# Innovative Instrumentation for VVERs based on non-invasive techniques

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## Abstract :

Nuclear power plants, such as VVERs, can greatly benefit from innovative instrumentation to improve plant safety and efficiency.

In recent years innovative instrumentation has been developed for PWRs with the aim of providing additional measurements of physical parameters on the primary and secondary circuits : the addition of new instrumentation is made possible by using non-invasive techniques, such as ultrasonics and radiation detection. These innovations can be adapted for upgrading VVERs presently in operation and also in future VVERs.

The following innovative instrumentations for control, monitoring or testing purposes in VVERs are presented :

*1- Instrumentation for more accurate primary side direct measurements, for better monitoring of the primary circuit :*

*DECOR : a primary feedwater flowmeter based on cross-correlation of Nitrogen-16 time fluctuations (a much more accurate method than the method based on N-16 decay measurement), using detectors placed outside of the pipe thermal insulation ; high accuracy is independent of reactor power (measurement available from 10% to 100% of max power output) and of feedwater flow ;

*TEMPUS : a primary temperature measurement tool using ultrasonics, allowing for better temperature averaging than classical temperature sensors, and providing a fast response time ;

*WALLACE : a primary water level monitoring channel, fully non intrusive, based on ultrasonics, and providing a fast response time and very accurate measurement of level during an outage or for periodic test purposes ;

*2- Instrumentation to monitor radioactive leaks, for a safer plant :*

*VAMCIS : non-intrusive, fast response time monitoring channel of eventual primary to secondary leaks in the steam generator, by continuous monitoring of gamma ray emission of Nitrogen-16 in in the secondary side steam ;
*LEAK DETECTION ON VARIOUS COMPONENTS : a wide range of leak detection methods (used for valves, condenser, reheater, boiler, nuclear reactor, steam generator, pit, containment, piping.) was developed, based on various techniques (acoustics, acoustic emission, temperature and flow measurement, decrease in pressure, chemical and radioactive tracers,...).

*3-Instrumentation-related systems to improve plant productivity, for a cheaper kWh:*

*CLIP : on-line permanent thermodynamic performance monitoring on the secondary side to provide plant operators with help in detecting faulty instrumentation and wrong settings in plant components (position of valves, ...). CLIP helps to recover MWe.

* IMPROVING FLOWMETERING : improving flowmetering instrumentation is a key factor to significantly improve power output accuracy, ou exchanger performance, etc. An innovative approach combining modelling, technological mastery of industrial measurement systems, and experimental methods for validation.

* **Reliability Centered Maintenance (RCM) :** RCM is a method for optimizing maintenance costs, focusing on maintenance programs of most critical components for plant safety and availability.

## *1- Instrumentation for more accurate primary side direct measurements, for better monitoring of the primary circuit :*

### 1.1 DECOR : NITROGEN 16 MEASUREMENT OF PRIMARY FLOW RATE

**a) Goal and measurement principle**

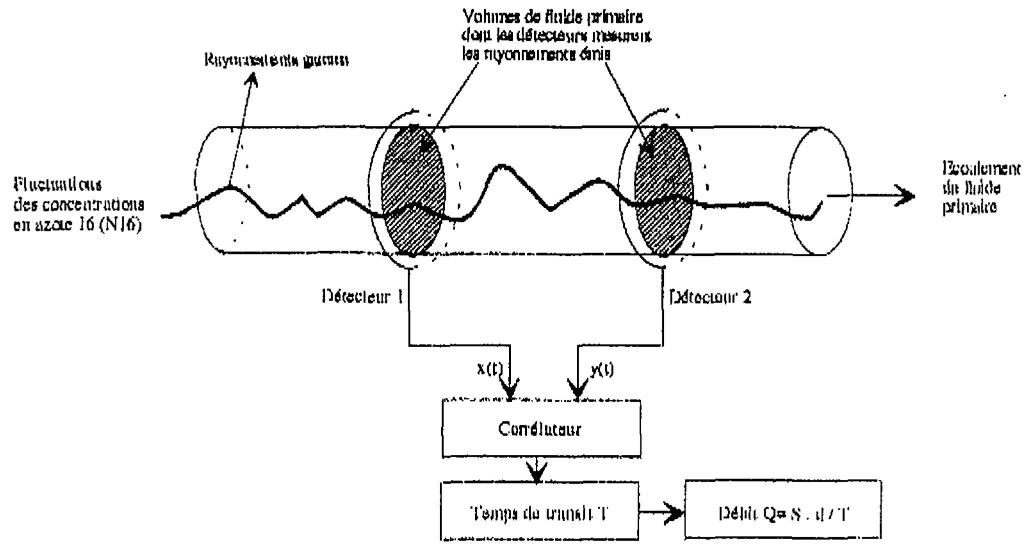


**Figure 1 : measurement principle**

The principle is to use nitrogen 16 which is conveyed by the primary coolant, at the same velocity. The nitrogen 16 fluctuations in time are measured to determine a transit time between two measurement sections, by means of cross-correlation (Figure 1).

