Annex I

EXAMPLES OF IN-SERVICE INSPECTIONS AND A TYPICAL MAINTENANCE SCHEDULE FOR LOW-POWER RESEARCH REACTORS*

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AIAU 24313
JUNE 2004

EDITED BY S. O'KELLY
SEPTEMBER 2004

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* Prepared for the IAEA under Contractual Service Agreement Pers/JCH/nbb/ior/NSNI/Rev.1. H. Böck, M. Villa (June 2004); edited by S. O'Kelly (September 2004).

Note: This annex has not been edited by the IAEA.

1. INTRODUCTION

In-service inspection methods for low-power research reactors are described in this module. Two practical examples of an in-service inspection and maintenance task at a Training, Research, Isotopes, General Atomics (TRIGA) reactor and at a materials test reactor (MTR) are given, and a typical maintenance schedule is presented in Annex 1. The inspection methods and the maintenance schedule are based on 42 years of operation and maintenance experience with a typical 250 kW TRIGA Mark-II reactor. Although this experience is related to a TRIGA reactor, most of the ISI methods and a large part of the maintenance schedule can be applied, with minor changes, to other types of low power research reactors such as ARGONAUT, SLOWPOKE, and MNSR type reactors.

The useful lifetime and the safe operation of a research reactor depends on two main criteria which are:

(1) Regular maintenance of all reactor components and systems,
(2) Periodic in-service inspection (ISI) using various non destructive testing (NDT) methods.

For a research reactor maintenance programme, a maintenance schedule has to be established. It should list all systems and components necessary for a safe reactor operation. These are, however, not only the direct related safety related systems and components but also auxiliary systems and components, which may have an indirect effect on the safety systems or the safety of the facility. The frequency of maintenance depends on the importance of the components and also on operational experience but it will usually be at least once a year. More frequent inspections should be considered for components that show an increasing deterioration rate, require frequent corrective maintenance or are operating significantly beyond their original expected lifetime.

In-service inspection (ISI) will be carried out with more sophisticated equipment using various methods described in chapter 3. During this ISI, one component is investigated in detail; usually an inspection report is prepared both for the operation license holder and, in many cases, also for the regulatory body. The ISI methods may vary from simple visual inspections and measurements to very sophisticated and expensive NDT inspections. The reactor type and its power level should be taken into consideration when selecting the appropriate inspection method. Typical examples of instances requiring more sophisticated inspections are the visual inspection of the reactor tank, of the reflector or the inspection of welds in the primary piping system by NDT methods.

The staff of the reactor operation group holds the responsibility for in-service inspections in many cases.. Experiences with a 250 kW TRIGA reactor has shown that the manpower involved in a simple monthly ISI is about 2 man-days but a complete yearly ISI may be in the range of 14 man-days [1-7]. The number of safety systems and fuel elements requiring inspection at facilities up to 1 MW are only marginally larger so the maintenance periods are similar to the 250 kW facilities. Larger, high power reactor facilities, may have more systems requiring routine maintenance but often their larger staff sizes will compensate.

2. RELIABILITY AND MAINTAINABILITY OF RESEARCH REACTORS

2.1. General Considerations

The development of a maintenance and in-service inspection schedule for a complex technical system must be based both upon certain theoretical considerations such as reliability of components, failure rates and upon practical past experience with components to be maintained. The evaluation of the facility needs may be quite complicated with several computerized databases generated. However, a facility may adequately evaluate the system components by maintaining a good written record of repairs and modifications to all equipment in the facility. The procedures given below may be used by the facility over the lifetime of a component.

2.1.1. Theoretical considerations

Ideally, failure data used for reliability analyses should be based on facility specific data. However, the availability of accurate facility specific data requires the expenditure of considerable resources to develop and maintain an extensive database. The collection of database source information from the field, i.e. from reactor maintenance and/or operation reports, requires a systematic approach and ongoing commitment, if the information is to be processed efficiently and kept up to date. In addition to the need for operational and maintenance staff to provide the raw data input, a software system and analytical personnel to process the raw data are also required. Data processing primarily produces component reliability parameter statistics and trend analysis data. The reliability parameter data is often formatted so that information can interface directly with Probabilistic Safety Analysis (PSA) studies. For example, component failure rate data may be linked to a PSA specific basic event labelling format. The use of generic data by themselves will not provide an adequate data source to aid in a trend analysis of facility specific system equipment. However, generic data can still indicate whether there may be facility specific features or facility specific equipment problems that may be considerably different from that predicted from international generic sources of other research reactors.

Component reliability is a function of design, use and maintenance. Components designed for specific research reactor application (especially safety related) are usually highly reliable and should be maintained as such during their lifetime. The reliability data, however, often show variations, which are related to operating conditions and practices, component application maintenance and testing practices. A brief discussion of the influence of each of these is given below.

Operating conditions and practices

A facility's operating conditions and practices may greatly influence component reliability. Some of the factors are:

- operating mode,
- operating time and demands,
- operating environment.

The operating mode has been recognized as influencing equipment reliability, especially on active components (such as pumps). Some data sources provide separate data for running, alternating and standby categories. In an IAEA survey [7] variations of more than two orders of magnitude have been documented for failure to run motor operated pumps, comparing alternating pumps, running pumps and pumps where no mode had been specified. This finding supports the view that failure data for similar equipment having differing operating modes should be kept separate.

A component's failure to start may be caused by a demand related stress (e.g. vibration), or stress in standby (e.g. corrosion) or a combination of both. Most data sources disregard these differences and provide data on failure to start either as demand related or time related. When time related data are provided, the failure rate denomination is usually calendar time, or sometimes plant operating time. Since similar components at different locations may have substantially different test intervals, the actual number of demands over a period may vary, which in turn may greatly influence the failure rate. Some data collection systems also collect information on the number of demands systematically; in others the number of demands is estimated on the basis of the costs of collecting the information.

