THE BEACON ON-LINE CORE MONITORING SYSTEM: FUNCTIONAL UPGRADES AND APPLICATIONS

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Abstract

The BEACON™ core monitor system has been in commercial operation since 1989 and was licensed by the USNRC for on-line core power distribution and thermal power limit monitoring in 1994. Since that time BEACON has been installed at 17 plants. Each of these customers has a different perspective on the use of data from BEACON and a different approach on the application of BEACON to support their plant operations. To support these varied needs and approaches the BEACON system has been divided into three operational levels to better match the system functions to the customer needs and approaches to system integration. Based on customer feedback, the BEACON system has been upgraded in some areas and streamlined in other areas to better support the needs of each customer. This paper will discuss the three operational levels of the BEACON system, the major product upgrades and system evolution that has taken place to support the needs and applications of our customers.

Introduction

BEACON™ (Best Estimate Analysis of Core Operations – Nuclear), is a core monitoring and operational support package developed by Westinghouse for use at PWR plants. The BEACON system is a real-time core monitoring system which uses existing core instrumentation data and an on-line nodal neutronics model to provide continuous core power distribution monitoring. The monitoring function uses plant instrumentation to develop and provide information on the actual core conditions and not a predicted core condition based on core follow data. As a result the BEACON core monitor system will survey core power thermal limits, including the minimum DNBR limit, as well as graphically show core anomalies such as dropped / misaligned rods, flow anomalies and xenon oscillations. With this information available to reactor operations personnel the BEACON system can be used for Technical Specification power distribution surveillance and plant operational guidance.

Accurate core prediction capabilities are also available to the user through the BEACON interface. These predict functions utilise a three dimensional (3D) nodal model that is continuously updated to reflect the plant operating history. The BEACON functions allow the user to access the continuously updated nodal model to perform automated calculations of estimated critical conditions for start-up, shutdown margin calculations for maintaining the minimum boron concentration after reactor trip, core depletion with optional coastdown calculations, and load manoeuvre predictions. The BEACON system predictive capabilities are discussed in more detail in References 5 and 6.

A core operating history database is maintained by the BEACON system and can be selectively displayed by plant operational personnel to help review and analyse core behaviour for pro-active control actions.

The following is a discussion on the operational levels of the BEACON system and recent major functional upgrades. The recent and planned applications of the BEACON system will be discussed to highlight the benefits of the system upgrades.

Background

The BEACON system was developed and released in 1989 with a licensed 3D nodal method that used one radial node per assembly, one and a half energy group theory coupled with a Green's function solution method that simplified the numerical solution by eliminating the inner iterations. This allowed the 3D nodal solutions to be obtained very quickly while running on the level of workstations available in late 80s and early 90s.

In February 1994, the core monitoring and flux map processing methodology used in BEACON was licensed by the USNRC. This allowed BEACON to be integrated into the plant Technical Specifications and used to satisfy core thermal limit surveillance requirements by recording data directly from the core monitor displays.

To support the varied customer requirements for the integration and application of BEACON at their plants, the BEACON system was broken down into three operational levels. These operational levels would allow customers to choose the level of system integration and usage that best matched their requirements for a core monitor and analysis system.

System operational levels

After the license approval of BEACON by the USNRC three operational levels of the BEACON system were developed to provide customers with a selection of system functionality that would more closely fit their requirements. The three operational level of the BEACON system were developed such that each higher level has the complete functionality of the lower level. The three operational levels were defined as (1) On-Line Monitor, (2) Tech Spec Monitor, and (3) Direct Margin Monitor.

The BEACON-OLM (On-Line Monitor) system level was developed to provide customers with the same level of functionality and application that was being used before the licensing of BEACON. This system level provides the base functionality of the BEACON system which includes continuous core monitoring, core predictive capability and operational history analysis. This system level is used for information and analysis purposes and does not require operational action based on results from the core monitor displays. This level of the BEACON system can be purely an information and analysis tool that plant operational personnel can use at their option. The use of the BEACON-OLM level can be integrated into the plant procedures. If this is done then the flux map analysis, estimated critical condition (ECC) functions and special nuclear material (SNM) report data from BEACON can be used to replace other off-line codes and procedures used for these calculations.

The BEACON-TSM (Tech Spec Monitor) system level was developed to provide customers with the functionality needed to integrate BEACON into the plant Technical Specifications (Tech Specs) for monitoring of current Tech Spec thermal power limits such as F_q, KW/FT, F_{xy} and $F_{\Delta h}$. BEACON-TSM includes all of the base functionality in the BEACON-OLM level. Added to this are the procedures, system operational status information and on-line calculations needed to provide the core monitoring capability for Tech Spec compliance. The licensing of BEACON for core monitoring allows the BEACON on-line monitoring functions to eliminate most off-line flux maps for normal and off-normal Tech Spec thermal power limit verification. Once integrated into the plant Tech Specs and procedures the BEACON-TSM system provides the following features:

- Continuous verification of core thermal limit Tech Spec compliance.

