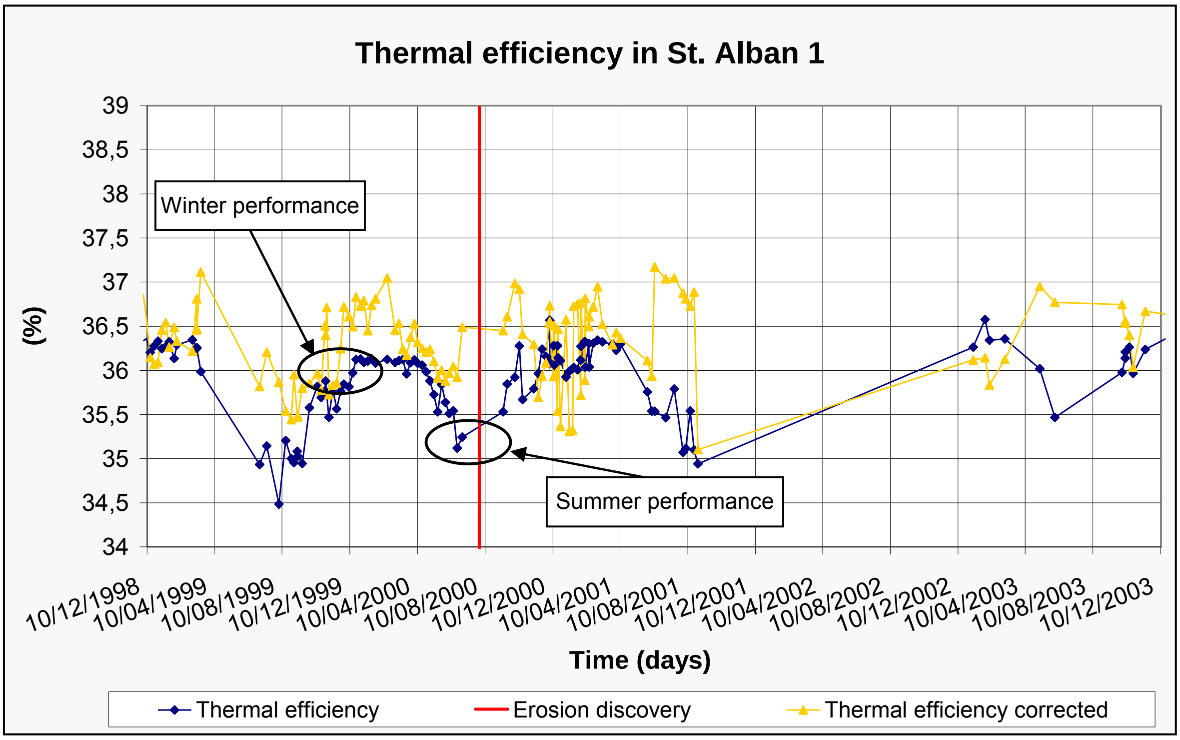
Thermal efficiency



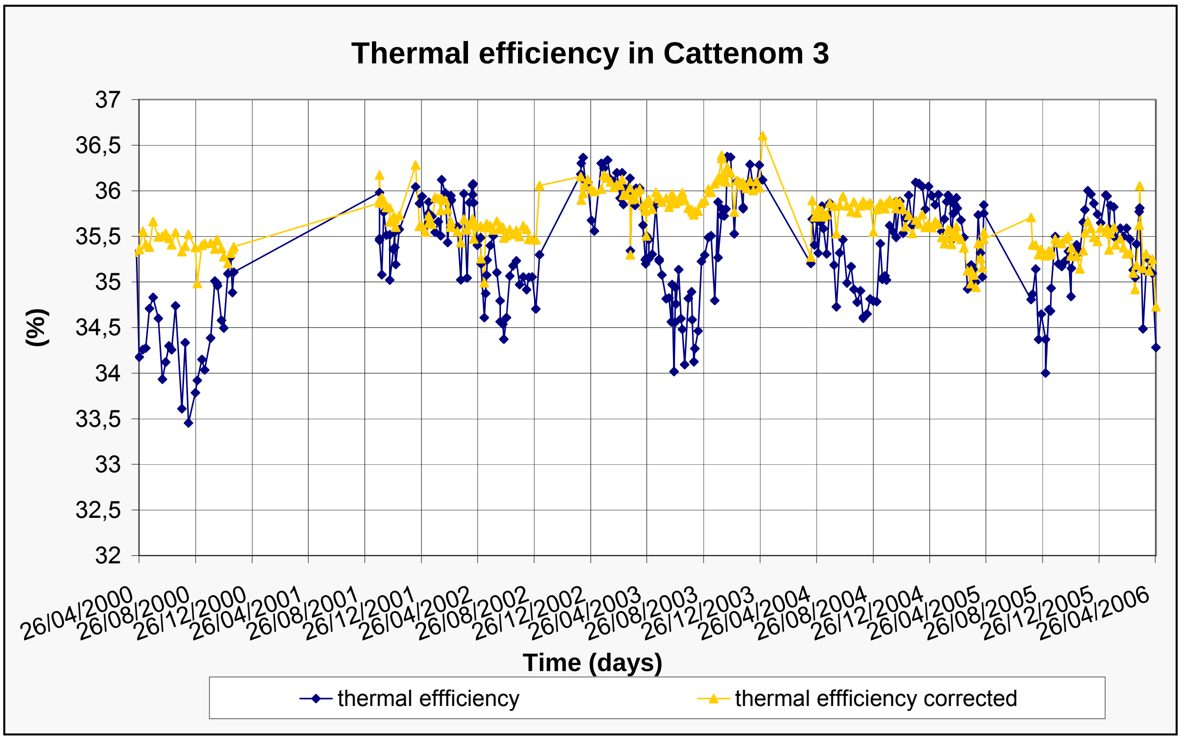
The thermal efficiency parameter is a good indicative of the secondary system performance. The most remarkable in the previous graphic is the thermal efficiency variation due to the seasonal variations (dark data). In winter the cooling water of the tertiary circuit is colder than in summer. Therefore the refrigeration works better and consequently also the unit global performance. The clear data show the thermal efficiency corrected form the outside constraints (power level, weather conditions, intake cooling temperature) in order to detect other possible causes of the thermal efficiency change. Nevertheless, at it has been previously commented, the deterioration in turbine performance comparing to the remaining cycle losses (leaky valves, regulation problems) is very little and cannot be detected in this graphic. The line indicating the erosion discovery does not display any significant performance changes between before and after the turbine overhaul. Thus, the thermal efficiency is not enough precise and does not provide any concrete information about turbine performance in Cruas.



Like in Cruas 4, the seasonal variations are very remarkable. In addition it can be seen an especially lower thermal efficiency in summer of 2003. That is due to the scorching heat that took place in France at that period, which caused the scaling of the condenser in addition to a warmer than usual cooling water. But there cannot be detected any sign of deterioration in the turbine.

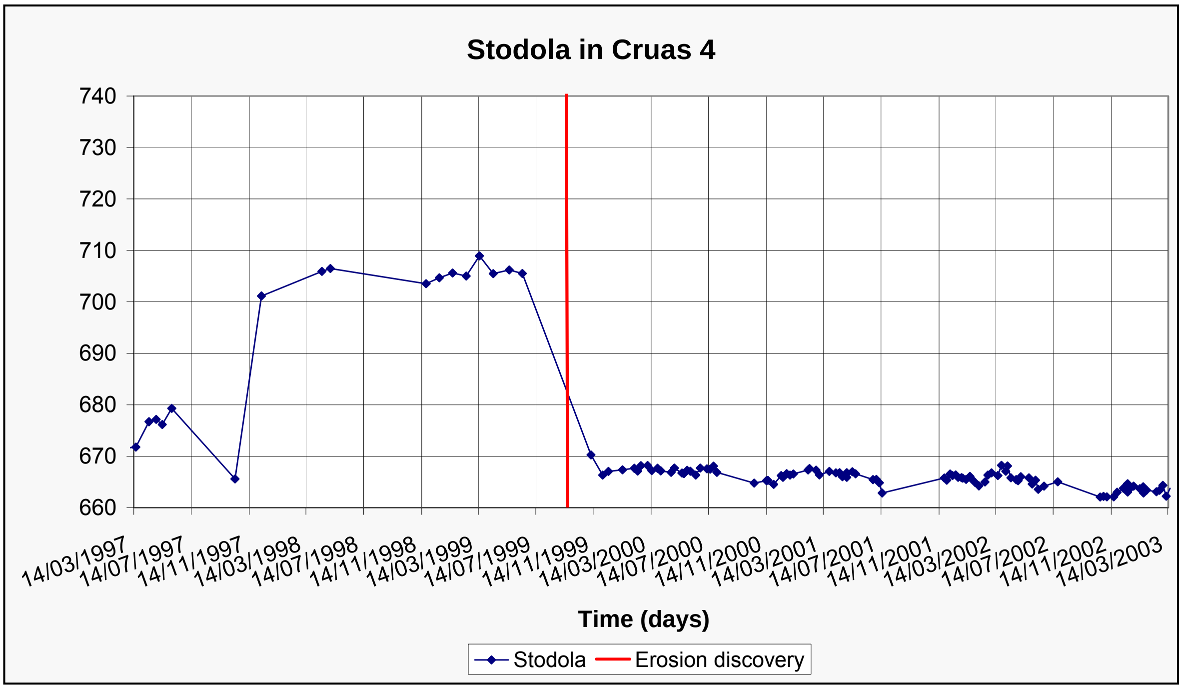


The data on the graphic in St. Alban behave like in Cruas and Chinon, for any turbine deterioration is visible.

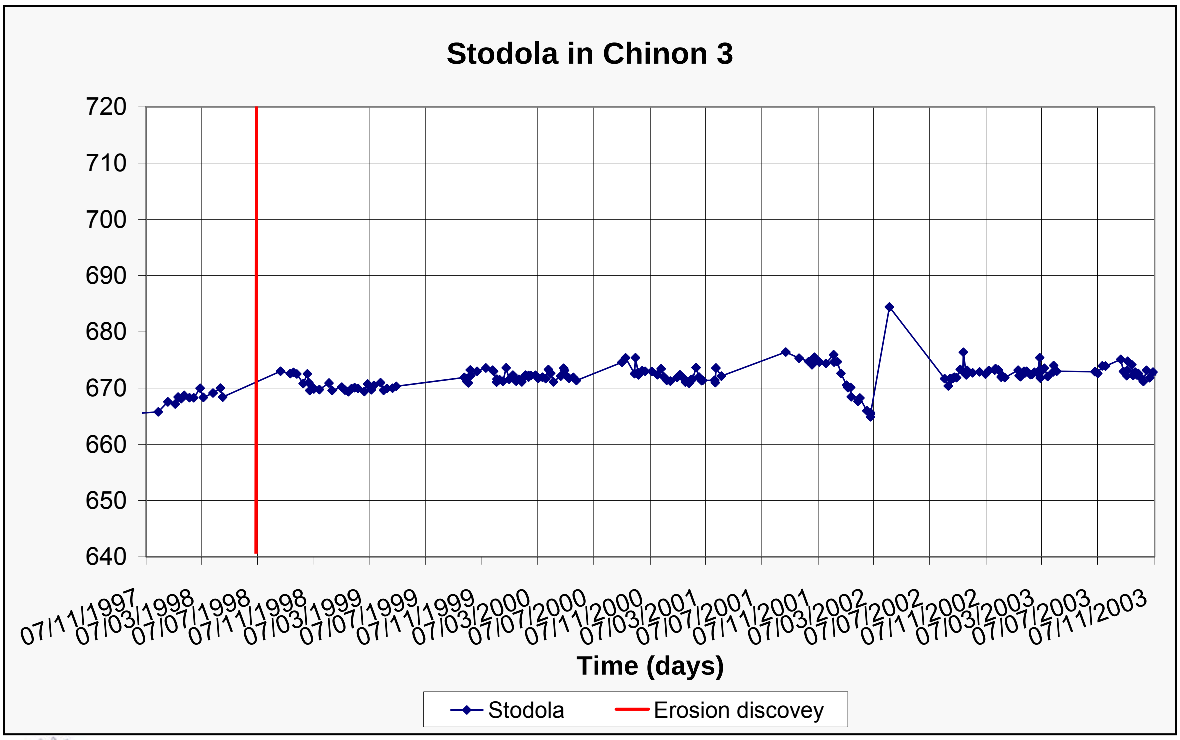


Effectively, the thermal efficiency parameter does not display any information about the turbine degradation in any of the four graphics, as it is not accurate enough. In conclusion, this parameter is not significant for the turbine erosion.

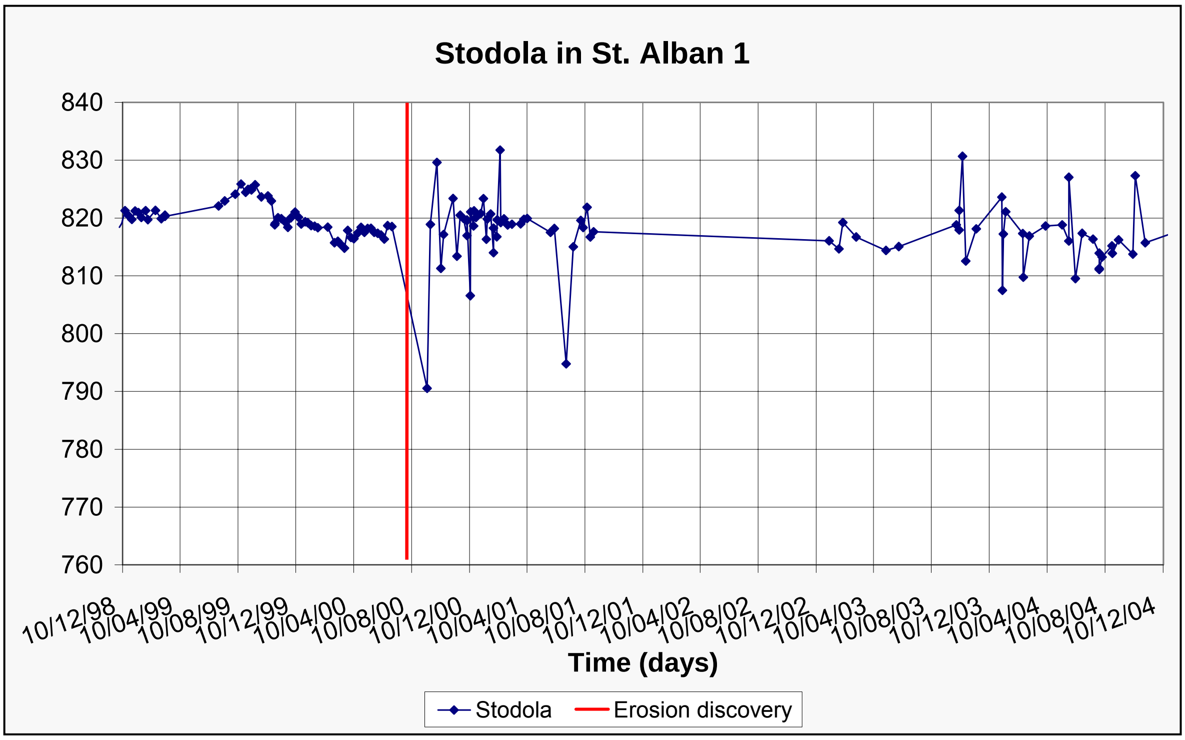
Stodola



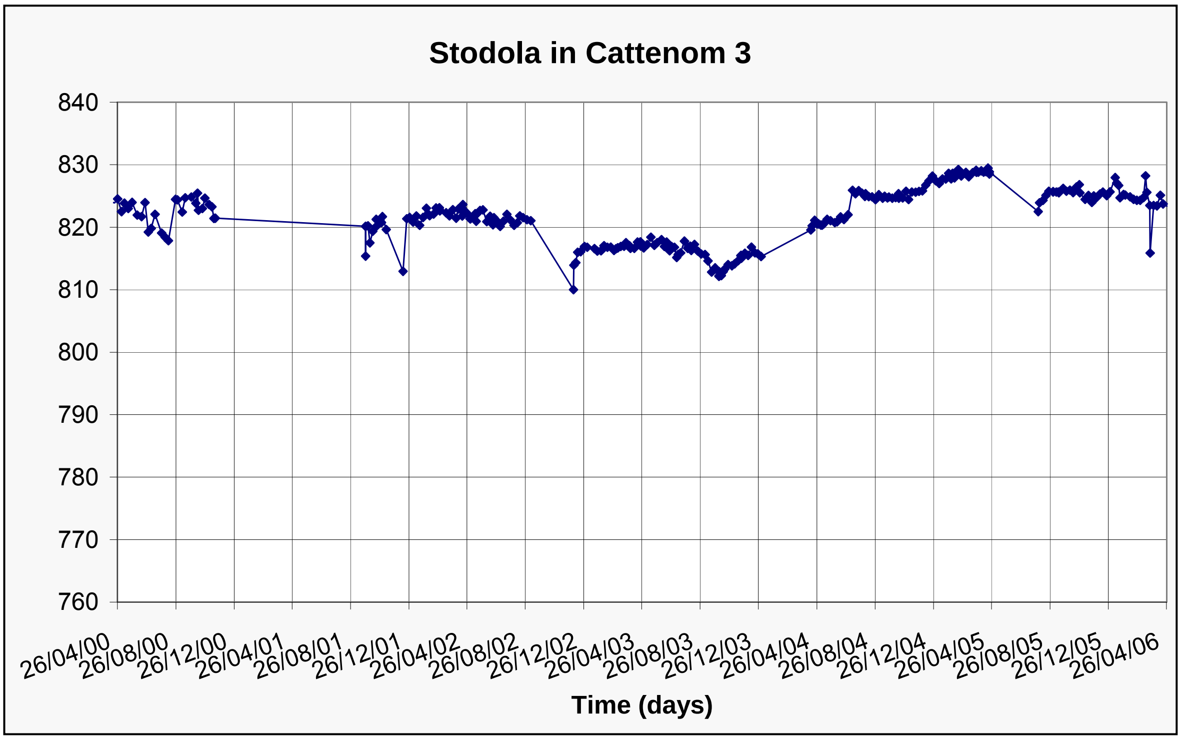
The data of the graphic show a significantly higher Stodola number before the erosion discovery. Its value remains high from the beginning of 1998 to June 1999, which is the last test made before the turbine visit. Between the tests made before and after the overhaul there is a great decrease. That means that the turbine performs much better after the discovery of the problem and its resolution.



In comparison to the Cruas graphic, the Stodola number does not seem indicative for the erosion discovery in Chinon 3.This parameter remains slightly constant.