**b) Innovative aspects**

The detectors used are circular radiation detectors mounted on a frame (collimator) around the reactor coolant pipe (Figure 2). The advantage is that the circular detector has minimum sensitivity to the velocity profile and to any deformation of this profile in time or in space : a theoretical study has shown that the discrepancy between the velocity measurement using circular detectors and the real velocity is on the order of 0.1% for profiles with a linear unbalance, whereas it can reach 4% for one quasi-point detector and 1% for a pair of diametrically opposite quasi-point detectors. Furthermore, the number of interactions in a circular detector is around 10 times higher than in a point detector. This greater number of events per second proportionally reduces the detection noise and enables improved measurement precision for a given response time.

The correlation method which was chosen following an optimization study is another innovative aspect (Figure 3).

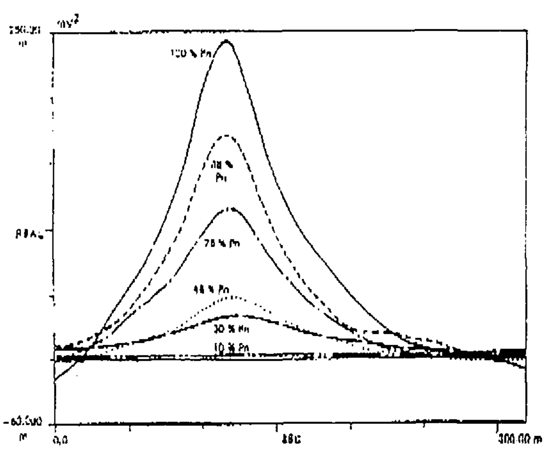

**Figure 2 : cross-correlation**

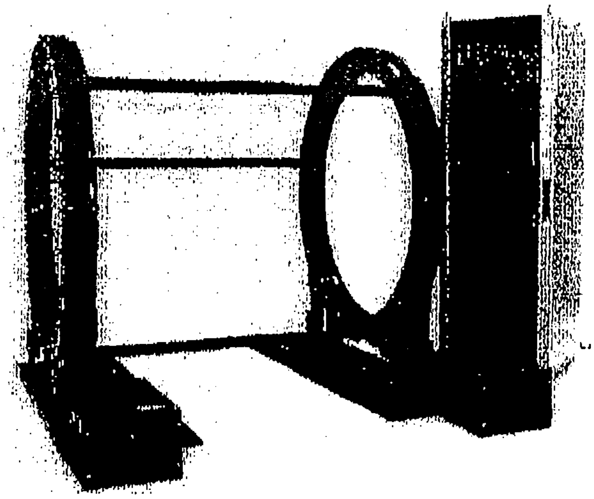

**Figure 3 : circular radiation detectors and data processing unit**

**c) Specific benefits - gains**

In both its principle and its application, **the method is absolute** in nature, since flow rate is calculated from a volume and a transit time.

In addition, it is a **totally non-invasive** method, given that the detectors are placed outside the primary coolant pipe

Accuracy is ± 1.5% for the flow rate in each loop at nominal reactor power, and does not deteriorate markedly up to 10% of nominal power. Laboratory acceptance tests, basqed on actual plant data have shown significant gains in accuracy (statistical uncertainty, resulting from the number of cross-correlations processed).
Finally, specifications and final development of the measurement system are based on the "smart sensor" concept, which makes it possible to integrate **validation and quality indicators in real time,** facilitating configuration of the measurement system and communication with its computer environment.

**d) Feedback**
This method was implemented with success at the Gravelines, Dampierre and Chinon plants in the Eighties. The successive tests enabled validating the technological choices (detectors, instrumentation), the signal processing (cross-correlation, filtering) and the representativeness of the measurements (effect of the velocity profiles).
The flow rate measurement method is now being applied at Chooz (N4). Significant developments in the technology, instrumentation, and signal processing techniques have made it possible to implement a far more efficient measurement system which, in addition, is largely based on standard off-the-shelf products.

## 1.2 TEMPUS : ULTRASOUND MEASUREMENT OF PRIMARY COOLANT TEMPERATURE

**a) Measurement principle**

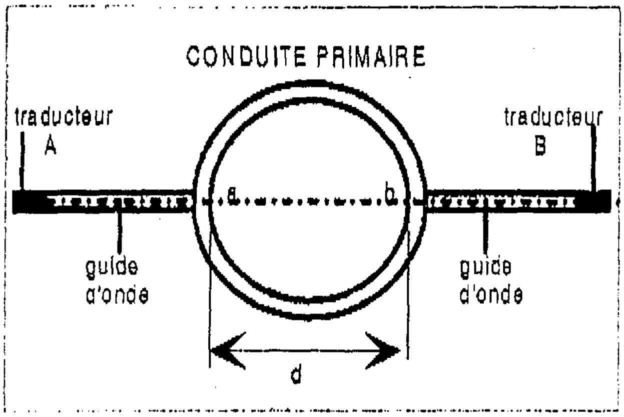


**Figure 4 : Measurement principle**

A beam of ultrasonic waves at 1 to 2 MHz is emitted by transducer A, through the metal of a pipe and the fluid it contains, then received by a similar transducer B, diametrically opposite (Figure 4) Measurement of the propagation time $t_{ab}$ of the wave in the liquid enables calculation of the velocity of sound, or $c = d/t_{ab}$. The existence and calibration of the relation c=f(T,P) enables determination of the temperature, given measurements of P and c.

