The Role of Regulatory Authority in Safe Operation of Research Reactors

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Abstract. The regulatory authority plays a very important role as a supervisory body in safety operation of nuclear reactors, both research and power reactors. This role is in general described by many publications of IAEA but should be transformed to every day practice of regulatory authority. In case of Poland it refers to National Atomic Energy Agency and is limited to operation of the MARIA research reactor. The examples of such activity as preparatory steps for introducing new LEU fuel, modernizations of dosimetric system, new I&C for technological parameters, new locations in a core for isotope production, improving conditions for a natural convection during decay heat removal etc. will be presented.

1. Introduction

The role of regulatory authorities in industry is not new. The earliest was the railway safety legislation in England (Regulation of Railway Act) in 1840 [1]. Later regulations were issued for high pressure equipment, cranes etc. As the starting point of regulatory authority in nuclear industry may be considered establishing of Atomic Energy Commission in USA (July 1946), which was allowed to license private companies to use nuclear materials and building and operate nuclear power plants [2]. Nowadays it is highly recommended (unfortunately not required by international organisation) that every country developing nuclear energy should have two independent offices (agencies), one responsible for promoting nuclear energy and second responsible for nuclear and radiological safety. The situation in Poland follows this recommendation. There is a department in Ministry of Economy responsible (among other duties) for research institutes in nuclear field and in particular for operation of research reactor (since August 2001). Independently, there is regulatory authority called National Atomic Energy Agency (NAEA) under Ministry of Environment responsible for nuclear and radiological safety. Generally speaking the activity of regulatory authority should cover many levels, as design, construction, operation and decommissioning of nuclear reactors. In case of Poland it is limited to operation of research reactor and repositories of radioactive waste and spent fuel.

The safe and secure operation of research reactors depends on several factors. One of them is the activity of country (local) regulatory authority. It is not enough to follow the well known international guidance, e.g. the IAEA Code of Conduct for research reactors, Safety Guidance, etc. but training and experience of inspectors contributes significantly in this fields. The activity of regulatory authority on a level of operation of nuclear reactor should be concentrated in many directions, as follows:
(1) issuing licences for operation,
(2) granting permission for technological or procedural changes in operating instructions,
(3) requiring and/or authorizing technical modifications,
(4) verifying of periodical reports submitted by operating organizations,

(5) performing of own safety analysis (also by independent experts).

The tasks of the NAEA in respect to the MARIA research reactor in Poland will be presented accordingly.

2. General rules governing activity of regulatory authority in Poland

The basic legislation relating to nuclear safety and radiation protection was established in 1986 as an Act of Parliament on peaceful use of atomic energy (Atomic Energy Act). It was updated many times according to changes of different IAEA documents, Polish law and accession of Poland to European Union. The last modification was done in year 2007. This Act is based on internationally accepted basic nuclear and radiation safety requirements. The Act defines duties and responsibilities of the National Atomic Energy Agency (NAEA) as a regulatory authority not as an agency promoting development of nuclear energy in Poland. It also defines a position of NAEA president and its relations to other governmental bodies. On this basis several governmental decrees and regulations have been issued.

The Act and the regulations created an adequate legal framework and regulatory infrastructure, oriented to solve the nuclear and radiation safety problems related to research reactors and application of radiation sources. In case a nuclear power programmes will be developed in future some further amendments will be required. General procedures of licensing of nuclear installation (research reactors, radioactive waste and spent fuel management facilities) in phases of construction, commissioning, operation, decommissioning or closure are established by this Act. An applicant for a licence must provide full documentation for the nuclear facility which includes: the technical description safety analysis report, quality assurance (QA) programme, detailed procedures of operation, instructions and manuals. On the basis of review and assessment of documentation and on inspections performed by regulatory inspectors the NAEA President grants a licence for a fixed time period of operation (postulated by an operator) and sometimes adding specified conditions, if necessary.

According to the Atomic Energy Act, the regulatory body's responsibilities include in particular, the inspections of nuclear facilities. The regulatory inspectors are entitled to:
(1) access a nuclear facility (at any hour of day or night),
(2) examine documents dealing with nuclear safety and radiation protection,
(3) verify activities, required permissions and their compliance with nuclear safety provisions, etc.,
(4) undertake independent technical and dosimetric measurements (if necessary).

The regulatory body has an adequate power to enforce compliance with safety requirements imposed by laws, regulations and licence conditions. Depending on the regulatory assessment of a particular situation, the following enforcement actions can be undertaken:
(1) issuance of a written warning or directive to the licensee,
(2) ordering the licensee to curtail activities,
(3) suspension or revocation of the licence,
(4) financial penalty collected by mean of administrative execution proceedings, punishment by fine or detention,
(5) recommendation of prosecution through the courts of law.

The regulatory inspectors have an authority to take on-the-spot decisions about operating conditions in situation when safety of an installation or personnel is threatened.

3. Regulatory authority practice

The regulatory practice is a very important part of regulatory body duties and in our case is based on experience of operation of research reactors in Poland (the first went critical in 1958). There are internal procedures elaborated for NAEA tasks as:

- preparing and performing inspections,
- granting financial support for actions connected directly with nuclear safety,
- issuing permissions for different activities.

