IAEA COORDINATED RESEARCH PROJECT ON THE ESTABLISHMENT OF A MATERIAL PROPERTIES DATABASE FOR IRRADIATED CORE STRUCTURAL COMPONENTS FOR CONTINUED SAFE OPERATION AND LIFETIME EXTENSION OF AGEING RESEARCH REACTORS

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ABSTRACT

Today more than 50% of operating Research Reactors (RRs) are over 45 years old. Thus, ageing management is one of the most important issues to face in order to ensure availability (including life extension), reliability and safe operation of these facilities for the future. Management of the ageing process requires, amongst others, the predictions for the behavior of structural materials of primary components subjected to irradiation such as reactor vessel and core support structures, many of which are extremely difficult or impossible to replace. In fact, age-related material degradation mechanisms resulted in high profile, unplanned and lengthy shutdowns and unique regulatory processes of relicensing the facilities in recent years. These could likely have been prevented by utilizing available data for the implementation of appropriate maintenance and surveillance programmes.

This IAEA Coordinated Research Project (CRP) will provide an international forum to establish a material properties Database for irradiated core structural materials and components. It is expected that this Database will be used by research reactor operators and regulators to help predict ageing related degradation. This would be useful to minimize unpredicted outages due to ageing processes of primary components and to mitigate lengthy and costly shutdowns. The Database will be a compilation of data from RRs operators' inputs, comprehensive literature reviews and experimental data from RRs. Moreover, the CRP will specify further activities needed to be addressed in order to bridge the gaps in the new created Database, for potential follow-on activities. As per today, 13 Member States (MS) confirmed their agreement to contribute to the development of the Database, covering a wide number of materials and properties.

The present publication incorporates two parts: the first part includes details on the pre-CRP Questionnaire, including the conclusions drawn from the answers received from the MS. In the second part, an overview of the MS approved research proposals is reported, emphasizing only the offers made by the applicants. The 1st Research Coordinated Meeting is scheduled to be in Vienna on November 2013. For more details, please refer to the IAEA information (CRP code T34002 - webpage: http://www-crp.iaea.org/html/rifa-show-approvedcrp.asp).

1. Introduction

Presently about 60% of operating Research Reactors (RRs) are over 40 years old and about 75% are over 30 years old [1]. Age-related material degradation mechanisms can result in lengthy shutdowns and the need for additional regulatory activity, which could have been prevented by utilizing available data for the implementation of appropriate maintenance and surveillance programs. Therefore, ageing management is one of the most important programmes to address in order to ensure for the future availability (including life extension), reliability and safe operation of these facilities. The programme, unique for each RR, has to include a comprehensive effort of engineering, operations and maintenance actions to control, within acceptable limits, the effects that could impair the ability of a structure, system or component (SSC) to function within its acceptance criteria (ageing degradation) [2] [3]. Management of the ageing process requires, among others, a continuous effort to predict the behavior of structural materials of major components subjected to irradiation, such as the reactor vessel and the core support structures, many of which are difficult or impossible to replace [4].

The new IAEA Coordinated Research Project (CRP) intends to provide a forum for input and discussion on physical and mechanical properties data of the relevant materials, from the open literature, operating and maintenance experience with RRs and unpublished experimental old and new data, leading to the establishment of a "Research Reactor Irradiated Structural Components and Materials Properties Database". This information bank will be used by IAEA Member States (MS) RRs Operators and Regulators to predict ageing related degradation [5], and will specify further activities needed to address the identified data gaps for potential follow-up activities.

Prior to the initiation of the CRP, and in order to collect information on the needs and types of research activities, a Questionnaire was made available to MS operating RRs through the IAEA website. Following the content of the responds to the pre-CRP Questionnaire, the IAEA invited the MS to apply research proposals for the CRP, and thirteen (13) programmes were approved to be included. The present publication incorporates two parts: the first part includes details on the pre-CRP Questionnaire, including the conclusions drawn from the answers received from the MS. In the second part, an overview of the MS approved proposals is reported, emphasizing only the offers made by the applicants, without some comments and remarks by the IAEA, which will be agreed in the upcoming 1st Research Coordinated scheduled to be in Vienna on November 2013.