**b) Innovative aspects**

- Determination of the relation between c, T and P : measurement surveys (500 triplets) have been conducted with various boron concentrations (0, 600, 2000 ppm) and in the following thermodynamic range: 100 °C < T < 330 °C and 80 bars < P < 160 bars. Following an optimization study, the relation c = f(T,P) was represented in the form of a 15-term 4th-order polynomial for variables T and P (Figure 5). This optimization provides accuracy of ± 0.1 °C in representation of the polynomial under the thermohydraulic conditions of a PWR primary cooling system (250 °C-330 °C and 140-160 bars).
- Waveguides : the measurement technique requires the implantation, on each collimation line, of a pair of waveguides welded on the outer side of the pipe, using a procedure developed by FRAMATOME which was followed in building the Blayais 4 and Chooz B1 units. The design for a waveguide was fine-tuned by EDF and its industrial partners . It provides a guarantee of the integrity of the transducer and of its acoustic coupling by maintaining the set-up at a temperature below 80 °C under adverse operating conditions (temperature, radiation).

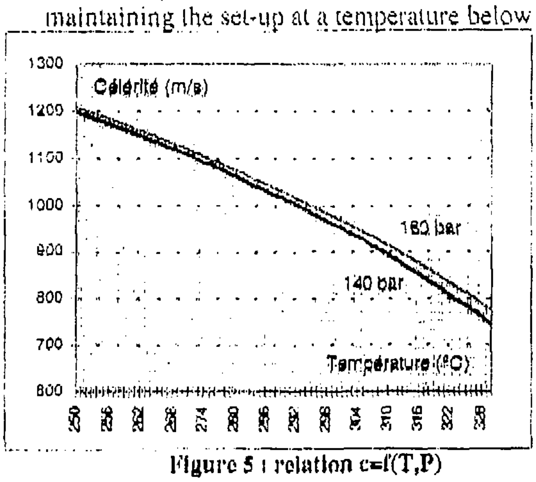


**Figure 5 : relation c=f(T,P)**

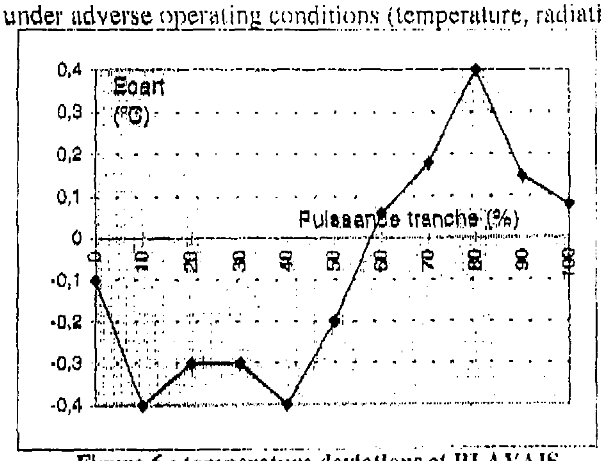


**Figure 6 : temperature deviations at BLAYAIS**

**c) Specific benefits - gains**

The principal benefits of the method are the following :

- non-invasive method,
- a principle by which a mean measurement is acquired over at least one diameter and not in one point,
- low response time.

**d) Feedback**

A feasibility study was undertaken in 1992 at the Blayais 4 PWR plant. The measurement principle was validated with the prototype equipment. Good results were obtained during the power increase from 0 to 100% : Figure 6 gives a comparison of the temperature measured by ultrasound in the hot leg with the operating temperature measured in the by-pass.

The results with respect to the metrological and technological aspects over a period of five years of operation indicate that the process can be used for test measurements.

Based on the results at Blayais, one of the primary coolant loops at Chooz B1 was equipped two acoustic collimation lines on each hot and cold leg. The results are very satisfactory and meet the expected performances.

## 1.3 WALLACE : WATER LEVEL BY ACOUSTIC COMPUTERIZED EQUIPEMENT

**a) Measurement principle**

An ultrasonic wave pulse is emitted and then received by a transducer which is in contact with the primary circuit pipe.

The travel time of the ultrasonic pulse allows the height of the water in the pipe to be accurately determined. The detection and processing of the composite signal resulting from multiple echoes within the pipe wall and from the surface of the water ensure a very reliable and accurate measurement of the water level in the pipe.