Normal activity of regulatory authority in respect to research reactor consists of:
(a) review of technological parameters submitted after end of operation (production) cycle, normally of one week (100 hours from Monday to Friday),
(b) reviews of quarterly reports of reactor operation, and
(c) performing regular or special inspections.

The activity in last few (four) years was concentrated on granting permissions for:

- operation of MARIA reactor for 5 years until March 31, 2009 based on review of updated version of Safety Analysis Report,
- increase of maximal burn-up of fuel elements (based on very good performance of fuel from the last delivery),
- reducing coolant flow in fuel channels from 29 to 25 m^3/h (the reason was an increase of number of channels due to reduction of enrichment and unchanged parameters of cooling pumps),
- operation of fuel channel cooling system with number of heat exchangers from 3 to 6 (previously 4 exchangers were required).

All the above-mentioned activities will be described in detail showing the role of the regulatory body.

4. Description of the MARIA reactor

The description of the MARIA reactor for the purpose of this presentation will be limited to three aspects as general information and basic information about I&C systems for technological parameters and vibration analysis.

General information
The MARIA high flux research reactor of 20 MW thermal power was put into operation in 1975. It is used mainly for an isotope production and physical experiments and is operated on a one-week long cycles, from Monday through Friday. It has a unique construction in research reactors, i.e. separately cooled fuel channels (up to 28 individual channels) placed in beryllium matrix located in a water pool. The fuel has a form of six concentric tubes with enrichment of 36%. The reactor has three separate cooling circuits: for fuel channels and reactor pool which constitute primary circuits and a secondary circuit with water cooling towers. In cooling system for fuel channels there are four pumps and it is required to keep two of them working during a cycle (Fig.1).

From the regulatory authority point of view, beside a control and safety systems, the most important are two I&C systems for:
(a) measuring technological parameters (system GTREMA)
(b) digital vibration monitoring system (system VMS)
results of measurements performed by both system are transmitted to NAEA on Monday following the end of operation cycle for detailed analysis.

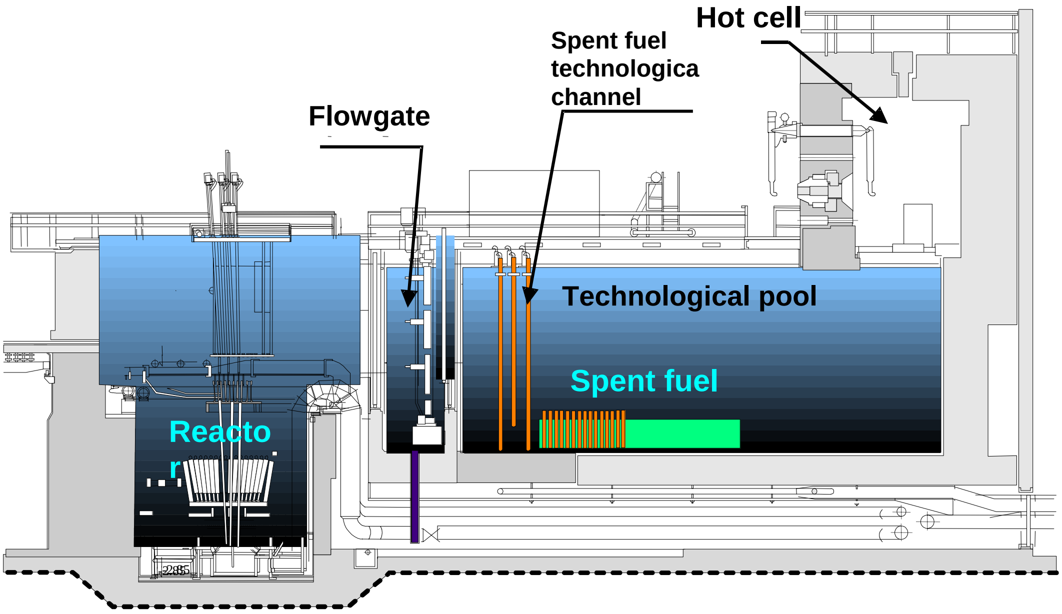

Fig.1. Vertical cross-section of the MARIA reactor

The GTREMA system (General flow and Temperature for REactor MAria) for measuring, recording and visualisation of the main technological parameters as temperature and flow rate in every fuel channel, global parameters of cooling circuits as temperature and flow rate and one special signal giving value of pressure drop over a core matrix (it is the crucial parameter for this reactor showing ability for cooling of reactor beryllium matrix containing control rods by the reactor pool cooling system). Signals are coming from resistant thermometers and flow meters located at chosen parts of cooling circuits. The first two parameters are independently connected to a reactor shut down system. The system measures the signals on a close loop basis (shorter than one second) and calculates a thermal power of every fuel channel according to a simple, dedicated equation. The measurements are recorded on disk when change of global power (calculated as a sum of power generated in individual fuel channels) is changed more than by 10% in comparison to previous calculated value, when reactor power is greater than 8 MW (in other case only when power increased by 100%) or at full hours. Additionally to GTREMA system there is a small subsystem called KD3 for recording outlet and difference outlet-inlet temperature from three cooling circuits measured unconditionally every 30 seconds. The reactor staff in control room is observing on-line results presented by both systems (mean values and trends) and serves as basis for detailed analysis in case of unplanned reactor scram.