- USNRC approval for increasing the time interval between in-core flux maps to 180 EFPDs. These maps are only required for BEACON calibration and ex-core detector calibration because BEACON is providing core surveillance information on Tech Spec compliance.

- USNRC approval for continued operation with a misaligned rod without a reduction to 75% power with the BEACON system operational. All requirements for in-core measurements due to misaligned rods or inoperable rod position indicators (RPIs) are replaced in the Tech Specs with the BEACON core monitor function.

- USNRC approval for reduced in-core detector instrumentation down to 50% of the available instruments after plant cycle start-up and reduced thermocouple instrumentation down to 25% of the available instruments. The BEACON system uses surface spline fitting to compensate for sparse instrumentation and adjusts the applied thermal limit uncertainties allowing for operation with reduced instrumentation.

The BEACON-DMM (Direct Margin Monitor) system level was developed to provide customers with the full functionality and benefits of the BEACON license granted by the USNRC. BEACON-DMM includes all of the functionality of BEACON-TSM and also provides for direct monitoring and use of DNBR as the main thermal limit in the plant Tech Specs. The DMM level of BEACON will also perform continuous on-line margin trade-off between thermal parameters such as $F_{\Delta h}$ and F_q while providing continuous verification of the Tech Spec DNBR limit. This allows nearly all available margin to be used for core operations or for fuel cycle cost benefits on a cycle specific basis. The customer can then choose how and when to use the available margin. The DMM level requires that the BEACON system is integrated into the reactor control room for use by the reactor operators to monitor reactor core conditions and determine responses to Tech Spec limit alarms. BEACON-DMM provides the following additional features over the TSM level.

- USNRC approval for continuous verification of the DNBR limit.
- On-line trade-off of margin between core thermal limits such as peak power (F_q) and peak rod power ($F_{\Delta h}$) when DNB margin is available.
- USNRC approval for elimination of AFD or ASI Tech Spec requirements. The continuous verification of the DNBR limit will make AFD or ASI Tech Spec requirement redundant and unnecessary.
- Relaxed Quadrant Power Tilt Ratio (QPTR) requirements. The continuous verification of the DNBR limit will allow QPTR to be eliminated in most cases and relaxed to support the worst case accident analysis.

Table 1 shows a summary of the BEACON operation levels and their basic applications. These operational levels have allowed customers to easily integrate and adapt a BEACON system to their requirements without the need to address unwanted functionality. Table 2 shows the customers and plants that have had BEACON installed, their initial installation date and the current system operational level.

Major system upgrades

The BEACON system has been in operation since 1989 and is currently installed at 17 units world wide. Based on years of operational experience, customer feedback and advances in computer hardware, Westinghouse and Mitsubishi Heavy Industries (MHI) have recently integrated a number of major upgrades in the BEACON system to better target our customer needs. The focus of the MHI upgrade effort is to support the customer requirements in the Japanese market while the Westinghouse effort is focused on the customers in the remainder of the world market.

The major upgrades to the BEACON system discussed below include the following.

- Nodal solution method updated to a full nodal expansion method consistent with the Westinghouse core design and safety analysis method.
- Core monitoring methodology expanded to include the use of Fixed In-core Detectors (FIDs).

- Core monitor on-line calculation of soluble boron-10 (B-10) depletion from the neutron flux in the reactor coolant.

- On-line surveillance of the special thermal power limits for mixed oxide (MOX) and gadolinium bearing fuel assemblies.

NEM solution method

The BEACON system was developed and initially released with a licensed 3D nodal method that used one radial node per assembly, one and a half energy group theory coupled with a Green's function solution method that simplified the numerical solution by eliminating the inner iterations [1]. This allowed the 3D nodal solutions to be obtained very quickly while running on the level of workstations available in the late 80s and early 90s. A NEM (nodal expansion method) nodal solution method with four radial nodes per assembly has replaced the original solution method because of the increased speed and capacity of current workstations and the need to accurately model offset fuel assemblies in non-Westinghouse cores. Figure 1 shows a typical offset peripheral assembly design for a Combustion Engineering core. The NEM nodal solution method with four nodes per assembly can easily model this core configuration, includes a detailed pin power reconstruction method and is consistent with the nodal method used in the Westinghouse ANC [2] core design code. This consistency between nodal methods allows the same nodal model and nuclear parameters used in the core reload / safety calculations to be used in the BEACON core monitor and predict functions. The benefit of this is that it allows plant personnel using the BEACON system to use the same model and neutronic solution method that was used by the core design group to perform the reload safety analysis work. Therefore all predictive calculations performed by the plant reactor engineering personnel have the same pedigree and accuracy as the calculations performed by the core design personnel. With four radial nodes per assembly and the ANC NEM solution method in BEACON, the computer running time increases by a factor of 10 for nodal calculations. However the speed of the current workstations used for BEACON has increased by factors of 20 to 40 over the workstations used in 1990 and have basically eliminated the need for the approximations used in the original neutronic solution method.

