Implementation of Surveillance & Diagnostic Systems in NPP CNA-I-II for On-Line Vibration Monitoring of RPV internals

LOCATION: Lima (100 km from Capital Federal)
OPERATOR: NA-SA
TYPE: PHWR
POWER: 370 MWe (Gross Power)
THERMAL POWER: 1179 MWth
DESIGN: Siemens
CONSTRUCTION STARTED: June 1968
CONNECTION: June 1974
C.N.A-I

Dpto. Seguridad Nuclear

Div. Gestión de Combustible y Alerta Temprana
<table>
<thead>
<tr>
<th><strong>REACTOR:</strong></th>
<th>Type PHWR – Pressure Vessel design, cooled and moderated with heavy water.</th>
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<tbody>
<tr>
<td><strong>FUEL:</strong></td>
<td>Slight enriched uranium 0.85% refueled in operation</td>
</tr>
<tr>
<td><strong>PRIMARY SYSTEM:</strong></td>
<td>Two loop each with a main pump and steam generator</td>
</tr>
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<td><strong>SECONDARY SYSTEM:</strong></td>
<td>With a saturated steam turbine, in one AP stage and three BP stages.</td>
</tr>
<tr>
<td><strong>HEAT SINK:</strong></td>
<td>By means of a river water condenser</td>
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Reactor Pressure Vessel

References:

1 – Reactor Head Vessel
2 – Filler bodies (upper).
3 – RPV (upper part)
4 – Moderator tank
5 – CC
6 – Toroidal ring (lower part)
7 – Lower Plenum
8 – Lower filler bodies.
9 – Control rod guide tube
10 – Moderator Suction Piping
11 – Toroidal ring
12 – Moderator outlet nozzle
13 – Coolant inlet nozzle
14 – Coolant outlet nozzle
15 – Control rod drive mechanism.
Total Fuel Column of Atucha I:

- **Channel closure**
  - Hermetic closure
  
- **Filler Body**
  - Decrease $D_2O$ inventory

- **Fuel Element**
  - Coupling
  - Tie plate
  - Spacers
  - Fuel rod
  - Wavy rings
  - Spring loaded Sliding shoes
  - Spacer grid
  - Fuel element
  - Fuel rod
  - Placa soporte (Tie plate)
  - Distanciador (Spacers)
  - Barra de combustible (Fuel rod)
  - Tapón de cierre
  - Elemento combustible (Fuel element)
  - Tubo soporte
  - Disco compensador
  - Vaina
  - Pastilla
  - Anillo soporte
  - Tapón de cierre
**FUEL ELEMENT**

- **Uranium total load**: 38.6 ton.
- **Clad outside diameter**: 11.9 mm.
- **Clad wall thickness**: 0.55 mm.
- **Average Burnout**: 6500/11000 MWD/ton.
- **Moderator/fuel volume ratio**: 16.8
- **Thermal flow average density**: 62 W/cm².
- **Fuel rod mean lineal power**: 232 W/cm.

### MAIN CARACTERISTICS

<table>
<thead>
<tr>
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<th>EC37BC</th>
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<tbody>
<tr>
<td><strong>Pellet length cm</strong></td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Diameter cm</strong></td>
<td>1.062</td>
</tr>
<tr>
<td><strong>Cladding Material</strong></td>
<td>Zircaloy 4</td>
</tr>
<tr>
<td><strong>Density of the pellets g/cm³</strong></td>
<td>10.6</td>
</tr>
<tr>
<td><strong>Fuel column length cm</strong></td>
<td>532.7</td>
</tr>
<tr>
<td><strong>Cladding outside diameter cm</strong></td>
<td>1.19</td>
</tr>
<tr>
<td><strong>Cladding inside diameter cm</strong></td>
<td>1.08</td>
</tr>
<tr>
<td><strong>Number of fuel rods per assembly</strong></td>
<td>37</td>
</tr>
</tbody>
</table>
Why Neutron Noise Analysis in CNA-I?