The independent analysis at regulatory authority is performed at the end of operation cycle (usually next Monday) using special (dedicated) computer programs. They were prepared solely for this purpose taking into account results recorded by both GTREMA and KD3 systems. The following quantities are calculated:

- thermal power generated in an individual fuel channel,
- sum of power generated by all fuel channels,
- power generated by the reactor pool and secondary cooling systems,
- estimated power generated at a position of the most effective control rod.

The obtained results together with:

- outlet temperature and flow through fuel channels and
- pressure drop over reactor core

are presented in a form of plots or tables and are compared with prescribed limits for:

- minimal coolant flow through fuel channels,
- maximal outlet temperature from fuel channels,

- maximal power generated in fuel channels and at the position of control rod,
- minimal pressure drop over reactor core (this parameter is responsible for cooling of control rods and inadequate cooling in the past caused serious problems).

It may be stated, that the limits are fulfilled for all parameters but characters of signals suggested many times some failures in measuring equipment (measuring channels). This knowledge enabled the operator to make some repairs and regulatory inspector to check if these repairs were done properly and in time between consecutive operation cycles. The situation when results of GTREMA system are available for regulatory authority immediately after an operation cycle makes it possible to verify the correctness of performance during next cycle. The examples will be shown later.

The VMS system (Vibration Monitoring System) was put in operation for MARIA reactor in 1995 (moved from the first Polish research reactor EWA after it permanent shut down). The system uses input signals coming from 12 accelerometers located at bearings of fuel channel cooling engines (two accelerometers located at outer and inner bearing) and pumps (one bearing) and 12 resistance thermometers (signals are in parallel connected to indicators in control room). The additional input signals are reactor power (measured by nitrogen activity in fuel channel cooling system) and several binary signals specifying operating status of pumps in primary and secondary cooling systems. All signals are measured regularly every 3 minutes or when pumps are switched-on or switched-off. The mean and root-mean-square (RMS) values of accelerometer signal are measured with frequency of 2 kHz in a fixed length block (e.g. 512 measurements), calculated on-line and stored on disk. The results are shown to the operator as a table (together with minimal and maximal values and short-time linear trend) for all signals or as a plot from previous 27 hours. In case an on-line calculated RMS value is higher than specified limit a direct measured signal (with maximal frequency up to 40 kHz) is recorded for off-line statistical and power spectral density (PSD) calculations.

The software for VMS system consists of three main programmes:

- on-line data acquisition, elaboration, recording and presentation of main information suited for simple usage by operating personnel,
- off-line analysis of diagnostic signals with many different calculating methods with full presentation possibilities for system analysts,
- off-line analysis of vibration signals for analysis in time and frequency domains also for system analysts.

During the first years of operation of VMS system (1995÷2001) all programmes were constantly being improved and many suggestions from operating personnel were included in order to make it user friendly as much as possible. One of unique features of this system is the possibility to verify the electronic equipment (pre-amplifier, amplifier and long cables) by remote connection of electronic block simulating output form individual accelerometer in a form of sine wave of known frequency and amplitude.

The diagnostic parameters applied for VMS system were chosen upon obtained experience and consists of:

- root-mean-square (RMS) value for acceleration signals calculated from a block of 512 individual measurements,
- short- and long-time linear trends (minutes/hours and day) of RMS value,
- value of bearing temperature,
- short-time linear trend of temperature.

They are automatically checked against thresholds, which were established upon operating experience, and in case they are crossed a special warning signal is generated for the reactor operator, who has the possibility to analyse on-line all signals and diagnostic parameters by making appropriate plots, comparison with results obtained during previous fuel cycles for the same detector or other detectors, to record direct acceleration and temperature signals for detailed analysis in future, etc.

5. Examples of regulatory authority activity

The examples of analysis performed and action taken by regulatory authority are given below. Analyses are performed at the beginning of a week following an operation cycle or during a second part of a month following a quarter of year, i.e. January, April, July and October.

Quarterly reports
Since the restart the MARIA after modernisation in 1995, regular quarterly reports are required by the regulatory authority. The aim of this report is to present a detailed picture of the reactor's operation and to serve as a base for the evaluation of activity by President of NAEA. An example of general performance indicators applied for the MARIA reactor is given in Table 1 for the last seven years. It can be seen all indicators are stable, only collective dose increased about twice in years 2002-2004 which was caused by thinner cladding of new fuel elements. The appropriate step was already undertaken and a following part of fuel delivery already has a thicker cladding.

Table 1 Performance indicators for the MARIA reactor

Year	Work time [h]	Availability factors		No of unscheduled shutdowns	No of employees	Collective dose [man-Sv]
		total	per year			
2000	3748	99.0	43.0	5	52	0.085
2001	3580	98.0	40.0	10	56	0.094
2002	3814	99.5	44.5	6	58	0.170
2003	4010	96.0	46.0	11	57	0.190
2004	300	100.0	3.4	1	58	0.226
2005	3830	99.0	43.7	15	58	0.124
2006	4006	99.1	45.7	19	58	0.100

Remarks: The following definitions of availability factors were used:
- total: ratio of operation hours on power to sum of hours on power and sum of hours of unscheduled shutdowns
- per year: ratio of operation hours to number of hours in a year
- collective dose in based on personal dosimetry (monthly or quarterly readings), excluding natural background (all results below 0.4 mSv, which is the limit of film dosimeters, accuracy were put equal to 0.2 mSv).