Core monitoring with fixed in-core detectors

The core monitoring methodology in BEACON was licensed based on use of the movable in-core flux mapping system for periodic calibration. Nodewise calibration factors (MCF) are generated periodically when the nodal model is calibrated to the in-core instrumentation and are based on the following equation.

$$MCF(x,y,z) = \overline{\left(\frac{MRR}{PRR}\ (i,j,k)\right)}$$

Where:

MCF(x,y,z)	- Nodewise calibration factors
MRR, PRR	- Measured and predicted reaction rates at locations (i,j,k)
------	- Surface spline fitting of reaction rate ratios at each node elevation

At the same time the enthalpy rises from the core exit thermocouples are also calibrated to the measured power distribution. This allows data from the core exit thermocouples along with the ex-core power range detectors to be used to support the continuous core monitoring between system calibrations. With this methodology the BEACON system provides detailed information on the actual core conditions using all available and not a predicted core condition based only on core follow data. Reference 3 discuses in detail the BEACON core monitoring methodology.

The integration of fixed incore detectors (FIDs) for core monitoring in the BEACON system is based on the same methodology that was licensed for the movable in-core detectors and thermocouples. The FID system is used for periodic calibration of the BEACON system. After calibration, data from the FID system is used to support the continuous core monitoring instead of the thermocouple and ex-core data. The FID system provides detailed information on the core radial and axial power distribution making the thermocouple and ex-core data redundant and unnecessary. The nodewise measured power distribution is constructed using the following formulation.

$$P_m(x,y,z) = P_p(x,y,z)\,\overline{\left(\frac{Im}{Ip}\;(i,j,k)\right)}$$

Where:

$P_p(x,y,z)$	- Predicted nodewise power distribution
Im, Ip	- Measured and predicted detector currents at locations (i,j,k)
------	- Surface spline fitting of current ratios at each detector elevation

BEACON calculates the predicted detector currents on-line using the 3D nodal model power distribution. The predicted current calculation is based on basic physics principals. The equation used by BEACON to calculate rhodium detector currents is shown below.

$$Ip = C\left(\beta_1\ \sigma_{a1}\ \phi_1 + \beta_2\ \sigma_{a2}\ \phi_2\right)\ N_{rh}$$

Where:

N_{rh}	- Number density of rhodium
σ_{a1}, σ_{a2}	- Rhodium cross section functions f(N_{rh}, ppm, w/o, temp, mwd/mtu)
β_1, β_2	- Electron escape probability functions f(N_{rh})
ϕ_1, ϕ_2	- Fast and thermal neutron flux in the instrumentation thimble
C	- Conversion factor to current

Microscopic cross sections are obtained from the Westinghouse PHOENIX [4] code. Instrumentation thimble fluxes are obtained from the BEACON pin power reconstruction methodology. This on-line FID analysis method allows BEACON to process in-core flux maps at core powers less than 10% of rated power because the predicted currents are not based on correlation coefficients calculated off-line. The predicted detector currents are continuously calculated at the current core conditions. This allows the BEACON system FID map analysis function to replace other off-line codes such as CECOR and INPAX.

Soluble boron-10 depletion

Nearly all customers that currently have the BEACON system are base loaded plants which have had long periods of continuous power operation and experienced depletion of the soluble boron-10 (B-10) in the reactor coolant. This directly impacts the soluble boron measurements versus predicted results and also impacts the predictions for estimated critical conditions (ECCs) and other load manoeuvre reactivity predictions. Based on customer feedback, real time soluble B-10 depletion calculations were added to the core monitor functions in BEACON. The B-10 calculations use the integrated core neutron flux and accumulated makeup flows as shown in the following equations.

$$\frac{dB^{10}}{dt} = \int \left[-(\sigma_{a1}\phi_1 + \sigma_{a2}\phi_2) * B^{10} * \frac{V_{cor}}{V_{rcc}} \right] dv + \frac{FR_B}{V_{rcc} * \rho} * BC_{bat} * R_{bat} - \frac{FR_M}{V_{rcc} * \rho} * B^{10}$$

$$\frac{dB^{11}}{dt} = \left[\frac{FR_B}{V_{rcc} * \rho} * BC_{bat} * (1 - R_{bat}) \right] - \frac{FR_M}{V_{rcc} * \rho} * B^{11}$$

