CORE WATCH: ADVANCED BWR CORE MONITORING

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ABSTRACT

Conventional Boiling Water Reactor (BWR) Core Monitoring strategies, which are often based on adapted thermal margin estimations, are subjected to increasingly stringent requirements. These new requirements are necessitated by power up-rates, the use of advanced fuel concepts, aggressive operation strategies and longer cycles with resulting higher levels of heterogeneity in the core configurations. The use of modern core simulators enhances the modeling capabilities of these monitoring systems, although the adaptive approach relies primarily on the information provided by the in-core instrumentation. Core Monitoring basically deals with risk-of-failure estimations, and by operating closer to predefined limits, the "potential inaccuracies" of these estimations become more relevant. Therefore, a comprehensive assessment of the uncertainties involved in thermal margin evaluations becomes of prime importance importance. These uncertainties originate from the applied methods and the modeling assumptions as well as from actual limitations in the available process signals.

The present paper describes ABB's Core Watch concept, which relies on both off-line and on-line uncertainty evaluations together with best-estimate thermal margin evaluations. Some of the off-line uncertainty assessments require detailed information unavailable from the in-core instrumentation. For this purpose, additional measurements on the assembly as well as fuel rod level should be performed. Some of these activities are described here, with emphasis on gamma-scanning comparisons at fuel bundle on modern 10x10 fuel concepts.

1. BACKGROUND

Boiling Water Reactor Core Monitoring Systems (CMS) utilizing some kind of adaptive strategy to adjust predicted values to match measured data have been successfully employed in many plants for more than two decades. ABB Atom delivered its first system in 1974[1,2]. Other examples of similar systems are GE's 3D-Monicore [3] and Siemens' Powerplex [4]. This positive experience is, partly, due to the fact that a relatively high degree of conservatism in thermal margin evaluations has been required due to the limitations of core simulators to model complex physical phenomena taking place in the core. However, new and more stringent requirements have appeared in recent years as a result of power up-rates, the introduction of new fuel concepts and more aggressive operation strategies with smaller thermal margins. An example of the latter is the trend towards longer cycles or higher discharge burn-ups which leads to increased levels of heterogeneity in the core conditions due to higher inter-assembly burn-up mismatch, higher enrichment and an extended use of burnable absorbers. The above mentioned conditions and requirements have the potential to erode the previous conservatism, forcing a reconsideration of the reliability of the current strategy.

Better use of available information and modeling capabilities available, together with a more comprehensive assessment of current uncertainties in monitored thermal margins should contribute to improve the reliability and robustness required for these Core Monitoring Systems.

After a brief discussion about thermal limits in general, this paper describes the current Core Monitoring strategies with their present limitations before proceeding with a description of the components required for an improved monitoring. These components are included in ABB's Core Watch concept that will be described afterwards to finalize with a discussion about additional sources of information for the necessary uncertainty assessments.

2. THERMAL LIMITS (REVISITED)

Although well known, it may be worthwhile to define the nature of the parameters monitored and the assumptions behind their definitions.

The purpose of Core Monitoring is to contribute to the safe operation of the reactor by avoiding fuel damage both under normal conditions and anticipated operational occurrences. The fuel integrity is guaranteed by the definition of thermal load limits that should not be exceeded. These limits are established to cover different kinds of failures according to specific criteria.

For each thermal load (x) to be monitored a technical, or safety, limit (x_t) is defined prior to the start-up of the reactor. This is a design limit, normally defined by the fuel vendor, which can be expressed as a given value or as a function of multiple variables. In addition, the Reactor Operator defines an operational limit (x_{op}) that will be applied during the cycle. This limit takes into account the above mentioned technical limit together with a safety margin (s_{op}) based on the estimated uncertainty in the evaluated thermal load, i.e.

$$x_{op} = f\left(x_t, s_{op}\right)$$

The basic thermal loads monitored are:

- the critical power ratio (CPR) to avoid damage due to dry-out
- the linear heat generation rate (LHGR) to avoid thermal mechanical damage (primarily from fission gas release) and to protect against damage due to pellet-cladding interaction
- the average planar linear heat generation rate (APLHGR) to protect the fuel rods in the event of a loss-of-coolant accident.

The thermal margin (M_x) is defined as the "distance" to the operating limit of each of these parameters for a given reactor condition, with negative values indicating violations of this limit.

There is a clear trend, regarding the definition of technical and/or operational limits, towards a statistical evaluation of the risk of failure, and some limits are already expressed as "*a thermal load such that the probability of z% of the rods/bundles failing is less than y%*". In this case, not only the computed individual thermal loads (and their uncertainties) but also the global core conditions would affect the predicted thermal margins. The fact that several bundles may come closer to the limit implies a higher failure risk, even when at the "hot spots" the thermal loads are not necessarily higher than in a case with very few limiting bundles.

3. CURRENT CORE MONITORING STRATEGIES

BWR Core Monitoring Systems based on three-dimensional core simulators with relatively strong modeling capabilities have been in operation for almost two decades. As an example, ABB Atom has delivered its **Core Master System** including either the **POLCA** (**PO**wer **O**n-**L**ine **CA**lculations) or PRESTO core simulators to a number of different plants, as shown in Table 1. With the exception of the Leibstadt NPP, all the other plants operate with the POLCA (PRESTO)/UPDAT package using an adaptive strategy that adjusts the calculated nodal power distribution according to calculated vs. measured TIP and LPRM signal differences prior to the calculation of the thermal margins. The successful experience, in the form of very limited fuel failures after about 225 reactor-cycles, illustrates the soundness of this approach or, at least, the ingenuity in the determination of the limits for safe operation.

It is worth mentioning that the version of POLCA implemented in ABB's CMS has always been functionally equivalent to the off-line version employed by ABB and some of its customers in core design and in-core fuel management applications. This has resulted in an advantageous coherence between off- and on-line calculations. In addition, this has provided a comprehensive validation base for POLCA, under various realistic conditions, thus enhancing the understanding of its performance.