Operating conditions may also influence component reliability. Examples of this would be ambient temperature, humidity, chemical control, radiation fields and vibration.

Design and application

A component's design and application will have an important influence on it's reliability. The application of the component will determine the operating mode and the environment. Variation due to these causes has been discussed in previous sections.

Environmental conditions

In general, the failure rate of equipment depends on the environmental conditions. Therefore, these circumstances should ideally be taken into consideration in all data acquisition activities. However, few data bases provide the environmental application factors needed to do this and they are generally only available for electrical and electronic components [9].

The environmental application factor is a multiplicative constant used to modify a failure rate to incorporate the effects of other normal and abnormal environmental operating conditions.

Generic abnormal environmental conditions are:

(mechanical):	impact, vibration, high pressure, stress, grit, moisture, ...
(thermal):	over temperature, freezing, humidity, ...
(electrical):	electromagnetic interference, contact with conducting medium, power surge voltage or current, short circuit, ...
(radiation):	radiation damage, insulation failures, gamma heating, neutron activation, ...
(chemical):	acidic corrosion, oxidation, chemical reactions, poisonous gases, ...
(human interaction):	students in the control room, ...
(others):	missile hazards, explosion, ...

Maintenance and testing practices

Significant plant to plant variations for otherwise identical components can be identified. These variations are most probably caused by facility specific maintenance and testing differences. The influence of the testing interval and practice has been extensively investigated. The testing interval has an influence on the failure rate, but it is strongly related to the component type. The testing interval has greater influence on components where standby stress dominate failure probability (usually motor operated valves) and lower influence on components with higher demand stress (such as diesel generators or compressors).

In order to compare reliability data from different facilities for similar components, all data must be based on common definitions. A set of definitions also used within IAEA documents (i.e. [8, 9]) is given below.

Definitions related to the calculation of reliability parameters

Failure rate

The failure rate is a numerical value, which represents the probability of specified failures of a component per time unit. The all modes failure rate of a component is an aggregate of failure rates summed over relevant failure modes.

The failure rate $\lambda(t)$ of a system, subsystem or component is defined as

$$\lambda(t)=\frac{f(t)}{1-F(t)},$$

where

$f(t)$ ...... probability density for a failure of the device
$1-F(t)$... probability that the device did not fail up to the time t.

For many devices, the behaviour of $\lambda(t)$ follows the classic bathtub curve (Figure 1):

(1) Early in life, the failure rate for most devices is high because of 'break-in failures' or failures arising due to poor quality assurance during manufacturing or installation.
(2) During the middle of lifetime, failures occur at a rather uniform rate corresponding to random failures.
(3) Late in life, $\lambda(t)$ begins to increase because of 'wear-out failures' caused by equipment aging.

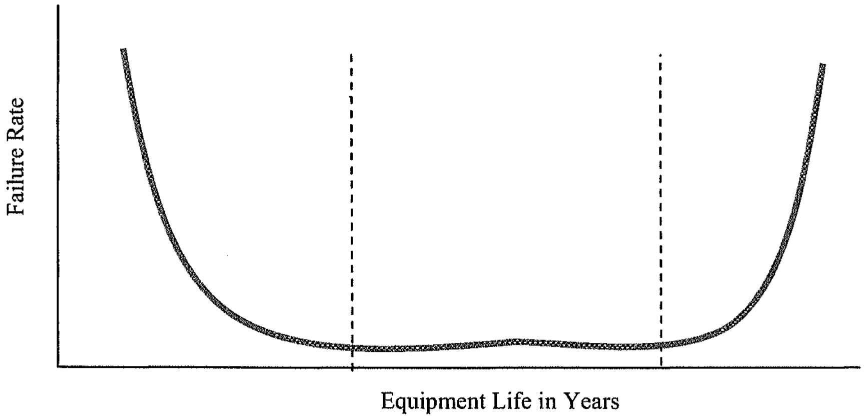

FIG. 1. Classic 'Bathtub' Reliability Curve.

Time related failure rates

Two time related failure rates are defined:

- operating failure rate,
- standby failure rate.

The failure rate for continuously operated equipment (operating failure rate) is the expected number of failures of a given type in a given time interval (failures per hour, per year) - while the equipment is continuously in use.

Examples of failure rates of continuously operated components:

(electronic):	capacitor short circuit failures per million operating hours while under nominal voltage,
(sensors):	self-powered neutron detector degraded current output failure per thousand full power days.

The standby failure rate is the expected number of failures per time unit for those components normally dormant or in a standby state until tested or required to operate. Data representing standby failure rates is often not available in practice.

Failure on demand

Failures on demand are relevant to failures occurring on periodically or cyclically operated equipment. Failure on demand is the expected number of failures of a given type during a given number of operating cycles on demand when required to start, change state, or function.

Example of failure rates of demand operated components:

(electromechanical):	relay contact failure per million switching cycles.

Operating time

The operating time is the accumulated time period during which an item, component or a system performs it's intended function within specified limits.

Standby time

The standby time is the accumulated time period during which an item, a component or a system performs it's intended function as standby equipment.

Outage time

The outage time is the time when the equipment is not available for its specified service due to failure or maintenance. Outage times can be divided into three categories: out of service, restoration and repair.

Out of service time

The out of service time is the time required to identify the failure, analyze it, obtain spare parts, repair, and return the equipment to service, including planned delays.

Restoration time

The restoration time is the time period from the moment the failure is revealed to full restoration to operable state. It is the same as out of service time except that planned delays are excluded.

Repair time

The repair time counts from when the failure is revealed, and includes the time to analyze the failure, prepare for repair, repair, test, qualify, and return the equipment to service. The repair time is, therefore, the time necessary to repair the equipment and restore it to operation or standby (this excludes all planned delays and waiting for spare parts and tools). The repair time is the same as the out of service time except for spare part waiting.

