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Application of non-destructive testing and in-service inspection to research reactors

Results of a co-ordinated research project

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FOREWORD

As per April 2001, 284 research reactors are currently in operation and 258 have been shut down, waiting for a decision whether to be refurbished or eventually decommissioned. In fact, more than half of all operating research reactors worldwide are over thirty years old and face concerns regarding ageing and obsolescence of equipment. Some of these reactors have been refurbished, so that the age in many cases is not a representative figure to identify degradation problems. These reactors are not only sharing common issues such as progressive ageing of their materials and components but also needs of assessment for taking decisions concerning their extension of operation or shutdown for refurbishment or decommissioning. Therefore, it is necessary to examine on a regular basis the structures, systems and components of the reactor facility for potential degradation to assess its effect on safety, on availability or to avoid high cost of repair or replacement.

Part of this examination is carried out through the maintenance and periodic testing programme. The establishment and implementation of a programme of maintenance, periodic testing and inspection is a general requirement in the legal framework of the IAEA Member States to ensure the operational safety of their reactors. However, the scope and format of such a programme depends on the national practices of each country. The approach adopted in the IAEA Safety Standards for research reactors covers a broad spectrum of international practices, which include activities related to: (a) preventive and corrective maintenance of structures, systems and components; (b) periodic testing intended to ensure that operation remains within the established operational limits and conditions; and (c) special inspections pursuing various objectives and initiated by the operating organization or the regulatory body.

These special inspections, which are performed using specific techniques such as those based on non-destructive testing (NDT), are generally called in-service inspections (ISI) and, together with the above specific techniques, are the subject of the present TECDOC. The main objectives of the TECDOC are to present a number of these special techniques and to give guidance for their application. The guidance and recommendations given in this publication form the basis for the conduct of ISI of research reactors with limited hazard potential to the public.

This TECDOC is based on the results of a Co-ordinated Research Project (CRP) on the Application of Non-destructive Testing and In-service Inspection to Research Reactors that the IAEA organized in 1995 to supplement its activities on research reactor ageing within its Research Reactor Safety Programme (RRSP).

Because of the importance of such in-service inspections within the programmes for the management of ageing in research reactors, this TECDOC will be useful to a large fraction of the currently operating research reactors that are over 30 years old.

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1. INTRODUCTION

1.1. BACKGROUND

The number of research reactors that have been constructed worldwide for civilian applications is about 651. Of the reactors constructed, 284 are currently in operation, 258 have been shut down and 109 have been decommissioned. Since the 1980s, a significant fraction of operating research reactors all over the world was exceeding thirty years of continuous operation. In fact, as per April 2001, more than half of all operating research reactors worldwide are over thirty years old and face concerns regarding ageing and obsolescence of equipment. During the lifetime of a research reactor, structures, systems and components are subjected to environmental conditions such as stress, temperature and irradiation. These conditions may lead to changes in the properties of materials of the reactor structures, systems and components (ageing effects) that may affect their assigned safety functions. Further information on management of research reactor ageing is included in Ref. [1].

1.1.1. Ageing issues in research reactors and the need for their assessment

Safety is not the only concern associated with research reactor ageing issues. In addition, these old research reactors were designed and constructed using standards, materials and components meeting industrial practices in the country of origin at the time of construction. Although in general there were acceptance criteria with tests that these components and materials were required to pass, there was not sufficient experience to predict reliably the expected lifetime for most of the components and materials even if exposed only to benign environments and operating conditions. Exposure to aggressive environments and operating conditions (such as stress, irradiation, corrosive agents, vibration and fretting, etc.) will cause accelerating degradation of some of the materials and components due to ageing effects. These reactors are not only sharing common issues such as progressive ageing of their materials and components but also needs of assessment for taking decisions concerning their extension of operation or shutdown for refurbishment or decommissioning. Moreover, safety standards, which include requirements on ageing issues and safety reassessment, should be utilized when considering ageing related degradation [1, 2]. Therefore, it is necessary to examine on a regular basis the structures, systems and components of the reactor facility for potential degradation to assess its effect on safety, on availability or to avoid high cost of repair or replacement.

For all these reasons, an understanding of degradation mechanisms, assessment techniques and appropriate mitigation processes (such as those considered in an effective management programme for ageing) are necessary in order to develop corrective responses and to maintain safety in the operation and utilization of these reactors.

Part of this examination is carried out through the maintenance and periodic testing programme (see Section 2.1.1). But in some cases these examinations and subsequent assessments require the use of special techniques which are not usually considered during the maintenance activities because their use require additional resources which are not generally available to all operating organizations. Examples of these techniques and methods are non-destructive testing (NDT) techniques and procedures to conduct special inspections with varied objectives, which in general are safety-related and oriented to cope with the above mentioned issues.

These special inspections which are performed using specific techniques (such as those based on non-destructive testing) are generally called in-service inspections (see Section 2.1.2) and together with the above specific techniques are the subject of the present TECDOC. The methods and techniques of examination used in these inspections are categorized as: visual, surface and volumetric. Each of these groups describes a general method permitting a selection of techniques or procedures appropriate to that method. These techniques are described in detail in Section 2 of the present publication.

The IAEA started early to address the above issues in its Programme and Budget. Within its Research Reactor Safety Programme (RRSP), the IAEA has been undertaking activities on research reactor ageing for the past decade. In addition, many of the publications (e.g. [2], [3]) issued during this period include recommendations to give appropriate and adequate consideration to all matters related to research reactor ageing. To supplement these activities and to respond to individual requests of representatives of Member States during IAEA meetings, the IAEA organized in 1995 a Co-ordinated Research Project (CRP) on the Application of Non-destructive Testing (NDT) and In-service Inspection (ISI) to Research Reactors.

1.1.2. Objectives of the co-ordinated research project

The objectives of the CRP were:

- to develop and apply new and existing techniques to different research reactor types;
- to demonstrate in-service inspection as it is applied to specific components of research reactors;
- to review NDT methodology for ISI of reactors; and
- to make recommendations on the requirements for qualifications and certification of NDT personnel involved in ISI of research reactors.

1.2. OBJECTIVES

The main objectives of this TECDOC are:

- to present a number of special techniques that are used in the operation and utilization of research reactors to examine and monitor the condition of reactor structures, systems and components for their assessment in relation to the safe operation and general management of the reactor;
- to present NDT methodology for use in ISI of research reactor of various types;
- to give guidance on the requirements for qualification and certification of NDT personnel involved in ISI of research reactors;
- to identify appropriate methods and procedures to be used in ISI of research reactors of various types; and
- to give guidance for the preparation of appropriate programmes, including documentation, of such ISI and for their implementation.

1.3. SCOPE

The guidance and recommendations embodied in this report apply to the special inspections, including the used methods, testing techniques and procedures, of all research reactors to the extent that is reasonably practicable, taking into account the particular design and operating environment of the research reactor under consideration.

The guidance and recommendations given in this publication form the basis for the conduct of ISI of research reactors with limited hazard potential to the public. ISI of research reactors with several tens of megawatts of power, fast neutron spectrum research reactors or small prototype power reactors may require additional considerations and the use of safety guides and practices for power reactors may be more appropriate. No specifications for such a transition to other safety guides and practices are included in this TECDOC.

1.4. STRUCTURE

Section 2 presents the various techniques which are currently used during the operation of research reactors. The section was split into three subsections: The first subsection describes the general requirements and recommendations on maintenance, periodic testing and inspection, and in-service inspection of research reactors; the second subsection describes the techniques used in the maintenance and periodic testing programme and they are usually applied to demonstrate that the structures, systems and components are in compliance with the approved operational limits and conditions; the third subsection presents the typical testing techniques used in ISI with the purpose to demonstrate compliance with a specific requirement of the regulatory body or to follow up the operational conditions of one or more items important to safety; and the fourth subsection describes specific techniques that have been developed or analysed in the CRP on Application of NDT and ISI to Research Reactors which do not belong to the previous types of techniques.

Section 3 gives general guidance on how to prepare an ISI programme. This section also includes specific guidelines on particular aspects of the ISI programme such as establishment of a baseline, training and qualification of personnel, organization and responsibilities, qualification of procedures and equipment, QA considerations, etc.

Section 4 gives guidance on how to implement the ISI programme. This include specific guidelines to select the individual components for the inspection and areas to be examined, the detailed definition of the inspection techniques and associated conditions, as well as the evaluation and reporting of the results.

The Appendix presents a list of selected contributions from the participants in the CRP, which are available separately on request from the IAEA. Annex I presents a summary of the topics that were addressed by each of the participants during the CRP. Finally Annex II presents an example of in-service inspection and maintenance programme for a research reactor.

2. ROUTINE TESTING AND IN-SERVICE INSPECTION TECHNIQUES

2.1. GENERAL REQUIREMENTS AND RECOMMENDATIONS ON MAINTENANCE, PERIODIC TESTING AND IN-SERVICE INSPECTIONS ACTIVITIES

The establishment and implementation of a programme of maintenance, periodic testing and inspection is a requirement normally included in the license for research reactors in the IAEA Member States. However, the scope and format of such a programme depends on the national practices of each country. The approach adopted for research reactors in the IAEA Safety Standards for research reactors [3] covers a broad spectrum of international practices, which include activities related to:

- preventive and corrective maintenance of structures, systems and components as recommended by designers, constructors, manufacturers and support groups and adopted by the operating organization of the facility;
- periodic testing intended to ensure that operation remains within the established operational limits and conditions; and
- special inspections pursuing various objectives and initiated by the operating organization or the regulatory body.

2.1.1. Maintenance and periodic testing activities

Any maintenance and periodic testing activity should be conducted in a way that the reactor control is ensured at all times and its safety not reduced or jeopardized. Although maintenance and periodic testing are sometimes included in a single programme and may be performed by the same operating personnel, a clear distinction between these two activities is made in the above-mentioned document.

Maintenance is usually divided into two categories: preventive (also referred to as routine or scheduled) and corrective (or remedial). Preventive maintenance consists of regularly scheduled inspections, tests, servicing, overhaul and replacement activities. Its purpose is to assure the continuing capability of the reactor structures, systems and components to perform their intended functions and to detect incipient failures.

Corrective maintenance (or remedial maintenance) consists of repair and replacement activities not occurring on a regular schedule. The preventive maintenance programme will reduce the need for corrective maintenance and may result in extended availability and cost reductions. However, the total elimination of need for corrective actions cannot be achieved. Adequate resources, such as manpower, spares and budget should be allocated for corrective maintenance.