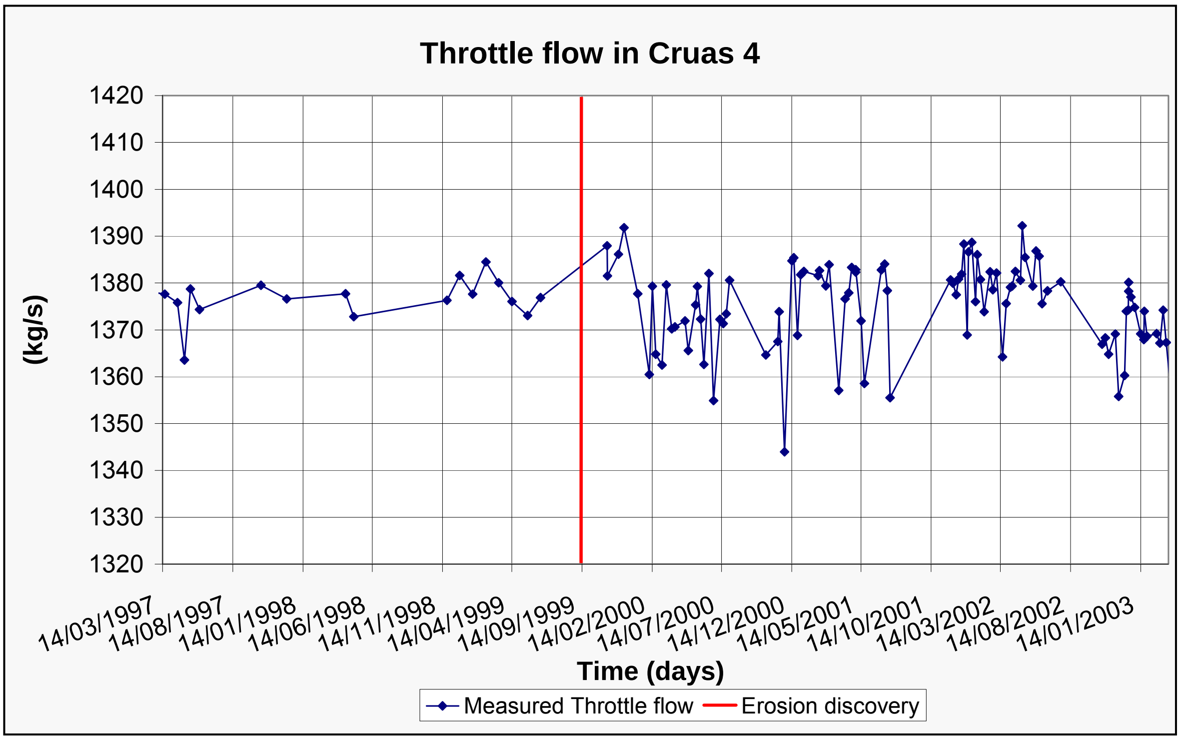


Like in Chinon 3, the Stodola number does not change between before and after the overhaul. The first test made after the turbine visit shows a smaller value, but just afterwards the value increases again into the same gap of values as before.

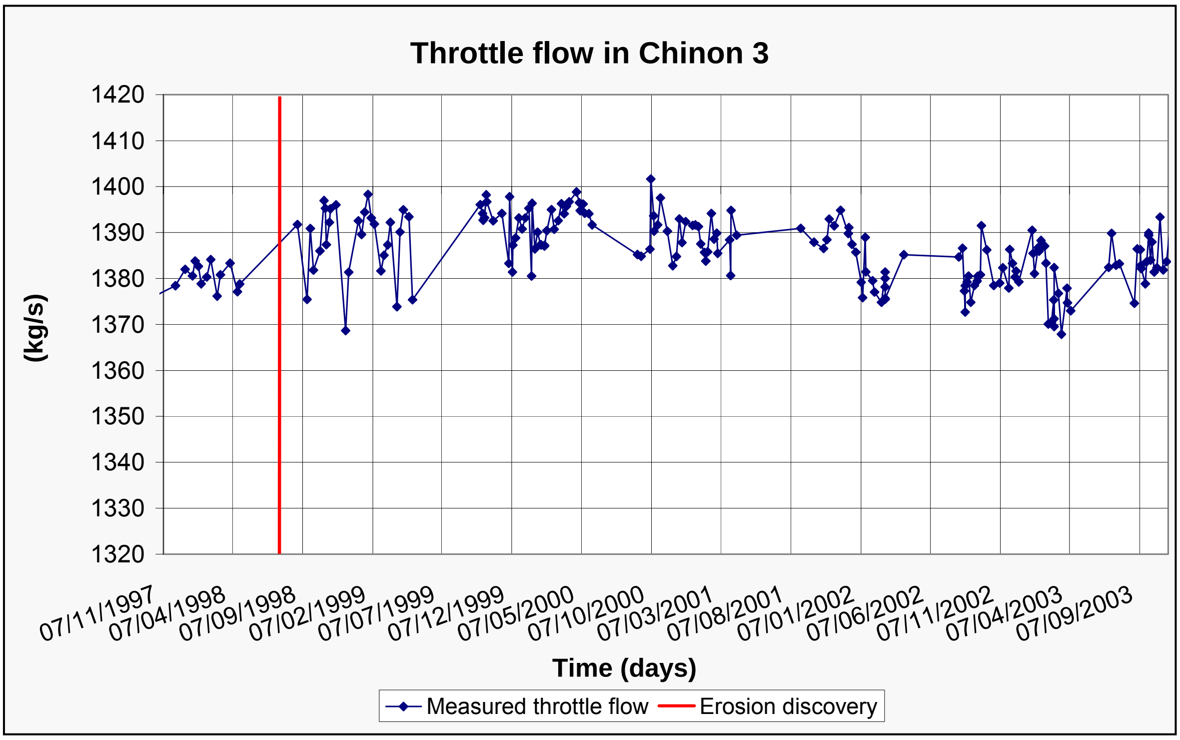


The Stodola behaviour in Cattenom 3 according to the time is very similar to the behaviour in Chinon 3 and in St. Alban 1. In conclusion, this parameter could be indicative for the blade erosion in Cruas 4, but it does not seem to be useful for the joint face" erosion of in Chinon and St. Alban.

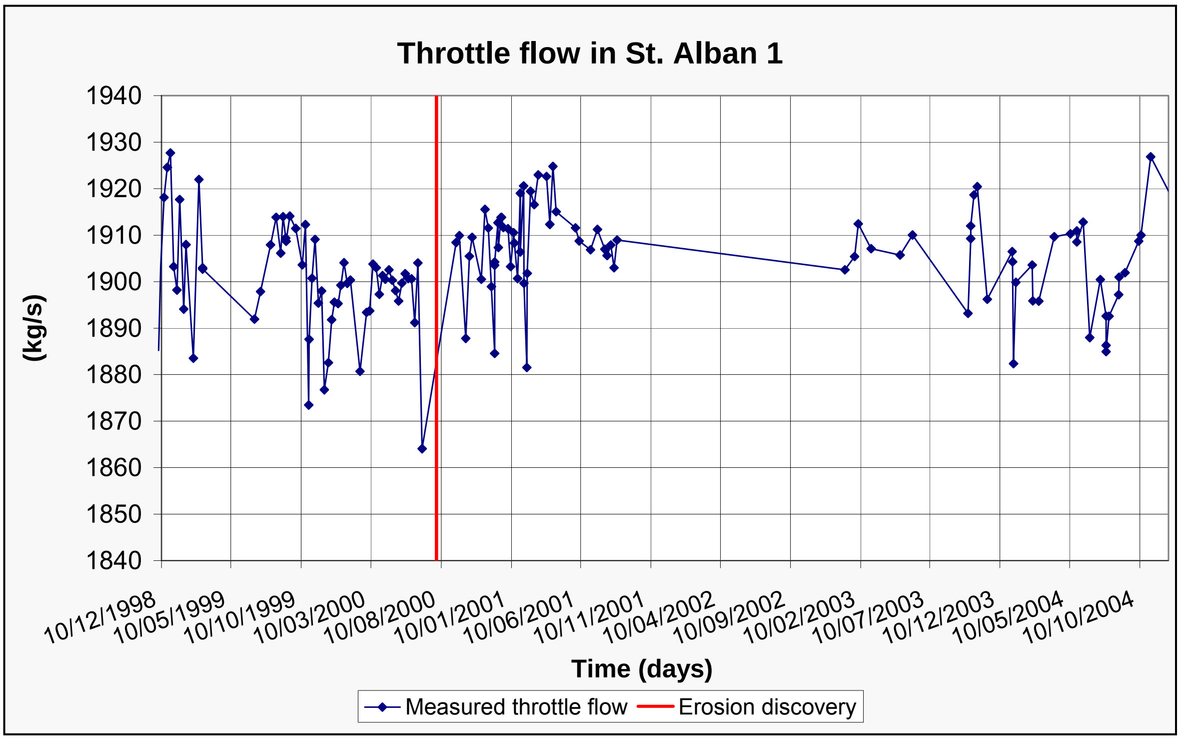
The throttle flow



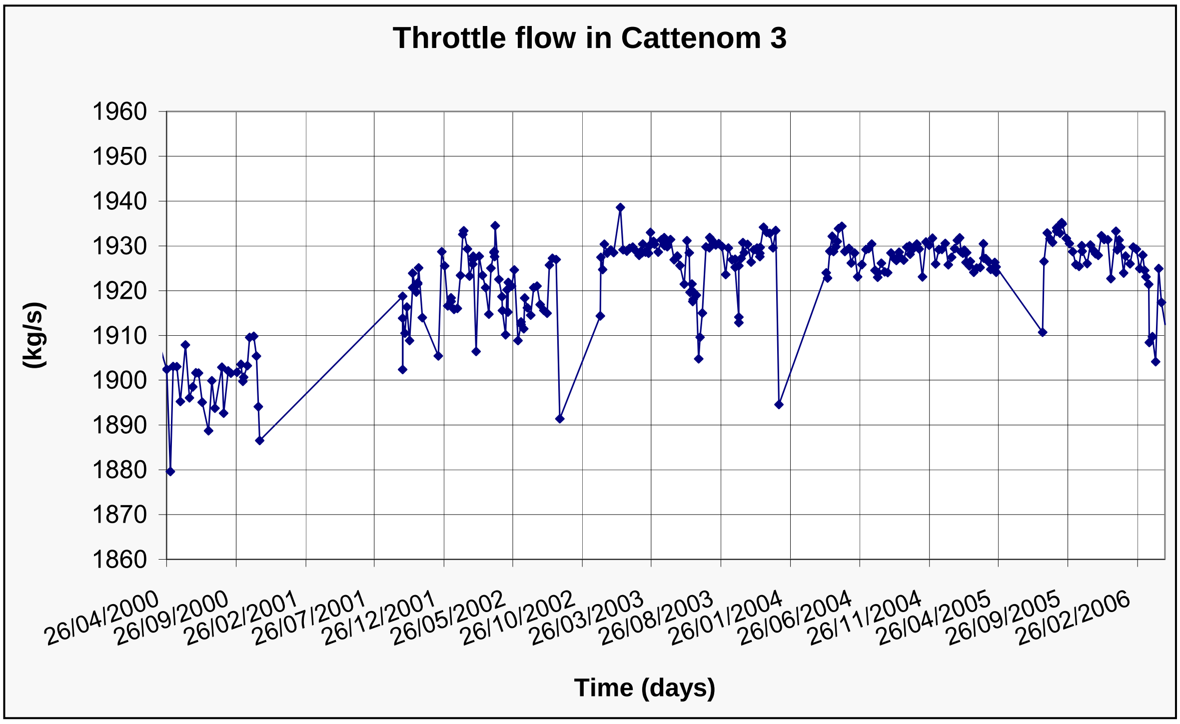
As it can be seen in the previous graphic, the throttle flow does not show a special behaviour between before and after the erosion discovery. Its value oscillates. As the throttle flow is coming directly from the steam generator, it can be observed that it must depend most of all of the steam generator performance. Thus, even if the throttle flow seems to increase before the discovery of the problem and its resolution, it keeps on increasing afterwards.



As the case of Cruas, the throttle oscillates during all the timeframe with a significant variation (according to EDF, a variation of 15 kg/s is equivalent to 10 MW), and it is values are imprecise. There is neither nothing detectable according to the turbine performance.

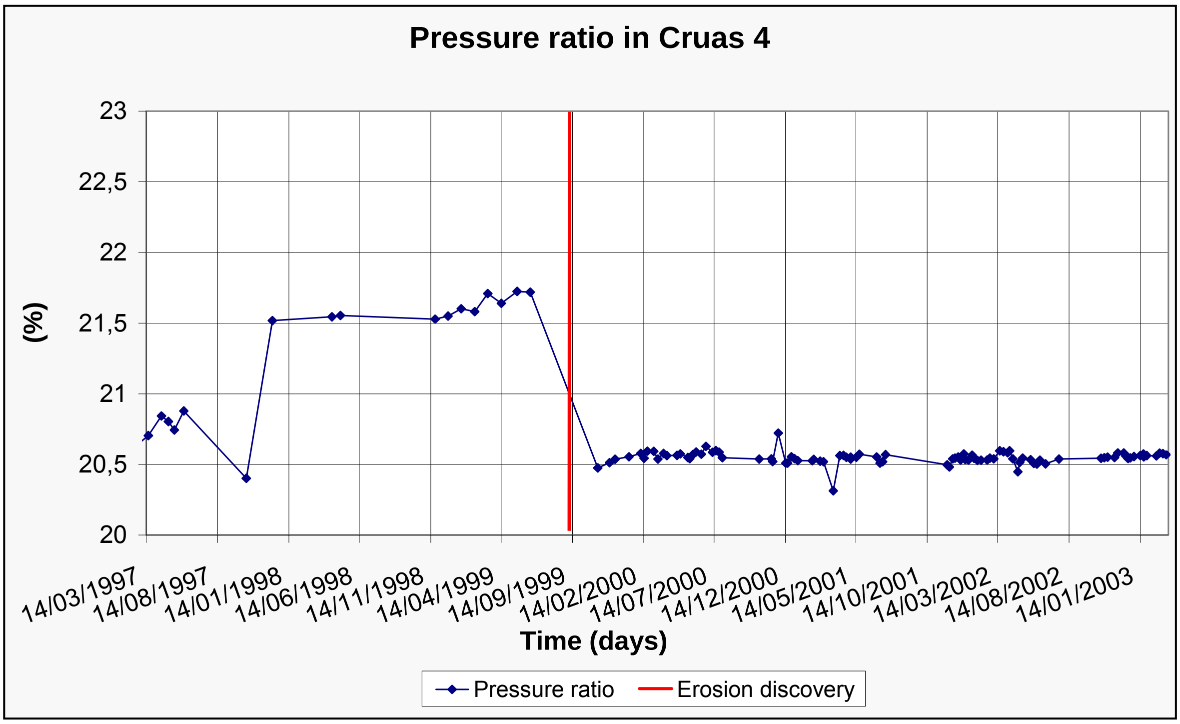


In the data on St. Alban any turbine deterioration is not visible either.

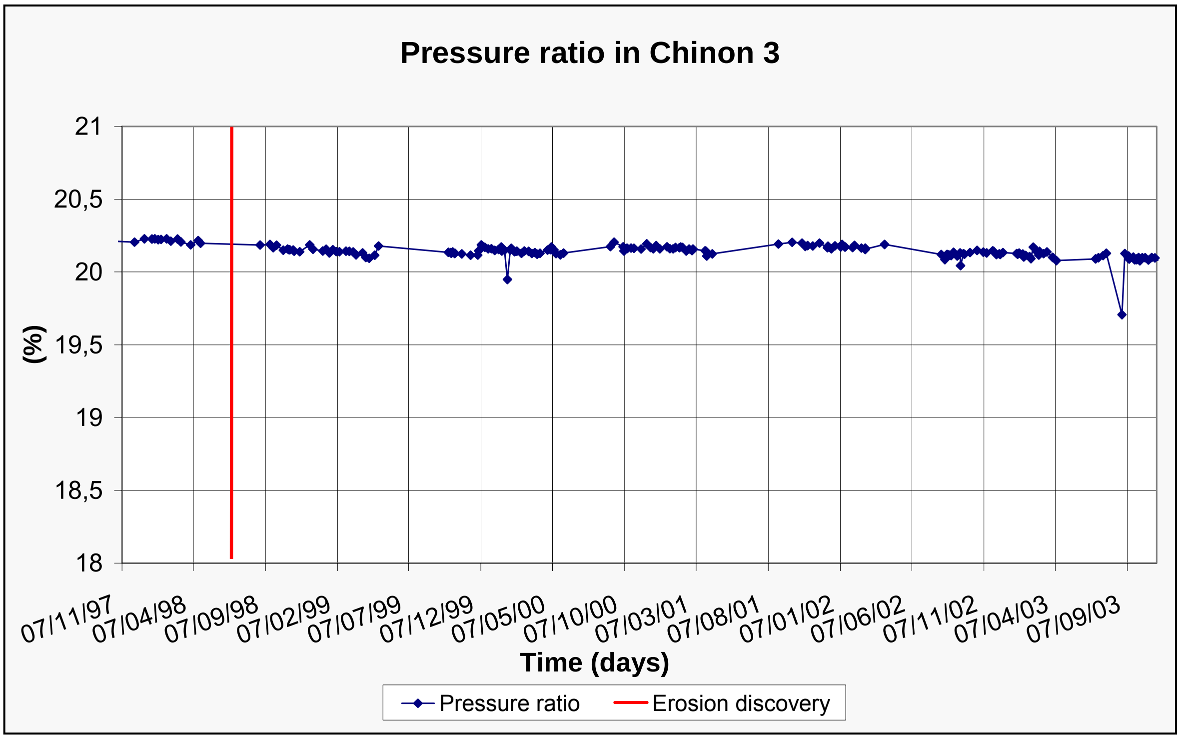


Like the thermal efficiency parameter, the throttle flow does not display any information about the turbine degradation in any graphic. In conclusion, the turbine erosion is not sufficiently big in comparison with the whole cycle, so the throttle flow is not accurate enough for this study case.