2. The pre-CRP Questionnaire

In order to evaluate the interest in the CRP and to collect preliminary information on the data needs and types of activities considering the prediction of ageing related degradation of core components, the IAEA has made available to MS (in RRS/NEFW web-page) a Questionnaire containing the following five questions:

1) What are the components and materials affected by ageing in your facility?
2) What information is available to you for those materials?
3) What information is not available that you would like to have?
4) What form of Database would be most useful to you?
5) What specific monitoring and surveillance programmes are implemented at your facility to address ageing of core components and materials?

In order to facilitate and harmonize the responses, a list of the data needed for the evaluation of material capability to perform its safety function and a list of RR core components and materials were attached, as appendices, to the questionnaire. The two lists are reported in the following Tab. 1 and Tab.2.

TAB.1- Data needed for the evaluation of material capability to perform its safety function.

Environment:
• Definition of fast and thermal neutron energies • Fast to thermal ratio for each test • Fluxes • Irradiation and test temperatures • Coolant chemistry (e.g. for water: pH, conductivity; for NaK: mass ratio; for He: impurities)

Sample:
• Definition of un-irradiated specimen material (certificated composition and thermal-mechanical treatment, material properties, residual stresses etc.) • Standard used for specimen manufacture
Measurements and calculations:
• Composition changes (chemical and isotopic) (calculated or measured?) • Displacements per atom (with method of determination) • Formation of loops and dislocation density (m^{-2}) • Voids and bubble density and composition (^{1}H, ^{3}H, He) (% volume or m^{-2}) • Swelling (volume %) • Corrosion rate (dimensional, mass changes) • Changes in resistance to Stress Corrosion Cracking (SSR test, ECP-diagram) • Changes in UTS, yield strength, 2% yield (MPa) • Changes in ductility (uniform and total elongation) (%) • Changes in fracture toughness ($MPa.m^{½}$) • Changes in stress and strain driven fatigue properties (threshold stress; N_f with definition) • Changes in fatigue crack growth rate (da/dn)
Additional parameters should be provided, as appropriate, for materials with special applications. Some (non-exhaustive) examples follow:
• Epoxy resins and glues: initial curing conditions and subsequent bond degradation with neutron and gamma fluence • Fastening and joining aspects: bolting (relaxation, galvanic), welding (heat affected zone, galvanic), compatibility of materials • Graphite: Swelling, accumulation of Wigner energy • Zirconium: Growth, directionality of properties • Concrete: density, compression strength • Cable insulation: Insulation degradation

TAB.2 - Listing of typical RR core components and structures and the most common materials used. Components that are generally fixed and difficult to replace are indicated by (1) and those that are more readily replaced are indicated by (2).
Note: The complexity of replacement of components is determined by the RR design and the indications given may not be accurate for all designs.

Components	Materials
Pressure(Tank) vessel + connecting pipes	
Pressurized vessel (1)	Low alloy steel Aluminum alloys Stainless steel
Low pressure tank (1)	Aluminum alloys Stainless steel Zirconium

Components	Materials
Reflector Devices/Systems	
Heavy Water tank & accessories (1)	Aluminum alloys Zirconium Metallic sealing rings
Beryllium (1/2)	Beryllium Aluminum-Be alloy

Components	Materials
Connecting pipes (1/2)	Aluminum alloys Stainless steel
Beam ports/nozzles (1)	Aluminum alloys Low alloy steels Zirconium
Poolside irradiation facility (1)	Aluminum alloys Stainless steel
Liners (Pool type RR) (1)	Aluminum alloys Stainless steels Epoxy resins Ceramic tiles
Core support structure components	
Core support grid (1/2)	Aluminum alloys Stainless steels Low alloy steels
Other structural and internal support structures	Aluminum alloys Stainless steels Low alloy steels
Core box/vessel (1/2)	Aluminum alloys Stainless steels Low alloy steels
Guide Tubes (2) for:	
Control devices	Aluminum alloys Stainless steels Inconel Zirconium
Fuel elements	Aluminum alloys Zirconium
Experimental facilities	Aluminum alloys Stainless steels Inconel Zirconium
Isotope production	Aluminum alloys Stainless steels Zirconium

Components	Materials
Graphite (2)	Graphite
Beam related devices, highly irradiated portion (2)	
Cold source	Zirconium Aluminum alloys
Thermal column	Zirconium Aluminum alloys
Neutron guide tubes	Aluminum alloys Stainless steels
Shielding structures	
Concrete (1/2)	High density concrete Structural concrete
Lead (2)	Lead types
Tungsten (2)	Tungsten alloys
Other	
Cables	Organic insulation

3. Analysis of the Responses to the pre-CRP Questionnaire

Fourteen(14) MS have provided answers in eighteen(18) filled out Questionnaires. The analysis of the responses is presented below [6].