The plant was shutdown on August 15, 1988 because of a CC/FA rupture, detected by a strong oscillation in the neutronic signal of one of the power range ionization chamber, which in fact provides the hypothesis for determining the cause of the problem (other anomalies detected in relation to this event were an increase in the mean temperature of the moderator, loss of reactivity, primary activity increase). When the fuel assembly was removed from position R06 the oscillation was considerably reduced and rupture of the FA was verified through visual inspection.

The plant management and the Licensing Authority decided to implement among others the neutron noise surveillance in order to early detect this type of events. On January 1990 the plant returned criticality after repairmen’s works.

Other techniques were implemented: the on-line inspection of spent fuel which are removed from the reactor, the inspection is carried out in the Pool Building by means of a bent invert periscope; and the ND system which measure the force vs position of the FA during the stage of I/E.
Post-irradiation Inspection

- Mechanical interaction signs with channels or other body
- Debris
- Abnormal wear on fixed shoes
- Abnormal wear on elastic shoes
- Fuel rods enlargement
- Surface spots
- Other relevant news
Monitoring System ND

The ND system has two relevant tools to monitor the fuel elements (FE) during extraction operations and/or introduction in the cooling channels (CC):

- Pressure surveillance on cooling channels and detecting flow reduction due to possible foreign material, by means of pressure/position charts.

- Detection of mechanical interaction (between FE and the channel) during fuel column introduction and/or extraction manoeuvring, indicating interaction location by means of strength/position charts.
Diagrama Fuerza/Posición en una introducción de EC en Canal Refrigerante
Tanto en el EC C2966, 2967, 2968 y 2969, la Interacción Mecánica producida a los 6,58m es entre la placa portante y la boca inferior del mantel, por lo que se cree que la misma se encuentra fuera de tolerancia.
Neutron Detector Current: \[ I(t) = \langle I \rangle + \Delta I(t) \]

- \( \langle I \rangle \): Average value
- \( I(t) \): Time-dependent current

Graph showing a time-dependent current with a line indicating the average value and a fluctuating line representing the current at any given time.
SISTEMA DE MONITOREO DE LAS VIBRACIONES DE LOS INTERNOS DEL REACTOR POR RUIDO NEUTRÓNICO

Cámaras de ionización
Acelerómetros
V SPND Internos

Amplificadores de la planta

$ módulos
- Amplificadores de ruido
- Opto-aislador
- Filtro - Antialiasing

Análisis de Ruido Neutrálico
- Mal funcionamiento de los sensores
- Vibraciones anómalas
- Mal funcionamiento de los componentes
- Procesos termohidráulicos

CNA1
Use the following nomenclature:

BF3 – 2 proportional counters Gaseous ionization detector used as source range detectors.

CIC – 3 logarithmic DC compensated boron lined ionization chamber in the current mode for the intermediate range, 1 in the linear range and 2 in a vertical container inside the thermal shield

CInoC – 4 non compensated boron lined ionization chambers (current type) in the power range

SPN – 48 Self Powered Neutron detectors (vanadium type detectors), distributed in 6 lances each one with 7 detectors, and 2 short lances with 3 detectors each one
During the 2006 Peer Review some improvements areas were detected.

• What Atucha I made about that?

TARGET

Between years 1996 and 2005 all Coolant Chanel (CR), Control Rod Guide Tubes (TGBC) and Neutron Flux Guide Tubes (TGSFN) of the CNA I Reactor were replaced taking into account the Nuclear Authority Regulation requirement (ARN Nº 2507/99).

The reactor internals were designed to get more reliability and durability considering the experience with the original ones and the found degradation mechanism.

The task is to perform a In-service Inspection Program of CNA I internal components to get in advance information about material degradation.

CNA I is a PHWR prototype and there is no background of Standards Programs like in CANDU or PWR.

