NAJA: A NEW NON-DESTRUCTIVE AUTOMATIC ON-LINE DEVICE FOR FUEL ASSEMBLY CHARACTERISATION AND CORE LOADING CONFORMITY CONTROL

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Abstract

Presently, there is no physical measurement of the fuel assemblies which are loaded in the PWR core (except a visual control) and no fully automatic procedure to be sure of the core loading. Consequently, a video recording has to be performed prior to vessel closure and a large set of start-up tests has to be done. In order to improve the fuel management itself and the safety / availability of the power plant, an R&D project (called NAJA) is being carried out by CEA and EDF. It consists of developing a measurement device which combines nuclear methods and video control to evaluate the physical characteristics of each fuel assembly (burn-up, reactivity, initial enrichment,...) and to validate automatically the final core loading. Such a device would be placed on the passage of the fuel assembly between the storage pond and the reactor building and it would have no influence on the loading / unloading schedule.

Introduction

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It consists of developing a measurement device which combines nuclear methods and video control in order to evaluate the physical characteristics of each fuel assembly (burn-up, reactivity, initial enrichment...) and to validate automatically the final core loading.

Such a device would be placed on the passage of the fuel assembly between the storage pond and the reactor building. It should be useful for core loading conformity control and on-line core monitoring.

Objectives

The NAJA device is able to determine automatically for each assembly:

- The nature of the fuel element (fresh or irradiated, UOX or MOX);
- The presence and the kind of neutron absorber;
- The initial enrichment in ^{235}U for fresh UOX assembly;
- The identification number.

This information allows us to characterise the fuel assemblies accurately and to be sure, without human factor hazard, of the core loading conformity.

Description of the device

The NAJA device has been optimised in order to take into account severe constraints (no influence on the loading or unloading schedule, no need for human interface, no impact on operation). Such optimisation has led to the following conclusions:

- Without human interaction, the device controls each assembly which goes to the reactor building (loading) or which goes to the storage building (unloading).
- The device is located on the passage of the fuel elements on the pond building near the transfer tube (Figure 1).
- Three nuclear methods are applied to cover the whole fuel assembly panel (Active Neutron Interrogation, Passive Neutron Counting, Gamma Spectrometry).

- An ultra-sonic probe is used to monitor the different parts of the fuel element (foot, beginning of the fissile length).

- A video system linked to an Optical Character Recogniton (OCR) software leads to an automatic reading of the fuel assembly number.

In fact, two video systems are planned to be used: the first one is linked with the NAJA device in the storage pool and the second one is linked to the loading machine in the reactor building. These two video systems are necessary in order to be sure of the good appropriateness between the position X,Y of the fuel assembly in the core and its physical characteristics (UOX or MOX fuel, burn-up, initial enrichment in ^{235}U, kind of absorbent...). Successful tests of the OCR software have been performed even for “black” (e.g. corroded) fuel assembly numbers.

One of the big interests of the NAJA device consists of the combination between the nuclear measurements, the ultra-sonic probe and the video system which allows to associate each fuel element placed in the core to a fuel identification number and its physical characteristics without any information coming from the operator. The combination between the ultra-sonic probe and the nuclear device leads us to assert the reproductibility and the reliability of the fissile column measurement.

A description of the different modules is presented in Figure 4. The principle of the NAJA device is the subject of a patent deposit (under way at the moment).

Remark:

More precisely, the nuclear methods are as follows :

- A passive neutron counting which consists of detecting the neutrons emitted by the heavy nuclei of the irradiated assembly (spontaneous fissions and (a,*n*) reactions). This technique is particularly adapted for the evaluation of the average burn-up of the spent fuel, due to the strong dependence between neutronic emission and burn-up [1,2].

- An active neutron interrogation which has been developed in order to obtain interpretable information directly in terms of the multiplying factor of the assembly (related to subcriticality characteristics). Figure 2 describes the physical principle of the measurement and Figure 3 gives an example of “active and passive” neutronic signal along the assembly [3].

- A gamma spectrometry measurement which consists of measuring, along the assembly with two high efficiency gamma ray detectors, the activities of different fission and activation products and in correlating the results with physical parameters (burn-up profile.) [1].

All of these non-destructive methods have been developed and qualified for other purposes: safety-criticality control before spent fuel evacuation in nuclear power plants [3,4], nuclear process monitoring in reprocessing plants [1], safeguards of nuclear material [5,6]. Their application and optimisation for this NAJA project have been performed through the feasibility study which is described in the paper.

State of the work

At the present time, the feasibility study is over (both nuclear and optical aspects) and the work continues by a mechanical setting-up study and a prototype specification.