Periodic testing is carried out to ensure that the reactor is operated within prescribed operational limits and conditions and to verify the safety status of the reactor (Ref. [3], para. 901). The performance of periodic testing fulfils the surveillance requirements which in most Member States are incorporated into the license requirements (Ref. [3], para. 605). Periodic testing includes tests performed to ensure compliance with operational limits and conditions and to ensure adequacy of the safety status of the reactor. Maintenance may include tests similar to those performed under periodic testing (namely: inspection, operability checks and calibration), but which are not intended to ensure compliance with operational limits and conditions.

2.1.2. Activities related to in-service inspections

The general status of the research reactor can be improved if additional programmes involving special inspections are established in addition to the regular maintenance and periodic testing programmes. These special inspections can be considered a good practice for specific objectives. Some of these inspections may be requested by the regulatory body to assess the safety status of reactor equipment. On other occasions, they are initiated by the operating organization generally with the purpose of assessing the status of systems and structures regarding ageing effects or required modifications related to upgrading projects.

These inspections which are conducted for safety purposes and on a programmatic basis are called in-service inspections (ISI). Such special inspections should be aimed at determining the condition of components subject to corrosion, erosion, thermal stressing, fatigue or other ageing effects. These inspections constitute a major activity in the reactor operation.

Examples of in-service inspections are:

- Examination of the reactor tank, pool liner or cooling systems;
- Examination of reactor internals;
- Examination of beam tube inner surfaces;
- General examination of pumps and valves;
- Examination of spent fuel pools, liquid storage tanks, etc.;
- Electrical cabinets, transformers and cables; and
- Confinement and ventilation system.

Such inspections usually necessitate reactor shutdown and occasionally a total unload of fuel and coolant. Careful planning is necessary in order to ensure that all vulnerable components of the reactor are inspected. Certain components may be inspected during operation or routine shutdowns and this may give some indications of problems which are more widespread. The timing and scope of major inspections may be influenced by the results obtained in this way.

The decision to perform in-service inspections should be taken early enough to precede the failure of the component that likely to fail first. The scheduling should be based on conservative assumptions of deterioration rates.

Administrative aspects of ISI are very similar to those of maintenance and periodic testing. Detailed information on preparation of the programme as well as its implementation is given in Sections 3 and 4, respectively, of this TECDOC.

2.2. ROUTINE TESTING TECHNIQUES USED IN MAINTENANCE AND PERIODIC TESTING PROGRAMMES

Most of the routine testing in a research reactor is done under the programme of maintenance and periodic testing. Activities related to preventive maintenance are conducted on a regular basis. Periodic testing is usually performed in fixed time intervals but it also includes tests carried out at variable time intervals in conjunction with specific tasks (e.g. pre operational checks, testing related to new core configuration, etc.).

Periodic testing consists of the following activities: operability checks (qualitative testing); calibration checks (followed by recalibration when necessary); and inspection of structures, systems and components. An important testing activity, which may include various of the above types of testing is the reactor confinement leak tightness testing, which is considered separately in the present report.

2.2.1. Operability checks

Operability checks provide information on the ability of instrument channels to give correct signals and on the correct functioning of systems important to safety.

2.2.2. Calibrations

Calibration checks that a known input to an instrument or channel gives an output within specified limits.

2.2.3. Inspections

Inspection of structures, systems and components include several kinds of activities:

- Observation of equipment condition (e.g. leaks, noise, vibration) which is normally done during periodic walkdowns of the reactor facilities. For some systems, inspections may require devices such as telescopes and binoculars;
- Measurement of process variables and operational parameters either by stationary or by portable equipment;
- Monitoring;
- Sampling for chemical or radiochemical analysis; and
- Response time measurements of safety systems (e.g. control rods release time, control rods drop time).

2.2.4. Confinement leak tightness

Most research reactors with a medium or high power level have a dedicated confinement or even a containment building to prevent radioactive releases during unusual events.

The leak tightness prescriptions being derived from the Safety Analysis Report are normally part of the surveillance requirements and incorporated in the periodic testing programme.

Depending on the leak tightness requirements, i.e. the admissible leak rate, one of the following testing principles is employed:

- In the case of limited leak tightness requirements, usually for reactor buildings without a confinement or containment, the under pressure in the reactor building or the maximum ventilation rate could be used as an indication of the degradation of the leak barrier of the reactor building.

- For confinement buildings or containment building with modest requirements the leak-rate could be determined by measuring the decrease of overpressure of the reactor building during a prescribed period of time. The reactor building has to be brought to an overpressure (below the design pressure). The pressure can easily be measured with a water filled U-tube or a pressure gauge. The rate of change of the pressure is a measure of the leak rate of the reactor building.

- For containment buildings with stringent requirements (i.e <1 vol%/day), usually for research reactors with a higher power level, a simplified method as described above is not sufficient to prove compliance with the leak tightness requirements. Depending on the requirements the leak rate could be determined by calculation of the mass of the air in the pressurised containment building using the Van der Waals equation. The pressure, temperature and humidity at a number of positions or subsections in the containment building have to be measured. Based on the measured data together with the volume of the subsection the mass of the air in a subsection can be calculated. All the calculated masses of the subsections gives the overall mass of the containment building. The rate of change of the overall mass will give the leak rate of the reactor building. The number of pressure, temperature and humidity indicators, the subsections to be defined as well as the sample frequency are to be harmonised with the admissible leak rate.

2.3. METHODS AND TECHNIQUES USED IN IN-SERVICE INSPECTION

Methods and techniques of examination are categorized as: visual, surface and volumetric. Each term describes a general method permitting a selection of techniques or procedures appropriate to that method.

In contrast to the routine tests discussed in the previous section, the in-service techniques described in this section will be mainly applied during more major shut downs of the plant. This is particularly the case where core components are being examined. Many of the techniques discussed in this section can be applied without a great deal of expense and with relative ease. Visual inspection, for example, is perhaps the simplest and one of the most informative technique for assessing component integrity. Other techniques require more investment in equipment and operator expertise.

2.3.1. Visual examination

A visual examination is used to provide information on the general condition of the part, component or surface to be examined, including such conditions as scratches, wear, cracks, corrosion or erosion on the surface. It is one of the most powerful techniques for assessing component integrity and should be used as the preferred initial techniques; in that it can provide information which may suggest other techniques which should be employed.

The range of equipment available for visual inspection is wide. The most important aspect of the equipment's performance is the ability of the optical components to resist radiation-induced browning. This is particularly important in high dose regions such as the core. However, radiation hard cameras and lenses are expensive components and may not be appropriate in some cases. It may be more cost effective to lease the equipment, remembering that time must be set aside for developing the capability of the operators who will undertake the survey. Another option may be to use external contractors skilled in the use of the equipment. Some specific examples of remote visual inspection (RVI) equipment are given below.

Underwater telescopes: Underwater telescopes are optical devices similar to stellarscope with continuous magnification. They can be used for inspection of the reactor tank bottom, and other surfaces, from the top of the tank. It is usually mounted on a bridge across the reactor tank and penetrates one meter into the tank water, the water providing excellent radiation shielding. The telescope allows a very high resolution for side viewing mirrors and additional spotlights may also be necessary. However, remote areas may be difficult to inspect in which case one of the more sophisticated techniques described below should be considered. These telescopes have been developed by several companies and, in some cases the equipment can be hired. This may be of particular interest to small research reactor facilities where the purchase price may be beyond the budget for ISI programmes.

Endoscopes: Endoscopes are rigid optical devices that can be used for remote visual inspection of reactor tanks, beam tubes, thermal columns or any remote area as long as only straight access is required. As the device is located at the point of inspection, often several metres away from the viewing aperture, such endoscopes are modular devices of about one metre in length and 14 to 20 mm diameter. The individual modules can be coupled together vertically up to the required length. The bottom end of the endoscope is fitted with a strong spot light and with interchangeable viewing tips allowing either forward, sideways and even backward viewing. A camera or video equipment can be coupled to the ocular of the device for recording of images. Due to the small diameter of the endoscope this device can directly enter into an empty core position when the reactor is shutdown. (Appendix, Case Study 5).

Flexible fibre-scopes: Advances in opto-mechanical technologies have resulted in the development of industrial flexible fibre-scopes for remote visual inspection of difficult to access areas. The fibre-scopes incorporate high quality coherent fibre optic image guides complimented by advanced light guide systems which transmit maximum illumination from a remote light source to the area under inspection. A selection of fixed objective focus and interchangeable tips allow improved brightness and resolution as well as enhancing the direction, field of view and depth of field of the optical system. A wide choice of lengths and diameters are available from ultra-thin 0.6 mm diameters to 11 mm diameter systems. Most also have two or four-way angulation control for accessing difficult to reach areas.

Videoimage-scopes: Videoimage-scopes provide significant resolution and brightness advantages over conventional fibres-copes. In addition, the mechanical strength of the insertion tube and angle mechanism make them less susceptible to damage (compared to fibres-copes) in an industrial environment. A range of 6mm and 8mm videoimage-scopes using charge coupled device technology are available for generating high resolution real time images. Illumination is provided via a fibre optic light guide from a suitable source and scope lengths of 2 m to 16m are available. The instruments can be supplied with interchangeable tip adapters allowing a choice of field and direction of view to suit the application. Image management is achieved by coupling of the unit with a video analyser. Electronic processing techniques such as high gain and frame integration provide enhanced sensitivity.

Both fibre-scope and videoimage-scope have been used to inspect metal surfaces below the core lattice plate and to inspect primary piping and welds within a low power research reactor (Appendix, Case Study 4). The advantages of the fibres-cope allowed for fast all round viewing and ease of positioning. However, the limited length of the probe used may restrict penetration depth. Although longer probes are available the fibres are more prone to damage. The videoimage-scope produced crisp high resolution images with good depth of field. However the use of the instrument should probably be confined to areas where limited movement is required.

2.3.2. Surface and near surface techniques

A surface examination is undertaken to delineate or verify the presence of surface or near-surface flaws or discontinuities. It may be conducted by a liquid penetrant for surface-breaking discontinuities, magnetic particle, eddy current or electrical contact method for surface breaking and near surface discontinuities.

2.3.2.1. Liquid penetrant

Liquid penetrant testing can be performed on both magnetic and non-magnetic materials to detect and evaluate surface breaking flaws. The liquid penetrant technique is based on capillary action. The application of a coloured or fluorescent penetrant or dye is either sprayed, dipped or brushed onto a well cleaned surface of the area to be examined. Sufficient time has to be allowed for penetration into surface discontinuities. The surface has to be cleaned (from oil or dust) and in certain cases surface irregularities have to be removed by grinding prior to application. Generally there are two types of liquid penetrant methods which are the colour contrast method and the fluorescence method. In the first case the tested object is inspected under normal strong light while in the second case ultraviolet light is required.