It is necessary to plan the Inspection Program taking into account the Operator expertise and the Designer advise.
Reactor Internals

Actual situation

- 250 Coolant Channels with Fuel Elements
- 8 Guide tubes of Self Power Neutron Detectors (6 of new design)
- 2 Coolant channels with instrumentation for the measurement of the moderator level
The Program was implemented during 2006 & 2008 Plant Planned Outages.

Early diagnosis of hidden failures in material components could be detected by an Early Detection System using some physical parameters that could give us an indicative diagnosis. The interpretation could be enhanced by a complete collection of data included the manufacturer expertise. Taken into account all of these, the Engineer Department have develop the *Early Alert Program* (E.A.P), subdivided in subgroups that accomplish the function of performing a follow up and/or measurement of physical, chemicals parameters, evaluation of indicators and visual inspections.

*This subsystems are:*

- **Off-Line Spent Fuel Elements Inspection**
- **Nd On –Line System.**
- **Nd Off-Line System.**
- **Neutron Flux Noise System.**
- **Sipping System.**
- **Chemical Monitoring System**
CHANNELS METROLOGY
- Inner diameter measurement of the Zry 4 Shroud tube.
- Length measurement of the Zry 4 Shroud tube.

REMOTE VISUAL INSPECTIONS
- Inner inspect. Of channels
- Streets Inspect.
  a) 0.4 mm foils
  b) NFLGT
  c) Moderator tank bottom.
  d) Rules for differential growths indication
  e) Pins for CBGT
  f) Toroidal ring for distribution
  g) Injection bore piping

POST IRRADIATION TESTS
- Destructive tests
- Corrosion
- H/H2 intake
- Microstructural changes by neutron irradiation.

(*) Routine during the CNA I operation

WATER CHEMISTRY SURVEILLANCE (*)

(*) Routine during the CNA I operation
INPUT FORCE

Rotating parts of pumps

Transients

Coolant flow

Dynamics of adjoining components

SYSTEM

PRIMARY CIRCUIT

SYSTEM RESPONSE

Vibrations of RPV

Vibrations of main coolant piping

Neutron noise

Pressure fluctuations

Vibrations of:
- RPV
- Fuel assemblies
- Moderator tank
- Guide tubes of Control rod

Vibrations of:
- Reactor coolant pumps
- Loops
- Steam Generator

Vibrations of:
- RPV
- CC/FA
- Moderator tank
- Flux lances
- Control rods
- Guide tubes

Vibrations of:
- Reactor coolant pumps
- Structures
- Fluid Resonances
Data base

Enough data?
Yes  No

MONITORING

Normal Signals?
No  Yes

Normal Changes?
Yes  No

DIAGNOSTIC

Normal Classification?
No  Yes

ADDITIONAL INFORMATION

EVALUATION OF THE OBSERVED CONDITION
Nuclear power plants –
Pressurized water reactors –
Vibration monitoring of internal structures

Several incidents have affected the internal structures of pressurized water reactor (PWR) units (core barrel, thermal shield), and have resulted in costly repairs. Furthermore, with the ageing of the reactors, such incidents will become more and more probable. In order to improve maintenance on such components, it is desirable to detect all abnormal behaviour at a sufficiently early stage.

The use of non-intrusive methods has shown that detection of vibratory problems having an impact on these structures is feasible during reactor operation.