The panel of the fuel assembly characteristics which have been taken into account is large and representative of the French fuel cycle:

- Average burn-up of the spent fuel from 6000 MWd/tU to 48000 MWd/tU;
- Cooling-time varying from 1 to 90 days;
- Initial enrichment in ^{235}U for UOX assembly varying between 3 and 4 %;
- Nature of neutron absorbent: pins containing silver, indium, cadmium and / or pins containing silver, indium, cadmium and boron carbide (B_4C).

This feasibility study has been performed in a very precise way in order to take into account the different sources of uncertainty such as:

- Inexact knowledge of the irradiation history. This fact will give an error on the interpretation of the measured neutronic emission in terms of burn-up.
- Statistical uncertainty. This source is of particular importance in the case of low burn-up (first cycle in reactor).
- Calibration uncertainty.
- Measured profile uncertainty.

The study indicates the good performances which should be obtained with the NAJA device (for example ±2% as a global uncertainty at two standard deviations on the absolute average burn-up evaluation) without any influence on the loading or unloading timing.

Some results of the feasibility study are presented in the two following paragraphs.

Evaluation of the average burn-up

The study was focused on the penalising case which corresponds to an average burn-up of 6000 MWd/tU (e.g. lower neutron counting rate, that is to say higher statistical uncertainty).

The values of Neutronic Emission (NE) as a function of burn-up for different cooling-time are as listed in the following table (for an UOX 17×17 PWR assembly with 3.7% initial enrichment):

Neutronic emission (n/S/tUm)

BU (MWJ/tU) Cooling Time (d)	6000	8000	10000	12000
1	$1.80 * 10^6$	$4.38 * 10^6$	$8.89 * 10^6$	$1.59 * 10^6$
10	$1.74 * 10^6$	$4.24 * 10^6$	$8.59 * 10^6$	$1.54 * 10^6$
20	$1.69 * 10^6$	$4.10 * 10^6$	$8.30 * 10^6$	$1.49 * 10^6$
30	$1.65 * 10^6$	$3.96 * 10^6$	$8.02 * 10^6$	$1.44 * 10^6$
60	$1.51 * 10^6$	$3.59 * 10^6$	$7.24 * 10^6$	$1.30 * 10^6$
90	$1.39 * 10^6$	$3.27 * 10^6$	$6.56 * 10^6$	$1.18 * 10^6$

Considering an efficiency (evaluated with experimental and theoretical approaches) of about $2.6 * 10^{-5}$ c.s.$^{-1}$ / n.s.$^{-1}$, the average count-rate will be of about 43 c.s., which leads (for 36 s counting time) to a statistical uncertainty on the neutronic emission measurement (at 2 standard deviations) of 5%, that is to say an uncertainty on the burn-up evaluation of 1.6%.

Moreover, the inexact knowledge of irradiation history leads to a maximum error of 6% on the neutronic emission evaluation which corresponds to 1.9% error on the burn-up evaluation.

In the worst case, the uncertainty on the burn-up evaluation will be between 2.5% (BU # 6000 MWJ/tU) and 2.1% (BU # 12000 MWJ/tU).

Evaluation of the ^{235}U initial enrichment for fresh UOX assembly

The ^{23} U Initial Enrichment for fresh UOX assembly is obtained using an active neutron interrogation (creation of fission by an external ^{252}Cf neutron source and detection of the prompt fission neutrons).

The sensitivity study (using theoretical and experimental approaches) indicates that such a technique can give initial enrichment a precision at 2 standard deviations of about 1% (in relative) and that distinction between 3.25%, 3.70%, and 4% will be made without any problem.

Detection of the nature of neutron absorbent

The active neutron interrogation (giving an information linked to the effective multiplying factor K_{eff}) can separate the nature of neutron absorbent without any problem. The results of calculations are shown on the following table.

Assembly Type	K_{eff}	$2 * \Delta K_{eff} / K_{eff}$ %	Discrepancy* %
No absorbent	0.60727	0.50	ref.
S.I.C absorbent	0.54468	0.50	-10
S.I.C + B_4C absorbent	0.48354	0.50	-20

* Discrepancy % = (absorbent - ref) / ref. * 100.

Potential uses of the NAJA device

They derive directly from the two main functions of this device:

1. The core conformity control which allows us to increase significantly the safety level of the plant.
2. The absolute and accurate burn-up measurement of the irradiated fuel assemblies which allows us to improve the global availability of the power plant and to gain some investment benefits.

Increase of the safety level of the plant

The core loading error which is studied as a class 3 accident in the initial safety analysis report can be rejected. This is due to automatic reading of the identification mark of all the fuel assemblies loaded in the core. This information, combined with the X,Y position of the loading machine, permits to be sure of the final core loading conformity without human factor hazard.

