# RELIABILITY ANALYSIS AND EXPERIMENTAL RELIABILITY PARAMETER DETERMINATION OF NUCLEAR REACTOR EQUIPMENTS

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**Abstract:** This paper describes the experimental tests performed in order to determine reliability parameters for certain equipments manufactured in INR Pitesti, for NPP Cernavoda.

The tests were provided by Technical Specifications and test procedures. The laboratory tests were performed in such running and environmental conditions that correspond to the real operating ones from NPP.

A special attention was paid to the accelerated tests (intensive tests), where stress level applied is above the level established by reference condition (stated by design); the acceleration of the operating conditions in the sense of a time compressing may be considered, in the case of a product where it was stated that the reliability parameters depend mainly on the number of the operating cycles.

On the other hand, there are presented reliability improvement measures taken in order to check that the equipments would operate within design specification. The results of tests and the conclusions are given also.

It is also to be mentioned that this paper is a partial layout of the results of a Scientific Research Contract concluded with IAEA Vienna, where the Author have been CSI (Chief Scientific Investigator).

**Keywords:** Reliability, Experimental, Parameters, Laboratory testings

## 1. INTRODUCTION

The information regarding the reliability of products are obtained, in principal, by following the behaviour during the real operation or during the laboratory tests.

Each of these 2 ways presents, in the same way, advantages and limitations. In case of real operation all the phenomena appeared during product operating are recorded, [3 ].

At the moment of the conclusion formulation these may present just a historical significance, the purpose of the reliability tests being used to improve a performance level of the current manufacturing.

To these limitations of the methods of the real operation, are added the difficulties connected to accurate acquisition of data or deficiencies of the informational system, [4].

Without excluding these methods which present a lot of disadvantages it is necessary to use the method of the laboratory tests.

During the laboratory tests the samples (systems, modules), are operating in certain conditions close to the real ones, in the NPP, being necessary the existence of special testing devices and qualified personnel, [1,2,7, 8 ].

Considering the nature of the product (e.g. unique, great series), the observation of the behaviour and acquisition of necessary information may be organized following different schemes. In every case it is necessary that the operation of records to be conceived.

- *each product is regarded like a complex system with a hierarchical structure having many subsystem components, pieces, elements, etc.;*
- *for every product or component element the records of the information, essential to trace-out factors which concerned their reliability level.*
- *observation and recording of information have to be organized based on a certain purpose; considering the analysis and information processing, the decisions regarding the increasing*

*reliability* level of the product are grounded; a problem which must be taken into consideration is the organization of laboratory tests, and where necessary a very good practical experience;
- choosing of the essential considered parameter that must determine the reliability at a certain moment;
- establishing of environment and stress (required) conditions that the experiment is running and must take into consideration the practical situations in which the elements will operate..

During the tests a systematic record is necessary which will stay at the final decision of the test, such as:

- *The time (beginning of the test, the occurrence of failures, etc.).*
- *Details on the stress and environment conditions.*

The main parameter of reliability which will be considered will be the MTBF.
In the followings we will assume that the theoretical reliability law will be exponential.
A special attention has been granted to the accelerated tests, where stress level applied to the components is above the level established by reference condition (stated by design).

## 2. FAILURE MODE AND EFFECT ANALYZE (FMEA)

During laboratory tests (type and production tests) the performance failures which occurred have been noted, [5, 6 ].
For functional tests in normal operating conditions at NPP we got no failures. Environmental tests were carried out in two stages:

- *burn-in test* (to cover the initial failure period of "bath-tube" curve); - see Fig. 1, [ 3, 7 ] :
- *accelerated thermal aging tests* (to demonstrate that the life period for equipments which are intended to be used in NPP at SDS#1 must be 30 years).

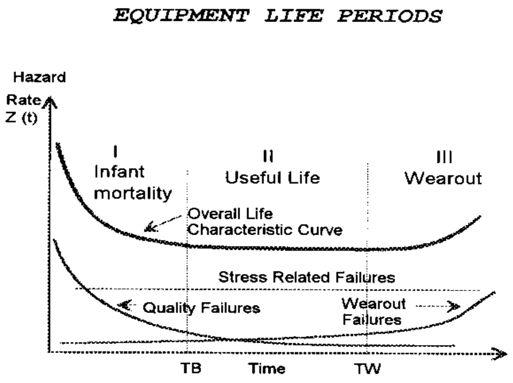

FIG. 1 Components of failure

The analyzed nuclear reactor instrumentations were [5, 6 ]:
- *Dynamic Signal Compensation Module (DSCM);*
- *Trip Test/Alarm Control/Buffer Amplifier (TT/AC/BA);*