All reports include charts of reactor power over last three months with exception of the fourth quarter report which submits a chart over the whole year. Example of such chart for the last year is given in Fig.2 with 40 fuel operation cycles. Visual observation shows a stable power generated by the reactor and 19 cases when reactor was scrammed. Analysis of causes of these scrams is included in Table 2. For the last year there were few scrams caused by failure in electronic equipment, namely wrong operation of some relays. Because they were in operation since reactor construction in 1974 they were replaced by new units.

The analysis of quarterly reports of last few years done by the regulatory authority come to the following conclusions/observations:

(a) reactor was operated without any significant problems,
(b) reactor power was lower than nominal but adjusted for irradiation needs,
(c) neutron beam (horizontal channels) were used for physical experiments with utilisation up to 48% of reactor operation time,
(d) all revisions and maintenance works were performed according to schedule,
(e) the unplanned shutdowns were due to:
    - loss of external power (caused by eg. winds, storms etc.),
    - leakage in fuel channel cooling system caused by failure of the sealing of one pump

- leakage in heat exchanger from primary to secondary cooling system

but the situation of shortening of operation cycle has happened only two to three times per year (due to lack of reactivity), in all other cases reactor was started within 20 minutes,

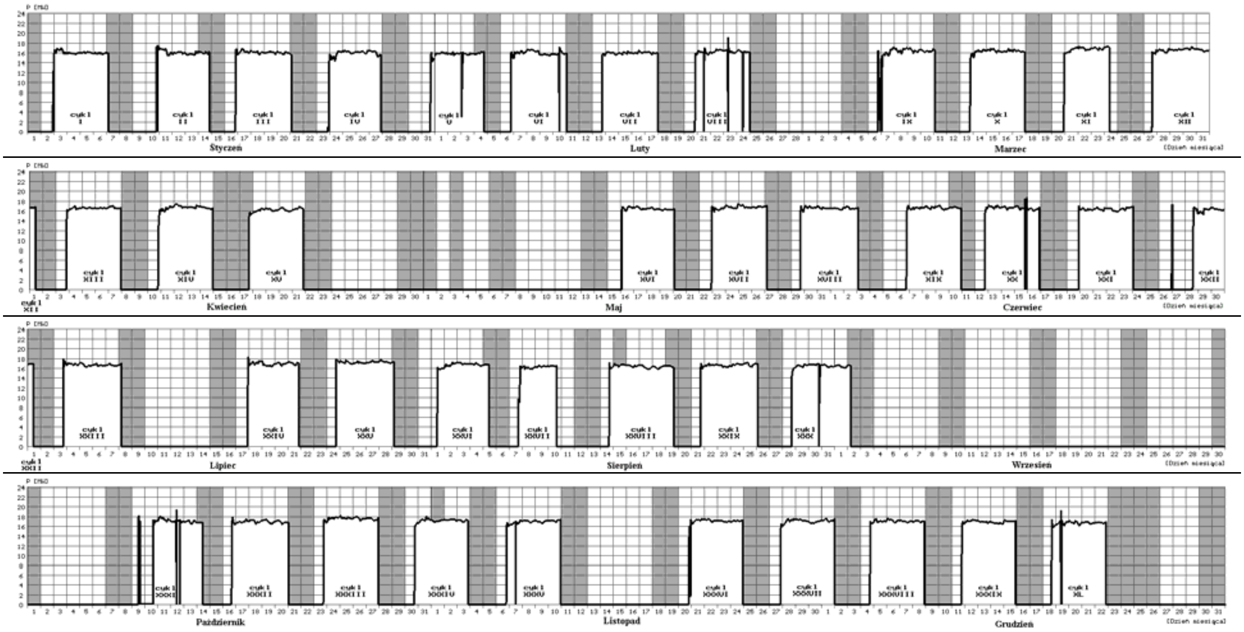

Fig.2. Chart of operational cycles of the MARIA reactor for year 2006.

Table 2. General information about operation of the MARIA reactor in for 2006

quarter of year		I	II	III	IV	Total
Number operation cycles		12	10	8	10	40
Time of work at nominal power [hours]		1201	995	808	1002	4006
Mean thermal power [MW(th)]		16.3	16.7	15.6	17.2	16.5
Total produced thermal power [MWh(th)]		19 599	16 608	12 630	17 256	66 093
No of fuel elements in core		22	23	23	23	---
No of unplanned automatic scrams		6	5	3	5	19
Causes of scrams	equipment failure	5	3	0	2	10
	loss of external power	0	2	1	1	4
	operator's error	1	0	0	1	2
	fault in equipment operation	0	0	0	0	0
	water activity in secondary loop	0	0	1	0	2
	crossing of operational limits	0	0	1	1	2
	unknown	0	0	1	0	1
Consequences	restart of reactor	5	5	1	5	16
	shortening of operation cycle	1	0	2	0	3
No of discovered equipment unit failures		5	1	3	0	9
No of repairs and maintenance works		10	17	25	15	67
No of tests and overhauls		8	29	42	7	86

In conclusion it may be stated that the regulatory body since a start of reactor operation in 1995 after reconstruction has no significant remarks concerning safety of operation.