The combination of the automatic recognition of a fuel assembly and its physical signature allows us to validate more deeply, by additional calculations, the core loading conformity. Under these conditions the core loading calculation error can be rejected and:

- The critical risk due for instance, to manipulating error during refuelling operation at shutdown conditions, or during reactor operation in the spent fuel pool (especially when a high enrichment is used) can be significantly reduced.
- The spent fuel checking, compulsory before shipment for reprocessing plant for high enrichment (higher than 4% for UOX and higher than equivalent 3.7% ^{235}U MOX) can be accomplished.

Remark:

The active neutron interrogation can be optional.

In fact this function allows to check the fuel manufacturer conformity (manufacturing conformity and sending conformity). If one postulate the global fuel manufacturer conformity (enrichment, amount of poison...), this function can be cancelled and so, the device would be simplified.

Improvement of the global availability of the plant and gain of some investment benefits

This device allows us to close the “measure / calcul loop” and to follow very precisely the fuel burn-up from the beginning to the end of its life. This fact permits to increase the global availability of the plant and to achieve some investment benefits.

- Increase the reactor availability:

  - Direct benefit due to the fact that the video recording actually done is on the critical path. NAJA device should allow us not to do that anymore.

  - Improvement of operating margins is expected, due to a reduction of calcul / measure uncertainties because of the better knowledge of the fuel burn-up.

  - Improvement of the reshuffling itself because of the knowledge of the measured fuel burn-up with a very accurate procedure.

- Gain some investment benefits:

  The reliability, the reproductibility of the NAJA measurements, and the fact that an automated procedure would be used, should normally allow us to take “burn-up credit” into account in design calculations.

  The corresponding benefits depend strongly of each specific case:

  - New design, refurbishing, or modification of an existing design;

  - Dry storage or wet storage;

  - Partial (spent fuel pool only) or total use (fresh fuel and spent fuel storage and transportation) of this concept.

At last NAJA device permits to perform precise and fine measurements:

- In hidden time during shutdown operation on fuel assemblies which will be reloaded;

- At any time on definitely discharged fuel assemblies in the spent fuel pool.

These fine measurements can be very useful for a better understanding of a typical problem (defect in a fuel assembly for instance) or for studies strongly sensitive to burn-up history.

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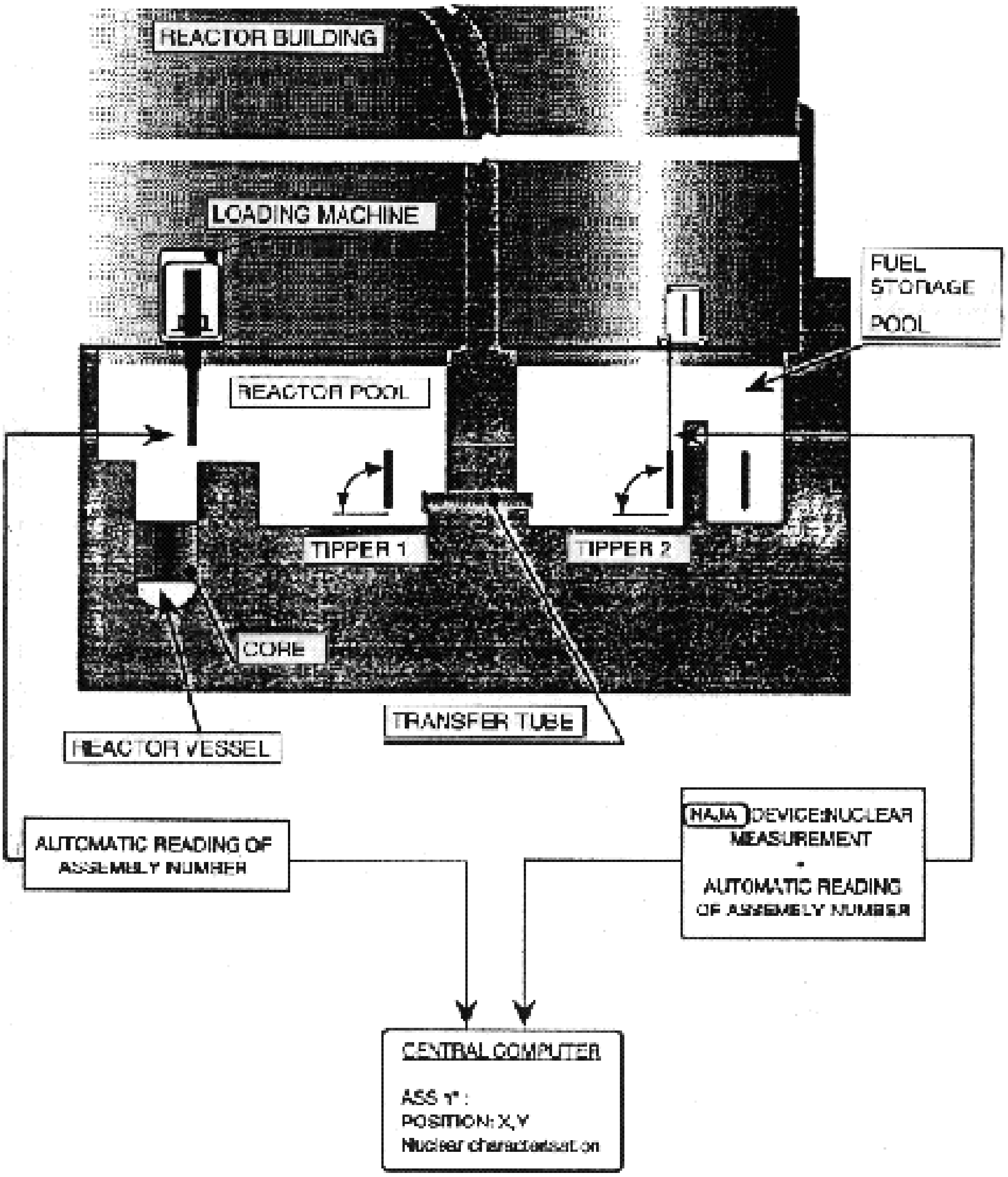
Figure 1.