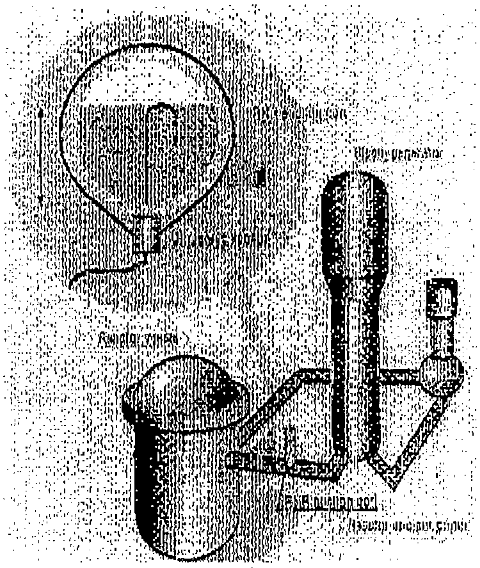

**Figure 7 : WALLACE**

**b) Innovative aspects**

Because of the specific electronic treatment, the measurements are insensitive to the following elements :

- perturbations of the surface of the water,
- boron-in-water concentration,
- turbulence due to the pump.

The transducers allows measurements form 5° to 80°C (41°F to 176°F) and they are suitable for all steel pipes (stainless steel : forged or cast).

**c) Specific benefits - gains**

- Ease of installation : the fast installation of the device reduces set-up costs and radiation dose.
- No modification of the primary pipe : the installation of the belt and the transducer support requires non preparation or intrusion into the pipe.
- Automatic calibration : after a user request, the device self calibrates automatically in seconds
- Alarm level monitoring : 3 alarm levels, user programmable by keypad.
- Precision : better than 1% at constant temperature and better than 3% for temperature changes from 10° to 70°C (50 to 158°F), including variations of the speed of sound in water.

**d) feedback**

The first tests were completed in 1993 in the CATTENOM 3 nuclear power station. The WALLACE device, as requested by EDF, is installed on every EDF 900, 1300 and 1450 MW PWR unit (56 systems).

## *2- instrumentation to monitor radioactive leaks , for a safer plant*

### 2.1 VAMCIS : A MEASURING CHANNEL TO MONITOR PRIMARY TO SECONDARY LEAK RATES INSIDE STEAM GENERATOR

**a) Measurement principle**

To monitor leaks od primary fluid to the secondary side, VAMCIS is a non-intrusive measuement system installed on the secondary side (steam pipes).

VAMCIS allows accurate and timely watch of leak development by providing :

- the transient values created by changing phenomena (every 100 seconds)
- the actual average value of the leak over time
- the average trend of the leak.

The detector is a scintillator including a built-in radioactive source and a temperature sensor. The detector set up requires no modification of the existing installation.

It is directly mounted facing the steam pipe heat insulation, outside the reactor containment.

The electronic box provides the spectral analysis ; and at least two adjustable energy windows are available. Self stabilisation of the energy spectrum is improved by taking into account the temperature drift of the reference peak.

the leak rates are continuously monitored. Two channel digital ratemeter readings can be displayed locally and in the reactor control room