Active repair time

The active repair time is the time, which is actually spent for the repair of a piece of equipment.

Maintenance time

The maintenance time is defined as the time required to plan, administrate, and prepare for test or inspection, test or inspect, and return the component back to service.

Active maintenance time

The active maintenance time is the time spent on the maintenance (test, inspection, ...) itself.

2.1.2. Practical Experience

First hand practical experience with the reliability of a given component originates from one's own facility and observant operators. Therefore, it is very important to maintain an accurate documentation on all experience gained during the history of a given component. A standardized format is highly recommended, i.e. Event Record (Annex 1) where all necessary data of a component failure are concentrated. If other facilities use the same component, an exchange of information between the operators is relatively easy. Due to the relatively few research reactors in the world, compilation of failure data is slow and the data is often limited or sparse. This makes is more difficult to calculate meaningful average failure rates or mean time between failures (MTBF). Another source of failure rate information are data banks established by several groups [10, 11], though they might be difficult to access in many cases due to costs and restriction. Failure rates for various components have been calculated based on the component failure data collection system used at the Atominstitut der

Österreichischen Universitäten since 1988 [12], and are listed in Annex 2. The inspection and maintenance frequencies for particular components are reflected in these failure rate values.

It is necessary to define all ***systems*** necessary for a safe reactor operation, following the license from the regulatory body, in order to establish a maintenance schedule for a low power research reactor. Typical systems to be maintained regularly are, i.e. the

- reactor tank and shielding structure,
- reactor safety system,
- reactor cooling system.

Once the systems have been defined each system has to be broken down into ***sub-systems*** or ***components***, such as

- reactor core
- nuclear channels
- primary pump.

Each of these sub-systems or individual components have to be maintained, inspected or recalibrated in different ***time intervals***, which may be

- once a month (1xm)
- four times a year (4xy)
- two times a year (2xy)

Other intervals, ranging from daily checks to once a year, are possible. After having defined the frequency of maintenance, it is necessary to define the ***type of maintenance*** work to be carried out. In many cases this would be just a visual check, it could be a test run (i.e. for a pump), it could be readings of a scale (i.e. differential pressure across filters) or it could be a complete recalibration using signal generators (i.e. for the nuclear safety channels).

Finally, for each maintenance task to be carried out it has to be defined ***who*** will carry out this task. Usually it is the reactor staff that has the best operating experience of all the systems and components. However, in some cases the reactor staff is either not qualified to carry out maintenance (i.e. reactor crane, emergency diesel generators) or is not authorized to do the work without supervision or control of an independent expert. In some cases the independent expert is appointed by and acts on behalf of the regulatory body.

It is now possible to establish a maintenance schedule for a low power research reactor. As an example, such a schedule is given in Annex 3 for a typical 250 kW TRIGA Mark-II reactor. Twelve systems, each one with several sub-systems or components have been identified. These sub-systems are maintained in periodic intervals by different personnel according to their qualifications. For each sub-system a maintenance check list has been developed as basis for the maintenance work. Long term experience has shown that a typical monthly maintenance period following the schedule requires about 2 man-days while an annual maintenance requires about 14 man-days of labour.

3. IN-SERVICE INSPECTION EQUIPMENT FOR A LOW POWER RESEARCH REACTOR

At low power research reactors, in-service inspection (ISI) is usually carried out on components that are not directly accessible due to a high radiation level; such as the reactor tank, the core structure, fuel elements, etc. For these ISI inspections tools and methods have been developed based on experience in non-nuclear applications and modified or adapted to the nuclear environment. Some ISI methods that are used at TRIGA facilities are:

- visual inspections using
  - underwater telescope

  - endoscopes
  - underwater cameras using radiation hardened systems
- replica method

Other non-radioactive components may be inspected with methods used in conventional industries. The following methods and tools are typically used in a TRIGA Mark-II reactor but may easily be adapted for any other low or even high-power research reactor.

3.1. Nuclear Underwater Telescope

Nuclear underwater telescopes are high resolution devices (resolution 0.1 mm) with continuously variable magnification. They allow remote underwater viewing of the reactor tank and core components such as fuel elements, core support structures, etc. both vertically and also horizontally. Such a telescope penetrates the water level while the water fills up the periscope tube, providing complete radiation shielding for the viewer. Since no radiation-sensitive optical element is built in at the lower end of the unit the optical image quality is not diminished of, due to radiation induced decolourization, reflection losses or distortions. In order to facilitate acquisition of the object and detail observation, the magnification can be continuously controlled. Photo and video recording is also possible for some equipment types.

3.2. Endoscope (Fig. 2)

For the inspection of the inner surface of neutron beam tubes or internal core structures, a modular endoscope is found to give excellent results. A typical system consists of a set of a 1-meter long (diameter 18 mm) ocular and rigid optical extension pieces. These modules can be coupled to the desired length, up to several meters. The front end of the endoscope houses the objective together with an integrated 100 W/12 V