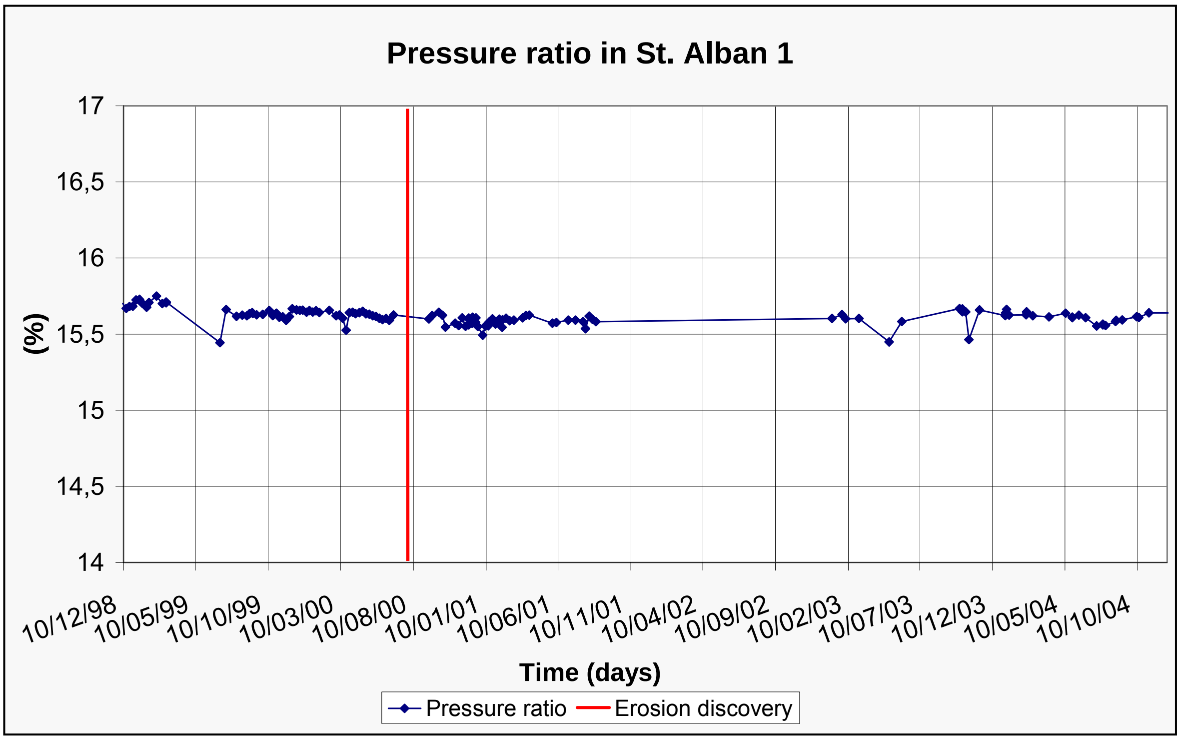
Pressure ratio between the HP turbine exhaust pressure and the throttle pressure



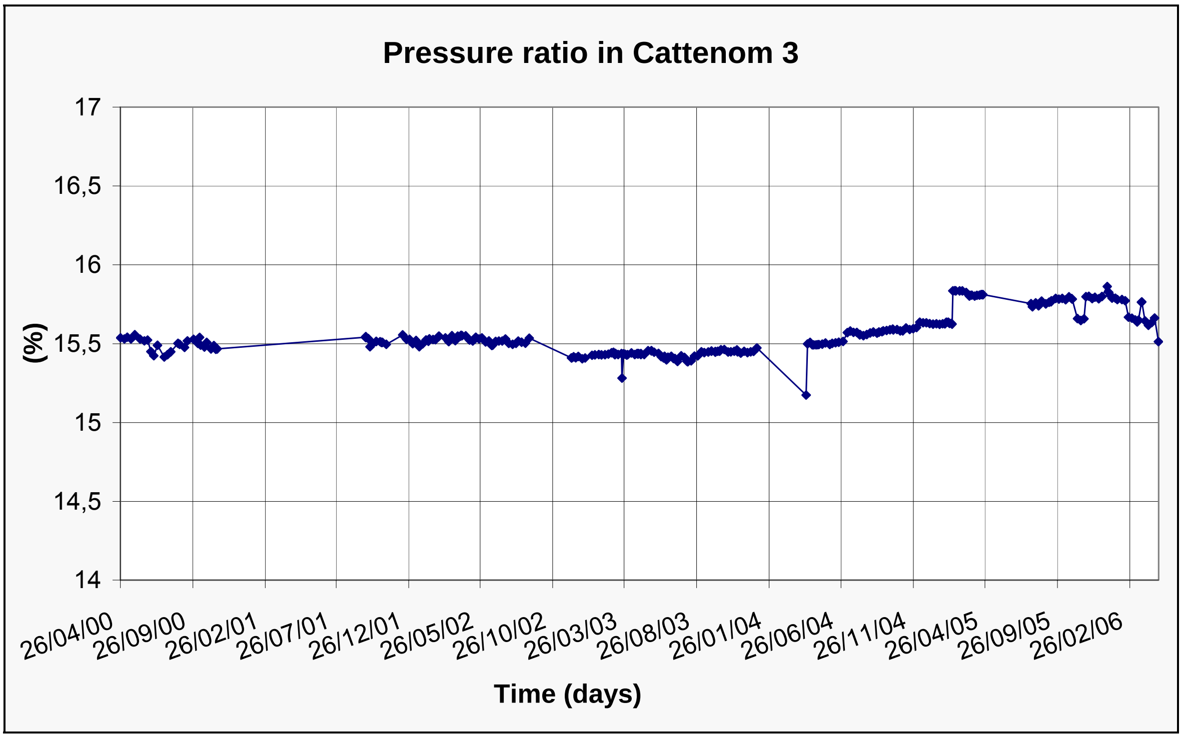
The data of Cruas 4 show a big change of the pressure ratio behaviour between before and after the turbine visit, like the Stodola parameter. Before the overhaul, from the beginning of 1998 to June 1999, the pressure ratio is about 1% higher than usual. That indicates a performance decrease during that period.



The pressure ratio in Chinon 3 remains constant during the entire time interval, including the timeframe before and after the erosion discovery. So, this parameter is neither indicative for the Chinon case.



As in Chinon, St. Alban 1 does not suffer any significant pressure changes.



The performance in Cattenom 3 also shows a constant pressure ratio. Therefore, the only graphic where a significant pressure ratio variation can be seen is the Cruas graphic.

7.1.3. Conclusions and propositions

The aim of this first study has been the study of the feasibility of a thermodynamic follow-up of the turbine performance and its degradations. Between the observed parameters, the Stodola number and the pressure ratio seem to be the best in order to characterize the case in Cruas, which is the only unit representing a blade erosion. Nevertheless, there are no significant parameters for Chinon and Saint Alban. That means that its phenomena of erosion are not enough important to be detected by the existing thermodynamic data. In case of the blade erosion, it is proposed to continue to observe more cases with this degradation in order to confirm these conclusions.

The fact of not having enough sensors in the turbine makes the thermodynamic follow-up difficult. It is impossible to instrument the inside of the turbine because of its delicate materials. But by adding a sensor for the steam moisture in the turbine outlet, the turbine would not be affected and the parameter of the turbine drop efficiency could be calculated directly (and with much more accuracy) instead of making the energy balance around the moisture separator reheater.

8. Second study: Rupture in a BONNA piping of the tertiary cooling circuit in the Nogent power plant

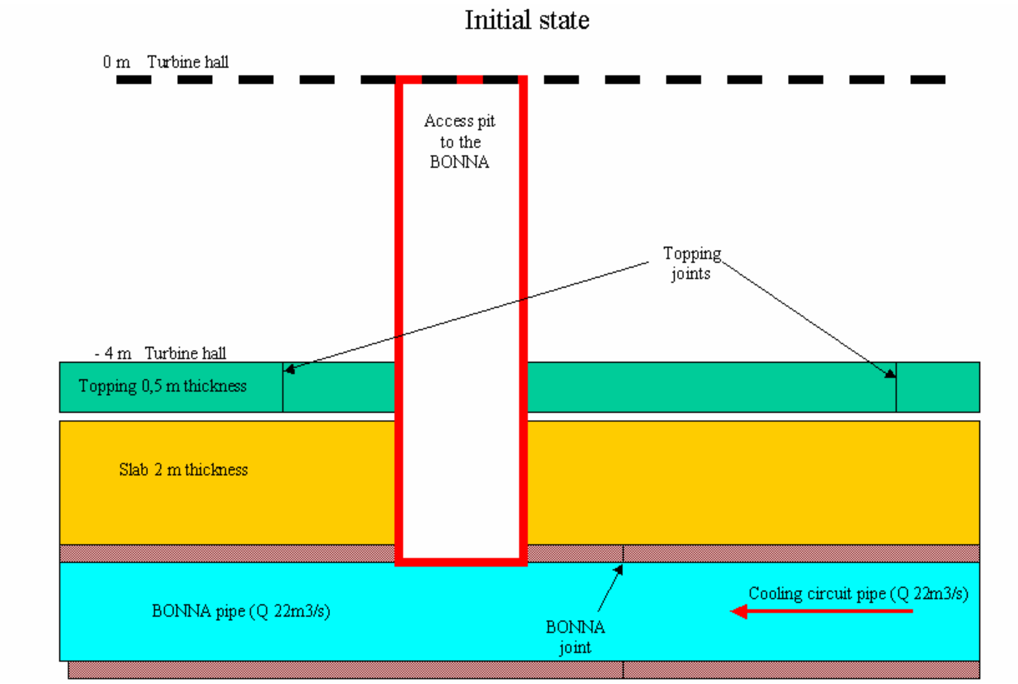
On February 18, 2006 at 19:10, an important water leakage took place in a BONNA piping of the tertiary cooling circuit in Nogent plant. The leakage was located at the discharge of one of the two circulation pumps of Nogent 2 and caused the rupture of the pipe. The basin of the cooling tower was then emptied out in the turbine hall of this unit, and water was propagated up to the turbine hall of the other unit Nogent 1 (see pictures in appendix C). In both turbine halls water reached a height in the order of one meter, which resulted in:

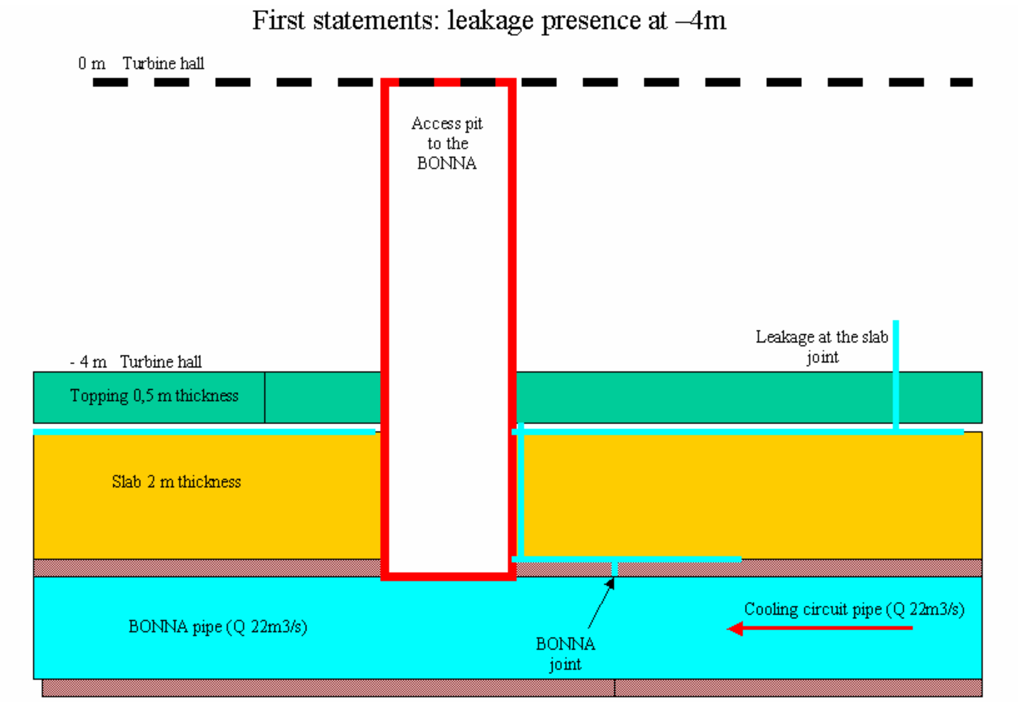
- A partial immersion of several components (pumps, motors…).
- A displacement of the auxiliary steam piping in the cable chase between the units.
- A partial immersion of the power cables of the pumps RRI (auxiliary steam generator drain cooling system).

The rupture of the BONNA piping led to the shutdown of the two units, Nogent 2 during 31 days and Nogent 1 during 25 days. This event induced a cost of approximately 165 million Euros (3 million for the repair work and 162 million of cost of alternative source of energy). The risk of the same event cannot be excluded in the nuclear power plants of Belleville, Golfech and Cattenom (8 units in all), since they present a similar design as the two units of Nogent. All correspond to a P'4 series with a semi-closed circuit.

The volute of the circulation pumps is realised in a concrete foundation and the piping at the suction and the discharge are of BONNA type (piping made of ferritic steel with concrete coating). The foundation is covered with a topping, built up by concrete plaques. There is an access pit in this slab that allows access to the piping and the volute for its periodic inspections and maintenance operations.

A design weakness at the top of the pit and at the volute of one circulation pump was detected. The pressure increase of the interface slab-foundation due to the water infiltrations caused rising then rupture of the slab of unit Nogent 2. Moreover, the series in a semi-closed circuit on a cooling tower are subject to intense scaling phenomena. Consequently, the cooling water of the condensers is treated with sulphuric acid, which has been identified as a factor aggravating the deterioration risk in the interface slab-foundation.





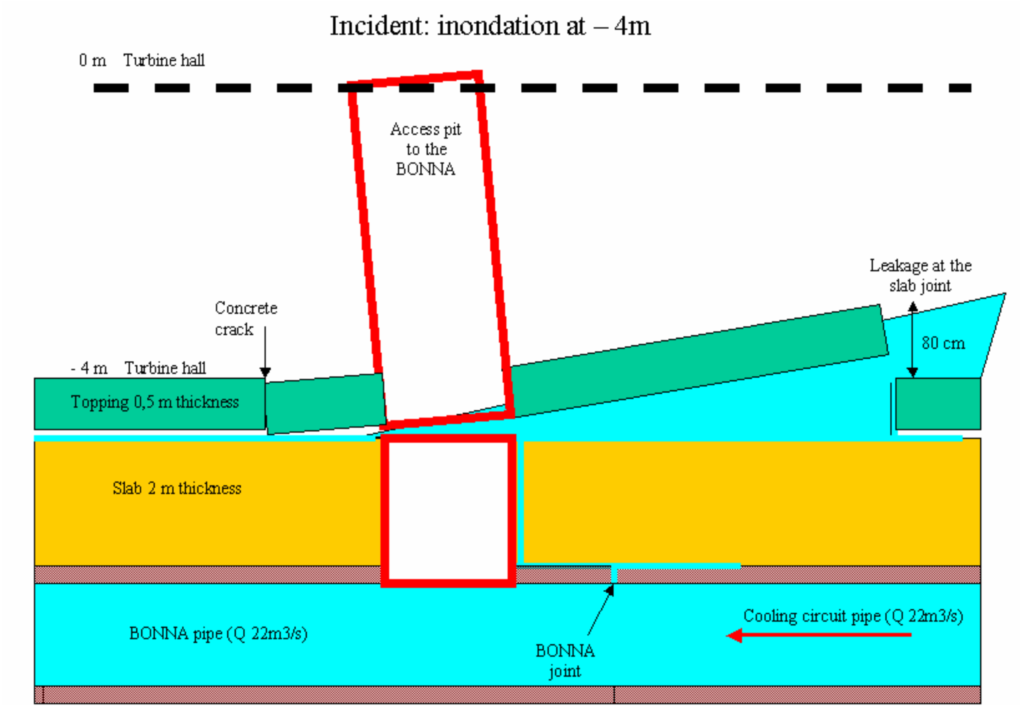


Fig. 8. Evolution from the water leakage to the rupture of the concrete slab EDF)

The CEF tool will be used to study if this event could have been envisaged to avoid its reappearance in the future. Like in the previous study, this case will also be divided up into two parts, the theoretical and the practical analyses.

8.1. Theoretical analysis of the water leakage in the tertiary cooling circuit

In this section there will be analysed the tertiary system in order to specify the main parameters that could inform about the system state. At next there is a schema with the simplified tertiary cooling circuit corresponding to a semi-closed system, like in Nogent.

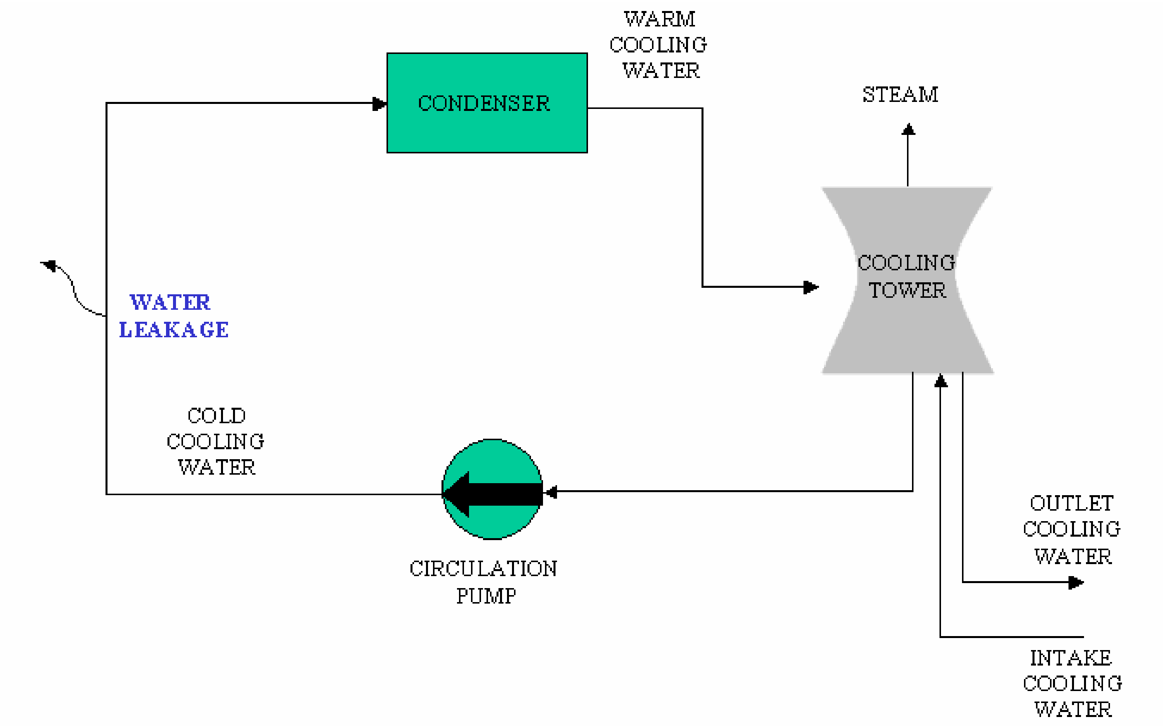


Fig. 8.1. Semi-closed tertiary cooling system

In order to find a new performance monitoring method for the detection of leakage at the BONNA pipes of the P'4 series, several thermodynamic parameters have been proposed in the following paragraphs:

1) The balance between the cooling water entering and leaving the tertiary system could inform about the flow behaviour inside the system. So, the first parameter is defined like:

$$K_1 = \frac{Q_{INTAKE\ COOLING\ WATER}}{Q_{OUTLET\ COOLING\ WATER}} \qquad \text{(Eq. 8.1)}$$

This parameter should remain constant in a normal situation. If the coefficient between the both flows becomes unstable that could indicate an irregularity in the tertiary system.