Table 1 – Core Master System deliveries and experience

Power Plant	**Country**	**In operation since**	**No. of cycles**
Forsmark 1	Sweden	1980	18
Forsmark 2	Sweden	1981	17
Forsmark 3	Sweden	1985	14
Ringhals 1	Sweden	1976	23
Barsebäck 1	Sweden	1975	23
Barsebäck 2	Sweden	1977	20
Oskarshamn 1	Sweden	1976	23
Oskarshamn 2	Sweden	1974	24
Oskarshamn 3	Sweden	1985	14
Olkiluoto 1	Finland	1978	20
Olkiluoto 2	Finland	1980	18
Brunnsbüttel	Germany	1989	10
Leibstadt	Switzerland	1991	8

3.1 PRESENT LIMITATIONS

The present strategy suffers from a number of limitations that are briefly described below.

The adaptive Core Monitoring approach is based on a combination of calculations and measurement-based adjustments to determine thermal loads. One of the drawbacks of this approach is the fact that it is almost impossible to estimate the uncertainty in these computed thermal loads. The reason for this is that, once modified via an approximate adjustment function, it is no longer possible to compare the adapted solution against any other reference data. When trying to estimate the conservatism (or lack of conservatism) of the assumptions involved in the computation of the thermal margins, this becomes a serious limitation.

In addition, the adaptive strategy relies more on the information provided by the detectors than on the predictions provided by the calculations, even when the available detector systems have inevitable design limitations, such as:

- The measured detector signal (gamma or neutron flux in the detector position, not power!) consists of contributions coming from the neighboring assemblies, thus masking individual contributions. The adaptation of the power distribution in nodes within the core volume covered by the detectors is performed with some kind of "interpolation" among the adjustments determined at the detector locations.
- The adjustment performed is strongly dependent on the number of reliable detector signals available. Moreover, an important fraction of the core is not covered by any LPRM, leading to dubious extrapolations. The fraction of the reactor core not covered by LPRM detectors (core periphery), could be more that 50% of the total volume.

- Channel bow and detector displacement (to which neutron flux detectors are particularly sensitive), detector depletion, etc affect the measured signals themselves. This leads to an increased uncertainty in the interpretation of the relationship between detector signal and nodal power.

The power adjustment strategy could, in fact, impair the accuracy of local thermal margin estimations. This could be the case of unfortunate channel bow conditions that lead to lower flux in the detector position, which may then be wrongly interpreted as lower nodal power in the surrounding bundles. If sufficient conservatism has been built into the operational limits, such undesirable interpretations could go unnoticed (without fuel failure).

4. COMPONENTS FOR IMPROVED MONITORING

A better utilization of the information provided by the calculations and the measurements is possible. With enhanced predictions (best estimates) from the core simulations and a more comprehensive uncertainty assessment, a more robust system could be developed. This is the basic idea behind ABB's **Core Watch** concept, which will be described shortly.

4.1 CORE SIMULATION

The successful development of modern nodal methods paves the way for core simulators that can deliver both increased accuracy and more detailed information with near real-time performance, as required in a CMS. Even for increasingly heterogeneous cores, core simulator prediction capabilities have become more reliable due to:

- more sophisticated nuclear data (cross sections) homogenization techniques
- the ability to predict pin power and pin exposure distributions
- more detailed models to describe the (in-core) thermal-hydraulics of the system

This is a continuous process and while there are still challenges ahead, current commercially available core simulators clearly deliver useful thermal margin estimations. At ABB, the code package including the above-mentioned capabilities is **PHOENIX4/POLCA7**. POLCA7 is already incorporated in the Core Monitoring Systems delivered to the three Forsmark NPP Units in Sweden and to the Hope Creek NPP in the USA. The performance of PHOENIX4/POLCA7 has been previously described in Reference 5.

4.2 UNCERTAINTY ASSESSMENTS

Technical and operating limits are defined based on assumptions that may influence the way Core Monitoring is performed. As an example, the technical limit could be defined in such a conservative way that some of the parameters involved in its estimation do not need to be monitored; this could be the case of conservative assumptions about existing channel bow.

Best-estimate strategies, which rely more heavily on calculations, impose additional requirements on the evaluation of the accuracy and reliability of both the core simulations and the process signals used.

Within the activities performed to define the operating limits for a given cycle, the uncertainties in the computed thermal loads must be estimated prior to the start-up. Uncertainty assessments could also be performed during the cycle in order to track any potential degradation in the accuracy of the relevant parameters. In both cases, the estimated uncertainties in computed thermal loads will be the result of several contributions:

- Uncertainties in the engineering data
  - Fabrication tolerances
  - Material composition
  - Thermal expansion
- Uncertainties in the process data affecting the calculation of the thermal load
  - Reactor power
  - Core flow measurements
  - Temperature measurements
  - Local flux measurements (TIP / LPRM), if they are utilized during the evaluation
- Uncertainties in the models for the calculation of the thermal load
  - Nodal or fuel rod power calculation
  - Bundle power calculation
- Uncertainties due to non-modeled phenomena
  - Channel bow
  - Void in inter-assembly by-passes
- Uncertainties in the determination of the technical limits (if not already included in the limit itself)
  - Uncertainties or limitations in empirical correlations (e.g. dry-out correlations)

4.3 NEW FUNCTIONS

The field of Core Monitoring in power reactors is not static and new applications are becoming or may become available in the near future. Examples of this are stability monitors, more advanced signal treatment with the use of noise analysis, the possibility of on-line re-evaluation of the operating limits and even transient calculations. Such applications, when subjected to the same conditions as the traditional Core Monitoring Systems, will extend the aid provided to the Reactor Operator.