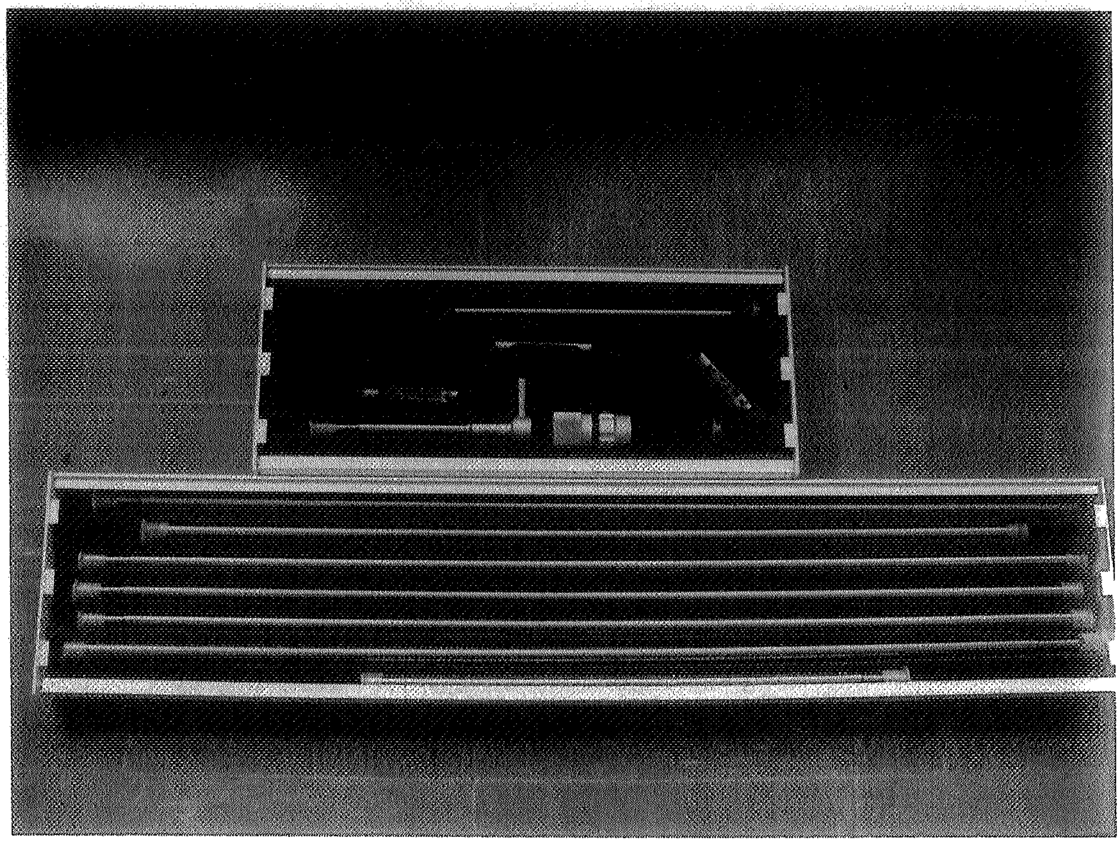

FIG. 2. Underwater endoscope.

lamp powered by a transformer. Various objectives with forward-, 45°-forward-, 90° and 45°-backward viewing angles are available. Photos or videotapes can also be taken through the endoscope for permanent record. In case of gamma radiation streaming out of the beam tube, the ocular can also be mounted at an angle of 90° and viewing can be performed from outside the radiation field. Some systems have flexible sections that may turn as needed to reach remote areas.

3.3. Underwater Camera

Some facilities may use specially designed underwater video cameras or place a video camera inside a watertight housing to perform routine or non-routine ISI. Often, a set of underwater lamps are necessary to illuminate the object deep inside the reactor pool. The output from the camera may be sent to a recorder or video monitor for inspection.

3.4. Replica Material (Fig. 3)

To determine the dimension of a corrosion spot (or i.e. the surface structure of small activated items in the core region) a two component silicon-based material (similar to that used by dentists) has been found very useful. In the present case, a plastic cap of a powder bottle was mounted at the end of an aluminium rod and filled with the mixed silicon paste. This material remains soft or pliable for about 3 minutes in ambient air. Then the rod was lowered into the reactor tank (water temperature about 30 °C) and immediately pressed on the corrosion crater for 4 to 5 minutes. Within this period, the silicon paste hardens completely and the system can be removed from the reactor tank. The hardened material gives an exact replica of the corrosion crater for further investigation.

FIG. 3. Replica material to determine the dimension of a corrosion spot.

FIG. 4. Tank cleaning pump with integrated filters.

Operators must control the type of materials that enter the reactor tank. Not all ‘impression clay’ is chemically compatible with materials in the reactor tank or could increase the pool water conductivity. Some materials may have a high neutron absorption cross section and become radiation hazards when the reactor is restarted. The chemicals in dental plaster or similar molding materials are likely acceptable because they are used in people’s mouths. However, materials coming in contact with fuel cladding (especially aluminium) must be careful evaluated to prevent the inspection from actually causing a failure.

3.5. Tank Cleaning Vacuum with Integrated Filters (Fig. 4)

Dirt or debris in the reactor tank may cause cloudiness or potentially cause thermal and hydraulic problems within the reactor fuel. The most effective manner of keeping the reactor tank clean is to eliminate the source by covering the pool with a transparent cover and remaining diligent to not drop materials into the water when working above the pool. Most research reactors have some system of purifying the primary coolant. These systems are generally not designed to remove relatively large debris that sinks quickly to the pool bottom. A conventional plastic pump used for cleaning swimming-pools has been found useful to clean the tank bottom from small debris. This system is equipped with a coarse filter to collect larger objects (such as screws) and twelve units of candle-type fine filters for collecting small particles. One advantage is that these fine filters are reusable, they may be washed and reinstalled into the pump. Some reactor facilities will perform a pool cleaning annually if the equipment is routinely available.

FIG. 5. Underwater jet to remove deposits.

3.6. Underwater Jet to Remove Deposits (Fig. 5)

One tool that has been found very useful in cleaning remote areas in reactor tanks from debris is a strong water jet (160 bars) produced by a portable compressor together with different types of jet nozzles. The material stirred up from the tank bottom or any deposits removed from the tank wall will ultimately by collected in the filters of the water purification system. However, it would be ideal to remove the material quickly with a local vacuuming system as described in section 3.4. Some of these jet nozzles are small enough to be inserted through a hole of the top grid plate right into the core volume and can be used to clean the core of debris or corrosion deposits. Operators must be cautioned that high pressure water jets can cause damage to sensitive reactor components and therefore the jet should not be aimed directly at fuel elements.