It is possible to design a system which can enable regular, reliable monitoring and interpretation by specialists and therefore is expected to reduce the frequency of inspections. Standardization of such monitoring and interpretation can facilitate comparisons on an international level.
Internos de Recipiente

- Upper filler pieces
- Control rod
- Coolant Inlet nozzle
- Moderator tank closure head
- Boric acid injection line
- Coolant channel
- Moderator tank
- Pressure vessel
- Moderator piping line
- Lower filler piece
- Control rod drive mechanism
- Control rod guide assembly
- Upper support grid
- Coolant Inlet nozzle
- Support column
- Upper core plate
- Fuel assembly
- Core shroud
- Pressure vessel
- Core barrel
- Lower support grid
- Flow skirt
3 Principles of internal structure monitoring

Vibration monitoring of internal structures is based on the identification, characterization and monitoring over time of the peaks corresponding to the vibratory modes of the structures. In line with the principles of vibration mechanics, degradation in the structures shows as changes in frequency, magnitude and shape of the peaks (see figures 5 and 6). Because of the large size of the monitored structures, vibratory modes essential to the monitoring process are in the low frequency range (for instance, depending on the reactor type, below 50 Hz or 100 Hz). Furthermore, experience shows that most of the phenomena (and most kinds of degradation) evolve slowly over time (kinetics of change approximately on a one-month scale). Detection of anomalies becomes operative when, for each peak, warning thresholds for the peak frequency or magnitude are defined and exceeded.

These peaks appear on the spectral signatures of neutron noise delivered by the existing ex-core neutron detectors (for further information on the principle of measurement by ex-core neutron detectors, see annex B and figures 7 and 8) or of mechanical vibrations delivered by sensors outside the vessel. The internal structures induce a forced vibration of the vessel via the water layer between the core barrel and the vessel and via the clamping between the internals and the vessel. Accelerometers or displacement sensors mounted on the vessel therefore detect vibration of the vessel itself and of the internals (see annex C and figures 9, 10 and 11).

The decision on the monitoring technique to be applied for vibration monitoring of internal structures (i.e. in particular on the type and number of sensors) may depend on the particular conditions. Factors which influence the decision are for example:

- type of reactor and/or specific problems with internals;
- availability of knowledge for the interpretation of normal and fault-influenced structure vibrations;
- intended degree of early detection and of reliability of diagnoses.

In order to perform vibration monitoring of the reactor internal structures, at least one of the following techniques shall be used: neutron noise (see 4.1) or vessel vibrations (see 4.2). To a certain degree, vessel vibration sensors are complementary and redundant to neutron noise which uses the existing neutron detectors. Because vessel vibration sensors are based on a measurement principle different from that of the neutron detectors, they can particularly help in distinguishing vibrations from reactivity phenomena. To improve the reliability of the diagnoses, both techniques should be used.
Standard signatures changes during an anomaly.
Typical mode shapes on beam modes of fuel assemblies and moderator tank.

Typical modal shapes on the shell modes of cylindrical moderator tank.
Normal Spectra of an Ex-Core Detector
Normal Spectra of an In-Core Detector

NAPSD del Detector: NU21X155 Canal: 5

FrecMin (Hz) | FrecMax (Hz) | IntTFrec (Hz) | Dir: C:\corridas\2010\JN031225
0.000 | 40.000 | 5.000

Ymin | Ymax | IntY
-120.0 | -80.0 | 10.0

Corridas.
JN031225

Values:
1 11:10 03/06/10
2 11:16 03/06/10
3 11:23 03/06/10
4 11:29 03/06/10
5 11:35 03/06/10
6 11:42 03/06/10
7 11:48 03/06/10
8 11:54 03/06/10
9 12:01 03/06/10
10 12:07 03/06/10
Normal Spectra during a refuelling operation
Operación de recambio:
• Extracción E.C. C3167 → Fin de operación: 2:31 hs.
  Quemado: 10567.74 Mwd/tnU235.
• Introducción E.C. C6009 → Fin de operación: 2:47 hs.
  Quemado: 9452.62 Mwd/tnU235.
Repair of the YX04X04 chain measurement including the replacement of the movable container chain, which are lowered through guide tubes to their measurement position. This guide tubes are mounted at the wall of the biological shield within the thermal insulation, and the container has wheels specially adapted to the inner surface of the guide tubes, which allows them to be easily installed and moved through the guide tubes.
Spectra of a detector in lance 6 showing a deviation in the spectra from the normal situation.
NAPSD del Detector: NU21X115 Canal: 6

NAPSD (dB/1Hz) vs Frecuencia (Hz)
Inspection in pools shows some deformation in the spacer Nr 15 in both FE. The plant was shutdown on 28/07/13 to perform an inspection of the N10 channel, inside and outside.