2) Regarding in the system inside, another flow balance could be useful to analyse in order to find a leakage disease. The idea is to compare the flowing going through the circulation pump and the one across the condenser:

$$K_2 = \frac{Q_{CIRCULATION\ PUMP}}{Q_{COND}} \cdot 100 \qquad \text{(Eq. 8.2)}$$

$$K_2 = \frac{Q_{COND} + Q_{LEAKAGE}}{Q_{COND}} \cdot 100 = 100 + \frac{Q_{LEAKAGE}}{Q_{COND}} \geq 100(\%)$$

Theoretically it is the same quantity because there are not any junctions between them (K_2 =100%). But in case of having a leakage, this parameter should increase. The worse is the leakage between both components the greater will become K_2, for the flow across the condenser will decrease.

3) It is proved that the vacuum pressure at the condenser, corresponding to the pressure in which the steam coming from the low-pressure turbines is condensed, is a very sensible variable. This pressure is controlled by the cooling system. It is linked to the flow and the temperature at the condenser inlet. In normal conditions, the flow of the condenser remains constant and the pressure at the condenser will only depend on the cooling circuit temperature. The colder is the cooling water, the smaller will be the pressure at the condenser, and the cycle working will have a better performance.

   The presence of a leakage will change the flow and consequently the pressure will vary too. If there is a smaller flow going through the condenser, the pressure will increase and decrease the unit performance. So, the vacuum pressure could also be a good lead for an abnormal situation and it will be represented like:

$$K_3 = P_{COND\ MEASURED} - P_{COND\ EXPECTED}\,(mbar) \qquad \text{(Eq. 8.3)}$$

$$P_{COND} = f(T_{COLD\,COOLING\,WATER}, Q_{COND})$$

$$\xrightarrow{if\ Q = constant} K_3 = f(T_{COLD\,COOLING\,WATER})$$

The CEF tool can be used to draw a graphic with the expected pressure at the condenser in the secondary circuit according to the temperature of the intake cooling circuit of a standardized P'4 series. By comparing the expected pressure with the measured pressure of the affected power station, this variation can give information about the cooling system state. In case of leakage, the measured pressure should increase in comparison to the expected pressure. The temporal evolution of the pressure increase can be analysed by drawing the difference between the measured and the expected pressure according to the time.

4) The flow drop produced by the leakage before the condenser will decrease its capacity to condensate the steam coming from the low-pressure turbines. So, the warm cooling water at the condenser outlet will increase its temperature in order to have a complete condensation. The forth parameter indicates the balance between this temperature and the cold cooling water temperature:

$$K_4 = \frac{T_{WARM\ COOLING WATER}}{T_{COLD\ COOLING WATER}} \quad \text{(Eq. 8.4)}$$

In case of a leakage before entering the condenser, the theoretical evolution of parameter K_4 should be an increase.

8.2. Adaptation of the theoretical analysis to the Nogent station case

To appropriate the theoretical analysis to the Nogent station, the thermodynamic variables from MOLENE database have been consulted. Between the four parameters previously defined, K_1 (balance between the inlet and the outlet cooling water flow) is not observable yet, because the outlet cooling water flow is not measured. Therefore, the remaining parameters are analysed in the following sections. Like in the first study, the graphics of Nogent 2 are compared to Cattenom 3. Then Cattenom corresponds also to a P'4 series with a semi-closed circuit besides of the high quality of its performance and the good precision of its data.

8.2.1. Follow-up of the K_2 parameter

K_2 is defined like the relation between the condenser flow (Q_{COND}) and the flow at the circulation pump (equation 8.2)(Q_{CP}). The flow at the circulation pump is given in MOLENE. At present, the tertiary cooling systems controlled by EDF have sensors at the admission and the discharge of the pump that indicate the value of both pressures. The flow at the circulation pump is automatically calculated from these values with the CEF tool by EDF. To calculate the flow across the condenser, the variables given in MOLENE are:

- The power given up at the condenser ($\dot{W}_{COND}$).
- The pressure in its outlet (P_{OUT}).
- The temperature of the cold and the warm cooling water (T_{CCW} and T_{WCW}).

There are no sensors that show exactly the pressure at the condenser inlet (P_{IN}). However there is very little difference between the pressure at the inlet and the outlet. EDF supposes a drop of 0,6 bar due to friction causes. This data enables to make an enthalpy balance in order to calculate the flow through the condenser in the tertiary system:

$$\dot{W}_{COND} = Q_{COND} \cdot (H_{OUT} - H_{IN}) \Rightarrow Q_{COND} = \frac{\dot{W}_{COND}}{\Delta H} \qquad \text{(Eq. 8.5)}$$

$$H_{COOLING\ WATER} = f(P,T)$$

The power given up at the condenser in the secondary circuit is equal to the acquired power in the tertiary circuit, and the enthalpy of the cold and the warm cooling water can be calculated from the pressure and the temperature in the inlet and the outlet of the condenser. If MOLENE did not contain the power given up at the condenser, this variable could be known with an energy balance in the secondary circuit, where:

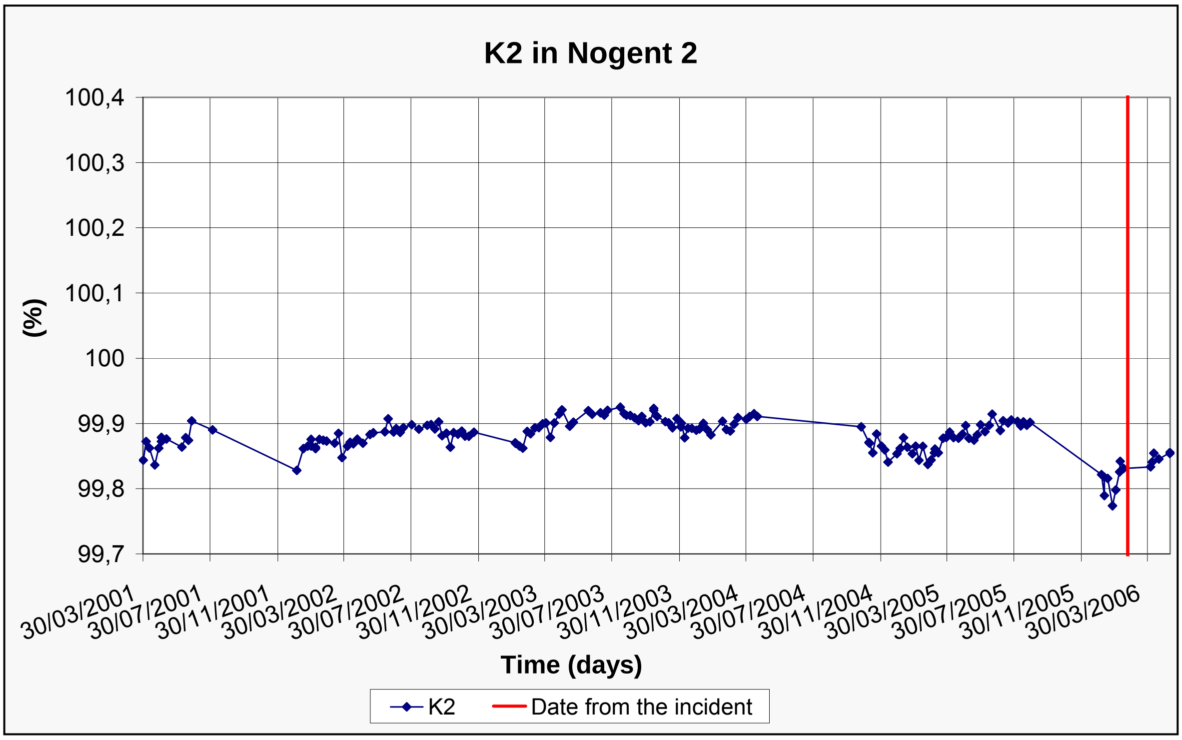
$$\dot{W}_{STEAM\ GENERATOR} = \dot{W}_{TURBINE\ HP} + \dot{W}_{TURBINE\ BP} + \dot{W}_{COND}$$

$$\dot{W}_{TURBINE\ HP} + \dot{W}_{TURBINE\ BP} = \frac{\dot{W}_{ELEC}}{\eta_{STEAM\ TURBOMACHNERY}}$$

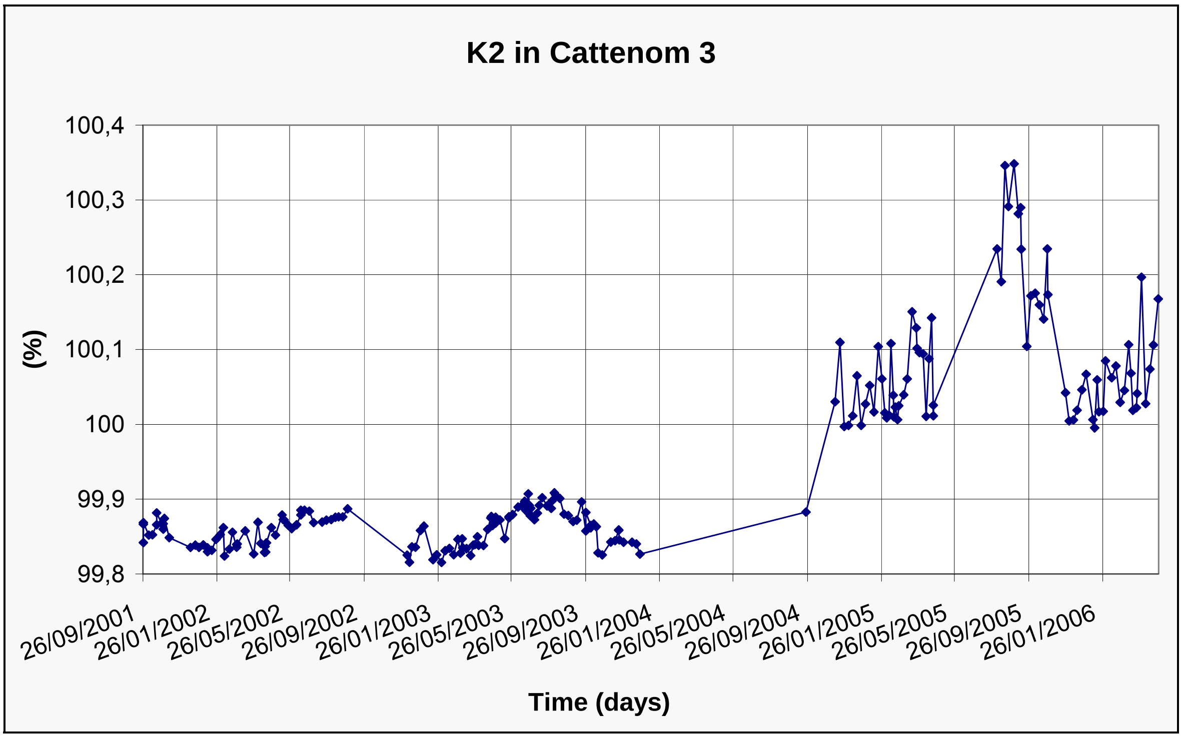
$$\dot{W}_{CONDENSER} = \dot{W}_{STEAM\ GENERATOR} - \frac{\dot{W}_{ELEC}}{\eta_{STEAM\ TURBOMACHINERY}} \qquad \text{(Eq. 8.6)}$$

MOLENE also contains the data about the power of the steam generator, the electrical power and the efficiency of the steam turbomachinery. However, the result is more exact by using the first option, which has less margin of error.

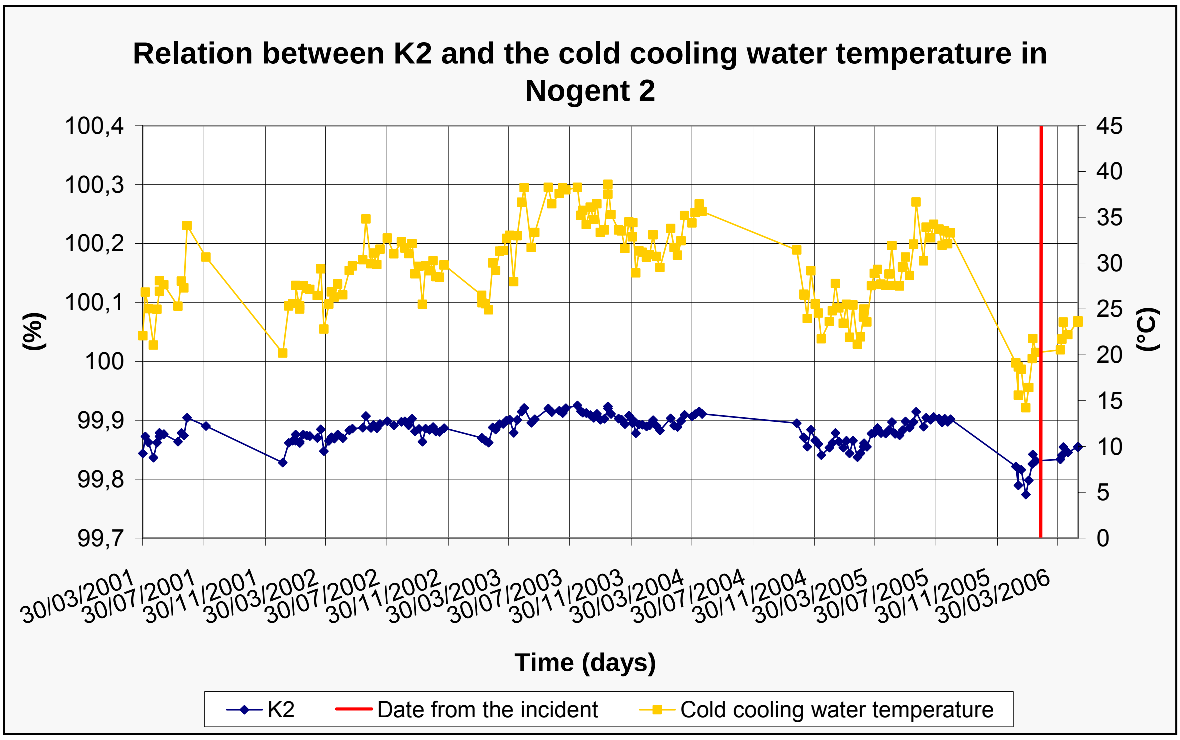
The result by dividing both flows in Nogent 2 is showed in the following graphic:



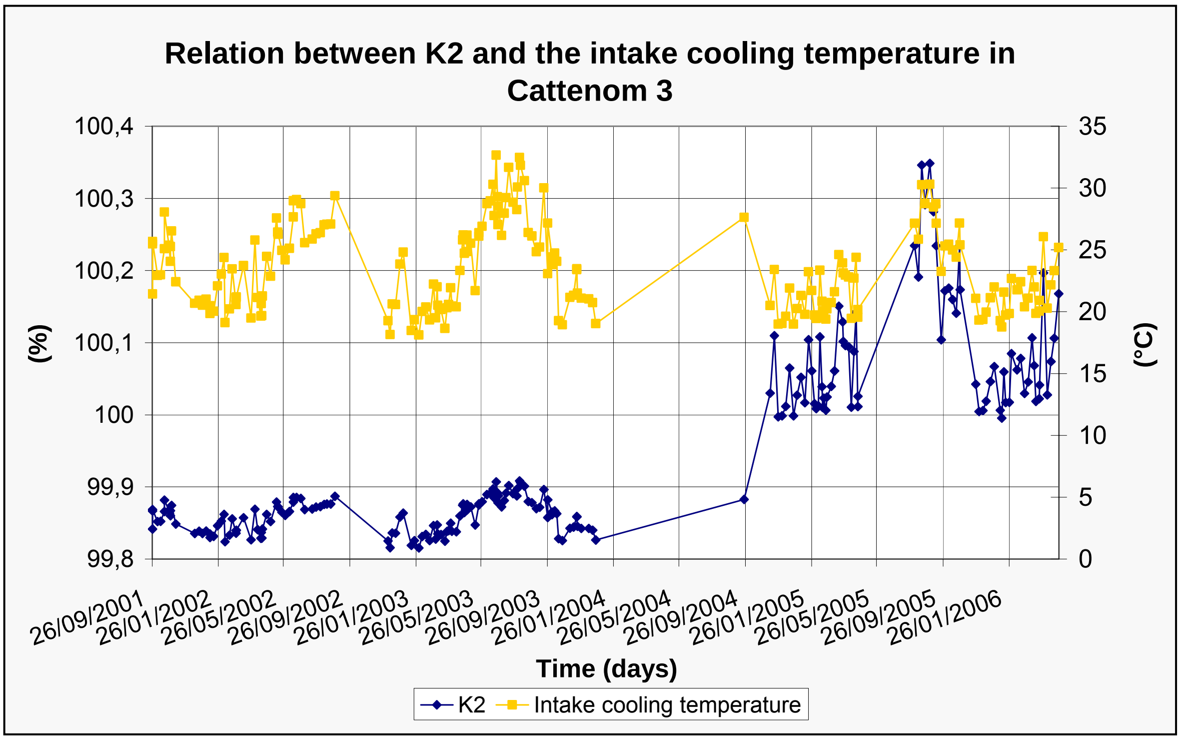
By observing K_2 behaviour in the interval from Mars 2001 to April 2006 in Nogent 2, there is no much difference between the test values. Theoretically, the circulation pump flow should be the same than the condenser flow. The results are not exactly like that because of the margin of error of the sensors, but they approach the value of 1. However, it is not as important to analyse the value but its evolution according to the time. Before the incident, there can be observed a little descent according to the previous values, and afterwards a raise of approximately 0, 07% of K_2 since January 2006. It is a very insignificantly increase and it does not seem to be very indicative.



In the graphic of Cattenom 3 there is a more significant variation in the value of K_2 than in Nogent 2: Its value maintains approximately constant until the end of 2004. Afterwards K_2 begins increasing. At the end of 2005 it seems to get stabilised, but under a higher interval than at the beginning (0,3% of increase approximately). In order to examine in more detail the performance of K_2 in both cases, several variables are going to be represented at next. At first, the previous graphics of this parameter will be represented with the cold cooling temperature, which is usually a significant variable for interpreting the performance of the tertiary system:



It is remarkable that K_2 and the cold cooling temperature are closely correlated.



Like in Nogent 2, both parameters are closely linked. In order to understand this correlation, by combining the equations 8.2 and 8.5, K2 develops like:

$$K_2 = \frac{Q_{CP}}{Q_{COND}} = \frac{Q_{CP}}{\dfrac{\dot{W}_{COND}}{H(T_{WCW}, P_{OUT}) - H(T_{CCW}, P_{IN})}} = \frac{Q_{CP} \cdot \Delta H}{\dot{W}_{COND}} \approx k(T_{CCW}) \qquad \text{(Eq. 8.7)}$$

The performance of Q_{CP}, ΔH and $\dot{W}_{COND}$ are represented in the appendixes C.1, C.2 et C.3 respectively.