3.7. High Intensity Underwater Lights

Miniature, strong underwater lamps are necessary to inspect remote areas in reactor tanks. Generally, this is done in conjunction with the use of an underwater camera or a pair of binoculars used at the pool surface. This 24 V DC lamp (13 cm length, 6 cm diameter) has a power of 250 Watts and can only be operated under water. The lamp, mounted on modular 1 meter aluminium tubes that are coupled to the desired length, can be directed to any desired position in the reactor tank for optimal viewing. Another useful system for illuminating objects underwater has been the high intensity directional lamp used from the pool surface. These 12 VDC lamps are usually extremely bright (1,000,000 candle-power) and focused in a very tight beam of perhaps 6–10 cm in diameter.

3.8. Rotating Underwater Brush

In many areas of a reactor tank, small surface spots of corrosion may be seen during inspections. If desired, these spots can be brushed away using an underwater rotating brush connected to a standard drilling machine by an extension shaft. Practically all areas inside the reactor tank can be cleaned using various types of brushes (radial, pot-type). As with other cleaning equipment used around the reactor, operators must be extremely cautious to prevent damaging the object they are attempting to clean.

4. PRACTICAL EXAMPLE OF AN IN-SERVICE INSPECTION CARRIED OUT AT A TRIGA REACTOR AND AT A MTR REACTOR

The TRIGA facility at the Atominstitut Wien (in Vienna, Austria) was requested to provide equipment for detailed inspection of core internals and remote cleaning of the pools of several research reactor facilities. The following equipment was provided:

- an underwater endoscope with 6.5 m length and three viewing angles (0°, 45° forward, 90°)
- a high pressure water jet to stir up debris from tank internals
- a circulation pump with coarse and fine filters
- a pick-up tool for small pieces
- photo and video equipment

4.1. Typical Inspection Programme at a Small Reactor Facility [13]

After setting up all equipment, the tank inspection usually starts in one sector of the tank and continues clockwise through the other sectors. The tank bottom, the reflector, the respective beam tubes and their connection to the tank are optically inspected by the endoscope in each sector. Many particles of different sizes are normally found and the larger particles or objects (e.g. bolts and screws) are removed with the pick-up tool developed at the Atominstitut. The optical inspection usually lasts for two days followed by cleaning of the tank bottom with the circulation pump.

After another visual check, the high pressure water jet is used to stir up all deposits and flush the tank surfaces. This task takes about half a day and causes the tank water to become very cloudy and semi-transparent due to suspended particles. At the same time, the circulation pump filters out these particles. The primary and the purification loops are kept operating overnight to filter the water and to remove the suspended particles. Normally, by the following day, all tank surfaces and the tank water are clean and no deposits are found at the tank bottom (Figs. 5 to 7).

4.1.1. Inspection of a 250 kW TRIGA type reactor

It was found in one particular case that the central thimble (CT) showed a deformation below the top grid plate and could not be moved more than 10 cm vertically. This was clearly seen in a video inspection using an underwater endoscope. The Reactor Safety Committee convened and reviewed and approved the removal of the top grid plate. All three rod drive mechanisms had to be disconnected and removed from the reactor bridge and the reactor core unloaded before removing the top grid plat. When the top grid plate was unbolted and removed the operators were able to cut the CT about 30 cm above the grid plate. The CT was then removed downwards through the center hole. The dose rate from the grid plate was about 0.5 mSv/h when pulled up within 30 cm below pool water level and measured at bridge level.

It was obvious during reinstallation of the grid plate, that the guide tube for the regulating rod was not firmly fixed into the lower grid plate. Optical viewing with the endoscope showed a 5 mm gap between the bottom of the guide tube and the lower grid plate. With the 90° endoscope, the bottom area of the lower grid plate was inspected and the locking device was found not fixed in place and probably damaged. Therefore, the whole regulating rod guide tube was removed from the tank and inspected behind an appropriate shielding. The