5. CORE WATCH

Core Watch is an advanced Core Monitoring strategy developed by ABB in co-operation with Swedish BWR utilities. A prototype has been in implemented at the Ringhals NPP Unit 1 in Sweden in order to evaluate the robustness of its principles. The concept has also benefited from the positive experience at the Leibstadt NPP, where a monitoring strategy without any adaptation to detector signals has been in operation for several years. In this case, a parallel evaluation of calculation/measurement deviations is performed periodically in order to detect sudden deterioration in accuracy of the detector signal predictions (≈ power) performed by the CMS.

5.1 BASIC PRINCIPLES

In a highly simplified way, one could say that Core Watch relies on three basic principles or assumptions:

- Safety limits are a measure of acceptable risk of failure.
- Thermal margin predictions are a measure of the risk level at given conditions.
- Process signals (i.e., on-line measurements) can be used as an indication of the reliability of these predictions.

Based on these principles, the key components of the Core Watch concept are:

- Evaluation of thermal margins with a 3D-core simulator (best-estimate)
- The uncertainties affecting the current thermal margins evaluation are taken into account
- The detector signals are used for a continuous estimation of the calculation uncertainty
- Punitive actions are introduced by the CMS if licensed uncertainty levels are exceeded
- Alternative operation modes are available in Core Watch in the event that significant systematic deviations, which make the calculations unreliable, are observed. This could also happen in the case of faulty or insufficient process data.

Figure 1 shows the main structure of Core Watch, where a separate module performs the on-line uncertainty evaluation used to complement the best-estimate thermal margin calculations.

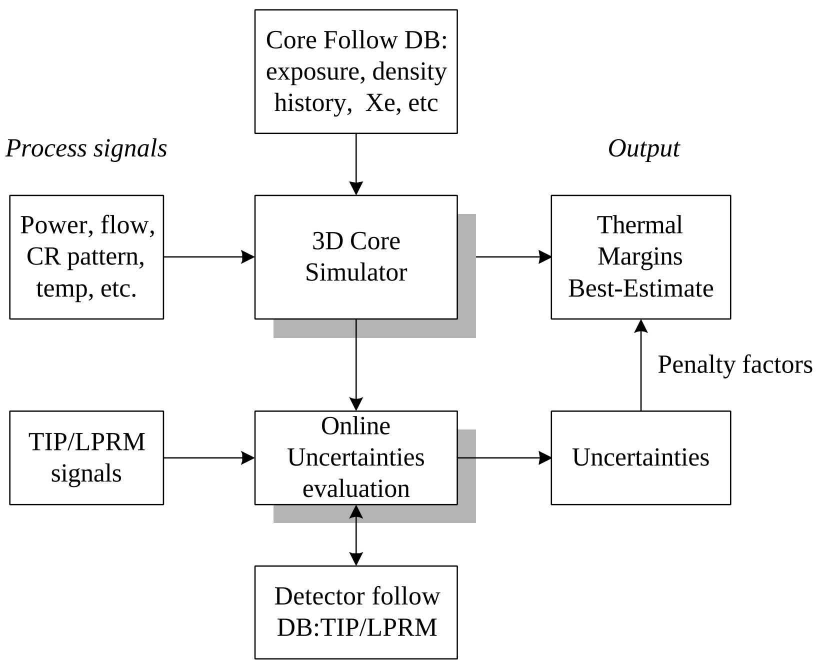


Figure 1 – Core Watch structure

The basic idea is that the thermal margin evaluations are performed under two different conditions:

- During core and fuel design and licensing of an upcoming cycle, where the different uncertainty contributions are estimated in a pre-established way.
- During operation, where on-line (up-dated) estimations of uncertainty contributions are performed.

As long as the on-line estimated uncertainties are within the range of the uncertainties assumed during the licensing activities, the best estimates of the thermal margins are used as final results. If, for any reason, the on-line estimated uncertainties exceed the licensed values, penalty factors are imposed on the calculated thermal loads (x_c, the best estimate). These penalty factors are calculated as the ratio between the licensed operating limit and an equivalent operating limit calculated with the on-line estimated uncertainty. Mathematically, this is expressed in the following way (for LHGR):

$x'_{op} = f\left(x_t, s'_{op}\right)$	(A new operating limit based on current uncertainties)
$f = x_{op} / x'_{op}$	(The penalty factor)
$M_x = x_{op} / \left(f \cdot x_c\right) - 1$	(The margin calculated with a penalized best estimate)

In this way, smaller margins are obtained without changing the operating limit itself (which could be disturbing for the reactor operators). Applying the penalty factor in this way is equivalent to a global penalization (over all bundles or nodes), because no rearrangement of their relative margins is performed. This kind of global penalization could be somewhat over-conservative, because the highest deviations are generally found in the low power regions, but it is a reasonable trade-off to keep the system simple. Moreover, by operating in a more aggressive manner, several bundles could be close to the limits and a global penalization should provide a more reliable estimation of the true safety margins. This is schematically shown in Fig 2, where two different operation conditions are illustrated. In both cases the thermal margin, according to a best-estimate calculation, is the same. However, the thermal load distributions and the uncertainties associated with them differ in such a way that the resulting risk of failure is clearly different.

As a consequence of this observation, the calculated and measured detector signals are utilized in a different way in Core Watch than they are in the adaptive technique. Instead of being used to estimate local power adjustments, as in the case of the adaptive strategy, they are used to produce global estimations of the calculation accuracy. In this way, the thermal margins and their estimated uncertainties are less dependent on individual measured-to-calculated detector discrepancies.