In normal conditions, the circulation pump flow should remain theoretically constant, because this flow is independent from the temperature. Effectively, except some detached tests, the graphics (see appendix C.1.) show that this flow remains approximately constant. There are little variations because of the pumping. Also in summer of 2003 a group of tests show smaller flow values than usual. This vas a particular period because of the scorching heat. It was been ordered to reduce the flow extraction from the rivers in order to not heat as much the river. There is nothing remarkable on the performance of the circulation pump in Nogent 2 before the incident.

To analyse the enthalpies at the terminals of the condenser in the tertiary system, the pressure remains practically constant (there are only little friction losses). Consequently, the enthalpy develops in the following way:

$H = U + PV$ (Intrinsic energy + work energy)

$dU = dW + dQ$

$$dH = d(U) + d(PV) = dU + PdV + VdP = dQ + VdP$$

Considering the condensation as an isobar process:

$dH = dQ = C_p \cdot dT$, where $C_p = \dfrac{dH}{dT}$.

Therefore, the enthalpy depends basically on the difference between the warm and the cold cooling temperature. In the section 8.2.3 it will be seen that this relation is controlled in the cooling system and remains approximately constant. Thus,

$$\Delta H \cong C_p \cdot (A \cdot T_{CCW} - T_{CCW}) \rightarrow \Delta H \cong B \cdot T_{CCW}$$

Effectively, by analysing the graphic of the enthalpies (see appendix C.2) it can be seen that the enthalpy at the outlet and at the inlet depend basically on the cold cooling water temperature, as well as its difference. Finally, by developing equation 8.6, the power at the condenser can be represented as:

$$\dot{W}_{COND} = \left(1 - \frac{\eta_{THERMAL}}{\eta_{TURBOMACHINERY}}\right) \cdot \dot{W}_{STEAM\ GENERATOR}$$

The graphics on appendix C.4 also show a close correlation between the condenser power and the cold cooling water temperature. This is very logical, because the vacuum pressure varies depending on the temperature. And the higher is this pressure, worse is the turbine performance and higher is the power dissipated at the condenser. So, an approximation of the thermal efficiency could be:

$$\eta_{THERMAL} \cong \frac{C}{P_{COND}} \cong \frac{C}{D \cdot T_{CCW}}$$

Thus, $\dot{W}_{COND} \cong \left(1 - \frac{C}{\eta_{TURBOMACHINERY} \cdot D \cdot T_{CCW}}\right) \cdot \dot{W}_{STEAM\ GENERATOR}$

The efficiency of the turbomachinery and the power given by the steam generator can be considered constant. Because the tests are made in a stationary status, this power does not change.

$$\dot{W}_{COND} \cong \left(\frac{E \cdot T_{CCW} - C}{E \cdot T_{CCW}}\right) \cdot \dot{W}_{STEAM\ GENERATOR}$$

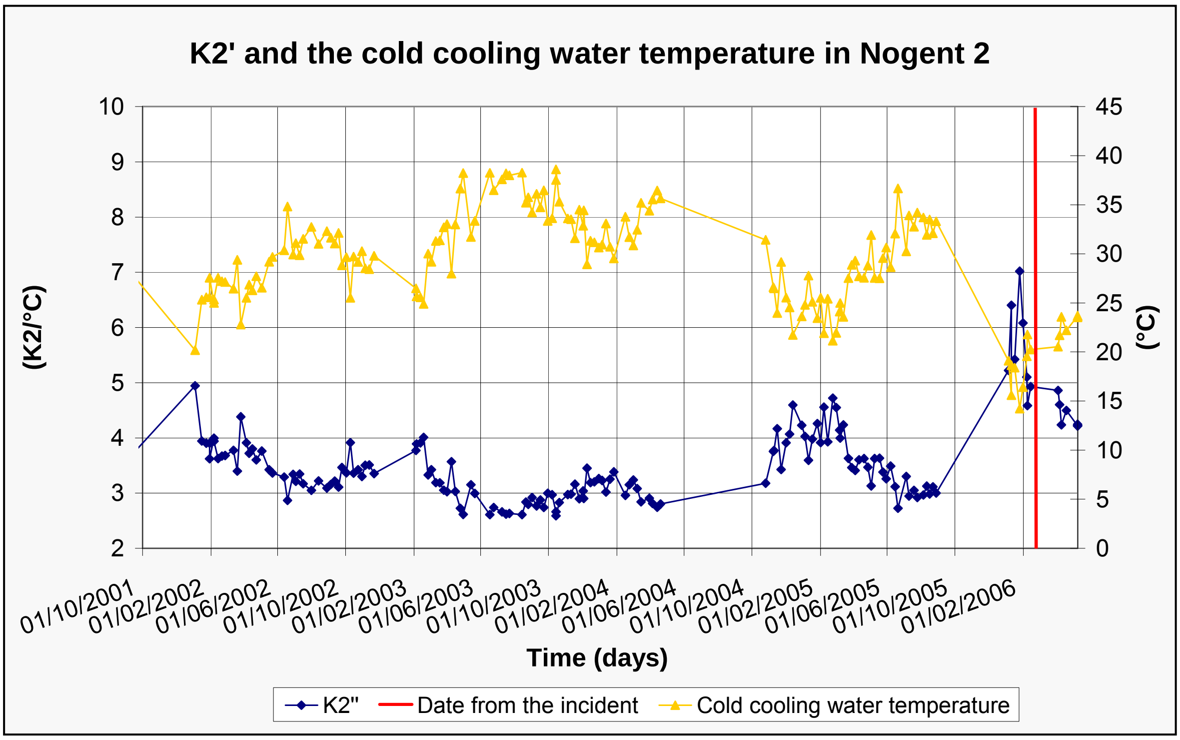
Therefore, by replacing the equation 8.7 by the previous approximations, K_2 results effectively like:

$$K_2 \cong \frac{Q_{CP} \cdot B \cdot T_{CCW}}{\left(\frac{E \cdot T_{CCW} - C}{E \cdot T_{CCW}}\right) \cdot \dot{W}_{STEAM\ GENERATOR}} \cong \frac{Q_{CP} \cdot B \cdot E \cdot T_{CCW}{}^2}{E \cdot T_{CCW} - C \cdot \dot{W}_{STEAM\ GENERATOR}} \approx k \cdot T_{CCW}$$

K_2 will be corrected in order to observe its behaviour by reducing the effect of the temperature. It is proposed to calculate the new parameter K_2', which will be represented as:

$$K_2' = \frac{K_2}{T_{CCW}}$$ (Eq. 8.8)

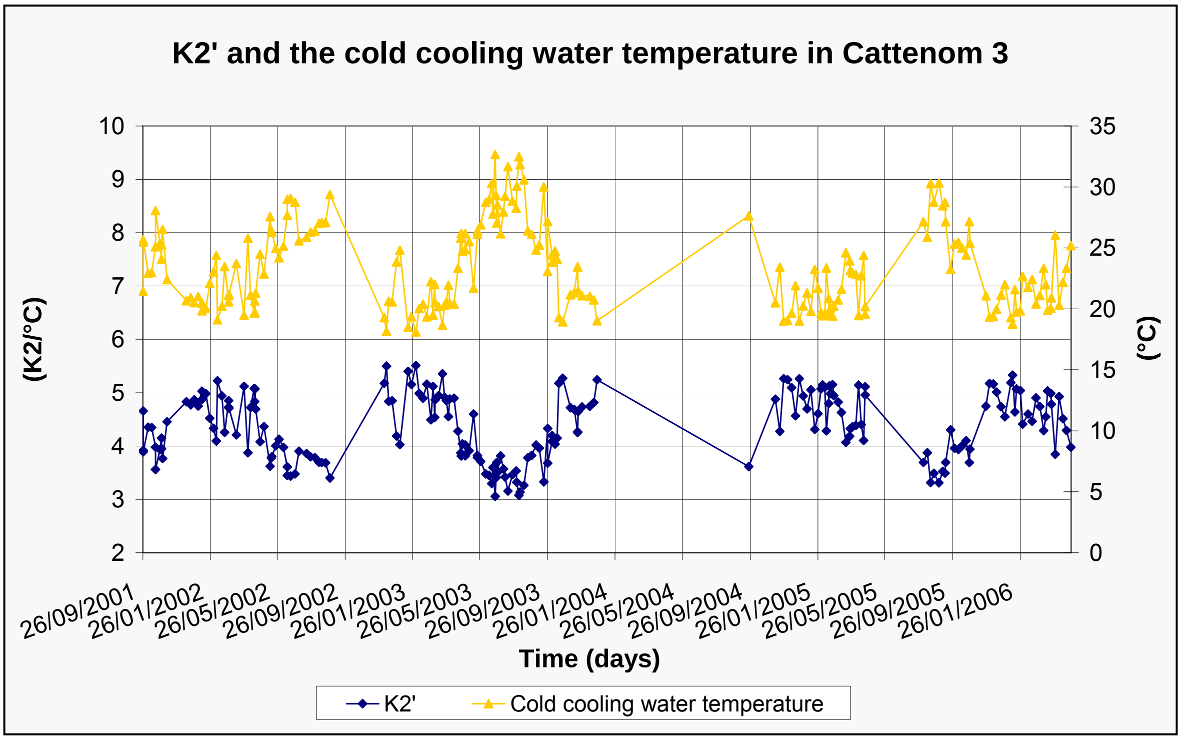
Thus, the performance of K_2' together with the cold cooling water temperature are showed at next in both units:



The first remark is that K_2' keeps up depending on the temperature. It has now an inverse proportion to the temperature. That means that the previous approximations must not be sufficiently precise, because the division of K_2 by the temperature has resulted a little excessive. Exaxtly, K_2 must be:

$$K_2 \approx k \cdot T_{CCW}{}^{\alpha}$$, where 0<α<1

$$K_2' = \frac{K_2}{T_{CCW}{}^{\alpha}}$$

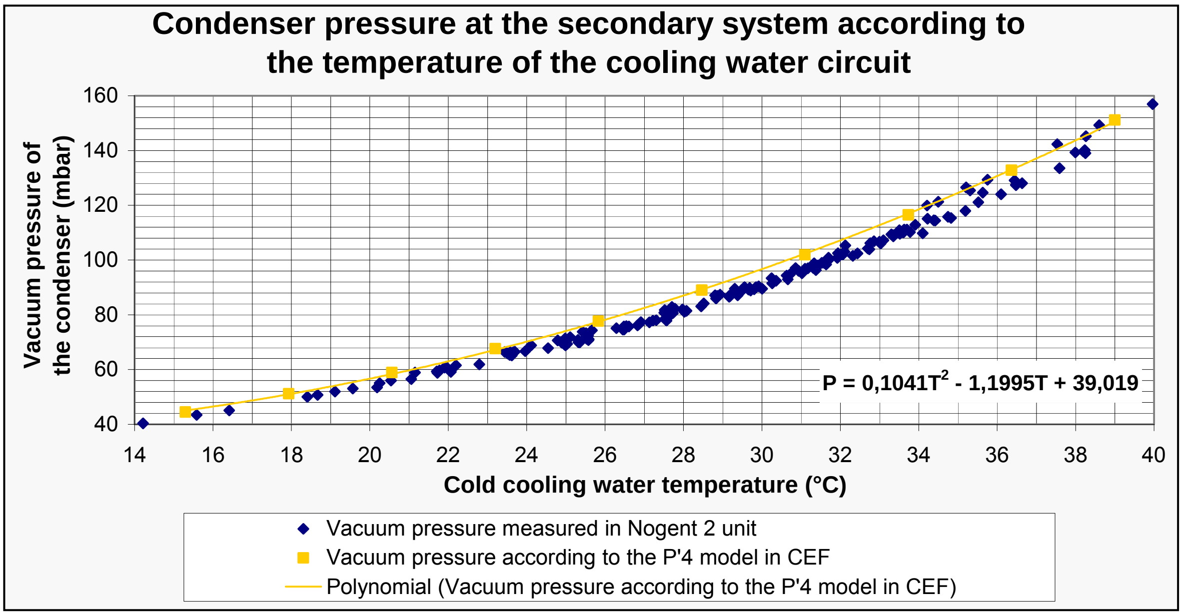


Like in Nogent, both parameters are propotional to 1/T. K_2' in Cattenom 3 does not have the abrupt change that was observable by K_2. On the other hand, it is in the case of Nogent where K_2' makes a great increase just before the incident. This increase is much more significant than before.

In conclusion, even if the corrected parameter of K_2 continues depending on the cold cooling water temperature, its results are closer to a possible indicator. It is important to continue to study it in order to accurate the value of α. The more precise will be α, the more reduced will result the effect of the cold cooling temperature.

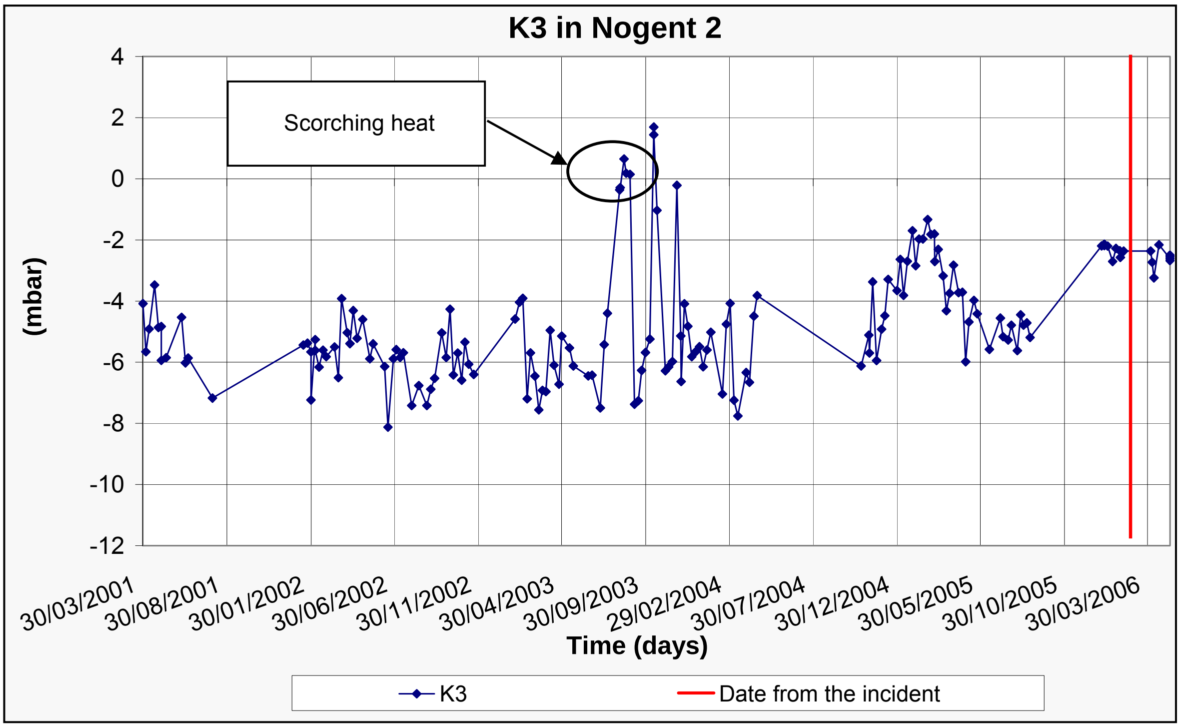
8.2.2. Follow-up of the K_3 parameter

As it has been described, the K_3 parameter indicates the difference between the expected and the measured pressure in the condenser (Equation 8.3). At first the following graphic of Nogent 2 has been designed. It shows the condenser pressure behaviour according to the cold cooling water temperature. The behaviour of the series P'4 has been taken from the heat balance model of the secondary system CITER, and the measured pressure has been taken from MOLENE.



According to this figure, the test data shows that Nogent 2 unit works at less vacuum pressure than the P’4 series model by the same temperature. That means that Nogent 2 has a better performance than it has been planed in the conception. At next, the polynomial equation of P’4 model has been used to make a theoretical approximation of Nogent 2 with its cold cooling water temperature values. K_3 results from the difference between the measured values and the calculated expected values from this equation:

$$P_{COND\ EXPECTED} = 0{,}104 \cdot (T_{CCW})^2 - 1{,}1995 \cdot T_{CCW} + 39{,}019$$



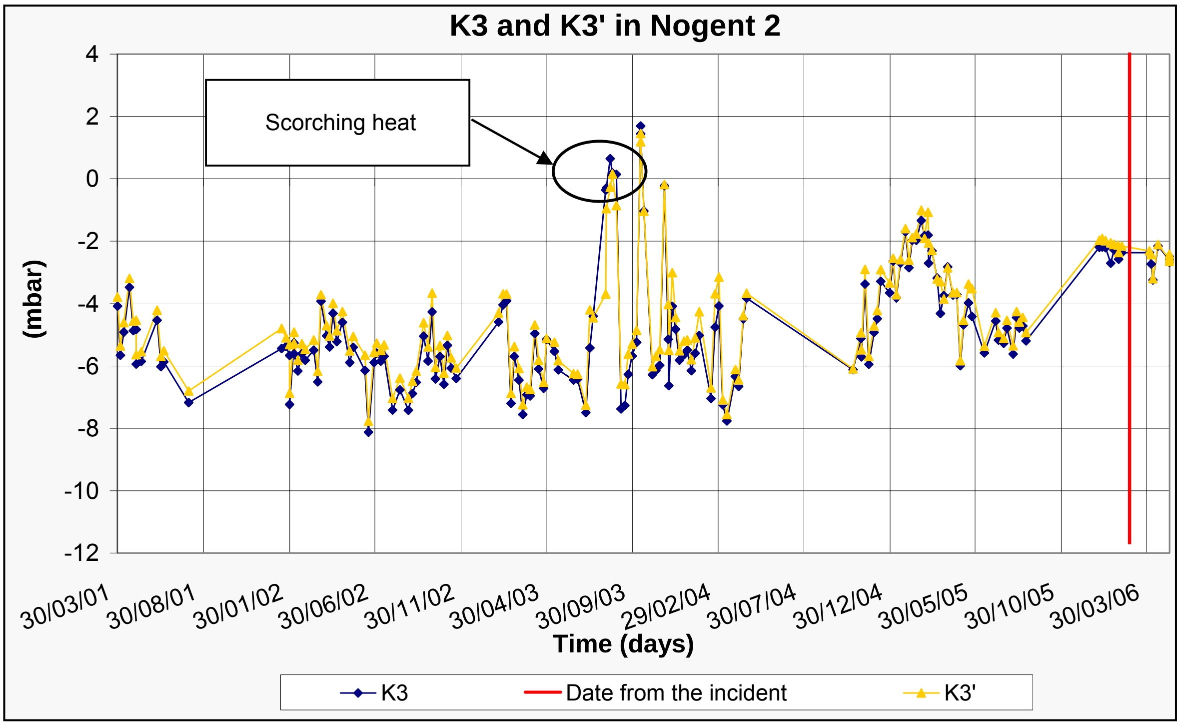
The previous graphic shows that effectively, the measured pressure is almost always smaller than the expected pressure in Nogent. Apart some detached tests, K_3 changes basically in three periods. The first period concords with the scorching heat in Summer 2003, where the measured pressure augments due to a worse performance of the cooling system. As it has been explained in the previous section, the scorching heat has induced the fouling of the condenser. Once this problem arrives, the condenser will never completely recover. It is necessary to clean up the condenser in order to reduce this degradation. The second period is between October 2004 and May 2005. In this timeframe there is an increase and a diminution. This must probably be another fouling relapse. The diminution indicates that the condenser has been cleaned. The third period arrives before the incident. Usually, after the periodic shutdown of the station (which coincides with the periods where tests are no made during approximately three months in order to clean up the circuit), like before the incident, K_3 should decrease. This is not the case, which means that anything is going worse than before. Nevertheless the parameters do not seem to change after the repairing of the cooling system, which seems to be a sign indicating that the increase is not due to the leakage. As the available data of Nogent 2 disposed in MOLENE are not yet actualised after May 2006, it is not possible to see a greater evolution of this parameter.