2.3.2.2. Vibration analysis

One of the features indicating the working condition of the components in research reactors is the vibration of the components. Most of the components in the reactor are in a static state in the normal condition when they are assembled or working properly. In addition, for moving and/or rotating parts of plant equipment (e.g. main pumps, motors, control rod drive systems etc.) the vibration induced by their function manifests itself in stable and uniform movements. Even the stationary components in the reactor might also give small vibration during their normal operation condition although their vibration possesses limited amplitude and is located in the low frequency range. On the other hand, if these components work improperly or some part of them is defective, the vibration characteristics given by these components will be abnormal, both in time and in frequency domain. For these reasons the vibration characteristics of a component can be one of the indicators of their working conditions. Vibration analysis of selected components is therefore a useful technique for in-service inspection.

Several examples of the defect-induced vibration, and the possible causes, are given below:

- Abnormal vibration of the fuel assemblies in the reactor core, due to wear or corrosion of the insertion seats or due to hydraulic effects induced by abnormal coolant or moderator flow;
- Abnormal vibration of control rods and their guide tubes, due to improper assembling, defective support or abnormal wearing of the control rod drive systems; and
- Abnormal vibration of the primary pumps due to wearing of the bearing rack, point corrosion on the bearing ball and improper assembling.

The generic principles for the technique of vibration analysis can be summarised in the following way. The required number of sensors (piezoelectric acceleration transducers or other similar devices) are applied to the component to be inspected. Signals from the sensors, after being amplified, are sent to an analogue to digital converter and the digital output is stored in a computer for filtering, processing, and analysis by appropriate software.

Two examples for fuel assembly vibration inspection and for main pump vibration inspection are given in the Appendix, Case Study 2.

2.3.2.3. Eddy current

Eddy current testing (ECT) is able to detect and evaluate surface-breaking and near-surface flaws in conducting materials. A particular application of eddy current examination is to establish the existence and depth of flaws in tubing and tubular configurations.

ECT involves the induction of currents into the test material surface by a coil, held in a probe, close to the material surface. When these eddy current signals are disturbed by the presence of surface breaking defects a measurable change in impedance of the probe coil occurs. The amount of impedance change is related to the size and nature of the defect.

The absolute coil test method is used to gauge the overall thickness of the material (tube) being examined. It should be used to assess the general condition of the material. Such a system has been used to investigate the core box corners of the high power research reactor (Appendix, Case Study 3).

Dual frequency, differential coil, ECT is used to detect very small defects with abrupt changes in boundaries. Dual frequency techniques allow the suppression of unwanted signals generated due to support structure deposits, wobbling, etc. This helps in detecting even very minor type of defects with its size and relocation. This information is useful in monitoring the defects at regular intervals to assess the suitability of the equipment for regular service. A differential coil ECT has been developed for assessing local defects in the calandria tubes and the heat exchanger tubes of the reactors described in the Appendix, Case Study 6.

ECT equipment should meet the requirement of any approved testing standard. The equipment is readily available with various ranges of specification. For each ECT the test probe as well as the reference standard are required to be developed.

Test probe: The test probe to be used to carry out ECT of a specific material has to be developed and tailored with consideration to various design aspects such as, stability of the test probe material to withstand the radiation field; physical properties of the material (tube) being examined; dimensions of the material (tube); fill factor of the probe to be as close to 0.98 (Appendix, Case Study 6).

Reference standard and calibration: Material of the reference standard should be the same as that of the material being examined. Artificial defects of various sizes and at different locations should be developed onto the reference standard as per the test and service requirement. The standard may be available commercially or could be developed in-house if the capability exists. Calibration of the ECT equipment and test probe is carried out against the reference standard to finalise the test parameters such as phase angle, gain etc. Laboratory trials should then be carried out to optimise these values. The calibration responses to artificial defects in a reference standard are given in the Appendix, Case Study 3.

Approval of the test procedure: The complete test procedure giving all the details should be prepared and put up for the approval of the competent authority. The approval procedure should be used for caring out actual examination with proper documentation. Typical procedures are referenced in the Appendix, Case Study 3.

2.3.2.4. Replication

Replication is the action of indirectly assessing the condition of a surface by some form of transfer method. A number of methods are available including the use of putty-like or polymer based materials which harden a specific time after being mixed, magnetic rubbers (useful for detecting surface breaking cracks in ferromagnetic materials) and acetate films, which are softened with acetone and then pressed onto the surface.

The application of some of these techniques to reactor components has been extensive with several organisations reporting its use in areas such as core tanks and pipe work. (Appendix, Case Studies 1, 4 and 5). A number of issues need to be addressed when employing replication; such as:

(a) **Sensitivity** — the ability of the materials to replicate fine detail differ between manufacturers. It is possible to employ nuclear power plant accredited material (Appendix, Case Study 4) or to use dental putty (Appendix, Case Studies 1 and 5). Both these materials have low chlorine and sulphur content.

(b) **Ease of handling** — a number of hardenable pastes have been used with great success and these are relatively easy to use with remote handling equipment. Care has to be exercised in ensuring the no material falls into the reactor interior where it cannot be retrieved. A fluorescent material can be mixed with the replicant in order to scan for material left behind after removal of the replica.

(c) **Safety aspects** — the hardenable pastes pick up a considerable amount of surface debris and caution should be exercised when removing them from reactor internal structures. Temporary storage in lead pots is recommended followed by decontamination by ultrasonic cleaning. In some cases it may be necessary to re-replicate the replica if the contamination is tightly adhered to the surface. Consideration should also be given as to the effect of the replicant on the surface.

The use of replication for analysis of corrosion induced pitting in a low power research reactor dump tank was carried out using polymer based materials (Case Study 4). The materials are two part synthetic rubber compounds which have been developed for high resolution, three dimensional replication of engineering surfaces. Both polymer and curing agents are dispensed using hand operated or pneumatic dispensers, the latter allowing for remote application in dry or wet environments. Mixing of the polymer and curing agent is carried out automatically in a disposable static-mixing nozzle during application to the surface.

The compounds have a resolution better than 0.2 μm and exhibit high contrast characteristics. Replicas are high strength and flexible enabling easy removal from difficult geometries without damage. The replicas do not suffer from shrinkage and are therefore dimensionally accurate for measurement and archiving purposes. The materials have low levels of chlorine and sulphur and are approved for use on stainless steel in nuclear plants.

Replication compounds can be obtained in both fluid and thixotropic versions. Fluid versions are typically used on horizontal surfaces and for very rough surfaces to minimise air entrapment. The thixotropic versions allow vertical and overhead surfaces to be replicated. The range of viscosities and curing rates allows suitable transport times for the material to the inspection site, over long distances. The elastic properties and greater strengths of some replication materials have allowed application within fuel elements.

The replicas can be examined and measured by techniques such as, conventional optical microscopy, scanning electron microscopy (SEM, with or without conductive coatings), laser scanning (for topographic information) and shadowgraph methods.

It is noteworthy that advances in SEM technology, primarily for the bio-medical applications, allow the replicas to be interrogated without coating thus extending magnification as well as archiving.

2.3.2.5. Hardness techniques

The measurement of hardness is a technique which can provide information on changes to the mechanical properties of some structural materials. The hardness can be correlated with tensile properties in some cases and can be used as a measure of radiation-induced property changes. This information is mainly of use in older reactors where the regulators may require information on changes from the constructed state.

The measurement of hardness can be made remotely if appropriate jigs and a manipulator are available. One of the most appropriate technique is the use of a spherical ball indenter which leaves a smooth indentation with no sharp edges.

2.3.3. Volumetric examination

A volumetric examination could be undertaken for the purpose of indicating the presence, depth or size of a sub-surface flaw or discontinuity, and usually involves radiographic or ultrasonic techniques.

2.3.3.1. Ultrasonic testing

The use of ultrasonic techniques is one of the most widely used inspection methods. The type of inspection can vary from simple thickness measurements to sophisticated multi-transducer imaging applications. The output of ultrasonic inspection, in its volumetric form, is usually the depth and length of defects and the items being inspected are usually welds. In the case of thickness measurements a number of components are being inspected frequently i.e. pipes, pool liners, tanks, etc.

Thickness gauging is a relatively simple but important technique which can provide a great deal of information on areas of research reactors which are subject to potential wall loss due to corrosion or by other means. The most important aspect of the technique is to present the ultrasonic transducer to the item being assessed normal to the surface. This is simple to achieve using contact coupling, where the transducer is in direct contact with the surface. However, it is more likely that contact will be through a liquid column (essentially an immersion technique) using either the water in the tank or in the pool or by some other means of providing a water column between the transducer and the component.

Information gained using this technique can give indications of wall loss and can provide valuable information for remaining life or structural integrity studies. Caution should be exercised, however, because thickness gauging is essentially a sampling technique — due to the fact that the thickness is being measured over the beam width in the component — small regions of thickness reduction, such as corrosion pits, may not be detected.

In Case Study 1 thickness measurements of the reactor tank and the down comer of the primary cooling water system using a 10 MHz broadband transducer are presented. A description of the rigs developed in-house is also given.

Ultrasonic testing is the most common method used to establish both the length and depth of sub-surface flaws in structural materials and utilises a beam of high frequency sound passing through the volume of the material to be inspected. Any discontinuities in the material reflect a proportion of the incident beam back to the probe, which converts the reflected sound energy into an electrical signal. The time taken until the echo is received indicates the distance of the reflector from the probe. The amplitude of the received signal, relative to a calibration reference reflector, can be used to assess the length of the sub surface flaw.

Ultrasonic investigations are often used for weld inspections and could need sophisticated multi-transducer methods to examine critical welds. In many cases dedicated manipulators are required to position the transducer(s) and the costs involved may be beyond the available resources of smaller reactor facilities.

While thickness gauging can be performed by the lower level of NDT technician, multi-transducer inspections require more skilled operators with extensive experience in both the technique and also the type of component being examined. Due to the required specialism and experiences ultrasonic testing is frequently contracted out to specialised inspection companies.

In Case Study 1 the survey of a number of main welds using ultrasonic testing techniques and the prepared sample welds are discussed. Another example of ultrasonic testing and the inspection equipment used have been presented in Case Study 3.

2.3.3.2. Radiography

Radiographic techniques, employing penetrating radiation such as X rays, gamma rays or thermal neutrons, may be utilized with appropriate image-recording devices, not only to detect the presence of flaws but also to establish the size of flaws, by determining mainly the length of sub-surface flaws in structural materials.