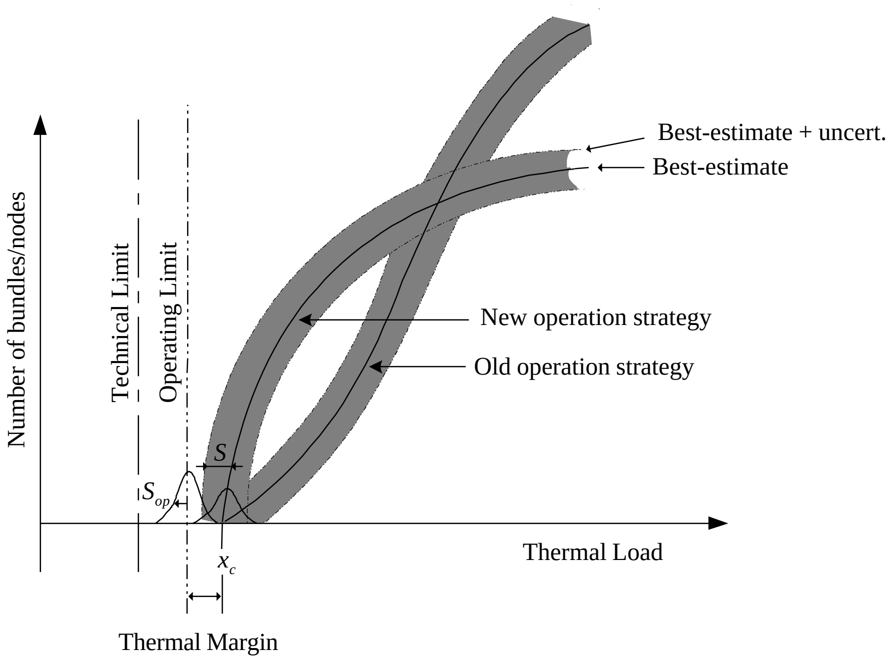


Figure 2 – Thermal loads distributions and associated uncertainties.

Additionally, Core Watch can deal in a very natural way with cases where the operation is performed with a temporarily reduced number of LPRMs, such as results from multiple detector failure. This is due to the fact that the confidence level of the uncertainty estimation is a function of the number of detectors involved in the comparisons. Therefore, a lower than expected number of LPRM signals will lead to an increased upper tolerance limit, even when the uncertainty (expressed as a standard deviation) remains unchanged, as shown in the following equation

$$x = x_{calc} + K \cdot s_{calc}$$

where K is the one-sided confidence level factor, which is proportional to $1/\sqrt{N}$, where N is the number of available detector signals,

Moreover, the frequency of LPRM calibrations could be adjusted with the support of the estimations performed by Core Watch in order to retain a given accuracy level, i.e. restricting the value of $K*s_{calc}$. In this case, a new calibration would be required only when the deviation, mainly caused by detector depletion, is such that the limiting value is exceeded.

By tracking the accuracy in the thermal margin evaluations, Core Watch is specially suited to detect degradations in the monitoring conditions resulting from abnormal behavior either in the calculations or in the process signals. The adaptive strategies, on the other hand, immediately compensate any difference, no matter its origin or cause.

Alternative operation modes are available to handle exceptional conditions that could lead to unreliable results if the normal mode, based primarily on core simulations, were used instead. These exceptional conditions could be related to either faulty or insufficient process data or to faulty or unavailable calculations. A restricted confidence in the core simulation is compensated with a stronger dependence on the TIP/LPRM signals. Two alternative operation modes have been proposed:

- CORR1D: it can be used in case significant axial systematic deviations are observed over a long period. In this case, an axial adjustment (1D), based on average detector signal comparisons at each axial level, is applied to the axial power distribution of each bundle, before the thermal margins are computed. This is a restricted adaptive strategy aimed at retaining, as much as possible, the on-line uncertainty evaluation capabilities.

- CORR3D: it can be used in case the core simulation results are unavailable or clearly unreliable (e.g. if transient Xenon calculation fails). In this case, a solution similar to the adaptive strategy (UPDAT) is used, with 3D-adjustment factors based on individual detector comparisons applied to the latest available calculated nodal power distribution. In this operation mode, only fixed (licensed) uncertainty estimations can be used.

Due to the more precarious understanding of the true core conditions when using these two approaches (but specially CORR3D), an additional uncertainty in power estimation must be introduced. Typically, this extra uncertainty is found by numerical experimentation or by higher methods, if available. Consequently, these modes are restricted to be used in abnormal situations. To sum up, the different alternatives included in Core Watch provide comprehensive coverage for a wide range of operation conditions.

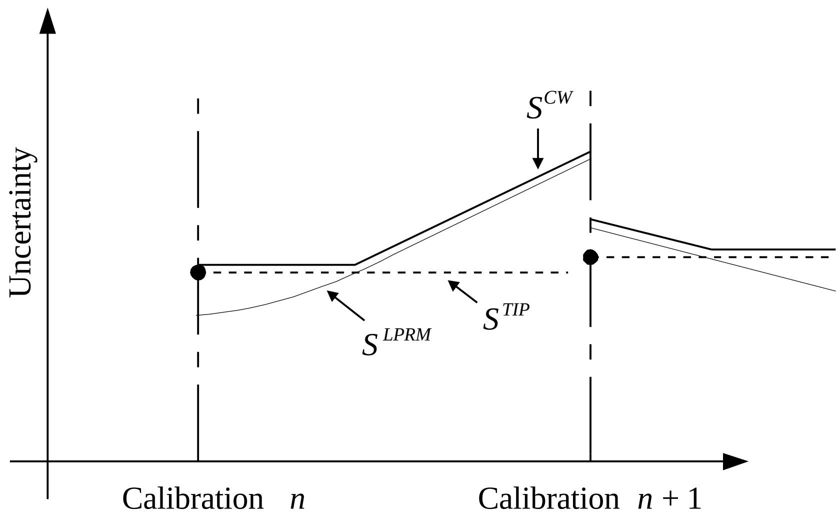
5.2 ON-LINE UNCERTAINTY ESTIMATIONS

Core Watch depends on a comprehensive assessment of all the possible uncertainty contributions mentioned previously (see 4.2). This assessment is done both during licensing (off-line) as well as during core operation (on-line). The uncertainty contributions may be reactor-, cycle- and/or fuel-dependent and they could be difficult to estimate. However, it is this detailed and up-to-date assessment that enables a better understanding of the status of the core, thus enhancing the reliability of the CMS predictions.