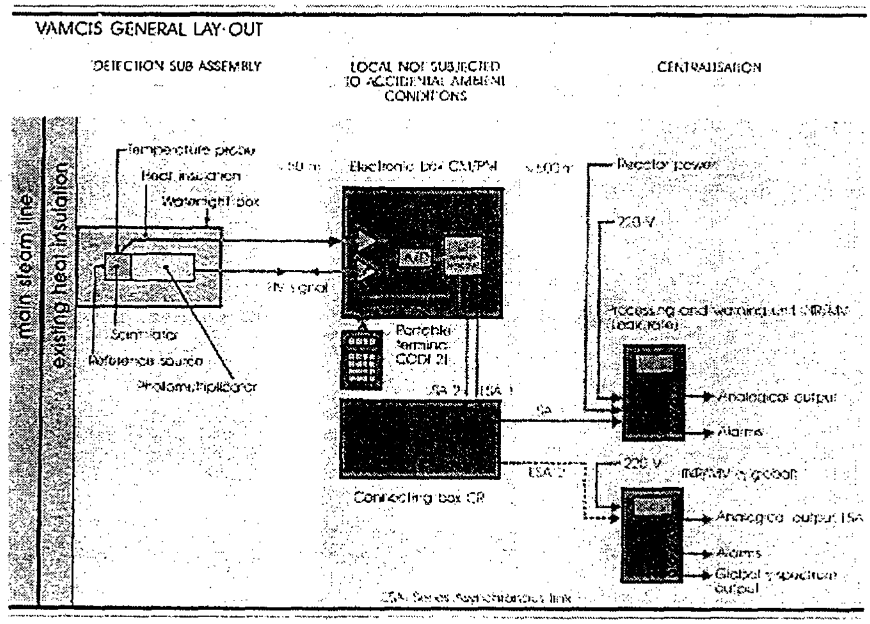


**Figure 8 : VAMCIS**

**b) Specific benefits - gains**

- Continuous monitoring of leak rate : VAMCIS allows continuous measurement of leaks from primary to secondary circuits in steam generators under all operational circumstances, whether the primary coolant contains fission products or not.
- High sensitivity : leak rates as low as 0.1 l/h can be easily and continuously monitored
- Fast response : an alarm level leak in a full powered reactor is measured within seconds
- Wide measuring range : leaks from 0.1 to 5,000 l/h can be measured
- Reliability : results are not affected by temperature variations at sensor location
- Detection of steam generator tube rupture : while the reactor is in operation, a sudden increase of the N16 activity triggers an alarm which indicates a tube rupture. Even though there are other methods to detect a catastrophic steam generator tube rupture, VAMCIS will provide automatically the information within seconds.
- VAMCIS operation is totally automatic and needs no attention or particular maintenance procedures

- VAMCIS can give information about the existence of leaks through plugged tubes by correlating N16 and gamma channel signals

c) **Feedback**
VAMCIS system has been successfully qualified for environment
All French PWR plants are equipped. In Belgium : Tihange 1 and 2, Almaraz and Asco in Spain and several US plants use the VAMCIS system for leak monitoring.

## 2.2 LEAK DECTECTION ON VARIOUS COMPONENTS

a) **Goal and principles**
Leaks are among the most common faults in industrial installations. They can affect a wide range of components: heat exchangers, valves, piping, boilers, tanks, pits, pneumatic and hydraulic circuits, containments, etc.
The existence of a leak may directly affect safety (e.g. leaks of dangerous products), efficiency (e.g. steam loss) or availability, or may generate unnecessary maintenance costs due to damage. The leak may also be an indication of the appearance of a degradation (e.g. cracking in a pipe) which must be repaired as quickly as possible, before it can deteriorate.
EDF has developed a wide range of leak detection methods, essentially used for: valves, condenser, reheater, boiler, nuclear reactor, steam generator, pit, containment, piping.
The main techniques used are: acoustics, acoustic emission, temperature and flow measurement, decrease in pressure, chemical and radioactive tracers.

EDF masters a wide range of measurement instrumentation well suited to the different detection techniques (traditional: flow, pressure, temperature, etc.; and specific: hygrometers, mass spectrometers, acoustic emission, etc.).
It also has:
- a test environment,
- extensive technical documentation,
- high-performance calculation resources.

**Figure 9 : Heat exchanger tubes destroyed by an undetected leak**

b) **Innovative aspects**
The different detection techniques are based on innovative instrumentation :
- In-service leak detection in conventional boilers by means of acoustic monitoring,
- Detection of micro-leaks in steam generator tubes by means of helium tests during nuclear plant shutdown,
- Helium test on superheater moisture separators in the plants,
- Leak-tightness tests on EDF PWR containments, during shutdown and continuous monitoring (SEXTEN),
- Hygrometric monitoring of vessel head penetration tubes in PWR units,
- Internal valve leaktightness testing by means of acoustic emission techniques.

c) **Specific benefits - gains**
In industrial production installations, leak detection and repair provides gains in safety, availability and maintenance costs.
The use of leak detection techniques thus leads to gains in safety, availability and maintenance costs in industrial installations.

d) **Feedback**
EDF has developped leak detection techniques for more than twenty years to meet the needs of its nuclear and fossil-fired plants, particularly at the time of the launch of its pressurized water reactor program in the Seventies. The leak detection techniques adopted in these plants contribute greatly to EDF's good performance in terms of safety, availability and well-controlled maintenance costs.

## *3 instrumentation-related systems to improve plant productivity, for a cheaper kWh:*

### 3.1 CLIP a system to monitor plant performance ratio and help recover MWs

**a) Goal and Principle**

CLIP is an on-line efficiency monitoring system able to determine drifts or shifts of an nuclear power plant. This system has been developed to help producing a most economical kWh from primary fuel for PWR plant.

The approach is based on the comparison of measured performance indexes and expected performance indexes according to associated uncertainties. This comparison is local for each measurement point and global with efficiency ratio for each significant component of the secondary system. The expected values are computed by a heat-balance model based on acceptance tests of the plant.

The actual plant efficiency is computed by the mean of measure plant data. The expected efficiency is computed given the outside constraints and status of secondary side. It finally compares these two estimations of the efficiency ratio. Any discrepancy between the two estimations - outside the uncertainty - is diagnosed and probable causes are then proposed (figure 10). The plant operators will carry out a verification to check the validity of the diagnosis and reconfigure the faulty plant component or its setting.