Gamma and X radiography

X radiography is one of the earliest NDT techniques and has been extensively employed in industry to determine discontinuities in materials. Gamma-radiography is also a well recognised and extensively used technique that complements X radiography. In both cases the penetrating radiation is electromagnetic. However, a typical X ray spectra is a continuum with characteristic X ray lines (K_α and K_β) and is produced by an X ray generator incorporating a source filament such as tungsten. In contrast gamma rays are produced from radioactive sources at discreet energies which are greater than X ray energies. Typical radioactive sources used in gamma radiography are ^{60}Co, ^{192}Ir, ^{169}Yb, ^{137}Cs and ^{170}Tm. Accordingly, the methodologies used for gamma- and x-radiography may be quite different. The use of radioactive sources has several advantages; the source is compact and independent of electrical and cooling supplies — therefore portable; the cost is relatively low and the radiation is monochromatic. However the shorter wavelengths of gamma rays may lead to a lack of contrast in the shadow image. Gamma ray sources are also of lower intensity than X ray generators leading to longer exposure times. A gamma ray source also remains a continuous radiation hazard whereas an X ray generator can be switched off.

The fillet welds in a tank have been examined by gamma-radiography using a ^{169}Yb source (Appendix, Case Study 4) and reactor fuel pins have also been examined by x-radiography (Appendix, Case Study 4).

The following points should be considered in order to obtain good high quality information from any radiograph:

- A preliminary visual examination in order to decide the orientation of the object relative to the source will help to enhance the image of inclusions or linear features;
- The energy of the source taking into account the composition of the object and the path length of the electromagnetic radiation through the object;
- Recording of the image requires careful consideration of many factors including the distance between the source, the object and the detector plane, the type of film, the exposure time, etc;
- Interpretation of the radiograph, including detailed knowledge of the specimens and the types of defects or features that might be expected, and the use of reference radiographs if available.

It should be obvious from the short description here that radiography is a highly specialised technique that requires detailed procedures and skilled technicians in order to be used effectively. Reference [4] provides a good overview of gamma and X radiography as well as other NDT techniques.

Neutron radiography

Neutron radiography (NR) is a non destructive testing method which is similar to gamma and x-radiography. In both techniques a radiation beam is attenuated by an object and the transmitted beam is registered on a special film or foil which is processed to show material variations inside the object. The main difference between NR and gamma or X radiography is the fact that gamma and X rays are attenuated continuously with increasing mass number of matter while neutron attenuation (absorption or scattering) depends on individual nuclides in the matter (i.e. hydrogen in metals or ^{10}B in steel). Therefore, with NR one can look selectively for nuclides with either a high neutron scattering cross-section (such as ^{2}H) or nuclides with a high neutron absorption cross-section (such as ^{10}B, Gd, Cd, U, Pu).

One drawback of NR is that the objects for analysis have to be taken to a NR facility at a research reactor. The technique is therefore not as easily available as gamma or X radiography. However, mobile NR facilities have been developed (see Ref. [4]), mainly for the aircraft industry, and could in principal be used in an ISI programme for research reactors.

In the nuclear field, NR is specially used for inspection of radioactive objects such as nuclear fuel or isotopic sources which cannot be imaged by x-radiography because of their interfering gamma ray emissions. In other more common fields, NR is extremely important for defect detection in low atomic number materials located in metallic casing or under metallic pieces. For example, NR is used for corrosion detection in aeronautic aluminium plate assemblies, detection of hydrogen in metals, moisture in materials, measurement of uranium, lithium and boron content in metals, visualization of two-phase flow in pipes, inspection of composite materials and ceramics. These and many other applications are described in Refs [5] and [6].

2.3.4. Other techniques

2.3.4.1. Leak and pressure testing

Leak testing utilises a tracer gas such as helium to detect leaks with a dedicated detector such as a mass spectrometer. Helium leak testing is one of the most sensitive leak detection methods. The components or systems to be investigated must be filled with sufficient concentration of helium. The leak can be located by using a so-called tracer detector.

In the case where the leak rate has to be determined, using helium leak detection, the concentration of helium should be well known and a special detector probe has to be used by a well trained specialist. In this case, the measured leak has to be compared with a clearly defined leak rate in order to be able to quantify the measurement.

Pressure tests are normally performed with liquid mediums. Gaseous mediums are normally only to be used with slight overpressure otherwise special precautions to eliminate the risk of accidental release in case of rupture should be taken. Soap bubble tests and pressure change tests are the mostly used techniques. An advantage of pressure testing is that the system or components can be tested under normal load conditions.

2.3.4.2. Stress analysis

In some cases it may be necessary to determine the loads and stresses being experienced by various components of a reactor structure. This can be performed by a variety of means. If the design calculations from the original design are available they can be used to determine stresses at key locations. If the design calculations are not available, as is likely to be the case of most of the research reactors in operation because of their age, alternative approaches may have to be taken. The type of structural analysis can be either analytical or by modelling.

Analytical solutions are available for many common structural forms and can be used to provide approximations of the stresses being experienced. In cases where analytical solutions are not available other modelling techniques can be applied. Such techniques include; finite difference, boundary element and finite element (FEA) techniques. The last two mentioned are particularly powerful and can be used to estimate loads under a variety of loading conditions. Some which have been employed are; steady state, thermal, fatigue, impact and seismic. While FEA techniques are very powerful they require experienced analysts to perform the analysis.

2.3.4.3. Surveillance and sampling techniques

Surveillance: Surveillance is the action of placing test pieces in specific areas of the reactor to determine the effects of the actual operating conditions within the reactor on materials from which it is constructed. Such surveillance programmes were not a common feature of research reactor design and construction in the 1950s and 1960s but have become much more wide spread in recent years — following from the extensive use in nuclear power plants. Their use is generally restricted to high power research reactors where some components may have a design life considerably less than the reactor as a whole.

Surveillance coupons can be used to assess the change in properties of materials under radiation and other environmental influences, such as corrosion. The main use of such test pieces recently has been to determine the degree of loss of ductility for materials used in the high fluence areas of the core. Such programs can be viewed as an essential part of the determination of the structural integrity of the critical safety systems of the research reactor.

The location and type of test piece to be used as a surveillance specimen has to be determined at an early stage in the design process. The materials should be the same as those being used in the real component and the location in the core should ensure that they receive a radiation dose of a similar level, and neutron spectrum, as the component would receive in service. The usual type of specimens to be put in as surveillance coupons are tensile coupons and compact tension test pieces for mechanical property measurements, and plate type specimens for corrosion coupons (see Ref. [1], Case Study 6 and Ref. [7]).

Sampling: Sampling techniques have been used by a few high power research reactor facilities. Sampling of metal material from reactor components, especially “retired” components remains a viable technique for examination of in-service degradation. Samples could be subjected to a range of tests (mechanical properties, toughness, chemical analysis, activation analysis, specialised SEM etc.) to provide validation for future safety justifications. Before sampling, “retired” components may be subjected to ultrasonic examination firstly to provide information on defect distributions for any probabilistic fracture assessment, and secondly to confirm that samples are extracted from sound material.

Some sampling systems can be applied to almost any type of critical equipment evaluation. They can be used to sample any surface of any object, internally or externally provided the precautions suggested in the previous paragraph are followed. The resulting sample can be used to characterise component material properties and damage mechanisms, including the physical characteristics of defects, base material composition and microstructure, corrosion and other surface attack, creep damage and fracture toughness (see Ref. [1], Case Study 6 and Ref. [7]).

2.3.4.4. Magnetic particles

The magnetic particle technique is based on the magnetic field leakage created when a surface-breaking and near surface discontinuity disrupts the flow of lines of force, leading the iron particles on the part surface to accumulate and to show indications.

A number of conditions have to be fulfilled with this method to obtain optimal results:

The surface of the component to be inspected has to be clean and especially free of grease and/or small debris or particles.

The specimen has to be magnetised by placing the component into a magnetic field. For optimal surface flaw detection the magnetic field direction should be perpendicular to the direction of the suspected flaw.

Magnetic powder particles have to be brushed or sprayed over the surface of the component especially at the area of the suspected flaw. The powder could also be suspended in H_2O or in a light petroleum distillate.

Good visible surface illumination is necessary. Subsequent to testing the work-piece has to be demagnetised. Further information on this technique is included in Ref. [4].

3. DEVELOPMENT OF AN IN-SERVICE INSPECTION PROGRAMME

3.1. CONTENT OF AN ISI PROGRAMME

The content of an ISI programme depends in general on the type of reactor and on the objective and scope of the inspection.

In the present report it is assumed that the ISI will consider the inspection of major items of a high power research reactor such as the reactor tank, primary pumps and heat exchangers. The following items should be addressed by the programme:

- Objective, scope and periodicity;
- Organization and responsibilities;
- Establishment of a baseline;
- Establishment of an examination schedule;
- Specification of methods and techniques to be applied;
- Qualification of procedures and equipment;
- Training and qualification of personnel; and
- Quality assurance considerations.

3.1.1. Considerations on research reactor types and categories concerning ISI programmes

The in-service inspection programme should be commensurate to the hazards potential of the reactors. Unfortunately, it is difficult to make a categorization with regard to the hazard potential of the existing research reactors based on a single parameter which may get a broad consensus amongst the research reactor community. The power has been used in some publications as such parameter. A “working categorization” not intended for safety issues has used the reactor power and has been included in some documents of the IAEA.

This categorization considers three categories:

(a) High power reactors (power >2 MW)
(b) Medium power reactors (power <250 kW and ≤2 MW)
(c) Low power reactors (power <250 kW).

These three categories may serve in principle to establish some “requirements” on the needs of conduct ISI of research reactors (e.g., establishing exceptions for category C reactors) and for grading the number of components to be subjected to the inspection (e.g., the reactor building would be only inspected for reactors of category A).

A more appropriate categorization could be based on the safety analysis of the research reactor and the need of ensuring the operational availability of key structures, systems and components to meet the acceptance criteria established by the national legislation or by the regulatory body.

In principle every research reactor requires an ISI programme and special NDT techniques which are tailored to its technical design. The periodicity of the ISI programme depends on the reactor power levels, the reactor design and on the operating schedule. It is obvious that requirements differ for low power reactors (<250 kW) compared to medium power (250 kW to 2 MW) and high power (>2 MW) research reactors. In many cases the ISI programmes are included within the overall preventative maintenance programmes, for low power research reactors, and the periodicity is therefore within the periodicity of the maintenance schedule. The following paragraphs outline typical examples from seven types of low power research reactors. In addition, Annex II presents a summary of a typical complete maintenance and ISI programme schedule for a TRIGA reactor (see also Appendix, Case Study 5).