Where:

B^{10}, B^{11}	- Number density of B-10 and B-11
ϕ_1, ϕ_2	- Fast and thermal neutron flux
σ_{a1}, σ_{a2}	- Fast and thermal B-10 absorption cross sections
V_{cor}, V_{rcc}	- Coolant volume inside reactor and reactor coolant system volume
FR_B, FR_M	- Boration and makeup water flow rates
Bc_{bat}	- Boron concentration in the boric acid tank
R_{bat}	- Atomic ratio of B-10 in the boric acid tank
ρ	- Average water density

BEACON accumulates the volume of makeup and borated water added to the reactor coolant system continuously using flow rate data from the plant computer. Plant personnel can also set the B-10 atom ratio in the BEACON system based on measurements taken from the reactor coolant. The B-10 depletion effect is shown as a delta ppm boron using the design bases B-10 atomic ratio as the reference. The depleted B-10 atom ratio can optionally be used in the BEACON predictive calculations allowing ECC and other load manoeuvre predictions to account for the depleted B-10 present at the beginning of the transient.

MOX and gadolinium fuel surveillance

Specific upgrades have been made by MHI to support Japanese utility needs. One of these upgrades includes the continuous surveillance and display of the mixed oxide (MOX) and gadolinium fuel rod thermal limits. These fuel designs typically have lower thermal power limits than a UO^2 fuel assembly. The BEACON system has detailed information on the core fuel loading and can monitor the MOX and gadolinium fuel pin powers separately. BEACON then displays the maximum linear heat rate and limit for both fuel types. This information is used to continuously verify that the MOX and gadolinium fuel satisfies the lower thermal limits that are required for these fuel designs.

Conclusion

The BEACON SYSTEM allows reactor engineers to quickly and accurately monitor the current core conditions and predict future core conditions. The recent upgrades and licensing of the BEACON system by the USNRC allows it to be implemented into the plant procedures for monitoring Technical Specification limits and eliminates the need for monthly flux maps. The system upgrades also allow BEACON to be used in plants with fixed in-core detectors and eliminates the need for an off-line FID map analysis code. The BEACON system now calculates soluble B-10 depletion in the reactor coolant system and tracks power peaking of MOX and gadolinium fuel designs. As a result of these upgrades customers can choose what level of the BEACON system capabilities they will integrate into their plant operations.

Customers are now using BEACON-TSM and have started the process of integrating BEACON surveillance requirements into their Technical Specifications to significantly reduce the number of flux maps that are taken. One customer is planning to upgrade to BEACON-DMM to monitor DNBR directly and gain access to the available thermal margins for fuel cycle cost benefits. Other customers using BEACON-OLM are using the system to replace or add various core predictive and surveillance tools including their off-line in-core analysis codes, ECC predictions, load manoeuvre predictions and special nuclear material data. The BEACON system increases the knowledge of core conditions and provides information to support efficient core management activities for Westinghouse and non-Westinghouse PWR plant types.

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Figure 1. Offset assembly pattern

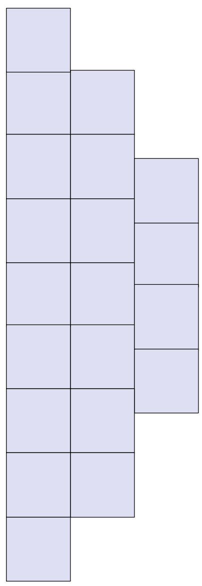

Table 1. BEACON operational summary

Level	Monitoring Function	Application
OLM	Information only	Replace off-line calculations for flux maps, ECC, SNM and core follow data
TSM	Monitor Tech Spec limits and eliminates need for power measurement flux maps	Up to 180 EFPD's between flux maps for calibration
DMM	Monitor DNBR and eliminates AFD/ASI Tech Specs and relaxes QPTR specs	Same as TSM

Table 2. BEACON installations and operational levels

Utility	Plant	Initial Installation	Current Operational Level
Korean Electric Power Co.	Kori 3	1991	OLM
Commonwealth Edison	Zion 1 & 2 Byron 1 & 2 Braidwood 1 & 2	1989 1990 1991	OLM[a]
South Carolina Electric & Gas	V.C. Summer	1992	TSM
New York Power Authority	Indian Point 3	1992	OLM[b]
Union Electric	Callaway	1993	OLM
Shikoku Electric	Ikata 3	1994	OLM
NOK	Beznau 1 & 2	1995	OLM
Florida Power & Light	St. Lucie 1 & 2	1995	OLM
Houston Power & light	South Texas 1 & 2	1996	TSM

a. Planning upgrade to DMM operational level in 1997.
b. Planning upgrade to TSM operational level in 1997.