**The result**: a fracture on the wall of the channel ~ spacer 12

Sequence
- Ext. C3786
- Intr. C6174
- Ext. C6174
- Intr. C3786
The CC in the N10 position was inspected in 2009, and his 2nd inspection was during the outage of 2013, nothing new were reported during these inspections.

The analysis of the film record in both external and internal faces of the channel after this event allow us to presume that the starting event was an external interaction with the CC in some moment during the transport from the decay pool to the reactor.
Spectra after the change of CC in N10 position

NAPSD del Detector: NU21X115 Canal: 1

Spectra after the change of the CC

Frecuencia (Hz)

NAPSD (dB/1Hz)
Monitoring the vibratory behavior of RPV internals, moderator and primary circuit components (Basic SÜS)

The components of the primary circuit including supports behave as a vibrating coupled multiple-mass system. Depending on the degree of coupling each sensor located on one of the components of the primary circuit provides vibration information of several components. This holds also for the moderator circuit. The vibration behavior can be characterized by vibration characteristic functions and vibration characteristic variables. At specified steady state normal plant conditions reference measurements are performed to carry out reference characteristic functions, reference characteristic variables and their values (reference values) of the reference measurement signals. These reference measurements are performed for the first time after commissioning of the reactor plant (zero reference measurement) and afterwards only in justified cases. During the following plant operation further measurements (operational measurements) at steady state normal plant conditions are preformed. In order to ascertain changes in the vibration behavior the characteristic functions and variables of the operational measurements are basically compared with the declared valid reference characteristic functions and variables.
The Vibration Monitoring System SÜS provides all necessary measurement and monitoring functions such as:

- signal acquisition,
- signal conditioning and calibration,
- signal analysis and monitoring,
- data storage and archiving,
- data display and documentation,
- announcement of system faults (to TXP), and
- announcement of threshold violations (to TXP).

The system is designed for measurement, monitoring and evaluation of the measurement variables in the frequency range 0.5 to 200 Hz.

- 4 absolute displacement transducers, on pressure vessel head,
- 8 accelerometers, on the hot and cross-over legs,
- 12 neutron flux signals (power range),
- 8 absolute frame vibration transducers, on the 4 moderator pumps

The selected monitored frequency range, transducer types and locations are based on the monitoring objectives, the applied rules and standards like IEC 61502, DIN 25475/2, KTA 3204, and KTA 3201.4 as well as on the experience with already installed vibration monitoring systems in pressurized water reactors.
Sensores de desplazamiento absoluto

Acelerómetros

Sensores Inductivos

Acelerómetros

Sensores temporarios

Sensores temporarios
Vibration monitoring of the reactor coolant pumps

For pump vibration monitoring the monitored parameters are determined from the measured signals in time domain (monitored parameters: maximum radial relative shaft displacement amplitudes between shaft and frame and maximum radial absolute frame vibrations) as well as from the vibration characteristic functions in frequency domain (monitored parameters: magnitudes of the speed harmonic peaks in the spectra of the measured shaft and frame vibrations).

The pump vibration monitoring in frequency domain is used for early warning purposes.
Figura 7. Espectro de los SG09 y SG10 colocados en la bc 30 del EC en BE-32, se indican las principales frecuencias identificadas y la coherencia entre ambas señales que está a 90º entre sí. Medición del 19/09/2013.
Figura 18. Amplitudes máximas de desplazamiento del plano II (composición de las señales de los sensores SG11 y SG12 en el canal BE32. Medición del 30/09/2013.
END
OF
PRESENTATION