During performing laboratory tests there were analyzed, through the FMEA (Failure Mode and Effect Analyze) method the nuclear instrumentations included in SDS#1 (Shutdown system no.1), manufactured in INR Pitesti, for NPP CANDU Cernavoda (see fig.2) :

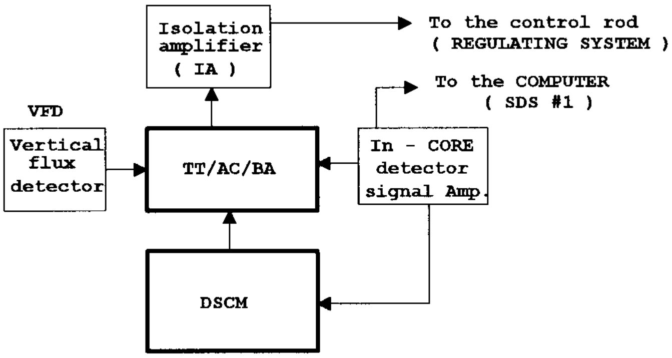

FIG. 2 Connection between DSCM and TT/AC/BA

Burn-in test was performed for these modules for a period of 240 hours, divided into 10 cycles of 24 hours each, and the following failures were recorded:

(a) **for DSCM**

- 2 due to the fuse (short);
- 2 due to the input cable (for the input signal) - short;

(b) **for TT/AC/BA**

- 1 due to the resistor incorporated in the supply part of the module;
- 4 due to the fuse;

As a consequence, the decision was to replace the fuse type, cable type and the resistor.
During accelerated thermal aging test we did not observe any failures. This test has been carried out in the following conditions:
- 14 cycles of 96 hours each at 65°C and RH = 30 ÷ 40 %. After every cycle, the temperature was decreased at 55°C, 1 hour, for reading the parameters. The test is based on Arrhenius's law, and the duration of the test was calculated taking into consideration the specific activation energies for every electronic component belonging to DSCM and TT/AC/BA reactor instrumentation (DSCM was exposed 1354 hours and TT/AC/BA 2007 hours).

The implied failure rate is less than .45284 $F*10^{-6}*h^{-1}$ (allowed $.5*10^{-6}*h^{-1}$).
Estimate of the relative probabilities of the modes, as percentage:

| Mode | Est. (%) of total failures* | Remarks |
|---|---|---|
| I | 57 | Fuse |
| II | 29 | Input cable |
| III | 14 | Resistance |

* See also Diagram 1

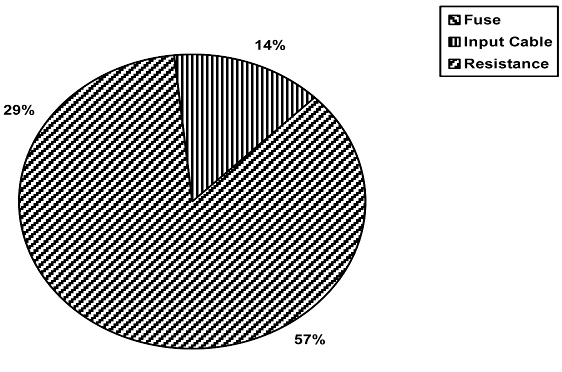

Diagram 1- Estimation of failure mode (as percentage)

Reliability actions taken as a consequence of these failures were:

a. - use of redundancy circuits for module supply system. As a result, the reliability increases as shown (see table 1):

**Table 1**

**Reliability ***

| | **No redundancy** | **with redundancy circuit** |
|---|---|---|
| **DSCM** | .8843 | .950784 |
| **TT/AC/BA** | .8568 | .98273257 |

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*** See also the Diagram 2**