REACTOR BUILDING
LOADING MACHINE
FUEL STORAGE POOL
REACTOR POOL
TIPPER 1
TIPPER 2
CORE
TRANSFER TUBE
REACTOR VESSEL
AUTOMATIC READING OF ASSEMBLY NUMBER
NAJA DEVICE:NUCLEAR MEASUREMENT
+
AUTOMATIC READING OF ASSEMBLY NUMBER
CENTRAL COMPUTER
ASS n° :
POSITION: X,Y
Nuclear characterisation

Figure 2. Physical principle of active neutron interrogation

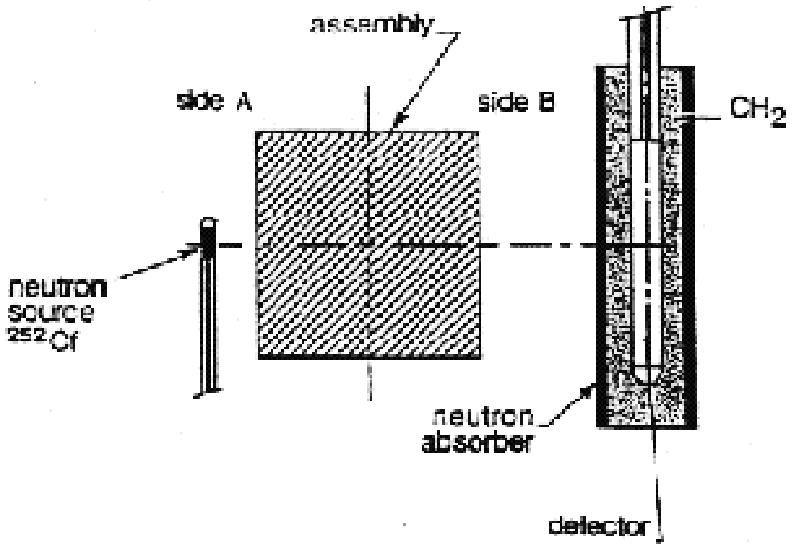


Figure 3. "Active and passive" neutronic signal along the assembly

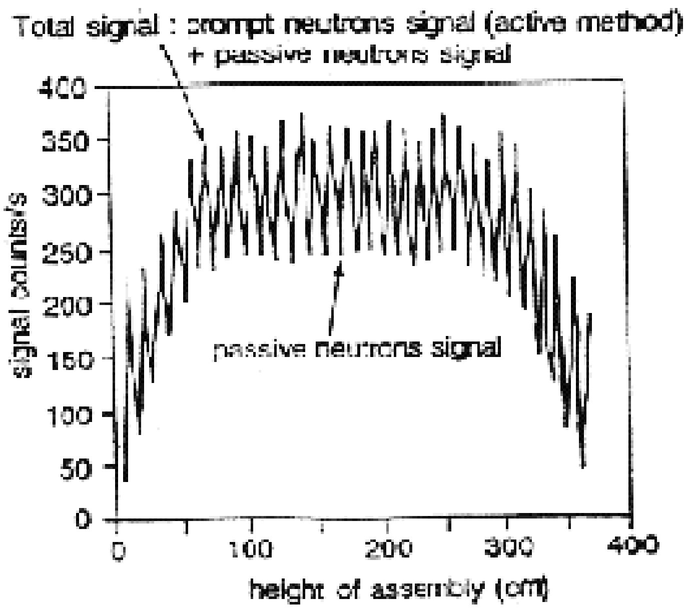


Figure 4. NAJA device setting-up principle in storage pool