<u>Regular or special inspections</u>

The list of inspections performed is given in Table 3. They are divided between regular inspections - normally two or three per year - and special inspections in order to clarify information presented in quarterly reports, in case of unexpected events or upon request of an operator. Regular inspections are generally devoted to some procedures or working conditions of a specified department of reactor operator, eg. mechanical, electrical, dosimetry etc. In this table they refer to:

a) procedure of fuel conversion,

b) fulfilment of requirements in irradiation process,
c) evaluation of documentation concerning design of new equipment (many drawing are successively transferred to electronic form)
d) evaluation of operational documentation (keeping log books),
e) radiological protection (dosimetric) system and requirement for its upgrading,
f) operation of computer GTREMA (for recording technological parameters) and VMS systems (vibration monitoring of fuel channel cooling equipment).

All inspections are concluded with special report and suggestions to be fulfilled within a specified time.

Table 3. List of inspection in the MARIA reactor in last 4 years

Date	Number	Type	Scope of inspection
22.04.2004	1/2004	special	inspection of fuel encapsulation
08.11.2004	2/2004	regular	inspection of operational documentation
09.12.2004	3/2004	regular	inspection of dosimetric department
02-07.02.2005	1/2005	special	loading of new fuel elements
21.04.2005	2/2005	regular	inspection of operating departments
11.07.2005	3/2005	regular	inspection of operating documentation
22.09.2005	4/2005	regular	review of physical protection
11.05.2006	1/2006	regular	review of 1st quarter operation
29.08.2006	2/2006	special	inspection of technical modifications
22.11.2006	3/2006	regular	review of 2nd quarter report
04.04.2007	1/2007	regular	inspection of operational documentation
29.05.2007	2/2007	regular	inspection of dosimetric department

<u>GTREMA system</u>

The operation of GTREMA system provides for regulatory authority information that very important safety parameters (specified in chapter 4) are within limits specified in permission for reactor operation (operational licence). The results are mostly obtained on Monday following an operational cycle and shows that during last 5 years when such requirement was issued all above parameters obey regulatory requirement.

Another application of this analysis is verification of measuring equipment and it plays the most important role. The typical examples of some doubts are given below and they are immediately passed to the operator. Most of them were already known to the operator, which have taken some action before starting a following operation cycle. Three examples are shown below:

(a) some disturbances in measured temperature for channel i-5, a repair in electronics was made at the beginning of next cycle (Fig. 3 and 4)

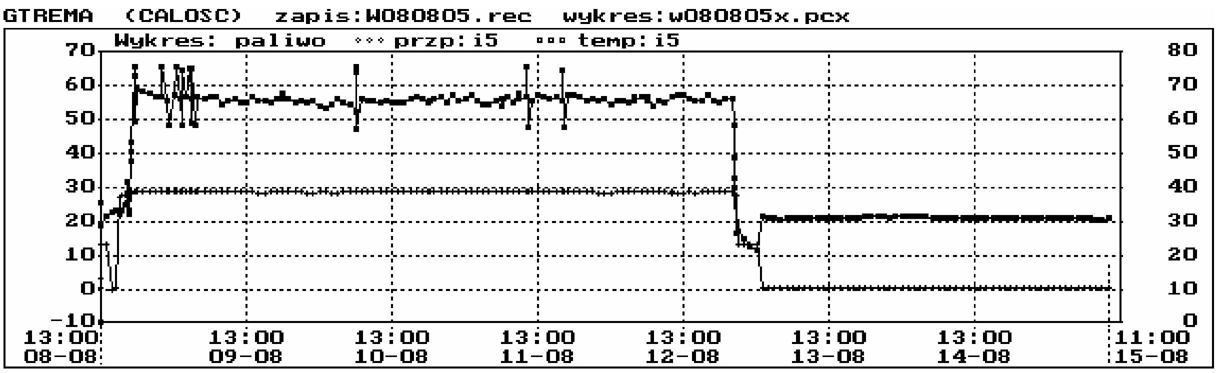

Fig. 3. Disturbances in outlet temperature from channel i-5 (cycle XXII starting August 8, 2005)

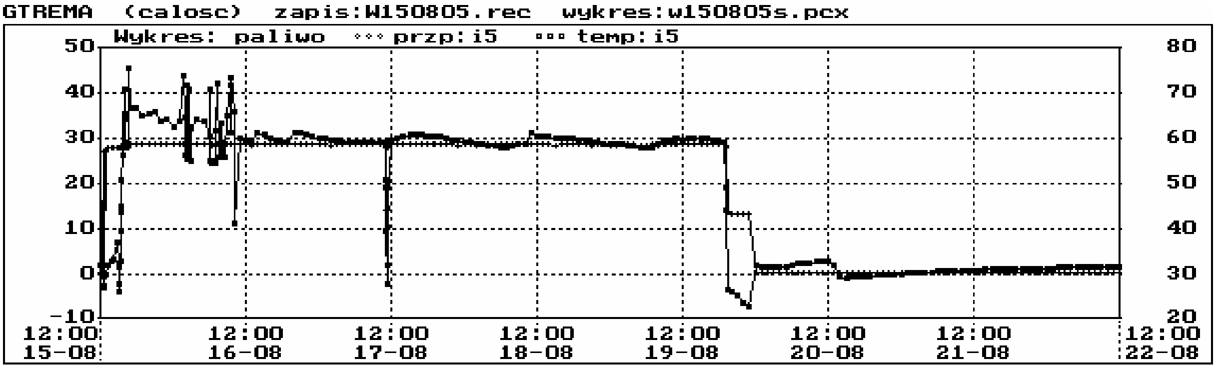

Fig.4. Disturbances in outlet temperature from channel i-5 (cycle XXIII starting August 15, 2005)