3.2. ORGANIZATION AND RESPONSIBILITY

The operating organization should be responsible for the establishment and the implementation of the in-service inspection programme, in particular:

- the preparation of the ISI programme, examination procedures and schedule;
- the assurance that examinations are qualified and performed by qualified personnel;
- the analysis and evaluation of the results of each examination and inspection, and the corrective actions to be implemented;
- the safekeeping and archival of records of the examinations and inspections, as well as the calibration and reference specimens;
- the submission of information to the Regulatory Body; and
- the review of the in-service inspection programme in taking into account, the experience and modified plant conditions.

All required examinations and inspections should be performed in a way limiting radiation exposures to the personnel as low as reasonably achievable (ALARA).

3.3. OBJECTIVES, SCOPE AND PERIODICITY

The main goal of the in-service inspection of nuclear research reactors is to demonstrate that the items important to safety, in particular those which must ensure the basic functions — to shutdown (e.g, items assuring the core geometry and the control rod alignment), to cool (e.g., main pumps, emergency core cooling system), and to confine and mitigate (e.g, reactor building, emergency ventilation) — will not fail in service.

The design philosophy for the critical structural equipment, such as the reactor tank, is that the reactor can operate provided that it can be demonstrated that the equipment contains no critical defect. This requires knowledge of the material properties of the equipment with and without neutron irradiation and of the likely defect presence.

The in-service inspection programme should include ultrasonic, eddy current, liquid penetrant, dimensional and visual testings. Other non-destructive testings (NDT) should also be used, such as the techniques mentioned in Section 2.2.

The programme for ISI should establish the periodicity in the conduct of further inspections. The intervals between successive periodic activities are usually set in terms of time frames with a certain range to allow for flexibility.

As in the case of activities related to maintenance, testing and inspection the frequency of ISI of individual structures, systems and components must be such as to assure adequate reliability, taking into account (para. 907 of Ref. [3]):

(1) their relative importance to safety;
(2) the likelihood of their failure to function as intended;
(3) the requirements established in the safety analysis report;
(4) designer and manufacturer recommendations;
(5) experience available to the operating organization; and
(6) reactor operation schedule.

However, the frequency of an ISI will also depend on its purpose. For example, if the objective is to assess the lifetime of the whole facility or a major item, the period between inspections may be of several years. Intervals of three to five years should provide a sufficient follow-up to monitor the equipment integrity during its service life.

3.3.1. Low power reactors

Seven research reactors have been considered which provide selected examples of reactors below 250 kW(th) (NEPTUNE, VIPER, ARGONAUT (Jason), CONSORT, SLOWPOKE-2, MNSR and TRIGA MkII). It is considered that the objective and scope of periodicity for ISI maintenance actually employed by these facilities provides sufficient detail and variety for demonstrating typical programmes. The various schedules demonstrate that any facility should be “SMART” (Specific; Measurable; Applicable; Realistic; Timely) in developing a programme.

In all cases daily (pre-critical and post-operational) checks are undertaken. In addition weekly and/or monthly routine maintenance is carried out and some form of prolonged outage is undertaken. Sub-critical assemblies may not employ such extensive programmes. As suggested above, such facilities should employ a “SMART” programme.

It is clear from the present investigation that low power research reactors employ quite detailed preventive maintenance and periodic testing programmes. Corrective maintenance is undertaken as and when required and usually to a prescriptive programme. However, some facilities do undertake ISI either on an Ad Hoc basis or as part of a maintenance schedule. The examples of ISI and maintenance programmes reported for the low power research reactors considered within this study are shown in Table I.

It is noteworthy that both SLOWPOKE-2 and MNSR facilities consider that their extensive preventative maintenance programmes are considered sufficient for their requirements and no ISI programme is planned.

TABLE I. ISI EXAMPLES FROM LOW POWER RESEARCH REACTORS

Reactor type	ISI examples
TRIGA MkII	RVI, replication
ARGONAUT	RVI, replication
NEPTUNE	X radiography Stress analysis
VIPER	X radiography, RVI
CONSORT	Intention to conduct RVI
SLOWPOKE-2	No requirements
MNSR	No requirements

It is considered that the objective and scope and periodicity for ISI and maintenance actually employed by these facilities provide sufficient detail and variety for demonstrating typical programmes. The following ISI techniques have been reported:

- Remote visual inspection (Section 2.2.1) for JASON (Appendix, Case Study 4), CONSORT and TRIGA MkII (Appendix, Case Study 5);
- Replication (Section 2.2.2.4) for JASON (Appendix, Case Study 4) and TRIGA MkII;
- Radiography (either gamma, X ray or neutron) (Section 2.2.3.2) for NEPTUNE (Appendix, Case Study 4), VIPER (Appendix, Case Study 4) and TRIGA MkII;
- Stress analysis (Section 2.3.3) for NEPTUNE.

In all cases daily (pre-critical and post-operational) checks are undertaken. In addition weekly and/or monthly routine maintenance is carried out and some form of prolonged outage is undertaken. Sub-critical assemblies may not employ such extensive programmes. Reference [12] gives a complete maintenance/ISI schedule for a TRIGA MkII reactor that is based on a daily, monthly and annual periodicity. The key elements from this programme are given in Table II.

TABLE II. MAINTENANCE PROGRAMME FOR A TYPICAL TRIGA MK II REACTOR

Schedule	Systems for inspection
1	Reactor building
2	Ventilation system
3	Reactor tank & shielding structure
4	Reactor core & fuel storage pits
5	Reactor safety system
6	Primary & purification system
7	Secondary cooling system
8	Area and stack monitors
9	Fuel element handling
10	Experimental facilities
11	Electricity & emergency supplies
12	Security system

Other examples of schedule and activities related to these programmes for low power research reactors in the lower end of the power range are shown in Table III.

TABLE III. EXAMPLE OF ALTERNATIVE MAINTENANCE/ISI SCHEDULE

Task	Day	Time	Programme of work
1	1	ALL	Instrumentation
	2	am	Instrumentation
		pm	Pulse rod
			Hydraulics
	3	am	Control rod major
			Reflector lid
		pm	Safety block minor
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2	1	ALL	Instrumentation
	2	am	Instrumentation
	2	pm	Safety block frit
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3	1	ALL	Instrumentation
	2	am	Instrumentation
		pm	Pulse rod
			Hydraulics
	3	am	Safety blocks major
		pm	Control rods minor
-----------------	---------------------	--------------------	---------------------------------
4*	1	ALL	Instrumentation
	2	ALL	Instrumentation
	3	ALL	Instrumentation
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However, the periodicity of maintenance and ISI programmes for some low power research reactors may not follow the same daily, monthly and annual programme as that given above. Additional maintenance and ISI activities are undertaken under Task 4 and these are given in the Table IV, which also presents an alternative example of maintenance periodicity.

TABLE IV. ADDITIONAL MAINTENANCE AND ISI ACTIVITIES

Additional Task 4	Periodicity		Programme of work
Every Task 4			Gamma shutdown channel
			Fuel pin change and inspection
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Every 2nd Task 4			T/c reference junctions
			Interlock tests
			Zeref reference junction
			Reactor power trigger
			Experimental gamma channel
			Temperature channels
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	Every 16 weeks		X radiography of 25 fuel pins
	As required		Visual inspection
	As required		Leak testing
	Ad hoc		Boroscope inspection

3.3.2. Medium and high power reactors

In addition to the considerations presented for the low power reactors additional requirements for medium and high power reactors should be derived for the preparation of the in-service inspection and non-destructive testing programme.

For the selection of the components and systems to be incorporated in the ISI programme special attention should be given to the high dose regions and to the regions with higher thermal and mechanical stress levels and those with discontinuities in wall thickness (e.g. welds between different wall thickness and at flanges and upper and top lids). The technique to be employed will also depend on the accessibility of the components to be investigated.

Although leak tightness tests of confinement or containment buildings are normally performed on a yearly basis, additional inspections could be beneficial in order to detect degradation in an early stage. Besides corrosion of the metal structure, sealing of the airlocks, the containment valves, pipe and cable penetrations should also be incorporated in the ISI programme. Although normally visual inspection techniques would be appropriate to detect corrosion some times other techniques such as replication or thickness measurements.

Since the changes of material properties due to high neutron exposure are obviously of particular importance for aluminium vessels, a vessel material surveillance programme should be prepared. This programme could consist of an irradiation campaign to irradiated sample material of the vessel combined with a testing programme. The irradiated specimens should be scheduled to be tested at different intervals depending on the expected (remaining) lifetime of the vessel. The irradiation position should be representative for the collected dose of the most exposed parts of the vessel.

In order to estimate the collective dose a neutron history file indicating the collective dose per irradiation position or core region should be available. Small neutron monitors (flux wires) could be placed in the same test rig in which the test samples for the surveillance programme are being irradiated to obtain the overall neutron dose.

Especially for older reactors normally no vessel sample or samples of the reflector matrix is available for the surveillance programme. In this case sometimes samples can be prepared from shielding material or structure material which don’t contribute to reactor or vessel structure but which already have received a neutron dose in the same order as the vessel or reflector material.

For reactors with a reflector the components of the reflector structure and the reflector material should be incorporated in the ISI programme to detect degradation, i.e. swelling and embrittlement of the Be or graphite matrix and corrosion of the D_2O tank, etc.

The surveillance programme for beryllium concerns normally regular visual inspections and dimensional control in order to detect swelling of the Be due to helium bubbling. For new reactors or new beryllium matrices an irradiation campaign similar to the irradiation campaign for the vessel material could be considered.

The irradiation campaign and the testing techniques to be employed should be agreed with the regulatory body and could consist of fatigue testing, fracture toughness testing and hardness, strength and ductility tests.

A typical example of an inspection programme of the primary system of a high power reactor is given in various cases of the Appendix.

Other examples of surveillance programmes for medium power research reactors are given in Refs [7] and [8]. Additional guidance that may be applied to medium and high power reactors can be found in Refs [9] and [10]. These references were prepared for nuclear power plants, so the guidance should be applied with due consideration to the limited hazard potential of the research reactors.

3.4. ESTABLISHMENT OF A BASELINE

In order to assess changes which may occur in materials and components during operation of a research reactor, it is necessary to establish a baseline of properties (materials properties, thickness, etc.) so that changes can be determined. The ability to establish a baseline of data will differ depending on reactor design and also with age. While it is clearly desirable to have a baseline which dates to reactor construction, this is not always possible, and a thorough survey at some later time may be all that can be achieved.

This section is divided into two parts; that associated with new reactor construction (or potentially where major components are to be replaced in an existing reactor) and that associated with plant which has already existed for some time (given the age of the installed research reactor capacity worldwide, it is clear that the latter will be the more likely position with research reactor operation).