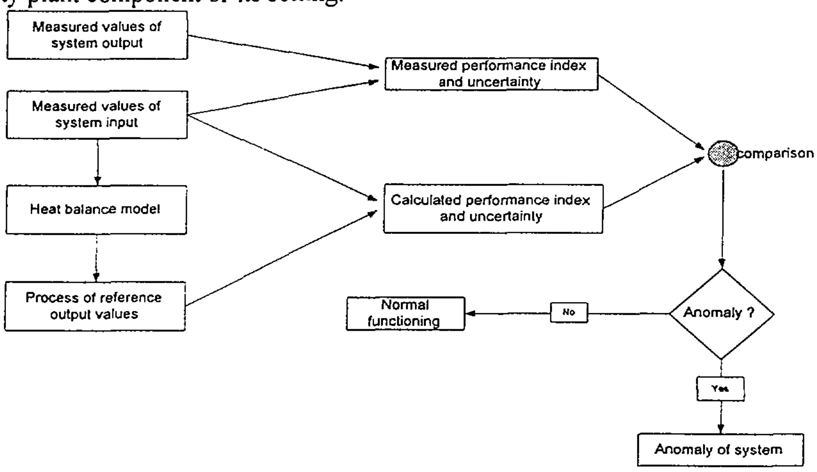


**Figure 10: CLIP overview**

**b) Innovative aspects**

CLIP includes a specific test instrumentation (around 100 sensors), a data acquisition system and a processing unit, which computes the current heat-rate efficiency ratio of the plant. It then computes an expected heat-rate efficiency ratio by use of a thermodynamical model of the plant : this model is fed with highly accurate data and performance parameters computed from earlier plant acceptance tests.

It finally compares these two estimations of the efficiency ratio. Any discrepancy between the two estimations - outside the uncertainty - is diagnosed and probable causes are then proposed. The plant operators will carry out a verification to check the validity of the diagnosis and reconfigure the faulty plant component or its setting.

**c) Specific benefits - gains**

CLIP diagnoses two types of fault:

*Local faults are checked for each measurement point according to uncertainties on measured value and expected value in the same conditions.

*Global faults are checked for a list of performance parameters according to uncertainties on actual value (which can be directly measured or elaborated by the mean of measurements) and reference value (decided on feedback experience and independent references for a type of power plant unit).

CLIP system is also used after an outage to save time in helping operators to reconfigure the plant faster in its optimal settings. During normal operation plant engineers periodically use it to gain better knowledge of their plant or some specific components.

**d) Feedback**

A demonstration system has been implemented at Flamanville plant (1300 MW) and tested by plant operators in industrial operating conditions. Then the monitoring system has been optimized with feedback experience and developed for 900 MW and 1300 MW plants. Since 1998, all EDF's PWR plants are using CLIP. Thanks to CLIP, plants recover from 0.2% to 1% of electrical power output.

CLIP provides a diagnosis on plant components which are not instrumented (localisation of possible leak, ...) and propagate uncertainties to provide diagnosis with accuracy.

It also helps to optimize maintenance plant planning. CLIP also helps utility management to compare plants over a same independent basis.
In other domains, such as production lines, CLIP system can also be used in order to optimize performances: preliminary studies in co-operation with the final users are required to optimize the system.

## 3.2 IMPROVING POWER PLANT EFFICIENCY AND SAFETY THROUGH BETTER KNOWLEDGE OF FLOW-RATES: THE EDF APPROACH

**a) Goal and principle**
In industrial conditions, flow-rate is often incorrectly determined due to various phenomena such as wrong calibrations and drifts, erosion or fouling of the flowmeters, incorrect installation conditions such as a lack of straight lengths required by the standards upstream from the meter... These phenomena may lead to systematic errors which can amount to several percents of the measured value.
Regarding the importance of the flow-rate and the related economic gains, Electricité de France has always been very concerned by the means to improve the actual accuracy of flowmeters. This part presents EDF's approach and means in liquid flowmetering and the related activities of its Research and Development Division.

**The experimental approach** is an efficient way to investigate and make a diagnosis of real situations. Within the Research and Development Division of EDF, the experimental studies of liquid flowmetering problems are supported by the EVEREST loop. A reference section is dedicated to reference flow-rate measurements. They are carried out with two different types of standards (differential pressure devices and electromagnetic or Coriolis flowmeters) that perform a measurement with an accuracy of ±0.3% of the reading. This value is very low; in comparison, the best accuracy found in a power plant is about 0.8% (that of the feedwater flowmeter) and the flowmeter usual accuracy in the industry is of several percents.
The testing section is variable, the pipe configuration can be modified to meet specific user needs in terms of singularities placed upstream from the meter (pipe fittings such as bends, valves, tees or reducers) that are frequently found in industrial sites. This section is of prime interest when in-situ calibrations are not feasible and piping duplication is necessary.

**b) Innovative aspects**
The rig is operated with a distributed control system which warranties high accuracy thanks to the digital communication, quality assurance thanks to historical and auto-diagnosis capabilities of smart devices and interoperability with most of the industrial flowmeters.

EDF's approach to improve flowmetering in plants is innovative in the sense that it combines :

- an experimental capability
- a modeling capability,
- development of high-performance innovations allowing use of non-invasive flowmeters in various environments
- practice of on-site measurement, experience feedback.