In the theoretical part it has been explained that in normal conditions, the flow of the cooling system remains constant and the pressure at the condenser will only depend on the cooling circuit temperature. The expected pressure values estimated with the theoretical model have been made considering a constant nominal flow (50 kg/s for Nogent 2). Nevertheless there are always little fluctuations of this flow (see appendix C.1), which has been commented in the previous section. At next K_3 has been corrected by considering this changes. K_3’ will add the pressure variation due to the circulation pump change to the previous expected pressure, therefore K_3’ results like:

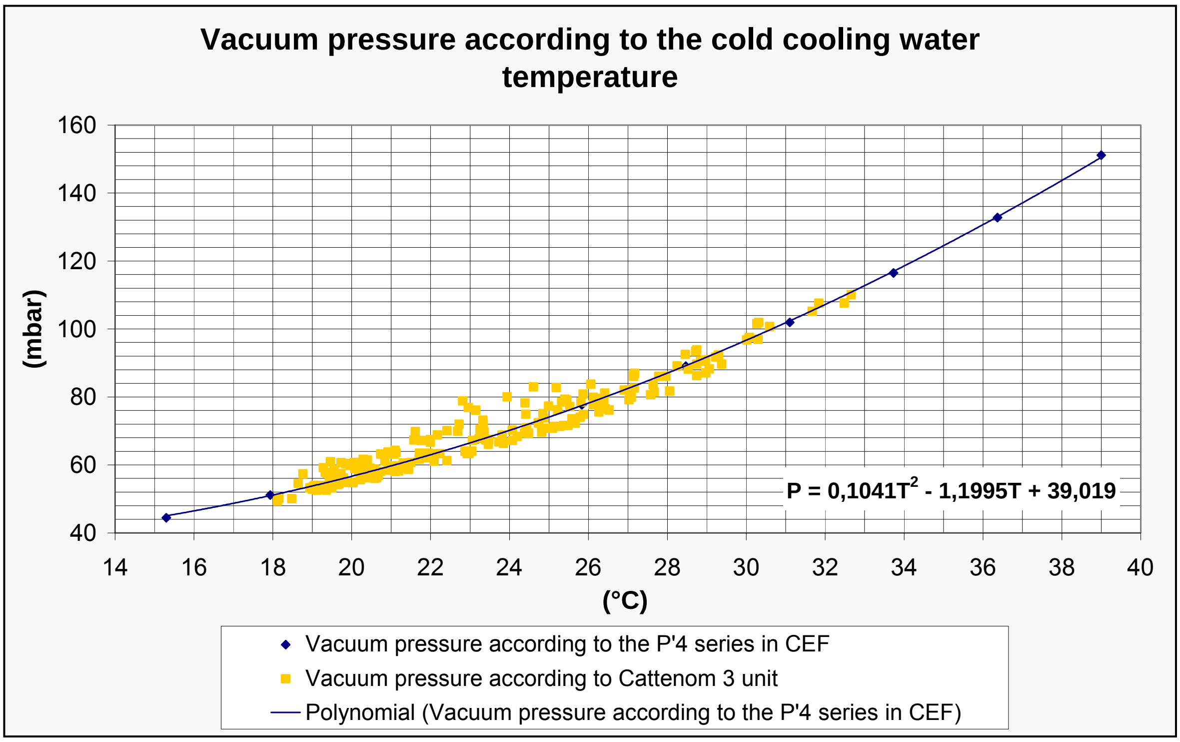
$$\boldsymbol{K}_3' = \boldsymbol{P}_{COND\ MEASURED} - (\boldsymbol{P}_{COND\ EXPECTED} + \Delta\boldsymbol{P}(\boldsymbol{Q}_{CP})) \quad (\boldsymbol{mbar})$$

$$\Delta\boldsymbol{P} = \boldsymbol{P}_{COND}(\boldsymbol{Q}_{CP\ MEASURED}, \boldsymbol{T}_{CCW\ NOM}) - \boldsymbol{P}_{COND}(\boldsymbol{Q}_{CP\ NOMINAL}, \boldsymbol{T}_{CCW\ NOM})$$

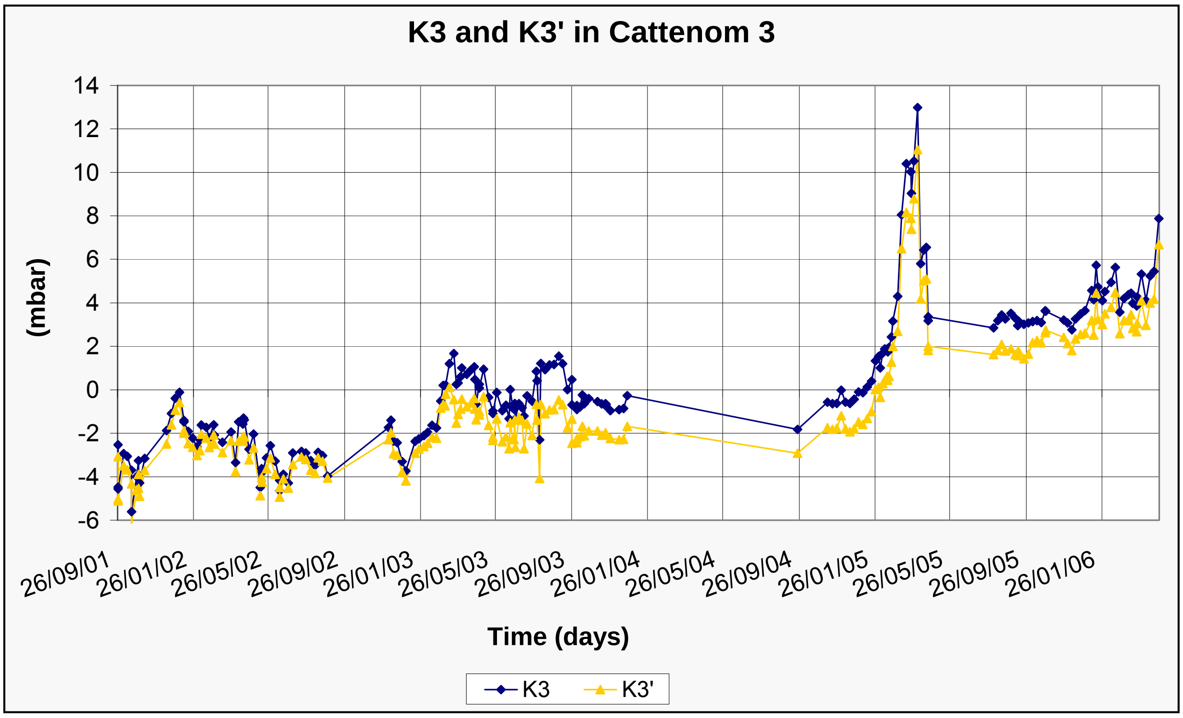
ΔP includes the pressure changes due to the variations in the circulation pump. The behaviour of the vacuum pressure according to the flow has been made with CITER and it is represented in appendix C.4. The resulting corrected graphic is showed at next:



Effectively the flow practically does not change the pressure values of the system, because of its very little fluctuation. Both parameters do not seem to be very significant for the leakage detection. At next the graphic with the condenser pressure according to the cold cooling temperature is represented for Cattenom 3:



In comparison to Nogent, this unit works at a smaller temperature gap and at pressure values over and under the theoretical value according to the P'4 model. The performance of K_3 (50,443 kg/s nominal flow in Cattenom 3) and K_3' is showed at next:

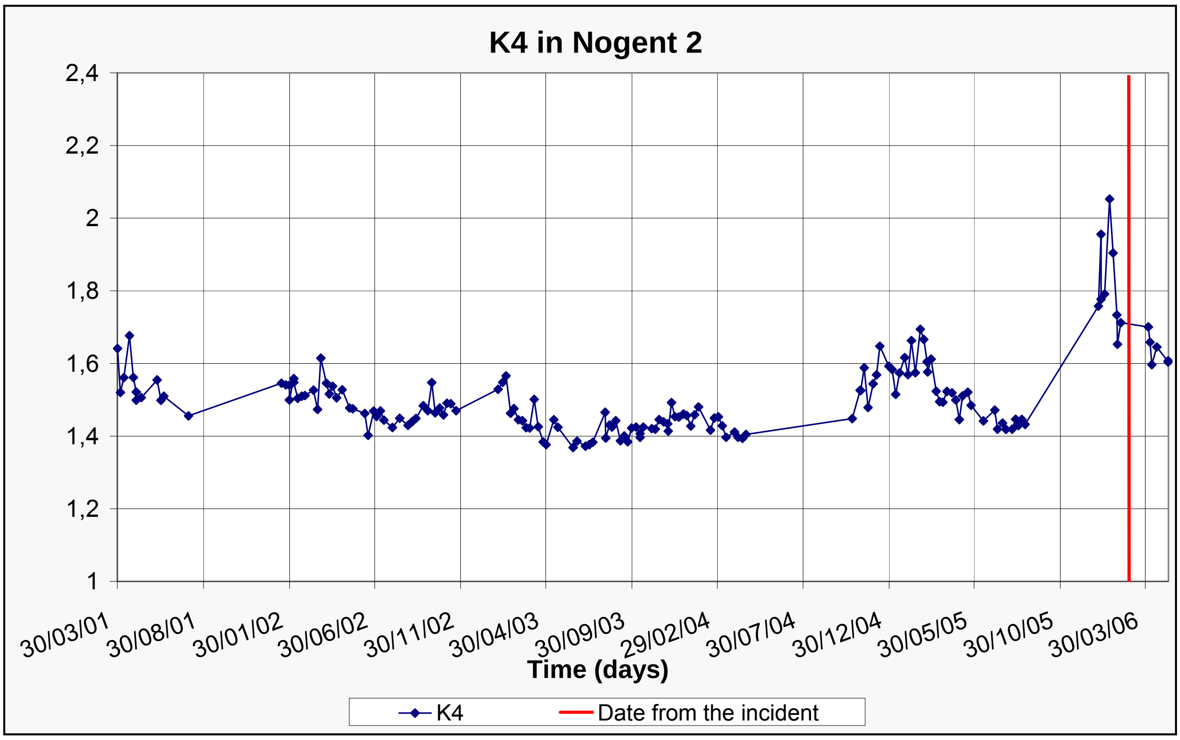


In Cattenom 3 the corrected K3 parameter differs more from its original value than in the case of Nogent, because its flow at the circulation pump is more irregular. Nevertheless, its behaviour remains the same. There is a period from January 2005 where the pressure difference increases significantly. According to the chapter 6, the pressure increase in a condenser can result from the condenser fouling or from an increase of the air intake level. The last time that EDF had controlled this unit, Cattenom had practically never had any problems concerning to the condenser fouling and the performance of the tertiary cooling system has been considered exemplar. This had been on 2004. Nevertheless up to 2004 the system has not been followed-up by the R&D.

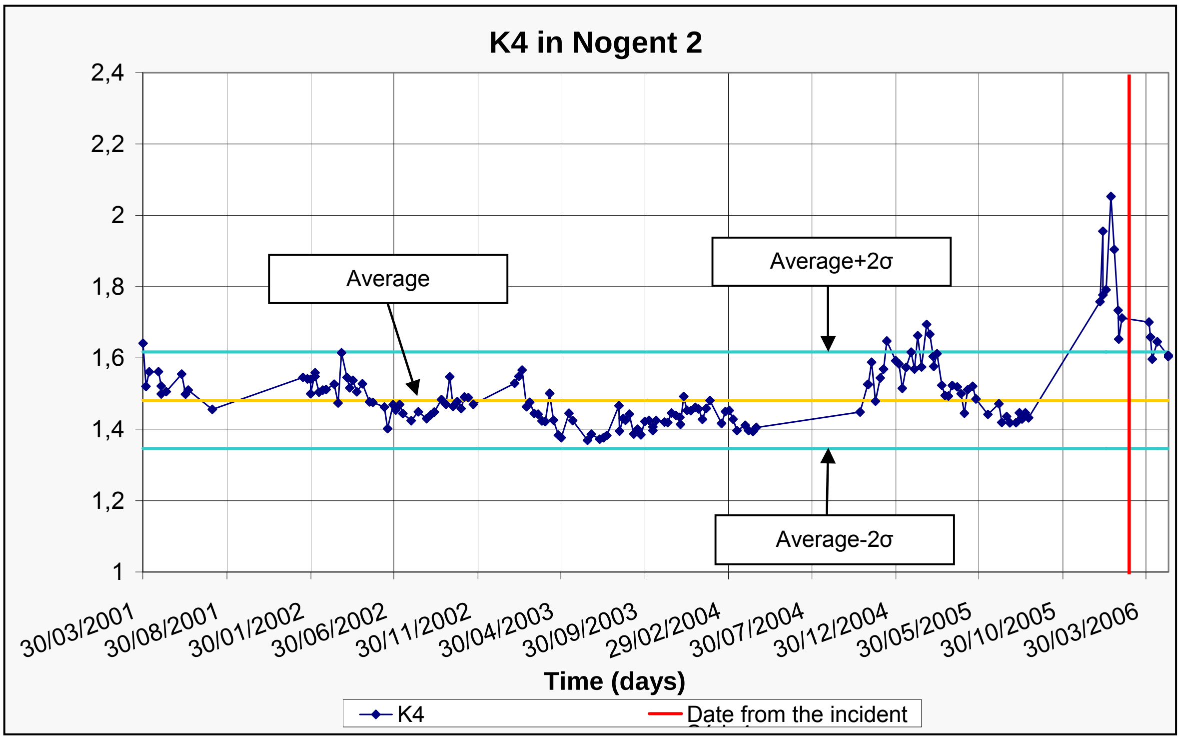
In conclusion, in both cases the difference between the measured and the expected pressure is most of all affected by the condenser issues, and basically by the condenser fouling. This factor seems to surmount the leakage degradation that existed in Nogent 2. Nevertheless, this parameter should be observed in order to know the evolution after the incident in Nogent.

8.2.3. Follow-up of the K_4 parameter

The K_4 parameter indicates the relation between the temperature at the condenser outlet and its inlet (equation 8.4). The resulting graphic in Nogent is the following:



Except the period before the incident, K4 remains within a constant gap. Until August 2005 an average value has been calculated with the respective standard deviation. The same graphic has been designed by adding the line with the average and the lines showing the gap of the average plus two times its standard deviation. The standard deviation measures the dispersion around the average.

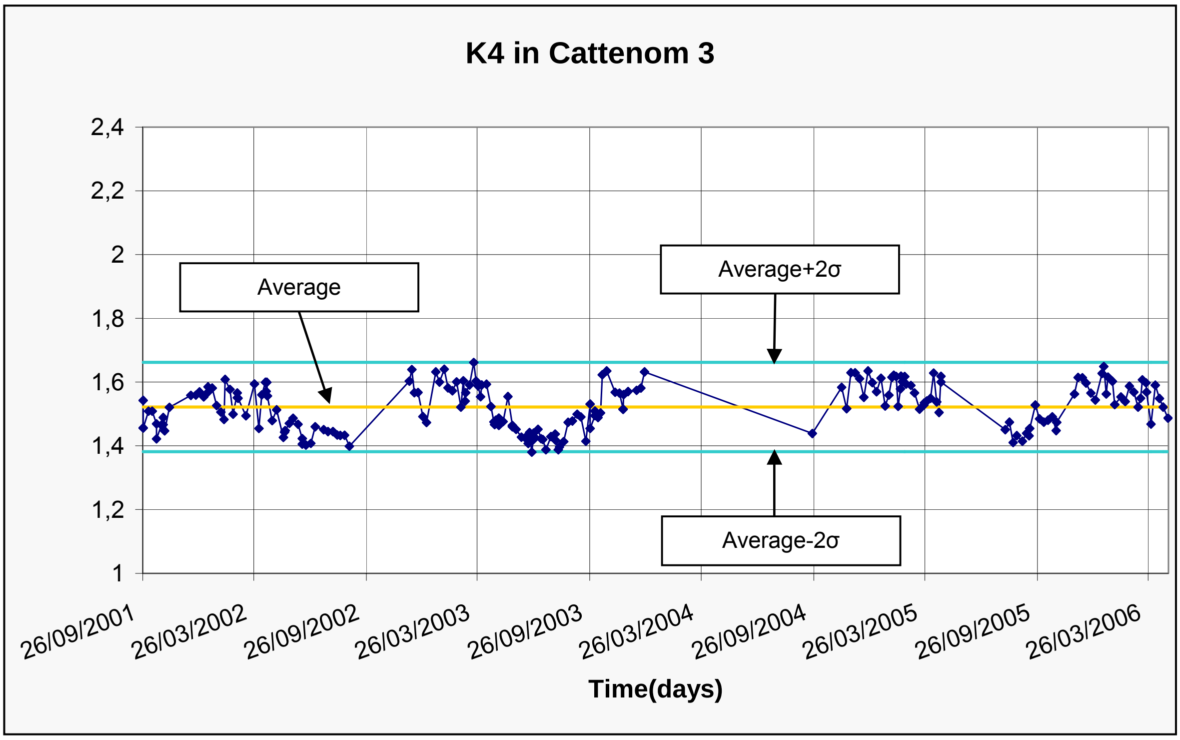


This gap contains practically all the data. The average value in Nogent 2 is 1,48 and its standard deviation is σ=0,068. The data out of this gap corresponds to some tests during the fouling of the period between the end of 2004 and the beginning of 2005 and up to January 2006. After the repairing of the BONNA pipe, K_4 returns into this interval.