(b) unexpected shape of coolant flow in fuel channel e-7 (Fig.5 and Fig.6 in details) when after slow increase of flow from 27.0 m^3/h equal about 1.5 m^3/h during 6 hours sharp decreases were observed some times correlated with changes in outlet temperature, the cause was not explained because it disappeared for the next operation cycle,

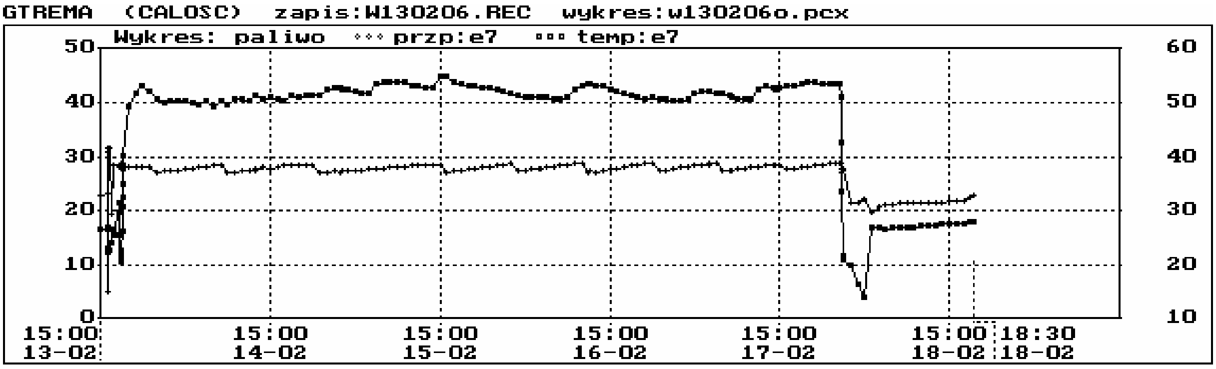

Fig.5. Disturbances in outlet temperature from channel e-7 (cycle VII starting August 15, 2005)

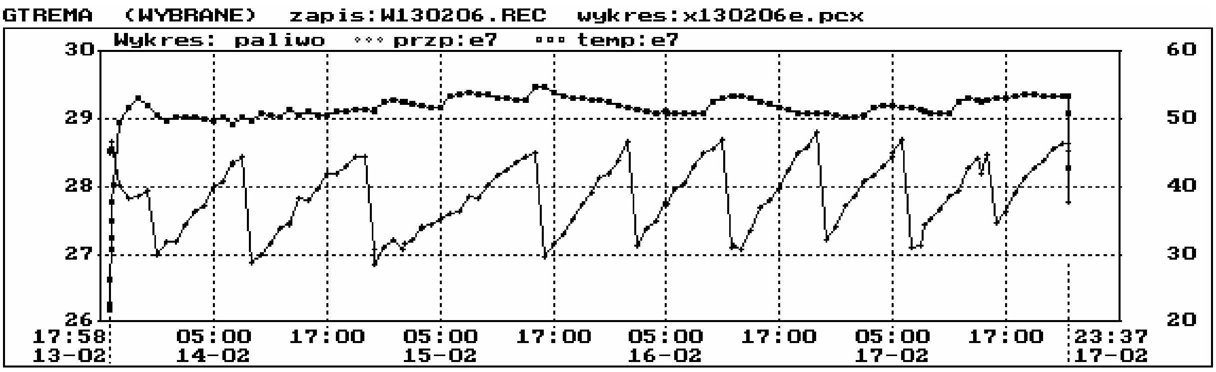

Fig.6. Disturbances in outlet temperature from channel e-7 (detailed presentation)
(cycle VII starting August 15, 2005)

(c) coolant flow in a fuel channel is showing sharp increase to about 10 m^3/h (i.e. 40% of nominal flow in this channel) about 10 hours after switching off pumps (Fig.7) and remains on this level until end of recording - operating staff of reactor declares that it is a fictitious flow because pumps are not operating, but this situation must be explained and operating staff was asked to search a cause of such observation (on a level of regulatory authority there is a hypothesis of such situation).