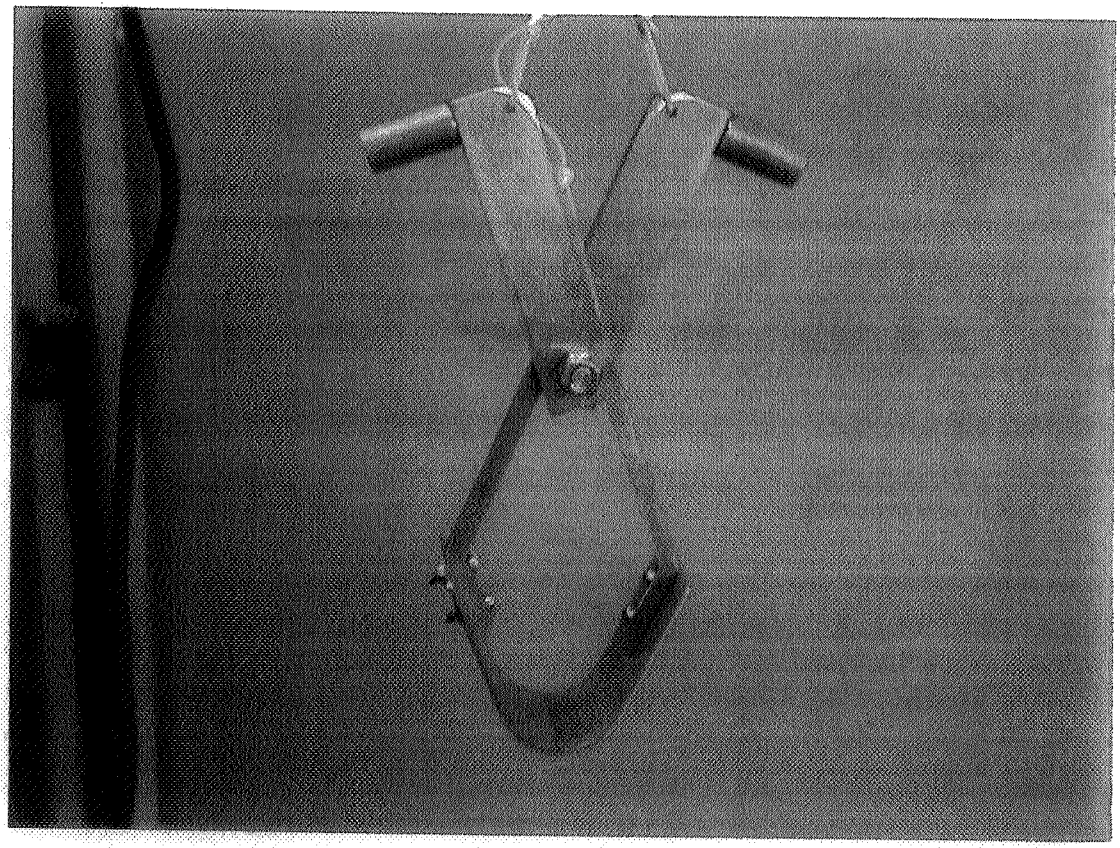

FIG. 6. Pick-up tool.

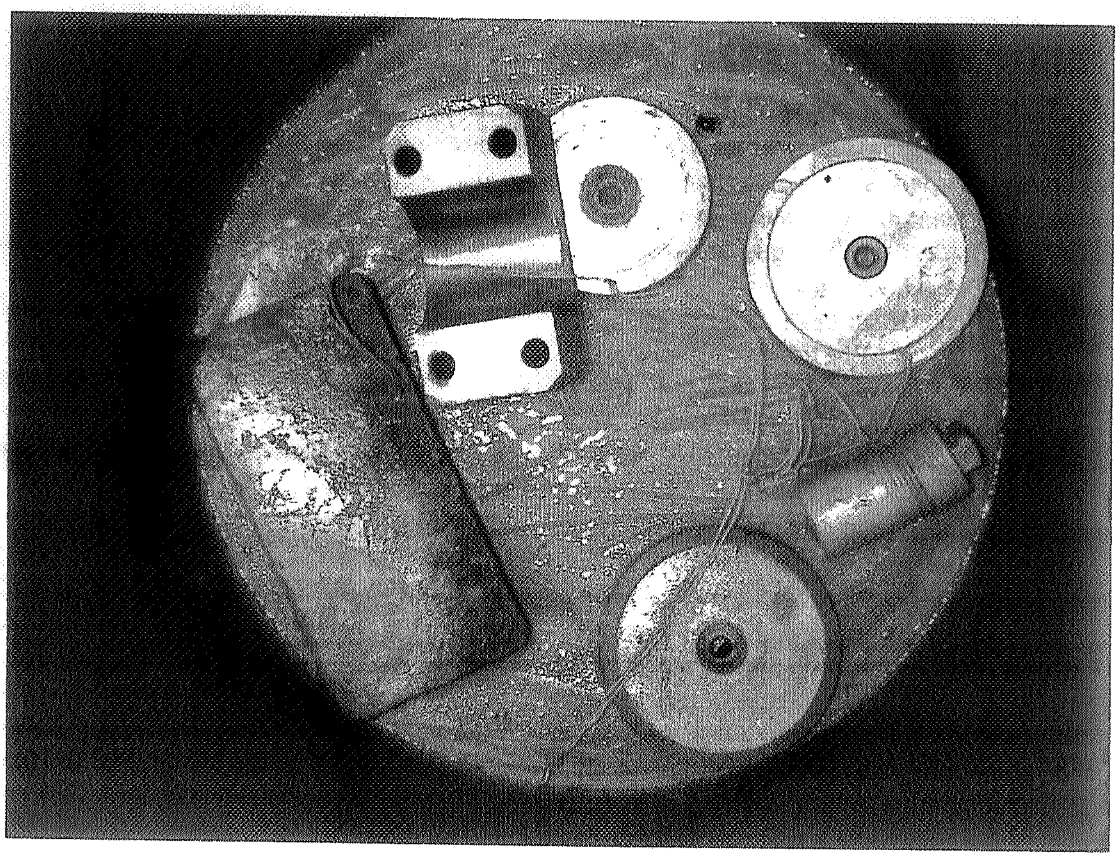

FIG. 7. Collected pieces with the pick-up tool.