3.4.1. New research reactors

The establishment of a baseline of materials and component properties in the case of a new reactor is an integral part of the design, construction and commissioning process. Information such as the mechanical properties of materials from which the core components will be manufactured should be part of the information supplied with the tender documentation before construction begins. Other information which is either essential or extremely useful in assessing condition includes:

- Material properties (tensile, fracture, fatigue, hardness, etc.)
- Weld procedure (process pre-heat, post weld heat treatment)
- Full NDT report (including procedures, defect location, size, form, etc.)
- Information on environmental conditions (fluence expected, fast/thermal ratio, gamma, chemical – pH, conductivity –, etc.)
- Design parameters such as expected life
- Inspection intervals (recommended by reactor supplier)
- Location and removal specification for surveillance specimens.

The above items should be determined during the reactor specification and become part of the final acceptance of the commissioning contract.

3.4.2. Pre-existing research reactors

During the initial rush of construction of research reactors during the 1950s and 1960s, the provision of complete information on materials properties and other factors affecting the reactor life were not as well established as is the case today. A large part of this can be explained by the relative uncertainty of the design life of the early research reactors caused by a number of factors including: lack of knowledge of changes in materials properties caused by environmental factors — such as radiation and chemical — and changing political climates which has resulted in some reactors being operated for longer than originally envisaged. Additionally, significant improvements in NDT technology, providing better discrimination of defect form and size, combined with better structural assessment techniques, have resulted in the significance of existing defects being better understood. These, combined with a better understanding of the change in materials properties caused by irradiation, have resulted in many research reactors being operated safely for times considerably in excess of the original design requirements or expectations.

3.5. ESTABLISHMENT OF AN EXAMINATION SCHEDULE

In addition to the frequency of examination, the ISI programme should establish an appropriate timetable to carry out the inspection. In this regard, adequate time should be allocated for discussion with the regulatory authorities or for approval if so required. Usually, a flow chart with the main milestones such as the one included in Annex II should be produced.

3.6. EQUIPMENT, METHODS AND TECHNIQUES

The methods and techniques for the examination should be in accordance with accepted national or international standards. In some cases the standards to be referred are to be agreed upon with the competent authorities. The examination method to be employed permits a selection of different techniques or procedures restricted to that method to accommodate varying degrees of accessibility and radiation levels of the component or structure to be examined. Example of equipment, methods and techniques are included in Section 7 of Ref. [9].

All equipment used for examinations and tests should be of a quality, range and accuracy acceptable in accordance with standards recognized by the competent authority.

Similar standards shall apply to calibration blocks, where they are needed. If such standards for calibration blocks are not established, these blocks should be of the identical material and surface finish and be subjected to the same fabrication (construction) conditions (such as heat treatment) as the component being examined. Where possible, the same calibration blocks used during manufacture and for pre-service inspections should also be used for subsequent in-service inspections.

All items of equipment together with their accessories should be calibrated before they are used. All equipment should be properly identified with calibration records, and validity of calibration should be verified regularly by the operating organization in accordance with the quality assurance programme. Items should be calibrated against standards recognized by the competent authority.

3.7. QUALIFICATION OF PROCEDURES AND EQUIPMENT

Good inspection planning starts with the setting of objectives of safety (or economy); this could be supported by risk analysis (risk based assessment). Safety objectives (or plant availability objectives), if correctly expressed as a function of the component and of the environment, can then be translated into inspection objectives which will be obviously different from one situation to another even if the safety objectives were fundamentally equivalent. These inspection objectives define performance targets for the inspection procedures: detection, location, classification and sizing of relevant defects in the component. Such performance targets can be used as a capability level that the inspection procedure must reach. The qualification of the inspection procedure will be the tool for such performance capability verification: it will "set" the effectiveness or capability of the inspection procedure in accordance with the targets fixed as a result of the safety or risk evaluation. This effectiveness, set by the qualification in each of the situations considered, corresponds to the necessary inspection effort in each of the case to reach the same level of safety or economic operation of a research reactor.

All equipment used for NDT and ISI should be qualified in view of the objectives set by the procedures. The NDT and ISI personnel shall have sufficient experience with using this equipment.

3.8. TRAINING AND QUALIFICATION OF PERSONNEL

All personnel operating the equipment should be trained before to undertake any In-service inspection. All non-destructive testing (NDT) personnel should be qualified to an appropriate and recognized standard, such as the ISO Standard 9712, the European Standard EN 473 or the American Society of Non-Destructive Testing (ASNT).

The ISI personnel shall also be qualified to carry out their responsibilities on the basis they have had experience with the same examination methods and with the same particular equipment as those that are to be used in the in-service inspection planned. Evidence should be provided that the examinations have been carried out by qualified personnel.

3.9. QUALITY ASSURANCE CONSIDERATIONS

The in-service inspection manager should ensure that the ISI programme is conducted in accordance with the applicable requirements of the quality assurance programme for the plant. The quality assurance aspects of the in-service inspection activities should be in accordance with the requirements of Ref. [11].

All maintenance, periodic testing and inspections (which includes ISI and other special testing) documentation (e.g. procedures, records, method statement, work instructions) and activities (such as contracting services, procuring equipment, performing tests) should conform to the requirements established in the existing QA programme for maintenance and periodic testing, which usually is part of the overall QA programme of the operating organization or management of the reactor (see Ref. [11], particularly the Code and the Safety Guide Q-13, Quality assurance in operation). The requirements and recommendations spelled out in this document are applicable to research reactors as well to nuclear power plants. The objective of the QA programme for maintenance, periodic testing and inspections, including

ISI and other special testing, is to ensure that the operational state of the reactor and its supporting documentation meet the requirements for safety as derived from:

- The safety analysis report;
- Regulatory body requirements;
- Reactor management requirements; and
- Manufacturer recommendations.

The QA programme should describe the system for controlling the development and implementation of the maintenance, periodic testing and inspections programmes. The provisions of the programme should be based on the following three principles[1]:

- Management provides means and support to achieve objectives;
- People performing the work achieve quality; and
- Evaluation of the effectiveness of management processes and work performance.

3.9.1. Management

For proper implementation of the QA programme it is necessary to address the three principles already mentioned. The management aspect of the QA programme should include:

- Quality policy
- The organizational structure
- Functional responsibilities
- Training requirements
- Levels of authority and interfaces for those managing, performing and evaluating the adequacy of the work.

Methods should be adopted for non-conformance control, corrective actions and change control. To ensure improvement, the root causes of such non-conformance should be determined, assessed and documented and action taken to prevent their recurrence.

Documents, including records, essential to the performance and verification of maintenance and periodic testing activities should be controlled by providing a system for their identification, approval, review, filing, retrieval, and where appropriate, disposal.

3.9.2. Performance

All maintenance, periodic testing and inspection activities should be performed in accordance with the QA programme. In establishing a QA programme related to maintenance, periodic testing and inspections, the most stringent requirements should be assigned to activities on systems important to safety. These activities should be performed in accordance with the QA programme and other guidance in the present document.

Equipment and items used for maintenance, periodic testing and inspections should be identified and controlled to ensure their proper use.

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[1] Note that principles are stated not in the form of requirements, but on the assumption that activities are carried out through good practices in current use.

3.9.3. Evaluation

Measures should be established for review and verification to ensure that maintenance, periodic testing and inspections activities are accomplished as specified in the appropriate procedure. These measures should include:

- Review of procedures;
- Verification by inspection, witnessing and surveillance;
- Review and verification of maintenance and periodic testing records, results and reports including non-conformance control and corrective actions; and
- Assurance of adequate and timely correction of previously identified degradation of equipment.

Verification of the effective implementation of the QA programme for maintenance, periodic testing and inspections is an important part of the overall QA programme and should be carried out by personnel not directly responsible for maintenance activities.

The above verification is performed through periodic audits that determine the adequacy of, and adherence to, all aspects of the QA programme during maintenance and periodic testing. The audits should pay particular attention to the interface and transfer of responsibilities between maintenance and operation groups.

3.10. EXAMINATION SCHEDULE

To establish an examination schedule for a research reactor it is necessary to define all systems which are necessary for safe reactor operation. Some newer facilities may have developed their examination schedule as part of the licensing requirements. However older facilities that have not already developed a formal examination schedule may wish to consider the recommendations given below. The examination schedule should be an integral part of the periodic testing and inspection programme of the facility. Typical systems to be examined at regular intervals are, for example:

- reactor safety system
- reactor tank and shielding construction
- reactor cooling system
- spent fuel storage.

Once the systems have been defined, each system has to be broken down into subsystems or components such as:

- reactor core
- nuclear channels
- primary pump.

Each of these subsystems or individual components have to be examined in regular intervals which may be:

- once a month
- four times a year
- two times a year
- once a year.

Other intervals are possible, ranging from daily checks to several years. The frequency of examination of a single component has to be established together with the supplier of that component and in agreement with the regulatory body.

In many cases examinations of a component could just be a visual check, a test run (i.e. for a pump), the reading of a scale (i.e. differential pressure across filters), a complete recalibration using signal generators (i.e. for the nuclear safety channels) or it could be a thorough and very detailed examination using sophisticated equipment.

Finally, for each examination to be carried out, it has to be defined who will carry out this task. Usually it is the reactor staff who have the best operating experience of all the systems and components. However, in some cases the reactor staff are either not qualified to carry out examination (i.e. overhead crane, emergency diesel generator) or they are not authorised to do the work without supervision or control of an independent expert. In most cases the independent expert (i.e. from a university or from a private company) is appointed by and acts on behalf of the regulatory body.

All examinations have to be planned well in advance and should incorporated into the regular operating schedule of the facility. The Appendix, Case Studies 4 and 5, give typical examination schedules for low and medium power research reactors.

3.11. DOCUMENTATION

For each examination a detailed examination checklist has to be prepared which includes:

- scope of application
- examination procedure(i.e. visual, test run, dimensional measurement)
- (normal) operating conditions
- safety limits
- environmental conditions during examination
- test equipment and calibration samples used
- acceptance criteria
- technician in charge
- supervisor in charge
- corrective actions to be taken for repair
- time limit for repair.

These examination documents (i.e. including photographs or chart recordings) have to be filed and archived with the reactor management throughout the lifetime of the facility. Annex I of Case Study 3 gives a typical overview of the items to be addressed in the final report.

4. IMPLEMENTATION OF IN-SERVICE INSPECTION PROGRAMME

4.1. INSPECTION OF INDIVIDUAL COMPONENTS

The inspection programme should specify the inspection of each of the items subject to ISI. The programme should include descriptions such as the designation of each item, designation of the examination areas , examination methods, techniques and procedures and other relevant details associated with the objectives, scope and schedule of the inspection.

Example of inspections programmes are included in the Case Studies of the Appendix and in Annex II.