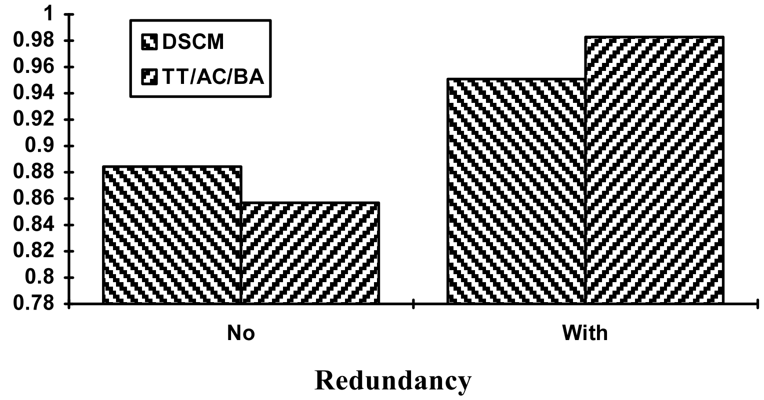

**Diagram 2-Improvement of Reliability (DSCM and TT/AC/BA) vs. Redundancy.**

b. - use of the specific screen to detect (eventually) the unreliable components when, particularly, failures modes or mechanism were known or suspected to be present,
[8, 9, 10, 14 ].

## 3. EXPERIMENTAL RELIABILITY DETERMINATION REACTOR INSTRUMENTATION FOR THE NUCLEAR, RELIABILITY TESTINGS.

During carrying-out laboratory tests for the equipments, no failures were recorded. In this situation, the experimental reliability determination parameters were calculated based on the parametric reliability model followings the behaviour of certain parameters vs. time, for every equipment taken into consideration, in the testing intervals. The failures occurred during *"burn-in"* tests were not considered because were repaired, in time, and there were not repeated during reliability tests. The following parameters were measured: **U0** (output voltage) for DSCM, the report neutron flux rate vs. neutron flux for FFLS, volume activities for HTSRM. It was stated that the sum of the determined errors can be assimilated with a straight line; therefore the Gaussian character of the repartition was assumed. To establish the defect fractions, the following steps were considered:

- *The ranking of the calculated errors values, from minimum to maximum;*
- *Determination for every "i" values of the repartition function, Yi=(i-1/2)X100/N, where N is the no. of the repeating measurements and "i" is the ranking number;*
- *graphical representation of the pair values"mi, Yi";*
- *Graphical representation of the envelope curve errors, for every interval;*
- *Determination of the defect fraction in every interval;*

The determined defect fractions were transferred in the Weibull probability paper, and using the graphical formula β, η and γ factors were determined. To calculate the experimental reliability parameters the following relations were used :

$$R(t) = \exp[-(\frac{t-\gamma}{\eta})^{\beta}] \qquad (1)$$

where β, η, γ are the above mentioned parameters graphical determined; MTBF was calculated with the formula:

$$MTBF = \gamma + \eta \cdot \Gamma(\frac{1}{\beta} + 1) \qquad (2)$$

where $\Gamma(\frac{1}{\beta} +1)$ is the Euler function, first type.

The hazard rate, z(t) , was determined with formula :

$$z(t) = \frac{\beta}{\eta} \cdot (\frac{t-\gamma}{\eta})^{\beta-1} \qquad (3)$$

where: β, η, γ, are specific parameters which can be determined in a graphic mode.

Practical example:

For HTSRM the following parameters were determined, as followings:

$\beta = 3.2$; $\eta=1{,}900$; $\gamma = 0$ ; $\Gamma=0.896$

$\text{MTBF} = \gamma + \eta.\ \Gamma(1+\frac{1}{\beta}) = 0 + 1{,}900 * 0.896*(1+ 0.325) =1702.4 * 1.03125 = 1756$ h

$\Sigma\lambda = 569.7$ F / 10^6 h

The activity carried out was focused on experimental reliability determination for the nuclear reactor instrumentation, manufactured in INR Pitesti, as follows:

- *Failed Fuel Location System (FFLS);*

- *Heat Transfer System Radioactivity Monitor (HTSRM);*

- *Dynamic Signal Compensation Module (DSCM);*

The reliability tests were performed in two steps: [11,12,13]

- *Qualification tests;*
- *accelerated tests;*

These tests were performed in accordance with the technical specifications for the equipment to be tested.

### 3.1 Experimental reliability tests for failed fuel location system (FFLS)

In a CANDU reactor the purpose of the Failed Fuel Location System (FFLS) is to locate and to find in what channel, what particular fuel bundle pair is failed. To do so, D2O samples from each channel are sequentially monitored to detect a comparatively high level of delayed neutron activity.
Qualification (type) tests (according to Technical Specifications) last about 1,268 hr. and the intensive tests, last about 496 Hrs in 12 cycles. Intensive tests were done for approx. 496 hrs within 12 individual cycles, each cycle consisting of 7 automatic scanning. During these scanning the following failures were noticed:

- *1 failure due to locking pin (failure to function);*
- *1 failure due to error in positioning of carriage (failure to remain in position).*

These events were not as a result of an electronic component failure, and were eliminated by increasing the hysteresis of the discriminator that treats transducer head signals, and by providing a constant force on the locking pin coil. These were done by changing a resistor value in the feedback loop of the discriminator. The performance of the reliability test (as shown above) on the FFLS equipment was in accordance with the specific reliability procedure prior approved by Canadian part.