**c) Specific benefits - gains**
Here after an example is described of a study based on the EVEREST loop, concerning EDF 1300 MW unit feedwater flow.
In some EDF 1300 MW units (those of the P'4 series), it has been calculated that an increase of 0.5% on the accuracy of the 4 feedwater flows corresponds to an increase of 0.25% on the thermal power accuracy. This increase represents a difference of 9 MWth, as the thermal power goes from 3817±15 MW to 3817±24 MW. In terms of electrical power, it may lead roughly to an annual loss of 3 MWe. In a year, this is evaluated as a loss of 300,000 US $ per unit. For the total number of 1300 MW P'4 units (12), this 0.5% uncertainty increase amounts to a total of 3.6 million US dollars a year.
This 0.5% increase is what is required by the ISO standards on the 1300 MW units since the feedwater flow orifice plate installation conditions do not fully respect ISO requirements. The orifice plate is positioned 26 pipe diameters downstream from a combination of a venturi tube and a 90° elbow, whereas the ISO standards require 28 pipe diameters for a guaranteed accuracy of ±0.7%. Although the difference may appear to be small, it forbids strict application of ISO accuracy values.
An experimental study was thus carried out on the EVEREST loop: the feedwater pipework was simulated and the influence of the orifice plate installation conditions was evaluated. Figure 11 depicts the pipework that was mounted in the EVEREST testing section.

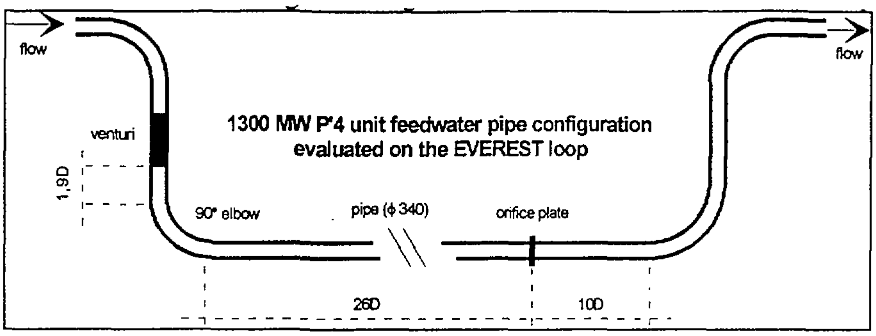


**Figure 11 Evaluation of orifice plate installation conditions on the EVEREST loop: pipework configuration**

Figure 12 represents the bias between the reference and the measured flow-rate for two series of tests done with the orifice plate positioned at 28 and 26 pipe diameters from the elbow.

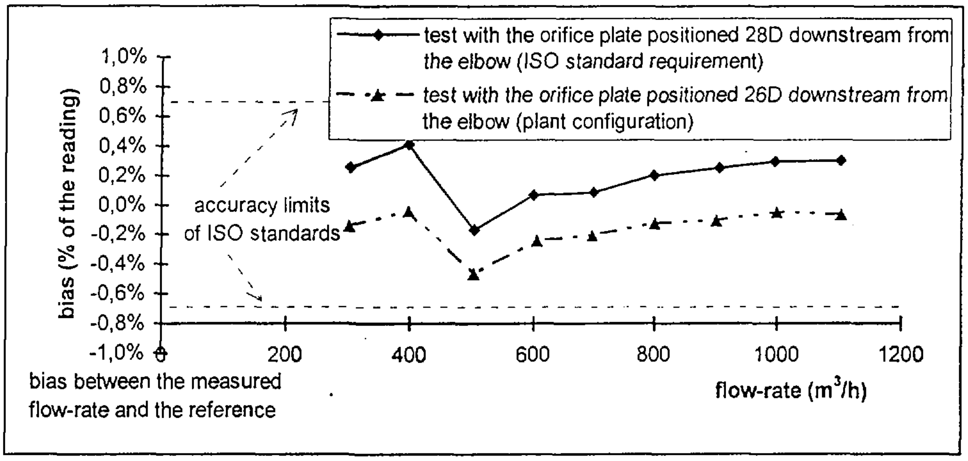


**Figure 14 Evaluation of orifice plate installation conditions on the EVEREST loop: bias versus flow-rate**

Figure 12 would seem to show a difference of about 0.4%, but since the curves of the bias versus the flow-rate are inside the accuracy limits of ISO standards, the accuracy of the orifice plate is considered not to be affected by the installation conditions.

Finally, it has been experimentally demonstrated that the uncertainty over-estimation of 0.5% was unjustified and this permitted to save the amount of money above-estimated (3.6 million US $ a year).

### 3.3: Reliability Centered Maintenance (RCM) for optimizing maintenance costs

a) Goal and principle

Every industrial installation needs efficient maintenance. Maintenance procedures on industrial installations have certain general objectives:

- limiting production outage and guaranteeing product quality,
- controlling global operating costs,
- protecting staff, the environment and equipment from any risks inherent to the process.