For security measures, the cooling system has three limitations that influence K_4:

- The maximal flow that can be taken from the river and returned to it.
- The difference between the intake and the outlet cooling temperature in the cooling system.
- The outlet cooling temperature in the cooling system.

Due to these limitations, K_4 should maintain between a constant gap. For example it is remarkable to observe that the period of Summer 2003 does not show an abnormal value of this parameter. This is because this period of scorching heat was specially controlled in order to not exceed these limitations. The data between the end of 2004 and the beginning of 2005 exceeds a little bit. But most of all the data before the incident are very distant from the average value, what means that there is a control loss K_4.



The average value in Cattenom 3 is 1,522 and its standard deviation is σ=0,07. None of the test data in the timeframe between 2001 and May 2006 exceed the defined interval. This parameter seems to be controlled by Cattenom 3. Also the period up to January 2005, which causes an abrupt change in parameters K_2 and K_3, maintains the values of K_4 near the average.

In conclusion, K_4 has an especially great value on the tests just before the incident. Therefore its performance can be very significant for detecting possible leakages in BONNA pipes of the P'e series.

8.3. Conclusions and propositions

Between the three observed parameters for this second study, the one that at present can be the most significant is K_4. Its values does not change very much in Cattenom 3, and only before the incident of Nogent a great increase can be detected.

K_2 could also be a good indicator, but it is necessary to accurate its relation with the cold cooling temperature. Therefore, it is commendable to continue its follow-up.

At last, K_3 gives a great information about the issues on the condenser that surpass the effects on a possible leakage. Therefore it is not as significant for detecting this kind of incident. However it is commendable to follow-up the case of Nogent in order to see a more actualised evolution. But even if it is not significant for this case, it is a very useful parameter for following the condenser performance.

Conclusions

The main objectif of this project has been to study the feasibility of the thermodynamic follow-up of some components belonging to the water-steam sytem and to the tertiary cooling system. It has permitted to identify some parameters that could help to prevent the apparition of the blade-erosion on the high-pressure turbines of the french nuclear stations and the rupture of the BONNA pipes of the P'4 units. Nevertheless the proposed indicators of the first study could not find any trails of "joint face" erosion neither in Chinon nor in Saint Alban stations, because this phenomena must not be enough important to be detected by the existing thermodynamic data.

Among the six proposed parameters in the first study, four could be used by the CEF software. Between them, the Stodola number and the pressure ratio characterize at best the blade erosion of Cruas. Moreover, the turbine drop efficiency could not be calculated because of a lack of instrumentation. It is proposed to add a sensor in the high-pressure turbine outlet indicating the moisture of the exhaust steam in order to know this efficiency. This parameter would be interesting for the whole performance of the turbine.

The second study on Nogent has permitted to test three parameters among the four proposed initially. The relation between the temperature in the inlet and the outlet of the condenser (K_4) seems to be very significant for indicating a leakage. This relation is controlled for security measures, but it only makes an abrubt change before the date of the incident. Another very interesting indicator for preventing this event could be K_2', which is the balance between the flow at the circulation pump and the condenser flow corrected from the effect of the cold cooling temperature. K_3, showing the difference between the measured and the expected temperature, is less convincing because other issues like the condenser fouling have a greater influence on it.

Therefore, the previous studies must be still investigated in order to confirm the validity of the succesful parameters. It is recommended to engage an engineer to continue with the monitoring and the analyse of its behaviour.

Agradecimientos

En primer lugar, quisiera agradecer especialmente el optimismo, la confianza y la ayuda aportados por el director de este proyecto a lo largo de todo este periodo, François Gachon. Quisiera agradecer igualmente a mi ponente Francesc Reventós, por el apoyo que me ha ofrecido desde el primer momento, y sin el cual no podría haber efectuado este proyecto en el extranjero.

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Evidentemente infinitas gracias a todas aquellas personas que me han acompañado durante estos seis últimos años de carrera, tanto en Barcelona como en Francia, y que de una manera u otra han contribuido a la realización de este proyecto.

Y por último, me gustaría dedicar este proyecto a toda mi familia. Y en especial a mis padres, a mi hermano Oliver y a mi abuela, por su dedicación y su apoyo que han demostrado a lo largo de toda mi vida.

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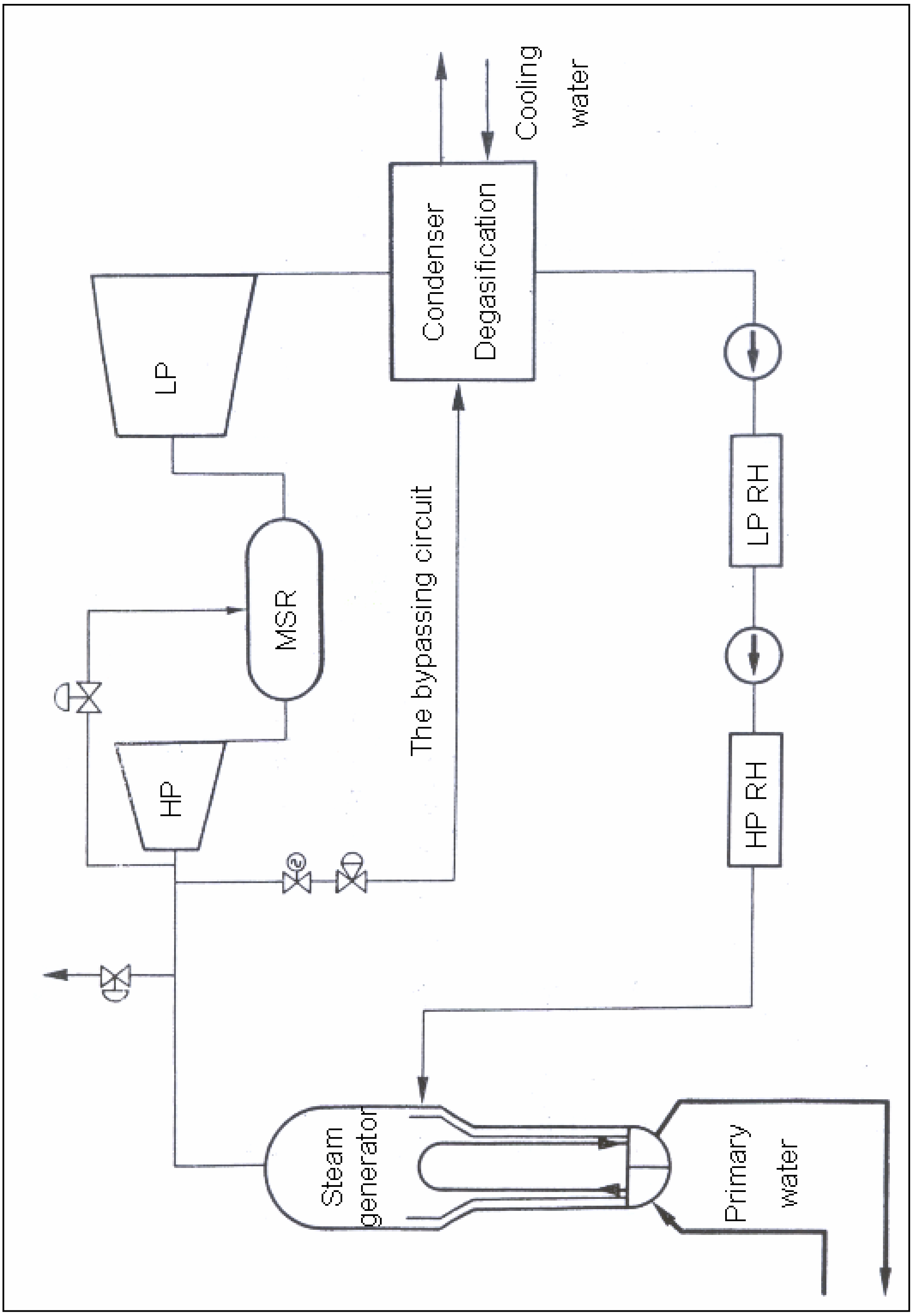
Appendixes

A. Distribution of the different components in the secondary system



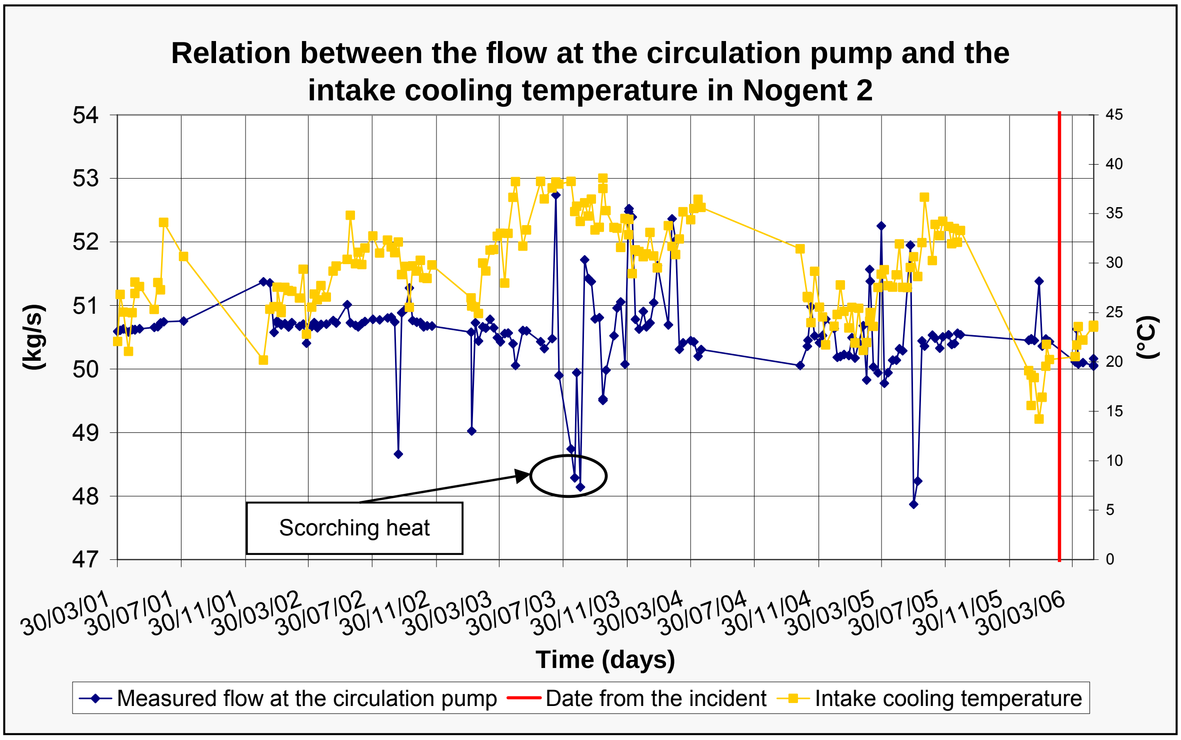
B. The main series characteristics

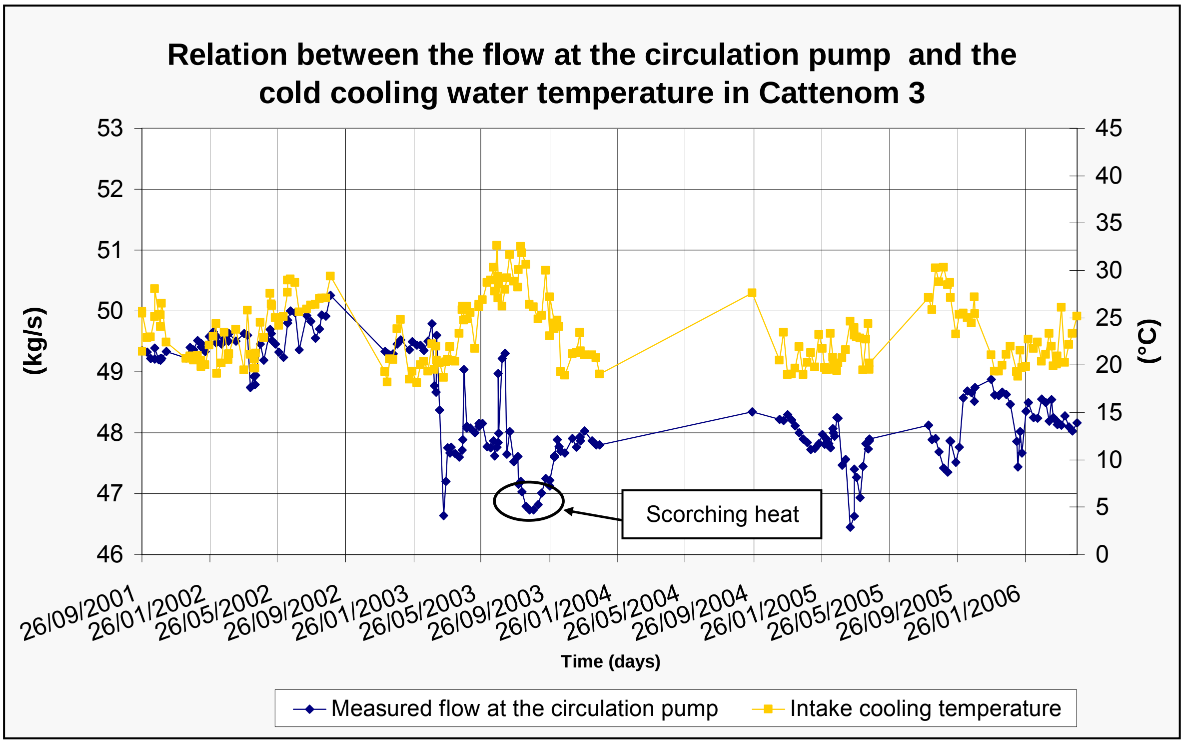
Series type	Central stations	Turbine power (MW)	Number of Steam generators	Turbine body	Reheating			Feed tank	Number of moisture separator reheater	Number of steam extractions
					HP	MP	LP			
CP0	Fessenheim	900	3	1HP+ 3LP	2*(R5+R6)	-	2*(RP+ 3*1/2R1+ R2+ R3+ R4)	No feed tank	4	6
CP1	Tricastin Gravelines Dampierre Le Blayais	900	3	1HP+ 3LP	2*(R5+R6)	-	2*(RP+ 3*1/2R1+ R2+ R3+ R4)	No feed tank	4	6
CPX	Bugey	900	3	1HP+ 3LP	2*(R5+R6)	-	2*(RP+ 3*1/2R1+ R2+ R3+ R4)	No feed tank	4	6
CP2	Saint-Laurent Chinon Cruas	900	3	1HP+ 2LP	2*R5+4*RCS	-	2*(R1+ RC2/RC3+ R2+ R3)	Feed tank	4	5
P4	Paluel	1300	4	1HP+ 3LP	2*(R5+R6) +4*RCS	-	3*(R1+ RC2/RC3+ R3)	Feed tank + degasser	2	6
H4	Saint-Alban Flamanville	1300	4	1HP+ 3LP	2*(R5+R6)	-	2*(R1+R2+R3)	Feed tank + degasser	2	6
P'4	Cattenom Belleville Nogent Penly Golfech	1300	4	1HP+ 3LP	2*(R5+R6)	-	2*(R1+R2+R3)	Feed tank + degasser	2	6
N4	Chooz Civaux	1450	4	1HP+1MP +3LP double flux	2*(R5+R6)	2R3	3*(R1+R2)	Feed tank + degasser	2 with 2 reheat stages	6

C. Accident of Nogent

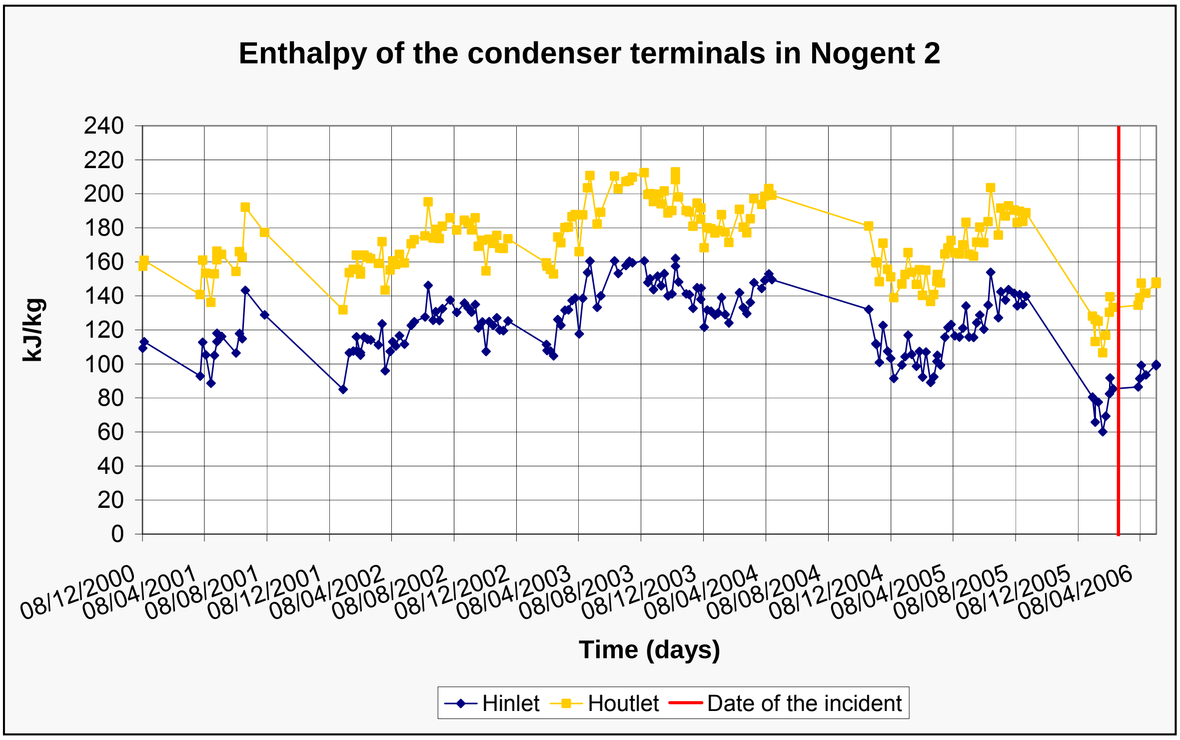
At next there are two pictures showing the consequences of the accident. The first picture shows the inundation at the turbine hall. The second one shows the rupture of the concrete slab in Nogent 2, which has been affected the most (the slab of 90m^2 has been raised up to approximately 80cm).