From the comprehensive list of factors contributing to the uncertainties in computed thermal margins described in sub-section 4.2, only two of them need to be monitored "on-line" during the cycle, namely

- **Calculated bundle power**
- **Calculated nodal power**.

For the remaining contributions an assessment performed during the licensing stage, prior to the start-up, suffices. Nevertheless, it should be kept in mind that this assessment migth be valid only under certain reactor conditions (e.g. at rated conditions). In this case, it is necessary to define proper actions to be taken when the reactor conditions fall outside the validity range. This could be the case of thermal margins that are evaluated only when reactor power exceeds a certain level. For the assessment of uncertainties in the computed bundle and nodal powers, only TIP and LPRM signals are available for calculation-to-measurement comparisons. It is possible to use either TIP or LPRM signals, or a combination of both. The latter represents the recommended approach. In this case, uncertainties are calculated utilizing the TIP-signals available at each LPRM calibration step. Between calibrations the LPRM signals are used instead. By selecting the maximum uncertainty predicted by any of them (the latest estimation using TIP or LPRM signals), one has a conservative methodology that combines the more detailed information provided by the TIP-strings with the more up-to-date, but scarcer, information provided by the LPRM-detectors. This is schematically shown in Figure 3.



$$S^{CW} = max \left(S^{LPRM}, S^{TIP}\right)$$

Figure 3 – Combining TIP- and LPRM-based uncertainty estimations

The comparison that can be performed during the on-line monitoring concerns calculated vs. measured detector responses (related to neutron or gamma flux). The observed differences will, therefore, be the combined contribution of three different uncertainties (or inaccuracies):

- Uncertainties in the power calculation of the bundles surrounding the detector string
- Uncertainties in the detector model, which converts computed power (or flux) into computed detector response
- Uncertainties in the measured detector signals

A proper model for the estimation of the last two contributions, together with the observed differences between calculated and measured signals, enables the estimation of the uncertainty in computed power. Core Watch combines the estimated uncertainty in calculated power with the other presumed (licensed) uncertainty contributions to quantify the uncertainty in the computed thermal load.

In summary, Core Watch can provide the following (on-line) estimations based on data from the in-core instrumentation:

- Uncertainty in nodal power based on TIP-signals
- Uncertainty in bundle power based on TIP-signals
- Uncertainty in nodal power based on LPRM-signals
- Uncertainty in bundle power based on LPRM-signals
- Uncertainty in nodal power based on TIP-signals, axially adjusted (CORR1D)
- Uncertainty in nodal power based on LPRM-signals, axially adjusted (CORR1D)

It is worth mentioning that one of the main results from the prototype installation was the verification that Core Watch reacts in a predictable way to the different perturbations in core operation. Additionally, there were clear indications that Core Watch could be advantageously combined with a previous "process data qualification" step, in order to avoid spurious alarms caused by inconsistent process data sets.

6. SUPPORT ACTIVITIES FOR UNCERTAINTY ASSESSMENTS

Specific procedures are required to estimate the aforementioned contributions to the total uncertainty in computed thermal loads. The uncertainty assessments, using proper statistical tools, have to be carried out by different entities, e.g. Fuel Vendors will need to perform and provide the fuel specific analysis, leaving to the Utility the reactor specific assessment. In order to have a formally rigorous treatment of uncertainties, the following factors must be considered:

- The potential consequences of normalization and re-normalization
- Assumptions on variable independence/dependence (correlated vs. non-correlated variables)
- Systematic deviations
- Relative vs. absolute uncertainties
- Assumptions that errors follow a normal distribution
- Conversion of (other) uncertainty distributions to equivalent normal distributions
- Combination of uncertainties in functions of multiple variables

Realizing that the plant measurement devices are limited in their functionality, an effort must be made to estimate the impact of different phenomena on the different uncertainties even beyond the capabilities of these instruments. Therefore, alternative sources of information should be sought. Three of them, which have received special attention at ABB Atom, are described below, namely: gamma scanning at fuel bundle level, experimental evaluation of neutron physics parameters and void measurements on modern (10x10) fuel assemblies.

6.1 GAMMA SCANNING

There is a definite limitation in the TIP/LPRM capabilities: the lack of information about uncertainties in power distributions at the individual bundle and fuel rod level. From TIP and LPRM signal comparisons, it is necessary to infer the calculated power uncertainty at those levels without any support from the instrumentation. This lack of information can be partly resolved by means of gamma scanning of bundle and/or individual fuel rods during outages at the plant. By comparing, most typically, Ba-140 concentrations, a good estimation of the accuracy of the computed power predictions can be obtained. Two other "by-products" of this kind of exercise is the possibility of discovering exposure-related trends or deviations and the possibility of using these measurements to estimate the uncertainties of the power-detector response connection itself (in case the gamma scans are performed on TIP-string neighboring assemblies).

Gamma-scanning measurements should be performed specially when significant changes in the core characteristics are introduced. This could be the case with the introduction of radically new fuel concepts (starting with transition cycles), operation with increased discharge exposures or the existence of strong deviations from the assumed conditions (significant channel bow, CRUD, etc).

ABB has the capability to perform Ba-140 gamma scanning, both at bundle and individual fuel rod level, during normal refueling outages and a number of measurement campaigns have been pursued over the last few years. The information provided by them has been used primarily in the validation of ABB and/or the customer simulation packages. However, the same kind of information can be extremely useful for the estimation of some of the uncertainties in the power calculations, as mentioned before.

As an example, in one of the latest measurement campaigns, more than 40 **SVEA-96** (10x10-4) fuel bundles were scanned in a BWR/6-type European NPP during a normal refueling outage. By properly selecting a representative sample of bundles with low-to-high exposure, central-to-peripheral locations and in several positions surrounding TIP-strings, very useful information is available for the kind of uncertainty assessments required by Core Watch.