4.2. AREAS TO BE EXAMINED

Basically, service induced flaws can generate in any location of a component. However, according to experience there are preferred areas on which an ISI programme should be focused. For example due to stress distribution, the main areas or items subjected to ISI are:

- pressure retaining welds;
- base material and welds subject to fatigue stresses, corrosion, erosion, high irradiation, vibration, fretting and known anticipated mechanisms such as water hammer;
- construction welds of internal structures or support structures; and
- bolting, support and support structures.

At least the following areas of items should be included to the extent applicable for a particular type of reactor facility:

- Core structure, reactor tank, primary cooling system:
- All pressure retaining welds (100% over each inspection interval), welds and surfaces of primary cooling system pipes, including heat exchange tubes (in appropriate fraction).
- Other components and piping systems:
- Pressure retaining welds and areas with any discontinuities in the wall thickness such as welds between different wall thickness.

The in-service inspection programme should include a detailed listing of all areas to be examined.

4.2.1. Type and location of defect

In-service inspections are carried out to detect service-induced flaws as well as to confirm flaws from earlier examination or to determine if flaw growth occurred during the last operation period.

Flaw generation and flaw growth are strongly influenced by the operation conditions. The applied ISI programme, techniques and procedures should be adjusted to enable detection and evaluation of potential flaws, such as fatigue cracks, corrosion cracks, or wall thinning due to corrosion, erosion, orientation or fretting.

4.3. INSPECTION TECHNIQUES

4.3.1. Visual examination

With regard to means and requirements, the conditions for visual examination should be adjusted to the different examination tasks. Normally, direct visual examination is preferable, as interpretation is easier. Correct interpretation of remote visual examination is more difficult because of picture quality, resolution, accuracy, colour quality, illumination conditions, picture section, and relation to space. Visual examination should be undertaken by personnel trained in special examination tasks. The visual acuity of this personnel should be tested regularly.

The areas or components to be examined should be sufficiently illuminated and scaffolded. Restrictions regarding accessibility, distance angle as well as the use of aids should be reported and evaluated.

If remote visual examination is used, the equipment should have a resolution capability equivalent at least to that obtainable by direct visual observation.

For remote visual examination a baseline inspection with an optimal adjustment of equipment is recommended. Baseline inspection results should be stored, e.g. on magnetic tape, and the equipment used as well as the adjustment conditions should be reported in such a way as to make repetition possible.

Cracks or similar defects should be inspected with more detailed examination methods, e.g. surface examination or volumetric methods. They should be evaluated as indicated under ‘surface examination techniques’.

In the case of components of ferritic material and proper geometrical conditions, magnetic particle examination is preferred owing to the fact that, in relation to normal surface conditions, cracks or crack like defects will be indicated more sensitively than by liquid penetrant examination. The latter examination method is normally used for components of austenitic material, as well as for ferritic material with restricted access or in the case of indications which are to be distinguished from alteration of magnetic permeability of the examined material.

In addition to these, special examination techniques such as eddy current examination or ultrasonic examination with special transducers can be used.

The surface to be examined should be prepared properly. If surface examinations are combined with ultrasonic examinations, the surface examination should be done before ultrasonic examination because of remnants of the ultrasonic examination coupling medium which can have an adverse effect on examination sensitivity.

For components which are protected by painting, the examination areas should not be painted because of the difficulty in removing the paint. Instead of this, the examination areas should be protected against corrosion by other measures such as a thin primer which can be removed more easily.

4.3.2. Volumetric examination

A volumetric examination indicates the presence of discontinuities throughout the volume of the material and may be conducted from either the inside or outside surface of a component.

For better reproducibility of ultrasonic examination, a periodical check of the most important equipment parameters, including the sound field characteristics of the transducers, is recommended. The beam angles should be optimised so that surface defects as well as volumetric defects can be detected. Sometimes the examination calibration is performed with the help of cylindrical surface of drilled holes established the ‘distance–amplitude–correction’ (DAC) curve (Appendix, Case Study 3). In other cases a diagram, which is based on the comparison of the echo height of fat bottom holes in calibration blocks will be used.

To enable comparison with the following ISIs, the calibration method, once selected, should be retained or, if changed, a correlation with the previous one should be established to the extent practical.

To facilitate the interpretation of indications from the inaccessible surface, exact drawings and knowledge of the surface conditions are necessary. Wall thickness measurements are also useful.

In several cases the basic ultrasonic technique used for detection is not adequate for the sizing of a found indication (especially the depth); therefore a separate sizing technique (generally depth sizing) should be established. Some sizing techniques can also be used as a tool of confirmation of correct detection.

For radiographic examinations, a completed prior emptying of piping systems is generally recommended so that appropriate actions can already be taken during the construction period (e.g. piping gradient, emptying valves, avoiding ‘water-sacks’). To co-ordinated film indications to the weld configuration - particularly if the welds are ground or machined -location markers to identify the weld edges should be used and reported.

The examination results should be evaluated in accordance with appropriate standards which should be established for each of the different volumetric examination methods.

For ultrasonic examination, it is necessary to determine whether the indication originates from a flaw or is due to a geometrical shape. If the indication is definitely not due to a geometric shape, the relevant acceptance standard should be applied.

For radiographic examination, the evaluation standard is exceeded if alterations are found compared with former examinations which indicate cracks or crack-like flaws, corrosion or erosion.

For eddy current examination of thin-walled tubes, the reporting standard normally lies at 20% of the wall thickness. An evaluating standard is rarely established. In the case of this wall thinning being exceeded in a large number of tubes, the inspection interval can be reduced as the number of tubes tested is increased. The acceptance standard depends on many parameters, e.g. approving of the eddy current results with a refined examination technique. It is also recommended that apart from wall thinning, other indications, e.g. dents outer-surface deposits, also be reported if they appear with high frequency.

4.4. EVALUATION OF RESULTS, REPORTING AND FURTHER ACTION

4.4.1. Evaluation of results

Reporting and acceptance standards for visual, surface and volumetric examinations should be established before the programme implementation and should be submitted, as well as the programme, to the Regulatory Body for review, when required.

When acceptance standards are not relevant to a particular situation, establishment of relevant acceptance standards should be carried out by the operating organization.

Flaw indication exceeding acceptance standards may be further characterized by other testing methods.

When fracture mechanics analysis is selected for flaw investigation, the worst stress case should be selected.

When the evaluation concludes that further reactor operation is unacceptable, the component should be repaired or replaced, and a baseline inspection should be carried out.

Every time an in-service-inspection is carried out (as per the approved procedure) the observations should be reported in an approved format. These observations and the results thereof should be reviewed by the experts appointed by the plant operating organization. The experts shall analyse the findings along with the earlier observations available on the same equipment/system. If required, the experts can also ask for additional inspection to strengthen the analysis presented. After detailed review and analysis the experts shall give recommendation on the following lines:

(1) The equipment/systems is safe and approved for continued operation;
(2) A degradation trend has been observed but the system is still considered safe for continued operation with additional close control;
(3) Repair or replacement should be planned and programmed;
(4) Degradation is greater than specified and immediate action is required for repair or replacement.

4.4.2. Reporting

Analysis of the observations from the in-service inspection should be reported, along with its recommendations, to the operating organization in an approved format. This report should be reviewed in order to progress any action to be taken with respect to repair or replacement of the equipment/system.

4.4.3. Further action

The operation organization should give final clearance for carrying out any minor or major repair or replacement of the equipment/system. All appropriate safety practices should be followed during the repair or replacement programme. After the repair or replacement has been completed a detailed PSI should be carried out to certify that the equipment is safe for normal operations. The findings from the PSI should be kept as baseline data for future reference and analysis.

APPENDIX
CASE STUDIES ON APPLICATION OF NON-DESTRUCTIVE TESTING AND IN-SERVICE INSPECTION TO RESEARCH REACTORS

The following list of case studies includes the contributions of the countries and international organizations participating in the CRP on Applications of Non-destructive Testing and In-Service Inspection to Research Reactors. The complete versions of these contributions are available on request from the IAEA.

Case Study 1: Australia

Structural integrity assessment of the HIFAR reactor aluminium tank using remote non-destructive evaluation and visual inspection techniques

R.P. Harrison
Australian Nuclear Science and Technology Organisation
Menai

Case Study 2: China

In-service inspection to components in research reactors by vibration analyses

Jin Hua-jin; Wang ye; Xu Han-ming
China Institute of Atomic Energy
Beijing

Case Study 3: European Commission

Application of non-destructive testing and in-service inspection to a 45 MW tank in pool reactor vessel

M. Bieth
Institute of Advanced Materials
European Commission
Petten; Netherlands

Case Study 4: United Kingdom

In-service inspection programmes and techniques for low power (100 kW) research reactors

P. Beeley
Department of Nuclear Science and Technology
HMS Sultan
Hampshire

Case Study 5: Austria

In-service inspection and maintenance schedule for low power research reactors.

H Boeck
Atominstitute of the Austrian Universities
Reactor Department
Vienna

Case Study 6: India

ISI of Reactor Vessel Tubes of Cirus and Process Water-Sea Water Heat Exchangers of Dhruva

M.R. Ranada, A.K. Kundu, B.K. Shah
Bhabha Atomic Research Centre
Mumbai

ANNEX I
SUMMARIES OF THE ACTIVITIES CARRIED OUT BY THE PARTICIPANTS OF THE CO-ORDINATED RESEARCH PROJECT (1995–1998)

AUSTRALIA

Chief Investigator	R. Harrison
Institute	Australian Nuclear Science and Technology Organisation, Sydney, Australia

Title: Structural Integrity Assessment of the HIFAR Reactor Aluminium Tank Using Remote Non-Destructive Evaluation and Visual Techniques

Summary

HIFAR is a DIDO type heavy water reactor which has been operating for 40 years. During this period the HIFAR scientific staff have gained experience in performing remote visual inspections of reactor internals. This experience will be used in the proposed project. In order to ensure the structural integrity of the tank a more extensive ISI, including remote NDT techniques will be applied.

The proposed research project includes the development of methods and procedures to assess structural integrity and remaining life of the reactor aluminium tank, including investigation of tank material thickness and weld defects. Recommendations for future ISI will also be developed in light of the experience gained in the 1995 major shutdown.

The long range scope of this project is the development of in-service inspection techniques for tank-type reactor internals.

Mr. Harrison presented a general description of HIFAR ISI activities undertaken during the past two years. Items discussed included the PSA/RLA of HIFAR carried out during 1997. This study showed that the reactor was operating in a safe manner and that there were no issues of a safety related nature which could affect its continued operation.