The results of GTREMA system may be also applied for verification of measuring equipment. For example if a resistance thermometer is placed in hot water and later very fast removed then an exponential decay of temperature (Fig. 8 – right part) is observed which constant may be a parameter describing quality of measuring line. This is only an idea which should be tested in future and applied after verification. The measuring line of fuel channel temperature outlet are obligatory checked once per year by connecting a very accurate set of resistance

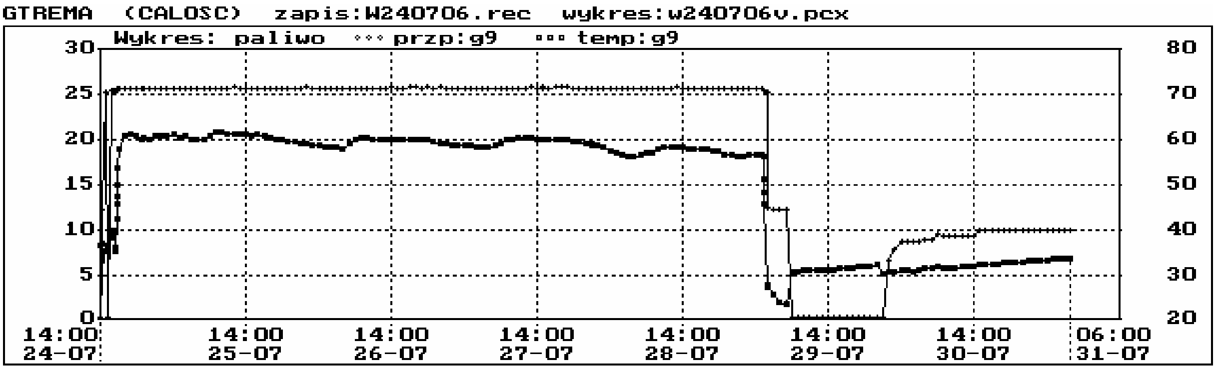

Fig.7. Disturbances in coolant flow rate in g-9 when pumps were not operating
(cycle XXV starting July 24, 2006)

instead of a resistance thermometer and checking a temperature shown by a system (Fig.8 - left part). Up to now it was done 'by hand" but the system should be used for this purpose. There is suggestion from regulatory authority to apply two above mentioned ideas in practice.

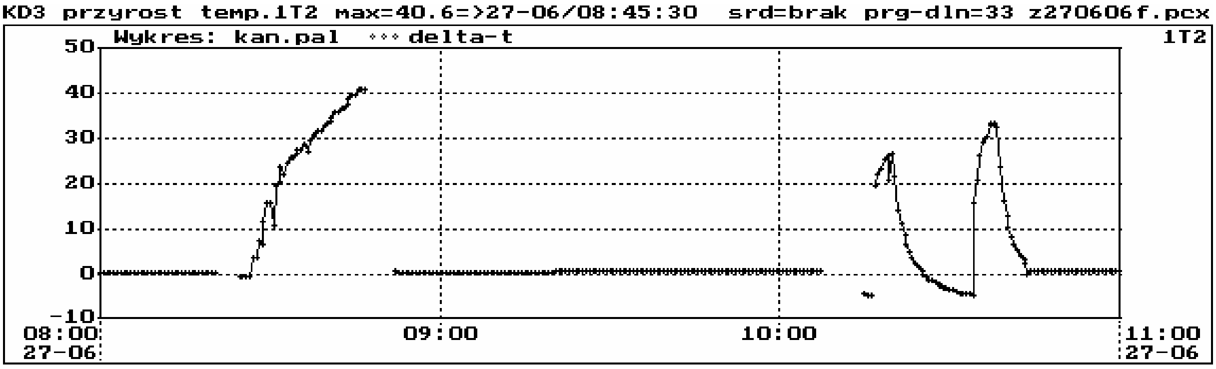

Fig.8 Measurement of temperature during testing of equipment (June 6, 2996)

<u>VMS system</u>

The operation of VMS system provides a regulatory authority another set of information concerning technical condition of the fuel channel cooling system. They consists of RMS (standard deviation) values of acceleration signals and bearing temperature. Two examples are shown below:

(a) In case the technical condition of bearing becomes worse the intensity of vibration is increasing as shown in Fig.9. The RMS value of acceleration signal increased about 3 times in 27 hours, remained stable but next 12 hours but in the morning of next day an operator decided to switch-off this pump avoiding probably more severe damage of a bearing in case a pump would operate a full cycle.

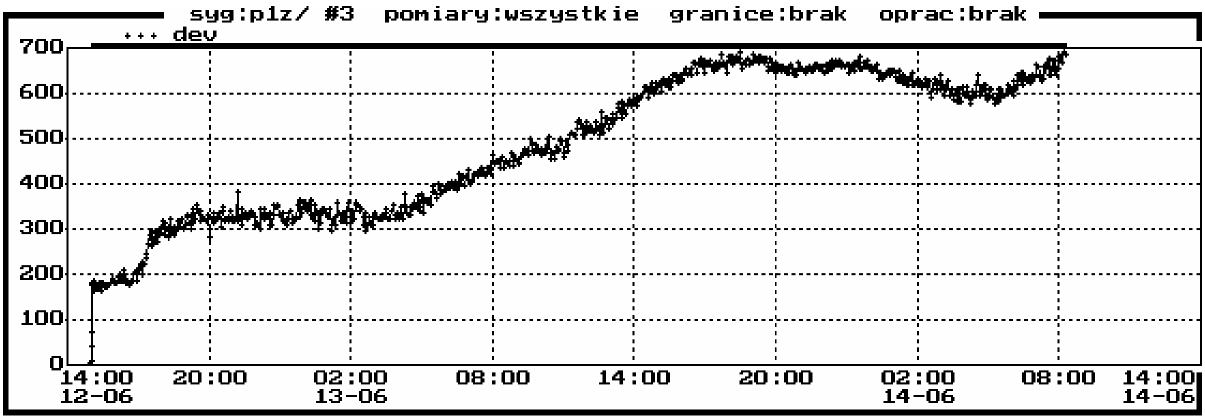

Fig.9. The RMS value of acceleration signal for pump no 1 (cycle XXVII starting June 12, 2000

(b) The bearing temperature (Fig.10) increased suddenly very sharply after 56 hours from the beginning of fuel cycle and warning signal by conventional limiting device was generated. But using this diagnostic system a warning signal based on calculation a temperature linear trend of the temperature would be issued at least 12 minutes earlier. More detailed description of this system is given in [6].