These procedures must nonetheless be carefully programmed, as maintenance is necessarily costly; it can lead to outage, have an impact on safety or expose humans to risk situations.

Technical and economic efficiency therefore requires certain compromises. Security, safety of staff and equipment, profitability and product quality must all be taken into account in a well-balanced maintenance strategy, optimized to the limit.

The solution is the RCM method : the fruit of developments in the USA in the field of aircraft maintenance, the Reliability Centered Maintenance (RCM) method takes a global approach to the problem.

RCM enables making optimum decisions with respect to the preventive maintenance measures the plant operator must take to control maintenance costs, achieve target levels of availability and, more generally, guarantee dependability in the installation.

RCM is a rational approach aimed at limiting the impact on an installation of failures stemming from equipment. It enables determining:

*where preventive measures are needed (on what equipment),
*what tasks must be performed,
*when (how often) they must be performed.

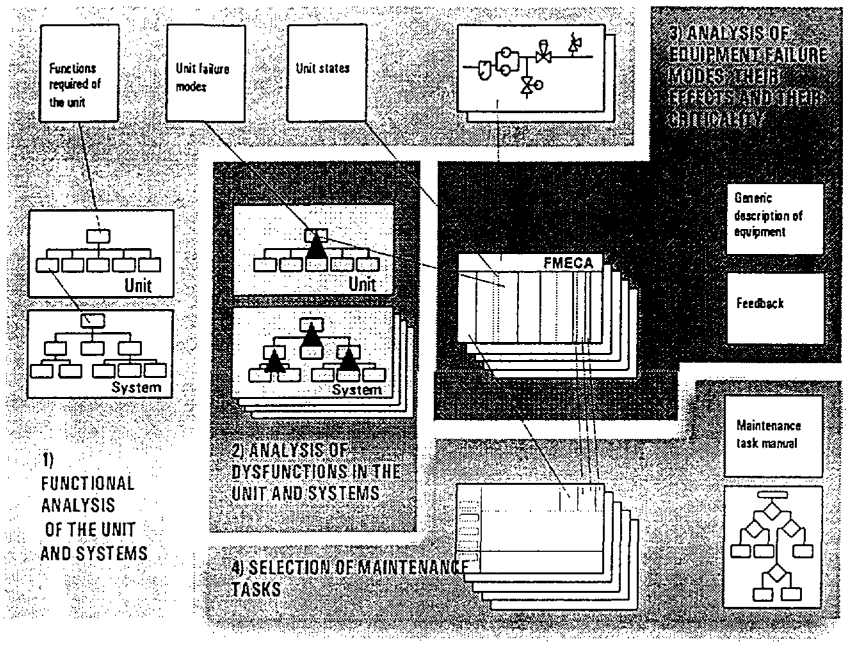


Figure 13 : Principle of a RCM study

**b) Innovative aspect**
The innovation lies in applying RCM method and techniques from the aircraft industry to another process industry with similar high reliability requirements.

**c) Specific benefits - gains**
Unlike TPM (Total Productive Maintenance) which primarily deals with organizational aspects, RCM is above all concerned with technical data. It is thus complementary to management methods, to which it adds the technical information useful in decision-making.
The benefits of the RCM approach are felt in many areas: maintenance costs, availability, safety, organization, involvement of personnel.
The many studies conducted at EDF have highlighted the benefits of the RCM method :

*economic gains, due to the reduced volume of preventive maintenance; the costs of the RCM study are paid off in very little time,
*an improved level of availability and greater consideration of safety imperatives,
*reorientation of traditional preventive maintenance toward condition-based tasks of inservice monitoring,
*greater synergy between operation and maintenance teams,
*a ranking of failures and of the corresponding preventive maintenance tasks, simplifying decision-making and maintenance management,
*awareness on the part of maintenance teams of the real effects of their work and the functional consequences of failures,
*direct exploitation of feedback and improved collection of feedback.

**d) Feedback**
EDF's development of a Reliability Centered Maintenance method dates from 1990. Several pilot studies have been conducted on power plant systems (including a complete analysis of a plant using a gas turbine). Since 1994, the approach has been generalized throughout the nuclear power generation capacity and, since 1997, the fossil-fired park. As concerns the nuclear park, expected economic gains have been estimated at some 100 millions USD per year.

## REFERENCES

CLIP : A system to increase the efficiency of production lines (presentation made for the SMI '99 conference, third international conference on plant maintenance, in Bologna, Italy, from February 17th to February 20th, 1999) - E. TOURNU ; F. CHABOT

Improving Power Plant Efficiency and Safety through better Knowledge of Flow-Rates: the EDF Approach - M. PIGUET (POWER-GEN EUROPE '98)

Primary Flow and Temperature Measurements in PWRS using Non-invasive Techniques - J.M. FAVENNEC, P. THOMAS, H. JEANNEAU