3.1 Components and Materials Affected by Ageing

The MS contributing to the answers of the pre-CRP Questionnaire have mentioned that the highest priority (i.e. named by more than half of the respondents) to direct the CRP towards the following components:

- Core basket and grid (plate support) structure
- Reactor vessel (tank)
- Irradiation facilities

The intermediate categories, mentioned by 6 to 8 respondents, were:

- Control rod absorbers, followers, guide tubes safety
- Reflector (elements)

- Pool cooling piping and support

Other subjects that were mentioned were:

- Beam ports/nozzles
- Cooling piping and support
- Pool liners
- Shields thermal (carbon steel)

The answers on materials selection for the new CRP Database showed that the highest on the list (i.e. named by more than half of the respondents) are:

- Stainless steel (AISI 304L, 316, 316L, 347)
- Aluminum AISI 6061 (T6), alloys, high purity

Beryllium was indicated 5 times, while Concrete and Graphite were brought up 3 times each. The remaining materials suggested were: Carbon steel (twice) and Boron-Carbide and Coating (once).

It should be noted that the two materials with the higher response: aluminum alloys and stainless steel are not really materials, but two classes of alloys: one on the basis of aluminum and one on the basis of iron, chromium and nickel. Because of their composition differences, though within the limits given for a particular alloy, they cover quite a wide range of materials and consequently properties.

3.2 Available Information on Materials

The responses on available materials information allow categorizing the answers into five information domains:

- Materials physical and mechanical properties
- Neutron transport analysis and measurements
- Operational information
- Visual records and geometrical data
- Documentation

The answers to this question indicate that some information is rather specific for the particular RR. Nevertheless, considering that the information domains on Materials properties and Neutron transport analysis and measurements have highly useful elements for wider application, the available information is necessary. More information was mentioned to be needed on: the temperature domain and the accumulated radiation dose/neutron, including that it will be very useful to know the measurement and the analysis technique of the radiation doses.

It should be mentioned that the three latter information domains are difficult for use in other RRs, and may have qualitative-indicative importance only.

3.3 Lacking Information that is needed

The MS identified the need for reference corrosion data as well as the data on radiation effects, expressed in three sub-domains. Corrosion properties have been extensively treated in recent IAEA publications [7] [8] [9], and therefore will be considered as a minor scope of the present CRP. More than half of the respondents' of the pre-CRP Questionnaire on lacking information mentioned radiation effects data. The MS identified seven areas related to the effect of neutron radiation on mechanical properties. With the exception of Hafnium absorbers, all identified materials to lack information are included in the listing of typical RR core components and structures (see Tab.2). In addition, five areas are related to the domain of Radiation effects on corrosion. Also in this case the identified items are in the scope of data needed for evaluation of material capability to perform its safety function.

The Dimensional stability domain comprises three elements: two have to do with the geometry of the core structures, and the remaining one indicates the need for verification of the design details in–situ, which goes further than dimensional checks: material composition verification is also recommended.

The domain of Optical/Visual examination contains the item for the video recording of core structures allowing the logging of eventual changes in the surface appearance and shape of the structures.

Dimensional stability and Optical/Visual examination results are strongly tied to the design of the RR. The intended data base can thus not address this need.
Two of the items in the miscellaneous domain contain two items that are highly linked to the availability of data on a particular reactor, such as availability of spare parts and manufacturing characterization data. The third item on leaking liners data is not defined in terms of materials properties or processes.
The list of needed data provided by the MS includes irradiated Core Component materials such as: Aluminum alloys, stainless steel 316, and Zircaloy-4, as could be expected. The MS made clear that they need mechanical data on neutron irradiation effects to support the analyses of the core structures.