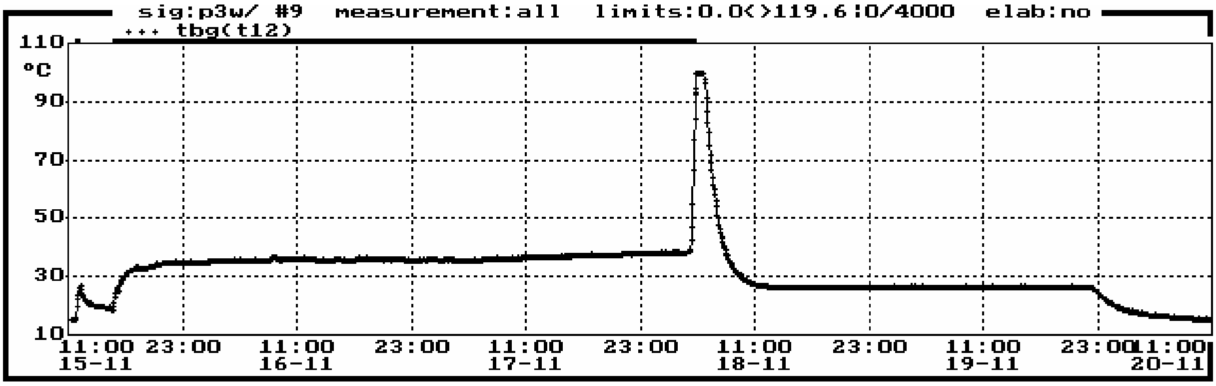

Fig.10. The bearing temperature for pump no 3 (cycle XXIV staring November 15, 1999)

6. Present and future developments

At present the following modernizations and improvements in technology and operation of the MARIA reactor have been already done:

(a) transformation from HEU to MEU fuel (from 80 to 36% enrichment) performed in years 1999÷2003 preceded by installation of a special fuel assembly equipped with thermo-couples in order to performed verification of thermo-hydraulic calculations,
(b) installation of new pressure transducers for measurement of flow measurements in fuel channels (2001).
(c) new neutron flux measuring system for reactor control and safety systems (2002).
(d) modernization of dosimetric system (2002-2006),
(e) installation of special pipe enabling working with 3 instead of 4 heat exchangers in fuel channel cooling system (2006),
(f) restoring of cooling pipes connecting two location of fuel channels, dismantled many years ago in order to place a special test loop (2006),
(g) heat exchangers between primary and secondary cooling system (exchange of 2 heat exchangers in 2006),
(h) power supply system,

Based on experience of regulatory inspectors and 33 years of reactor MARIA operation (since 1974) the following tasks may be formulated in order to keep safe operation of this reactor. The most important examples of such improvements in technical equipments are:

(i) transformation to LEU fuel (less than 20% enrichment, to be started in year 2008 or later) including testing of this fuel from new producer),
(j) preparation of new locations in a reactor core for isotope irradiation in higher neutron flux,
(k) improving of cooling conditions for a natural convection during a decay heat removal from fuel elements, etc.

There are also some points to be upgraded on operating level:

(1) improvement in communication between the reactor operator and regulatory body,
(2) revising of written operational procedures,
(3) reviewing on new version of Safety Analysis Report,
(4) development of research reactor safety parameter indicators (partially based on similar indicators for nuclear power plants),
(5) replacement of old graphite and beryllium blocks (due to high neutron fluence).

The last point seems very promising for the development of rational parameters applicable to judge reactor operation. For the last few years the following three parameters are being evaluated:

1) availability factor (total),
2) no of unscheduled shutdowns,
3) collective dose

as shown in Table 3, but they are no sufficient in our opinion. They should be appended for a typical research reactor by:

4) safety system performance stating the availability of all standby safety systems (as for nuclear power plants),
5) chemistry performance (activity of primary coolant in case of the MARIA reactor),
6) number of failures of irradiation capsules,
7) vibration parameters of primary coolant components (pumps, engine, piping, etc).

Work in this field is in progress for the MARIA reactor and may be of interest for other research reactor operators.

7. Conclusions

The activity of regulatory body in the field of safety can be never stopped. Knowledge should be always accumulated and passed from one to another generation of inspectors. In Poland such experience was transferred from EWA to MARIA reactor. The constant modernization of equipment is in progress together with new ideas making the work of operators easier and safer and also more transparent for inspectors of regulatory authority.

The other role of regulatory authority is suggesting technological changes and improvements in safety equipment, to be done in future as: modernization of vibration monitoring system, development of more friendly procedures for visualisation of information stored by signalling system, etc. In Poland the regulatory authority has some funds for this activity, which are coming from a state budget and granted once a year.

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