Figure 4 shows, for the mentioned campaign, the location of the measured bundles together with the TIP-string locations, while Figure 5 and 6 show some of the results obtained. In Figure 5, the average bundle error frequency distribution is given, showing the excellent agreement between PHOENIX4/POLCA7 predictions and the measurements over a wide range of bundle exposures (one to five cycles in the core).

In Figure 6, the nodal deviations (calculated - measured) of four neighboring bundles around a TIP-string location are shown (due to the presence of parasitic absorptions caused by structural materials in the pool, the measurements at some locations were strongly perturbed, leading to their exclusion from the comparison). This kind of information, combined with the observed deviations between measured and calculated TIP-signals, can be used to estimate either the uncertainty contribution from the detector models or the uncertainty in individual assembly (nodal) power that goes undetected by the in-core instrumentation due to signal integration. In addition, this information can be used as the "assumed" uncertainty in power calculations during the design phase, prior to the cycle, when the operating limits are established.

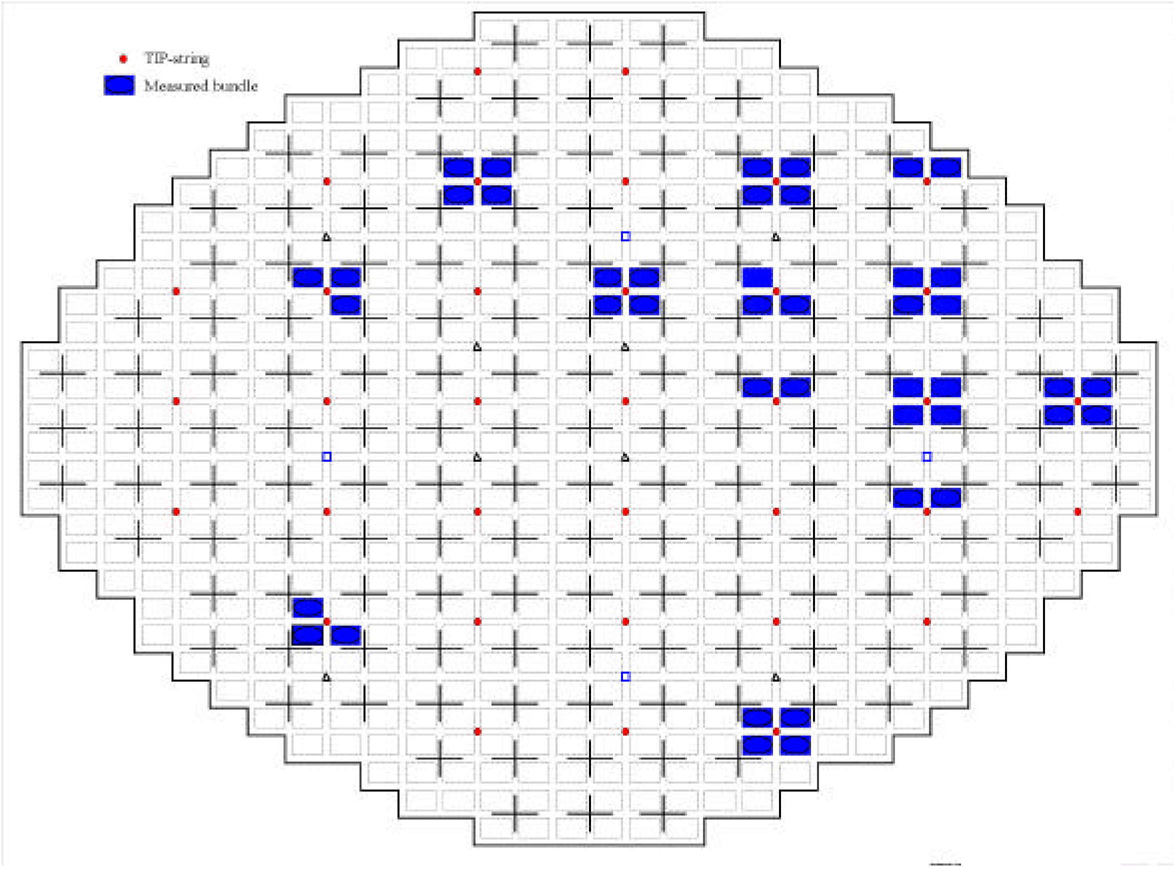


Figure 4 – Scanned bundles and TIP-string locations

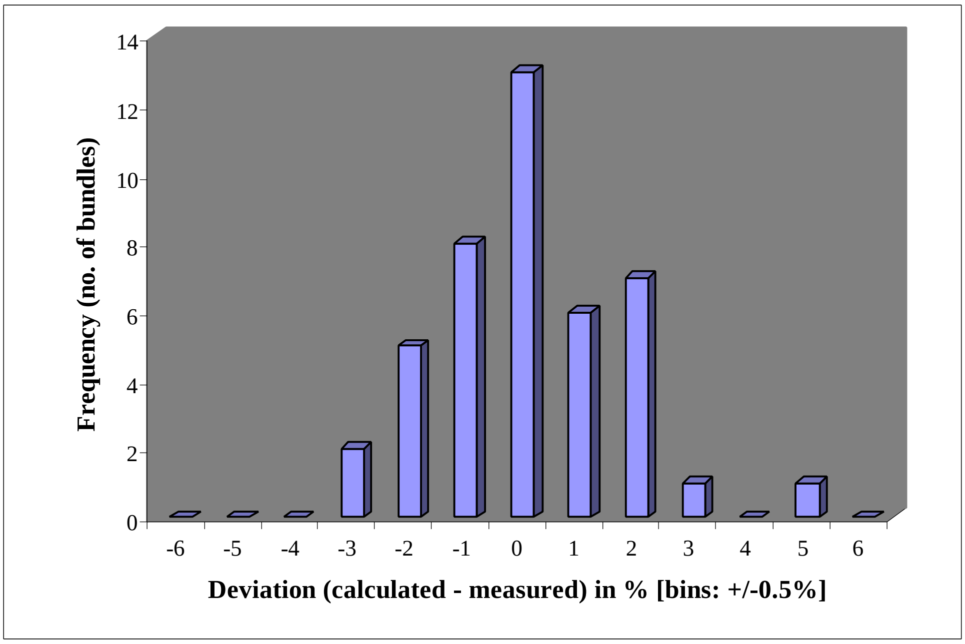


Figure 5 – Average bundle error frequency distribution

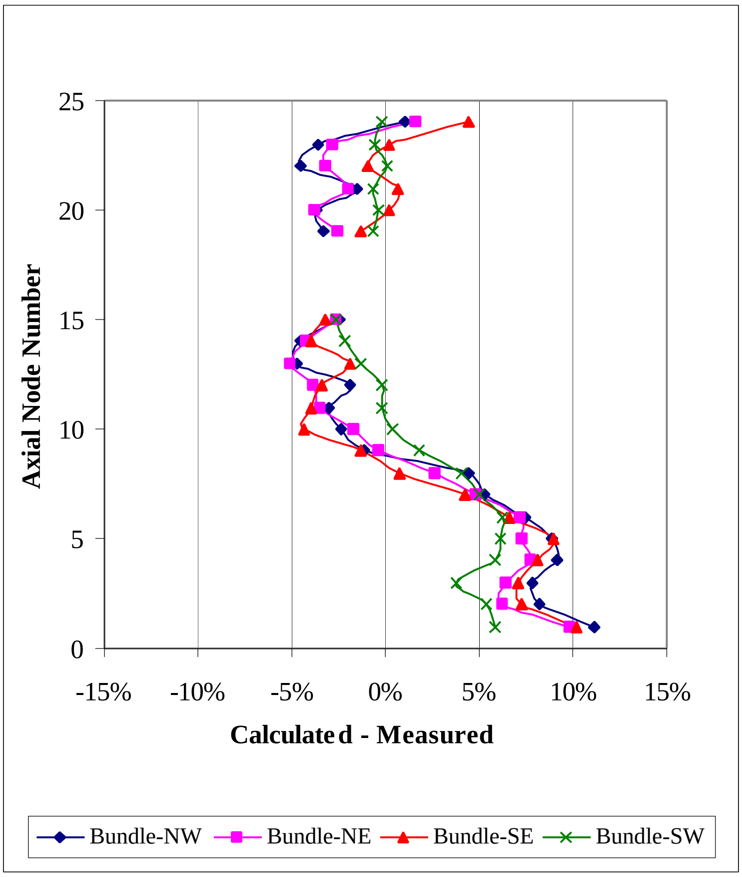


Figure 6 – Axial nodal deviations for 4 neighboring bundles at a TIP-string location

6.2 VALIDATION AGAINST CRITICAL EXPERIMENTS