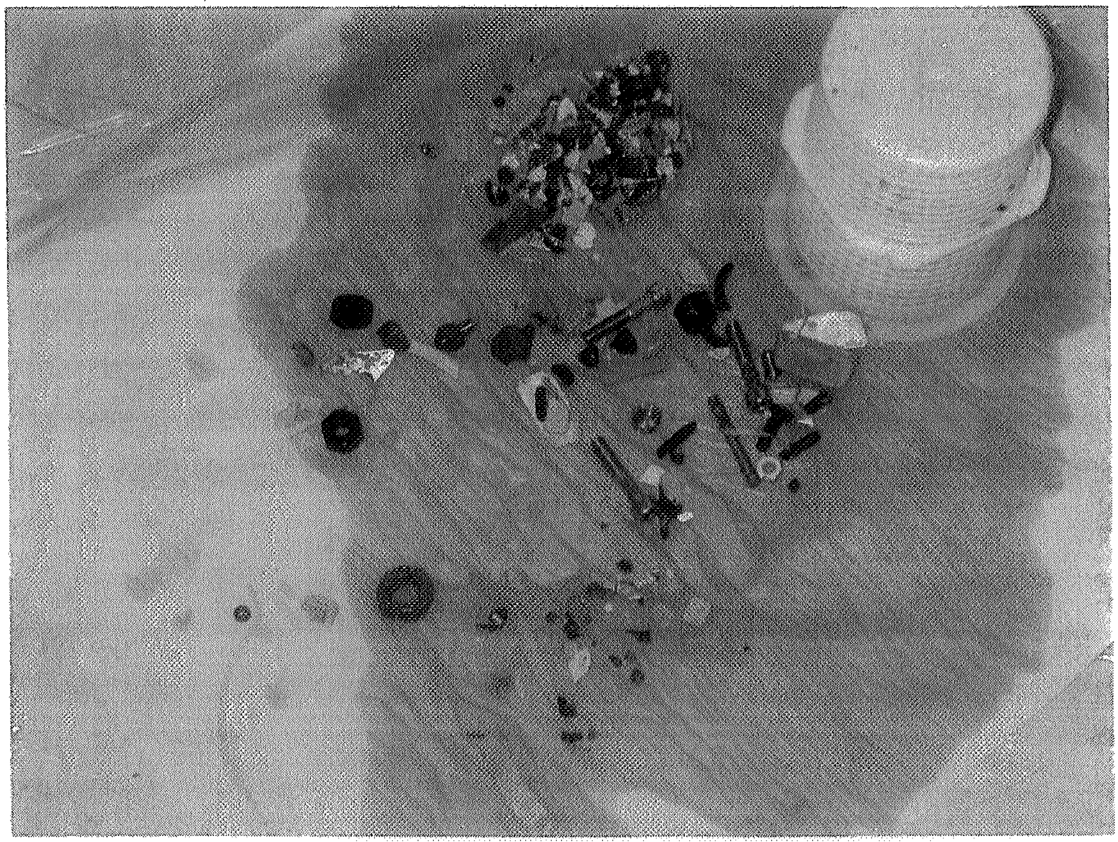

FIG. 8. Collected pieces in the coarse filter.

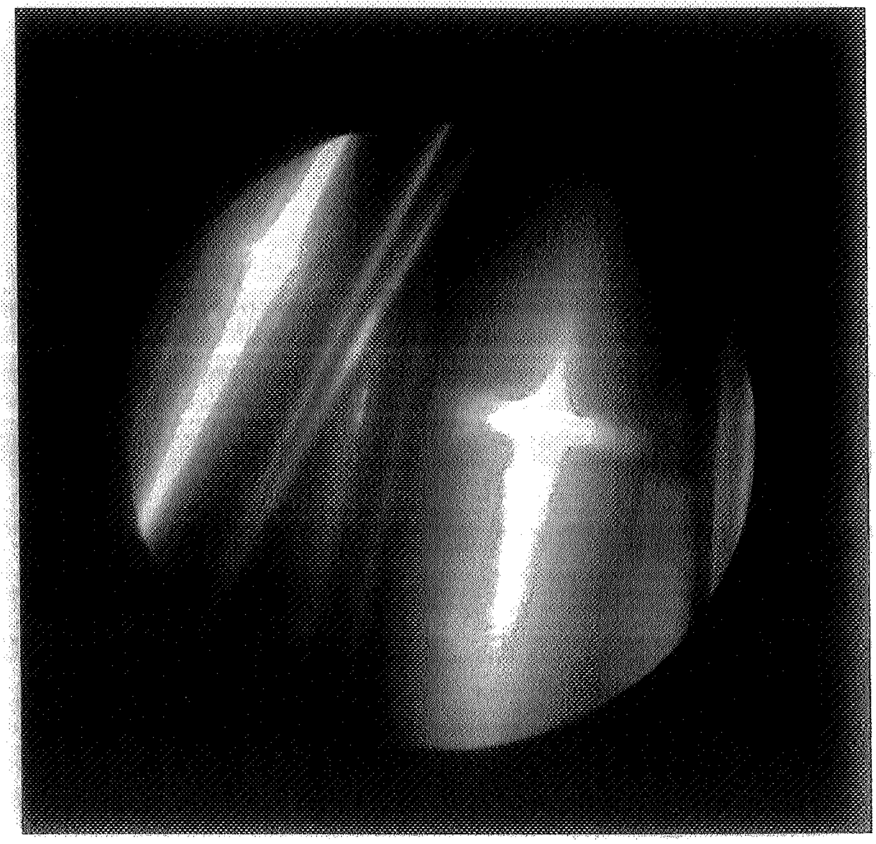

FIG. 9. Stored fuel element in the spent fuel storage.