The sum of these failure is less than $.1\ F*10^{-6}*h^{-1}$, and not affecting, significantly, the MTBF value, and also the operation of the tested equipment.

**Total test time**: 2**,016 Hrs**; **No. of failures: 2**

The experimental reliability parameters thus obtained (for non-parametric errors) are given in Table 2:

**Table 2***

| | Provided in TS | Experimental |
|---|---|---|
| **MTBF (Hrs)** | 936 | 1,008 |
| **R (10 Hrs)** | .9836 | .990 |
| **R (24 Hrs)** | .974 | .976 |
| **R (168 Hrs)** | .835 | .846 |

*See also Diagrams 3 and 4

MTR = 2 h

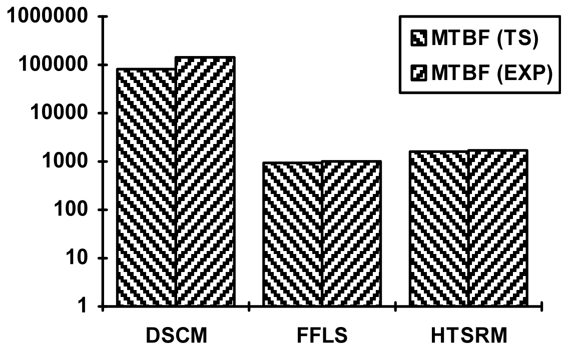

Diagram 3-Experimental determined MTBF vs. provided in TS

### 3.2 Reliability testings for heat transfer system radioactivity monitor (HTSRM).

HTSRM is a complex dozimetric equipment which check the state of the fuel from CANDU reactor by monitoring the fission products. Is an equipment complementary (as function) with FFLS and manufactured to measure the activity of 4 radionuclide's (Kr-88, Xe-133, Xe-135, I-131), characteristic for PHWR CANDU. The reliability testing was developed on the first sample of product by operation in laboratory conditions for 1,000 Hrs. During testing there were noticed no failures, and because of that, processed the parametric defects values, calculating the relative errors on the measured volume activities, by using Ba-133 source, consisting of 4 pairs of vessels in increasing order of decades.

The displayed values for volume activities, the activities in the currents and the detector-generated impulses constituted the data bank necessary for reliability performances calculation.

Experimental reliability parameters obtained from the reliability tests allowed the pointing out of the reliability performances of HTSRM product.

**The HTRSM experimental reliability parameter are given below in Table 3 :**

**Table 3***

| | Provided in TS | Experimental |
|---|---|---|
| **MTBF ( Hours**) | >1,600 | 1,756 |
| **R ( 24 hr**s) | .987 | .99 |
| **R (600 hr**s) | .721 | .97 |
| **R (1,200 hrs)** | .52 | .79 |