Improved modeling capabilities, even when physically sound, should be validated against higher order methods and/or experimental evidence as far as possible. The increasing complexity of fuel concepts, including higher enrichment and extensive use of different burnable absorbers, should be correlated with validation activities. ABB Atom, EGL (owner of the Leibstadt NPP) and the Paul Scherrer Institute of Switzerland are undertaking, for that purpose, an ambitious experimental program named **LWR-PROTEUS Phase I**, utilizing the PROTEUS facility at PSI[6].
The program includes extensive and accurate measurements in different critical configurations where the test zone consists of nine (3x3) full-scale **SVEA-96** bundles. This is schematically shown in Figure 7. The test tank is surrounded by a natural uranium buffer, a heavy water tank, a graphite buffer/reflector (both including enriched U rods) aimed at providing a flat flux and realistic spectrum in the test zone.

These experiments, which are performed under well characterized conditions, will provide detailed information about internal power distributions, reactivity worth of different components (fuel rods, control rods), etc. In addition, it will be possible to study the influence of such parameters or perturbations as partial length rods, instrumentation, low coolant density and channel displacements.

It is expected that these results will help to quantify the modeling uncertainties and, eventually, to identify areas where further methods development could be required.

The measurements performed so far are considered of superb quality and clearly useful for the verification of both global and local parameters in "normal" as well as "strongly perturbed" conditions as in the presence of control rods. Publications of some of these results are planned for the near future.