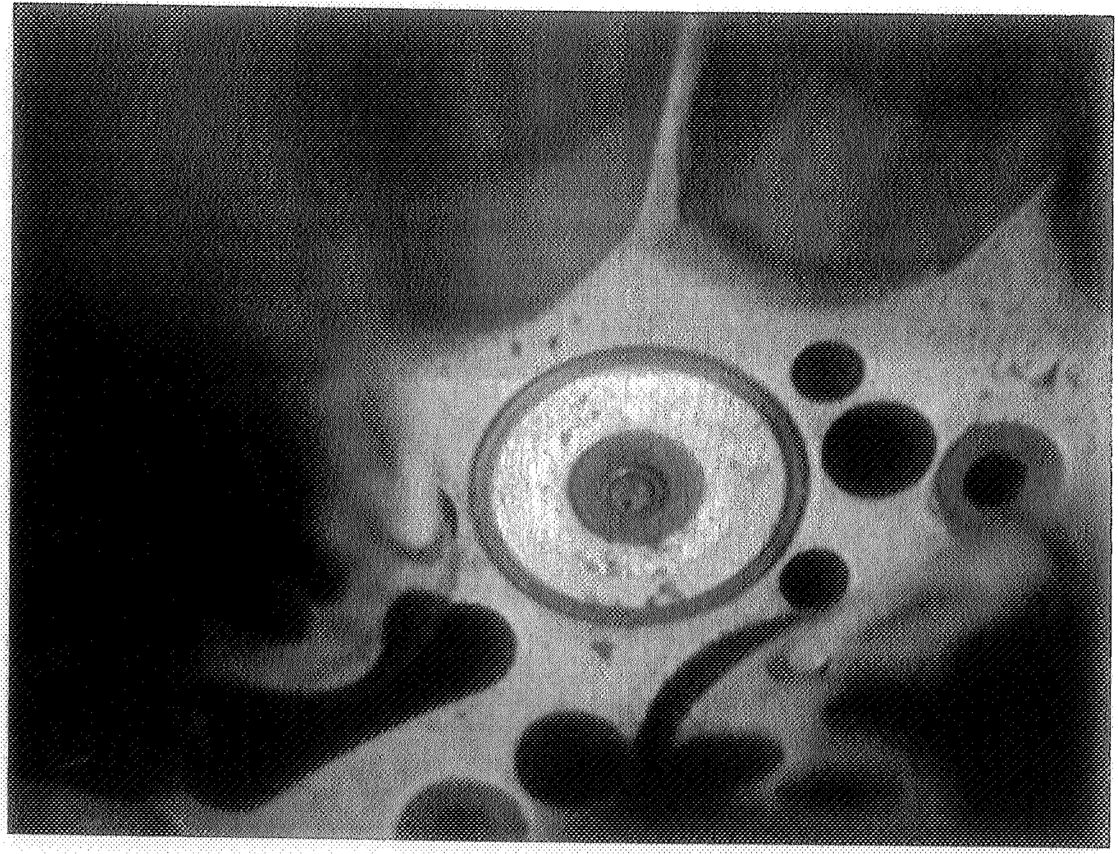

FIG. 10. Lower grid plate.

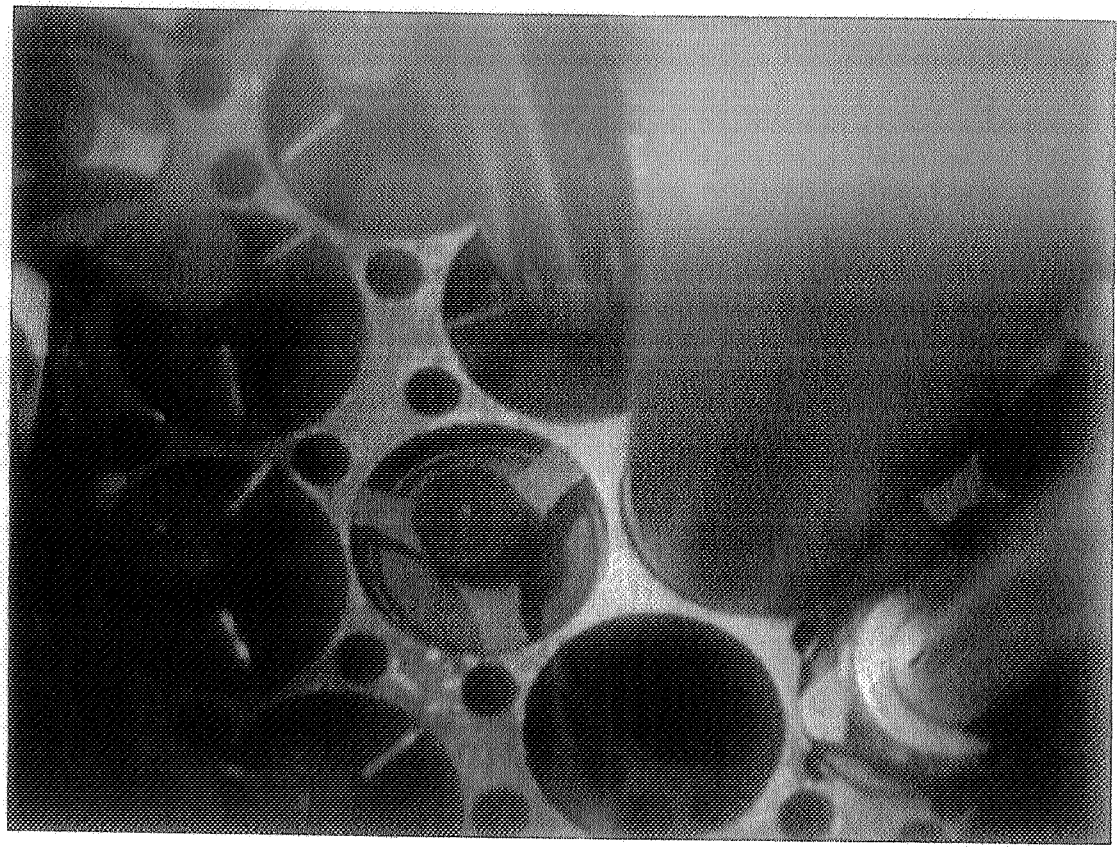

FIG. 11. Upper grid plate.

dose rate from the guide tube was about 0.1 Sv/h . It was found by direct inspection, that the guide tube locking wire did not penetrate fully into its position resulting in a very loose and unstable connection between guide tube and lower grid plate. The guide tube was returned into its position and the locking screw was tightened remotely from the tank top. The guide tube connection was inspected optically with the endoscope and documented by video to verify the position. The full task required approximately 30 Man-hrs to complete. After this task, the reactor tank and all the tank internals were inspected and found to be excellent condition, no major corrosion spots were found.

4.2. Inspection and repair at a 4 MW MTR reactor

A small crack in the primary circuit tubing of a 4 MW MTR reactor made an optical inspection and repair necessary. Using an endoscope mounted on a platform with reduced pool water level, the position of the crack was identified and a stainless steel sleeve was inserted to plug the crack. The correct positioning of the sleeve was inspected, verified and a pressure test was successfully carried out following the equipment repairs.

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