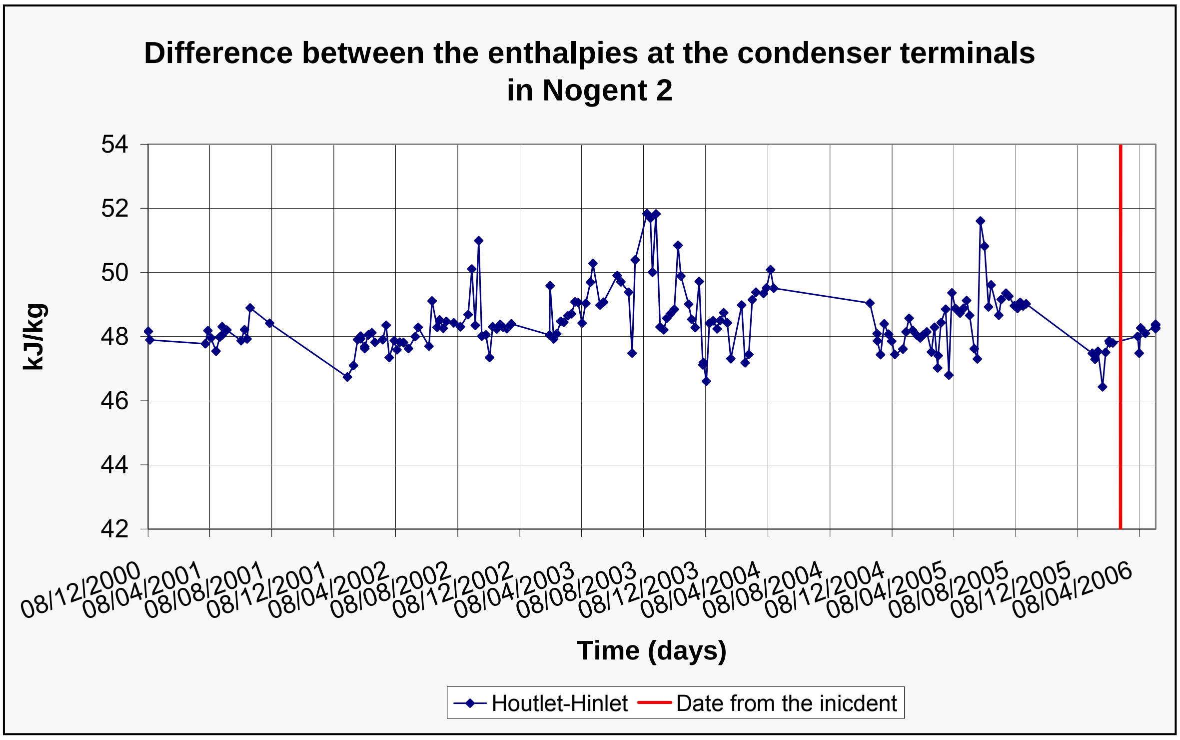
C.1. Relation between the flow at the circulation pump and the cold cooling water temperature

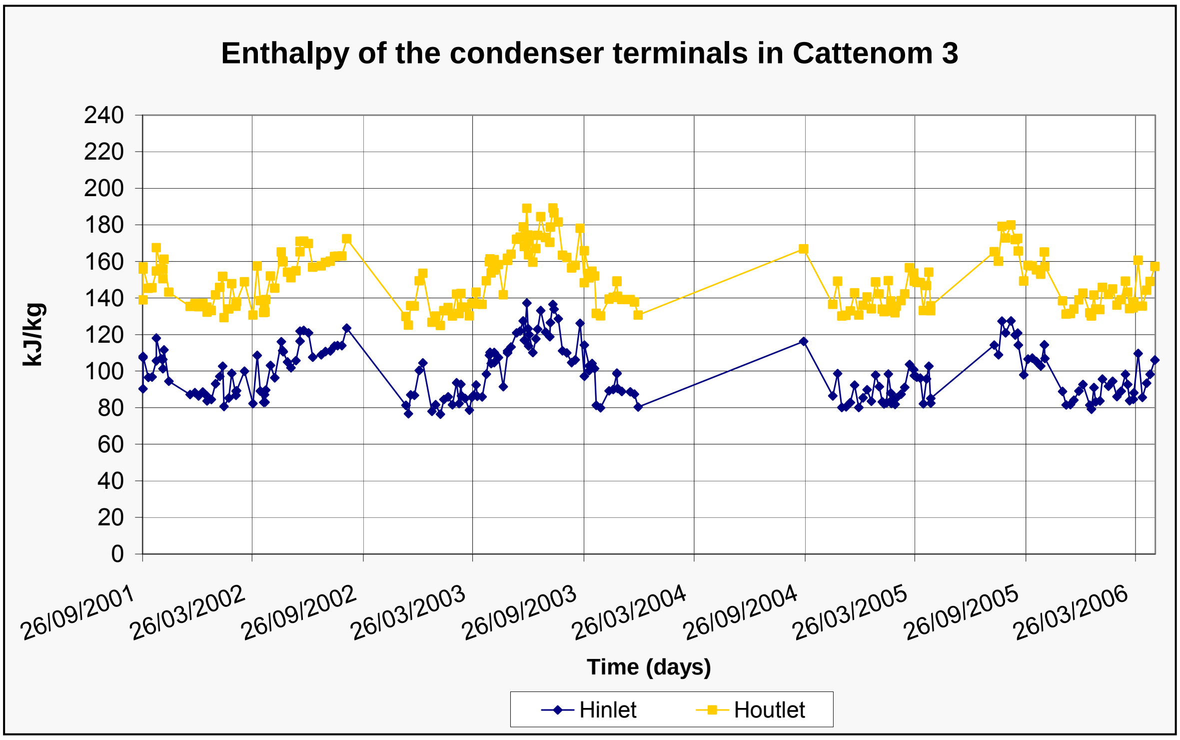


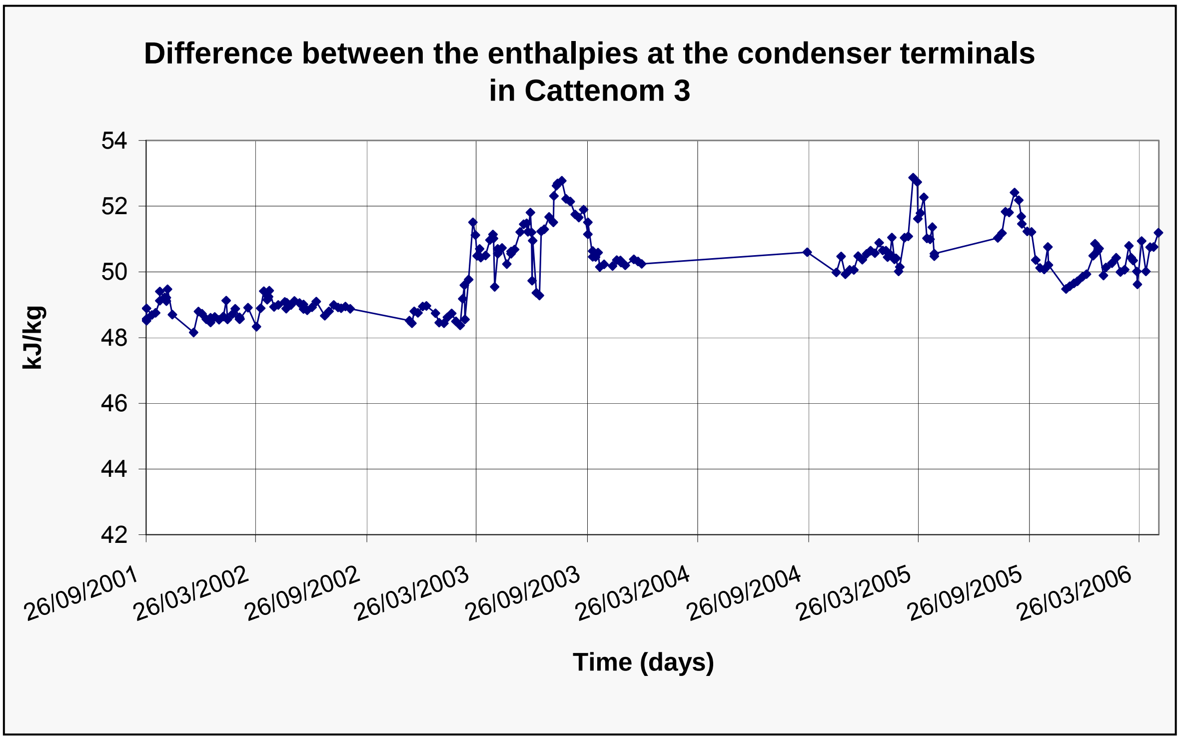


C.2. Performance of the enthalpies at the inlet and the outlet of the condenser

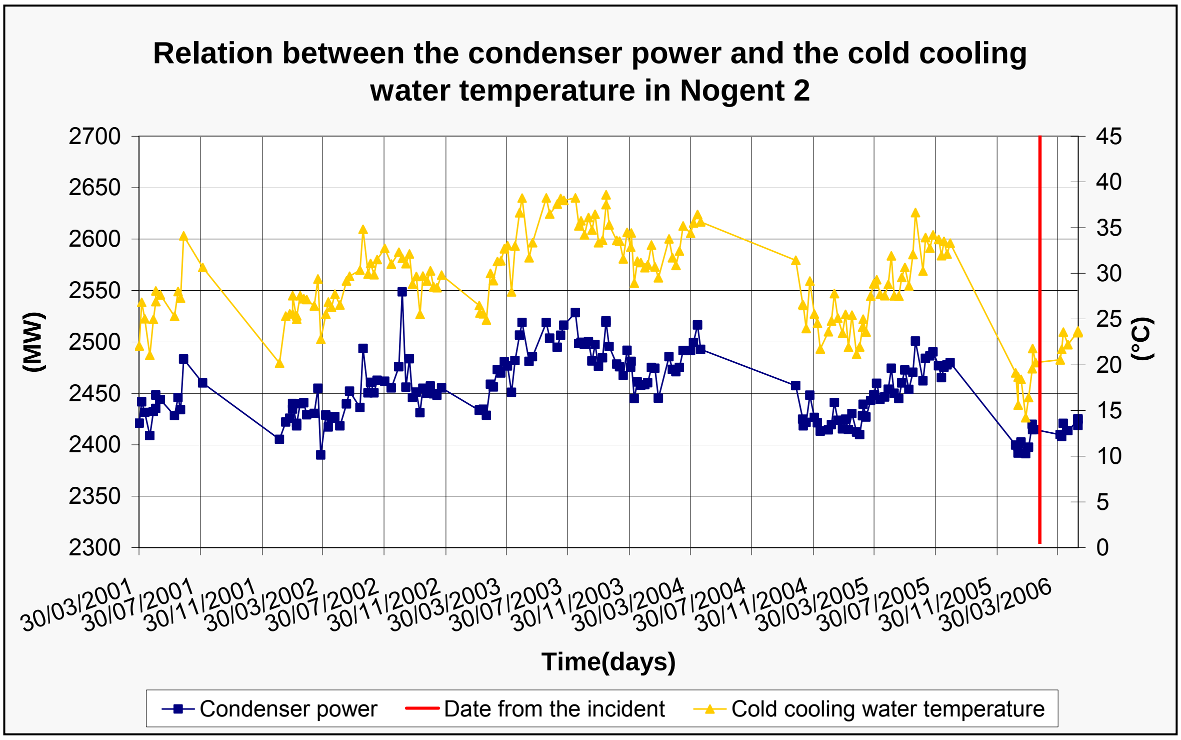


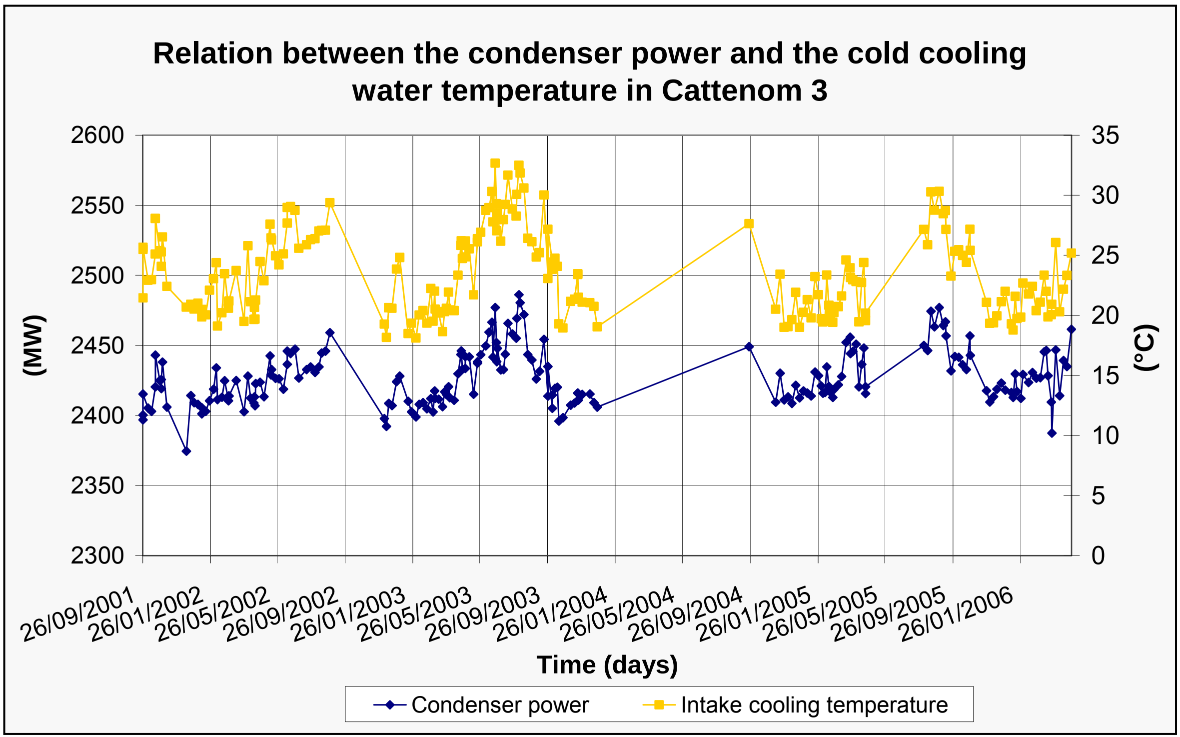



Enthalpy of the condenser terminals in Cattenom 3
kJ/kg
240
220
200
180
160
140
120
100
80
60
40
20
0
26/09/2001
26/03/2002
26/09/2002
26/03/2003
26/09/2003
26/03/2004
26/09/2004
26/03/2005
26/09/2005
26/03/2006
Time (days)
Hinlet
Houtlet

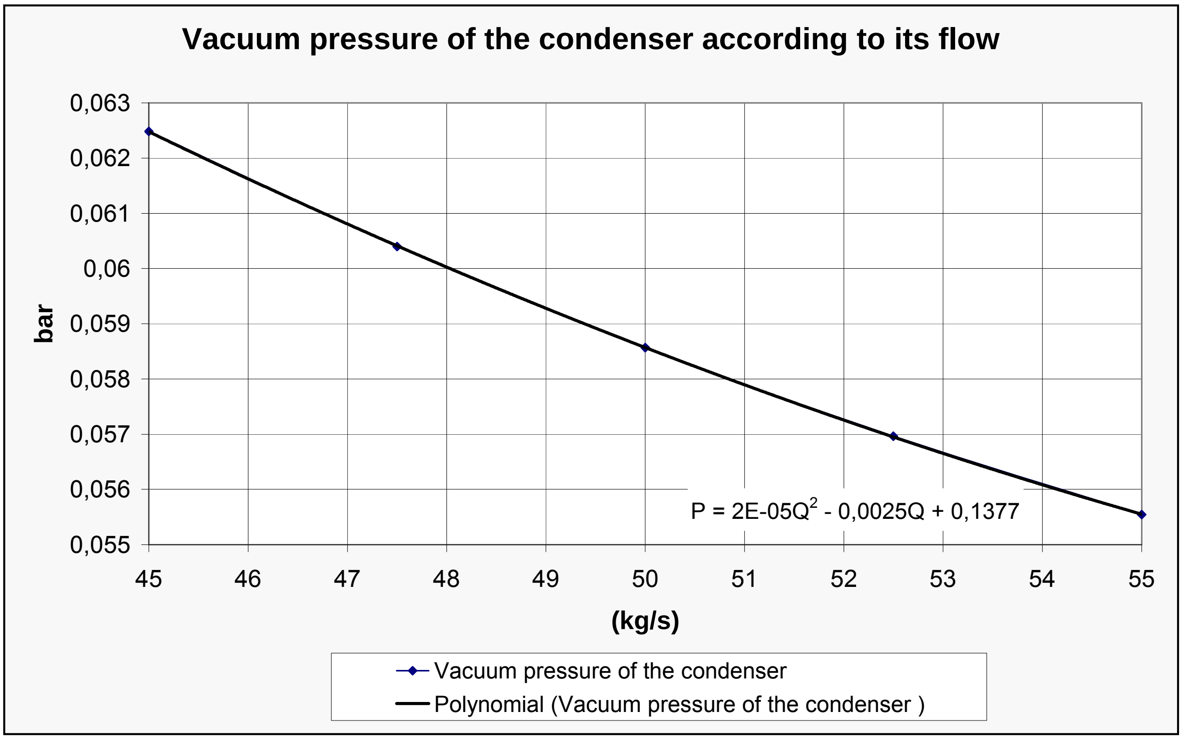

Difference between the enthalpies at the condenser terminals in Cattenom 3
kJ/kg
54
52
50
48
46
44
42
26/09/2001
26/03/2002
26/09/2002
26/03/2003
26/09/2003
26/03/2004
26/09/2004
26/03/2005
26/09/2005
26/03/2006
Time (days)

C.3. Relation between the condenser power and the cold cooling water temperature





C.4. Vacuum pressure according to the flow of the tertiary system in a P'4 series



D. Cost

In this chapter a study of the economical cost is carried out. Two resources for EDF have been used, which are the material and the human ones. Both costs are approximate and have been consulted in EDF.

D.1. Human sources

An engineer must be engaged to follow-up the parameters that are significant for the previous studies. EDF pays 100 000 euros at year for an engineer. This cost includes the salary of the engineer and all that the engineer is supposed to consume (like for example its office, the heating, air-conditioner…). This engineer will be able to follow-up the parameters for the both study cases.

D.2. Material sources

For the erosion case, it would be necessary to add a sensor in the turbine outlet in order to calculate the turbine drop efficiency. The sensor and its installation cost 3000 euros. Therefore, if this sensor must be installed in all the French nuclear units, the prize will be the following:

3000 euros for the sensor x 58 reactors= 174 000 Euros

As the life expectancy of all the units is of 24 years, the cost of this sensor at year will be:

$$\frac{174000\,\boldsymbol{Euros}}{24\,\boldsymbol{years}} = 7250\boldsymbol{Euros}\,/\,\boldsymbol{year}$$

Finally, the global cost of both sources is of 107 250 Euros/year.