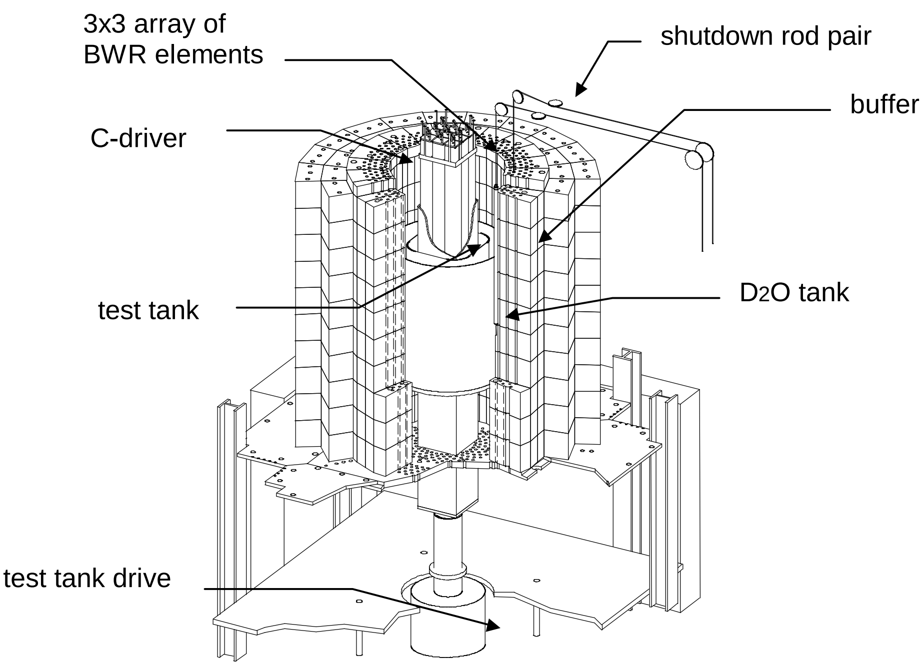


Figure 7 – LWR-PROTEUS Core layout

6.3 VOID MEASUREMENTS

Void (steam) measurements in realistic geometries are required in order to develop void correlations and two-phase pressure drop correlations. The introduction of fuel designs with 10x10 rods together with water channels of different geometry, partial length rods, etc., leads to increasingly different conditions from those under which previous void measurements were performed in the late 60's with simple 8x8 bundles. In recognition of this fact, ABB has performed new measurements in its retrofitted FRIGG-loop (see Figure 8) in Västerås, Sweden. Using collimated gamma rays on a full-scale quarter-bundle, the water density distribution is deduced with help of a computed tomography. This is done at different axial levels and in different polar orientations with help of a robot arm.

These measurements will help not only to improve the modeling accuracy of the core simulator by means of a more reliable void correlation, but also to quantify the impact of potentially limited modeling capabilities in transition cores, which can be difficult to detect from TIP/LPRM comparisons.

Miscalculation of channel void generation is one of the main contributors to uncertainties in BWR nodal power calculations. Therefore, a deeper understanding and an improved modeling of this phenomenon have a direct impact on the uncertainties in thermal margin estimations. The recently finalized measurements, together with realistic computer fluid dynamics modeling, have resulted in an improved void correlation, which is anticipated to improve core simulator power predictions.

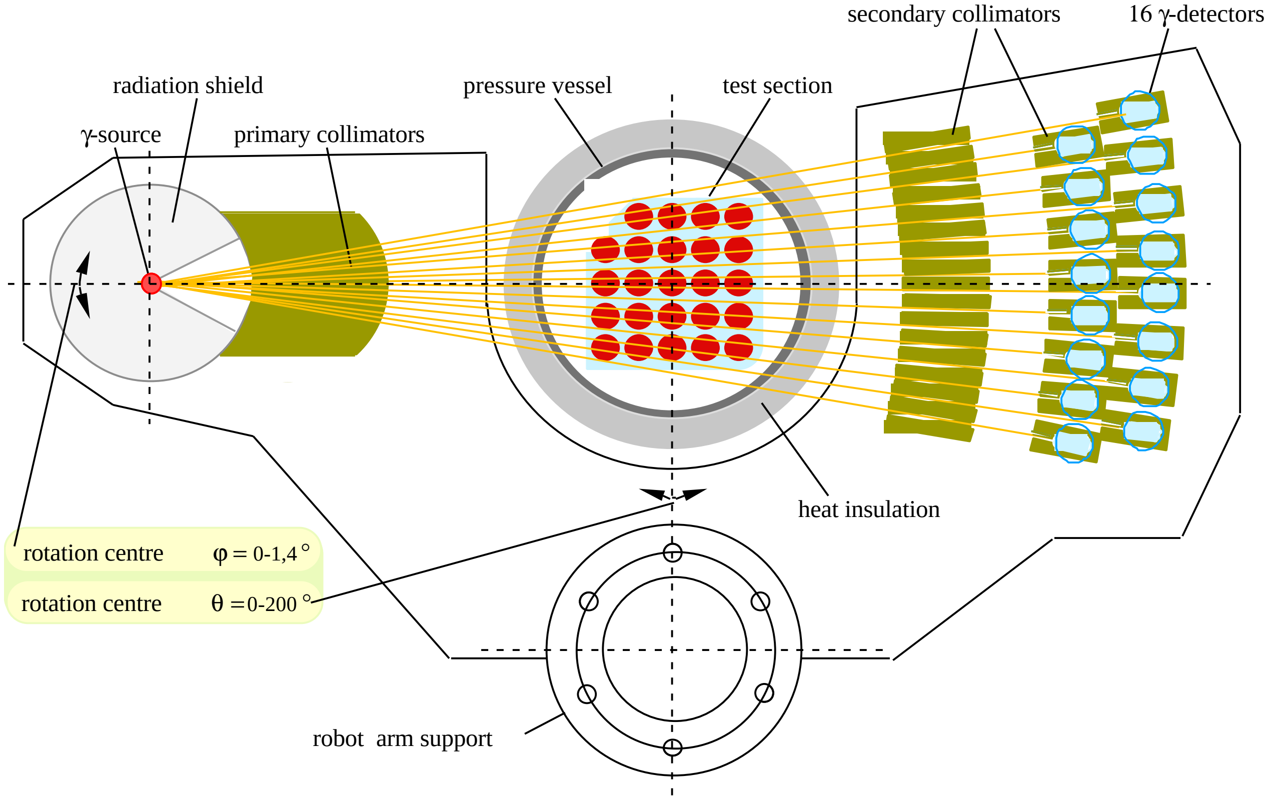


Figure 8 – Void measurements at FRIGG-loop (xy-plan)

CONCLUSIONS

In this paper the limitations in current Core Monitoring strategies and an alternative strategy have been discussed. The basic idea behind the new strategy is to perform a comprehensive assessment of the uncertainties affecting thermal margin evaluations in order to enhance the reliability of a Core Monitoring System through a better understanding of both the actual conditions of the reactor and the current modeling accuracy. Additionally, by relying on the computed power estimations (best-estimate) without adapting to measured signals, the new strategy takes advantage of the improved modeling capabilities offered by modern core simulators. This is the approach chosen by ABB in its Core Watch concept.

This strategy, however, requires uncertainty assessments to be performed frequently and in a structured way. These assessments require the support of additional experimental activities and/or higher order theoretical analysis. Examples of activities that could provide useful information for the above-mentioned uncertainty assessments have been provided here, with emphasis on gamma-scanning comparisons at bundle level. The described activities are or have been carried on with modern fuel concepts, which are used or in the process of being introduced in commercial BWR.

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