* See also Diagrams no 3 and 4

MTR = 8 h

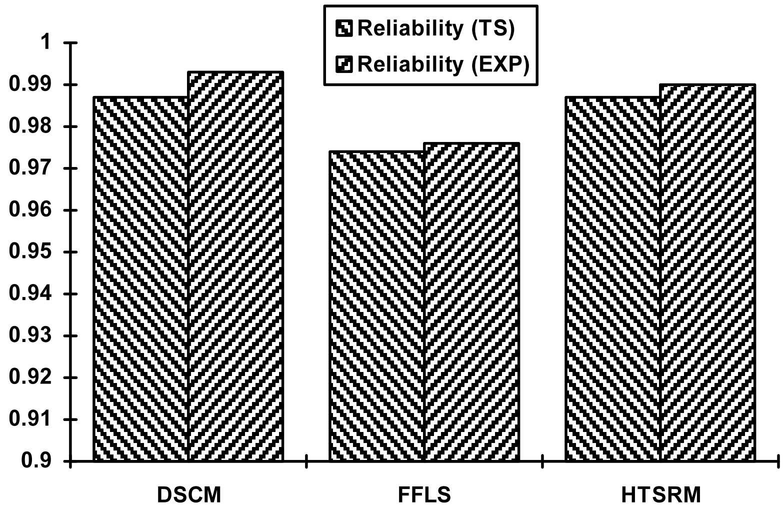

*Diagram 4- Experimental determined Reliability vs. provided in TS*

### 3.3 Experimental reliability tests for dynamic signal compensation module (DSCM).

The purpose of DSCM module is to eliminate the time constants of 30s and 2,500 s which appear within output signal of the Self - Powered Platinum Detector from SDS #1, specific for a PHWR CANDU Reactor Type. This module is associated with the TT/AC/BA( see also fig.2).
Reliability tests for DSCM were performed in two steps:

- *Qualification of tests* for a period of 200 Hr. (according to the Technical Specifications:
- *Accelerated tests*, for a period of 1,400 Hr., 4 devices (samples) being exposed in the following conditions: *temperature 55°C, RH =80 %.*

During these tests, the recorded parameter was U0 (output voltage). No failures have been recorded. The evolution in time of the parametric error corresponding to U0 parameter was followed.
The experimentally reliability parameters are shown in Table 4:

*Table 4*

| | Provided in TS | Experimental |
|---|---|---|
| MTBF (Hours)* | 81,500 | 142,572 |
| R (1,000 hr.)* | .987 | .993 |
| R (10,000 hr. | ..885 | .931 |
| **A** (Availability) | 99.96 | 99.97 |

** See also Diagrams 3 and 4*

*MTR = 4 h*

As a conclusion, the experimental reliability parameters are superior to those calculated by provisional standard methods.

## 4. IMPROVING THE RELIABILITY OF COMPONENTS AND SYSTEMS MANUFACTURED IN ROMANIA (UNDER CONSIDERATION) FOR NPP CERNAVODA BASED ON EXPERIMENTAL RELIABILITY TESTING PROGRAM.

Have been taken into consideration the followings:

- I*mproving the reliability of components and systems* manufactured based on experimental test program [1, 3,14,15].
- *Comparison of the generic data base being used for the PSA of NPP* Cernavoda with the specific results of components reliability experimental results [15, 16, 17].
- *The use of short test duration* to estimate the performance characteristics of components with respect to actual mission time, [2, 5, 6,18 ].

According to the objectives defined above, we reviewed a certain part of projects of the equipments taking into consideration the results of the experimental test program. The improvements are as followings :

### 4.1 For FFLS equipment the following reliability improvements have been done:

- Modifications of software, in certain parts, to assure a more correct operation of the "watch-dog" and for a better communication between those two microcomputers belonging to the FFLS;
- Improvement of the optical decodification system for carriage positioning (increased accuracy of positioning);

### 4.2 For HTSRM equipment the following improvements were performed:

- Modification of software in the acquisition system in certain subroutines ;
- Replacement of the step by step motors through direct- current motors for a better accuracy of the collimator positioning and a better operation of the equipment.

**Note**: *A soft-ware is subjected to failures at random times caused by errors present in the system. In order to evaluate the software failure phenomena for FFLS and HTSRM equipments, we applied (partially), the stochastic model, developed and based on a non-homogeneous Poisson process*, because of its applicability for the estimation of parameters when the available data are in the form of times between errors or as number of errors in given time intervals, [19].
The basic used model was:

$$m(t) = a[1 - \exp(-bt)] \qquad (4)$$

where: $a$ is the s-expected number of software errors to be detected, $m(t)$ is the s-expected number of software failures by time t and b is a constant of proportionality.
This method is under developing in INR Pitesti and the results are optimistic and will be presented in a separate paper, under publication.

### 4.3 For DSCM module the following reliability improvements measures were performed :

- *Use of redundant power supply circuits;*
- *Use of the components with a reduced stress factor;*
- *Replacement of the fuses with a new type of such components, more reliable;*

These reliability improvements measures, together with others, taken during the manufacturing of the above electronic equipment (use of military components with a lower failure rate, use of 100% screening before mounting, use of "*burn-in*" for electronic components and for the equipments), have contributed to the increasing of reliability parameters [1,2,14 ] as it can be seen in the comparative Table 5:

**Table 5**

| *Equipment* | **FFLS** | **HTSRM** | **DSCM** |
|---|---|---|---|
| **A. Failure rate** | | | |
| (F/$10^6$*h) | | | |
| - estimated | 1,068.37 | 625.0 | 12.171 |
| - experimental | 992.06 | 587.4 | 7.014 |
| **B. Reliability (R)** | | | |
| **for 10 Hr.:** | | | |
| - estimated | .9893 | * | * |
| - experimental | .990 | * | * |
| **for 24 Hr.:** | | | |
| - estimated | .974 | .987 | * |
| - experimental | .976 | .99 | * |
| **for 168 Hr.:** | | | |
| - estimated | .835 | * | * |
| - experimental | .846 | * | * |
| **for 600 Hr.:** | | | |
| - estimated | * | .721 | * |
| experimental | * | .97 | * |
| **for 1,200Hr**. | | | |
| - estimated | * | .52 | * |
| - experimental | * | .79 | * |
| **for 1,000 Hr.** | | | |
| -estimated | * | * | .987 |
| -experimental | * | * | .993 |
| **for 10,000 Hr**. | | | |
| - estimated | * | * | .885 |
| - experimental | * | * | .931 |
| **MTBF (HR.)** | | | |
| - estimated | 936 | >1,600 | 81,500 |
| - experimental | 1,008 | 1,756 | 142,572 |
| **Availability(A)** | | | |
| - estimated | .9978 | .995 | .9996 |
| - experimental | .998 | .9953 | .9997 |

*** Not calculated for that interval**.

## 5. COMPARISON OF THE GENERIC DATA BASE BEING USED FOR THE PSA OF NPP CERNAVODA WITH THE SPECIFIC RESULTS OF COMPONENTS RELIABILITY PARAMETERS EXPERIMENTAL RESULTS

A comparison of the generic data base used for our PSA analysis for NPP Cernavoda, with the specific results of experimental reliability results, is shown in Table 6:

**Table 6**

| Equipment | MTBF (Hr.) ** | | | Reliability ** | | |
|---|---|---|---|---|---|---|
| | TS | generic | exper. | TS | generic. | exper. |
| **DSCM** | 100,000 | 81,500 | 142,572 | .990 | .987 | .993 |
| **FFLS** | * | 936 | 1,008 | * | .974 | .976 |
| **HTSRM** | * | >1,600 | 1,756 | * | .721 | .970 |

*** Not available from Canadian sources**.
**** See also Diagrams 3 and 4**

These data are used in our PSA Analysis for NPP Cernavoda for Shutdown System 1 (SDS # 1) and Safety instrumentation, together with other generic data obtained from different sources including Canadian generic reliability data and, especially, IAEA reports.

## 6. USE OF SHORT TEST DURATION TO ESTIMATE THE PERFORMANCE CHARACTERISTICS OF COMPONENTS WITH RESPECT TO ACTUAL MISSION TIME.

The main reason to estimate the performance characteristics of the equipment with respect to actual mission time (30 years) by use of short test duration was to prove that such nuclear reactor equipment will be able to operate in safe conditions up to the last day of the mentioned lifetime period.
The short tests (accelerated thermal aging and intensive tests) were performed for the above mentioned equipment, separately.
Accelerated thermal aging was performed for the DSCM and intensive tests were performed for FFLS and HTSRM.
Procedures for intensive tests were approved by Canadian experts and the background for accelerated thermal aging has been based on Arrhenius law. The duration of test necessary to aging the electronic module for ca. 30 years at 23.5 degrees Celsius was calculated with respect to the specific activation energies of every electronic component belonging to the reactor instrumentation.
We continue to perform this kind of tests for the other electronic equipment to assure that the data resulted have a sufficient confidence level to be used in our PSA studies for NPP Cernavoda.

## 7. CONCLUSIONS

Reliability data are very important in a safe operation of a NPP, particularly in the Probabilistic Safety Assessment (PSA), [9,15,18 ].
We have not yet at our disposal the plant specific reliability data but only a few from the operating of some Canadian NPP, as far as I know. In the absence of the reliability data obtained from operated experience, for the equipment manufactured in INR (reactor instrumentation) we made the above mentioned laboratory tests. These tests have the advantage that the failure mechanism can be more easily identified, and testing can be accelerated.
The reliability data obtained were included in INR Reliability Data Bank, to be used for our PSA analysis [16]. The results obtained ascertain that the tested equipments are reliable, in accordance with design requirements.

## Acknowledgements

The Author would like to express many thanks to the International Atomic Energy Agency-IAEA Vienna for the continuous technical and financial support, under Scientific Research Contracts.

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