Information was also presented on the project to replace HIFAR with a pool-type reactor. Information was supplied on the approximate timescale of the replacement project including the decommissioning plan for HIFAR. Reference was made to the public ANSTO web page which provides information on the project - http://ansto.gov.au/

AUSTRIA

Chief Investigator	H. Boeck
Institute	Atominstitute of the Austrian Universities, Vienna, Austria

Title: In-Service Inspection Plan and Methods for a Typical TRIGA Mk II Type Reactor

Summary

The proposal is based on the maintenance and periodic testing and inspection practices developed for the TRIGA reactor Vienna, for which an elaborate re-inspection and maintenance programme has been used for 15 years to keep the facility in good condition. This programme includes methods such as visual inspection by remote equipment, control of various parameters, test runs etc., part of which have specifically been developed for TRIGA type reactors.

Dr. Boeck described some of his recent activities in the application of visual techniques to research reactors. In particular he mentioned the activities at two European research reactors, at Pavia in Italy (250 kW TRIGA) and Munich in Germany (4 MW pool type)

CHINA

Chief Investigator	Jin Huajin (Xu Han-Ming participated at the third RCM)
Institute	China Institute of Atomic Energy, Beijing, China

Title: ISI to Important Components of HWRR

Summary

The China Institute of Atomic Energy is operating aged research reactors, and has conducted preliminary studies on reactor power stability using noise techniques. Therefore the necessary equipment for the proposed research is already available in the Institute.

The proposed project will study the correspondence between signals and operation of the heavy water pump based on vibration analysis and also the vibration feature of the fuel assembly processing tubes. In addition, ISI of the reactor vessel and the spent fuel storage pool are planned using comparative methods.

Mr. Xu reported on the activities on the HWRR (a 10 MW reactor, heavy water cooled and moderated, age 40 years) and SPR (a 3.5 MW pool type RR with rod type fuel, Be reflector and age longer than 35 years). Information was also given on MNSR, a 30 kW reactor built in the 1980s.

HWRR and SPR are due to be shut down by about 2005 and plans are well advanced for a replacement to be called CARR (China Advanced RR) which will be approximately 60 MW and a tank-in-pool type multi-purpose RR.

Current activities on their existing RR's are aimed at vibration analysis of the main pumps on the SRP reactor, which was the subject of Mr. Xu's presentation, and vibration analysis of the fuel assembly processing tubes on HWRR. Since measurements on the latter subject are currently under progress, a new report covering the vibration analysis of the fuel assemblies will be submitted to the IAEA by the end of March 1999.

CZECH REPUBLIC

Chief Investigator	F. Peterka
Institute	1. Czech Technical University of Prague, Department of Reactors at FNSPE 2. Advanced Technology Group in Prague

Title: Application of NDT and ISI to Research Reactor in the Czech Republic

Summary

The objectives of the proposed research project are:

(a) to review the present status of ISI and NDT to VR-1 and LVR-15 research reactors.

(b) to be involved in the development of the ISI programme for VR-1 and LVR-15 research reactors and medium and high power research reactors of VVER type.

Dr. Peterka briefly described the activities on the VR-1 and LWR-15 reactors and presented an example of a procedure to apply liquid penetrant testing.

EUROPEAN COMMISSION

Chief Investigator	M. Bieth
Institute	Institute for Advanced Materials, Petten, Netherlands

Title: Application of NDT and ISI to the High Flux Reactor (HFR) Petten in the Netherlands

Summary

The High Flux Reactor (HFR) at Petten is a 45 MW tank in pool reactor that has been operating successfully for more than 35 years. The scientific and technical staff of the reactor have gained much experience in the evaluation of the reactor tank condition through the replacement of the reactor tank in 1984.

The proposed research project includes the development of an inspection programme for the reactor tank, including thorough methods and procedures for the detection and sizing of defects by using NDT methods.

Dr. Bieth reported on the last in-service inspection of the HFR reactor tank performed in 1997. Significant visual, ultrasonic, eddy current, and liquid penetrant inspections as well as dimensional checks are undertaken on the reactor tank every three years. No changes from previous inspections (1988, 1991 and 1994) were observed in the most recent inspection.

INDIA

Chief Investigator	M. Ranade
Institute	Bhabha Atomic Research Centre, Trombay, India

Title: ISI of Reactor Vessel Tubes of CIRUS and Process Water-Sea Water Heat Exchangers of DHRUVA

Summary

CIRRUS is a 40 MW(th) research reactor which has been in operation for the last 37 years. Various components were found to be showing signs of ageing and are in need of repair/replacement. A detailed study was undertaken to check the condition of the reactor components to assess their life expectancy. Under the CRP a special technique using eddy current testing (ECT) was developed to examine the condition of the reactor vessel tubes using the available MIZ-17 eddy current test equipment. A test probe and reference standard were developed for ECT examination. After satisfactory trials approval for the test procedure was obtained from the safety authorities.

Mr. Ranade presented the work currently under way. He mentioned that CIRRUS has been undergoing refurbishment since the end of 1997. Detailed inspection of all the reactor vessel tubes as per the approved procedure is in progress. Results available for the first 28 tubes inspected indicate that they are in a healthy condition.

DHRUVA is a 100 MW(th) research reactor which has been operating since 1985. Regular in-service inspections of the process water/sea water heat exchanger tubes are being carried out using ECT methods. Based on these examinations it was felt necessary to carry out a 3-D flow field analysis employing a validated computer code to get insight with simulated flow conditions to detect any zones which may be susceptible to flow induced vibrations. As per the preliminary report of the 3-D flow field analysis, the heat exchanger tubes coming in these zones are being monitored by ECT on a routine basis. Further ET examination will be carried out when the final results of the 3-D flow field analysis have been obtained.

UNITED KINGDOM

Chief Investigator	P. Beeley
Institute	Department of Nuclear Science and Technology, HMS Sultan

Title: Rationalisation of NDT, Remote Visual Inspection and Metallurgical Services for Ageing-Related Degradation in Low Power (<100 kW) Research Reactors

Summary

The objectives of the proposed research project are: a) formulate a database of ad hoc and generic ageing related degradation problems to low power (<100 kW) research reactors, and b) explore and investigate the application of selected NDT methods identified in a) (and rationalised within the IAEA Working Group) to examination of the JASON Argonaut reactor (33 year old).

Dr. Beeley reported on the recent shutdown and decommissioning of the JASON reactor. His presentation then focused on ISI and routine maintenance programmes for four UK and two Canadian low power research reactors.

ANNEX II
EXAMPLE OF IN-SERVICE INSPECTION AND MAINTENANCE PROGRAMME FOR TRIGA MARK II RESEARCH REACTOR

II-1. OVERVIEW

This annex summarizes the maintenance schedule for a typical 250 kW TRIGA Mark II reactor and focuses on special in-service methods applying visual inspection methods with an underwater endoscope. Some practical examples including documentary photos taken during in-service inspections are also presented.

II-2. MAINTENANCE SCHEDULE

To establish a maintenance schedule for a 250 kW TRIGA type reactor it is necessary to define all systems which are necessary for a safe reactor operation following the license of the regulatory body. Typical systems to be maintained at regular intervals are:

- reactor tank and shielding construction
- reactor safety system
- reactor cooling system.

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

- reactor core
- nuclear channels
- primary pump.

Each of these subsystems or individual components have to be maintained, inspected and re-calibrated in regular intervals which may be

- once a month
- four times a year
- two times a year
- once a year.

Other intervals are possible ranging from daily checks to several years. The frequency of maintenance of a single component has to be established together with the supplier of that component and in agreement with the regulatory body.

In many cases maintenance of a component would just be a visual check, it could be a test run (i.e. for a pump), it could be the reading of a scale (i.e. differential pressure across filters) or it could be a complete re-calibration using signal generators (i.e. for the nuclear safety channels).

Finally, for each maintenance work to be carried out, it has to be defined who will carry out this task. Usually it is the reactor staff who 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. overhead crane, emergency diesel generator) or it is not authorized to do the work without supervision or control of an independent expert. In most cases the independent expert (i.e. from an university of from a private company) is appointed by and acts on behalf of the regulatory body.

The maintenance schedule presented in this report is presented for the 250 kW TRIGA Mark II reactor Vienna and identifies 12 major systems each one with about 10 components (totally 120 components) to be maintained at regular intervals. For each of this components a maintenance checklist has been developed which is the basis for the maintenance work and which has to be completed. Long term experience show that a typical monthly maintenance work following the schedule requires about 3 man-days while an annual maintenance requires about 14 man-days of labour.

II-3. IN-SERVICE INSPECTION

At low power research reactors in-service inspection (ISI) is mainly carried out with components which are not directly accessible due to a high radiation level such as the reactor tank, the core structure, fuel elements, etc. For these 151 inspections tools and methods have been developed based on experience in non-nuclear applications and modified or adapted to the nuclear environment. The most common SI methods are:

visual inspections using
underwater telescope
endoscopes
replica method.

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

II-3.1. Nuclear underwater telescope

Nuclear underwater telescopes are high resolution devices (resolution 0.1 mm) with continuously variable magnification which 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, diminishing of optical image quality due to radiation induced discoloration, reflection losses and distortions are eliminated. In order to facilitate acquisition of the object and detail observation, the magnification can be continuously controlled, photo and video recording are also possible.

II-3.2. Endoscope

For the inspection of the inner surface of neutron beam tubes or internal core structures a modular endoscope has found to give excellent results consisting of an ocular and rigid optical extension pieces of 1 meter (diameter 18 mm) length each. These modules can be coupled together 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 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.

II-3.3. Replica material

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 as 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, being soft for about 3 minutes in ambient air. Then the rod was lowered into the reactor tank (water temperature about 30^0C) 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, giving an exact replica of the corrosion crater for further investigation.

II-3.4. Tank cleaning pump with integrated filters

To clean the tank bottom from small debris a conventional pump completely made of plastic as used for cleaning swimming pools has been found optimal. Such a pump is equipped with a coarse filter to collect larger objects (such as screws) and 12 units of candle type fine filters collecting small particles. One advantage is that these fine filters are reusable, they may be washed and reinstalled into the pump.

II-3.5. Underwater jet to remove deposits

One tool that has been found very useful to clean 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. Some of these nozzles are small enough that they can be inserted through a hole of the top grid plate right into the core volume and can be used to clean the core from debris or corrosion deposits.

II-3.6. High efficiency underwater light

Miniature strong underwater lamps are necessary to inspect remote areas in reactor tanks. 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 m aluminium tubes to be coupled together to the desired length, can be directed to any desired position in the reactor tank for optimal viewing.

II-3.7. Rotating underwater brush

In many areas of a reactor tank small surface spots from dark brown to orange can be observed being local surface attacks from different origin. If desired, these spots can be brushed away using an underwater rotating brush connected to a standard drilling machine by an extension shaft. Using various types of brushes (radial, pot-type), practically all areas inside the reactor tank can be cleaned.

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