4. The Member States CRP proposals

Following the analysis of the pre-CRP Questionnaire, the MSs were encouraged to send proposals for contributing in the scientific collaboration [10]. Under the IAEA CRP procedures for a research contract or research agreement, the applicant is supposed to provide information, amongst others, on the proposed research project, including: the scientific background; the problems to be addressed with general and specific objectives; the detailed work plan for the 1st year of the activity and the list of the expected outputs from the research. Moreover, additional information is requested on previous related work done and on the list of research facilities available and will be used for the project.
The call for participating in the CRP results in to thirteen (13) approved research proposals, from thirteen different MSs, as presented in TAB. 3. The proposals are a very welcomed mixture of contribution from experienced organizations, owning high and medium size of power young and ageing RRs, with sustainable programmes on age-management. Some of the proposals are to share information from in-situ monitoring experiments in young RR programmes (ANSTO, CRND, EAEA and KEARI), where some are interested in the Database for future advance designs of new RRs (BARC, CNEA, KAERI, NECSA and NRG). Another motivation expressed by the participants in the CRP is to enable in the near future the life extension licensing of old RRs (BARC, BATAN, JAEA-Orai, NECSA, NNC-RK, NRG-Petten and RIAR). Moreover, a part of the research proposals includes plans to irradiate materials in their RRs, to analyze the data and report the results during the activity (ANSTO, BATAN, EAEA, KAERI, NRG and RIAR), where others suggested to elaborate the existing information and compile it into the Database. Data base about corrosion effects in the Core Component materials is proposed by three organizations (BARC, CNEA and NNC-RK) It should be mentioned that two proposals are to share the valuable Database acquired for many years of activity from present formally shut-downed RRs (ANSTO-HIFAR and BARC-CIRUS). Finally, one proposal is offering to share a detailed and generic programme to develop the format of the Database as well as to develop advanced experimental tools in order to carry on typical tests and more advanced experiments needed in this IAEA programme (ORNL-Y12).
The tabulated information of all the research proposals is shown in TAB. 3 presents basic information on the CRP participant, the proposed research programme characteristics and some general remarks considering the project. Special emphasize was given to the list of materials that will be reported or tested to prepare the Database. Considering the offers, the list of proposals is very comprehensive and includes the most relevant Core Component materials inputs needed in the specific Database, as well as materials for Cable insulators, reflectors and control rods, etc...
As mentioned, this publication is presenting the proposals agreed by IAEA to be included in three to four years of international collaboration through a CRP, as suggested by the MS. It should be noted that some clarifications resulting in slight modification of the programmes are expected, following the 1st Research Coordinated Meeting in Vienna on November 2013.

TAB. 3: **MS proposals for the establishment of a Material Properties DATABASE for irradiated CORE STRUCTURAL COMPONENTS**

CRP Participant					Research Programme Characteristics		Remarks
COMPANY	**RR ID (Database)**	**Type**	**Nominal Power**	**Year of 1st Critically**	**Materials**	**Expected Outputs**	
ANSTO	• HIFAR • OPAL	Tank-WR MTR-pool	10MW 20MW	1958 2007	Al-6061, Al-99%	1. Data on irradiation effects of tested pieces of Al alloys from HIFAR. 2. Baseline data for Zr-4 and Zr-2.5%Ni from OPAL. 3. Data from surveillance programme and mechanical test results for Zircaloy-4, after 5 yrs. operation in OPAL.	• Outputs mentioned for the 3 years of activity. • New Hot cells will be available in the short future.
BARC	CIRUS	Tank-HWR	40 MW	1960	Al alloys Carbon Steel Graphite	1. Categorization of the data according in to different reactor components, mechanical properties and neutron fluence. 2. Data on corrosion. 3. Data on stored energy behaviour in graphite 4. Data on mechanical properties.	• Data based on information from CIRUS (shutdown in 2010). • Outputs mentioned for the 3 years of activity.
BATAN	• Kartini • Bandung	TRIGA II TRIGA II	0.1 MW 2 MW	1979 1964	RR core components (Al-6061, $AlMg_3$)	1. Literature survey of irradiation effects. 2. Results of tensile strength and hardness from in-pile material tests in a new Database system.	• Activities mentioned for 4 years
CNEA	• RA-1 • RA-3 • RA-6	Tank MTR-pool MTR-pool	0.04 MW 5 MW 3 MW	1958 1968 1982	Al-6061, SS - alloys, Zircaloy-4, concrete, graphite, etc...	1. Review of relevant operating experience and existing exp. data. 2. Database, including own information and results from open literature. 3. Data on corrosion.	• Study related to the design of the new RA-10. • Outputs mentioned for the 1st year of activity.
CRND	NUR	MTR-pool	1MW	1989	Al alloys Cable insulators Zircaloy-4	1. Data from irradiating Al alloys samples. 2. Data from irradiating cable insulators. 3. Data from proton irradiating ZrH samples	• Outputs mentioned for the 1st year of activity.
EAEA	ETRR-2	MTR-pool	22 MW	1997	SS (304L, 316L, 347), Al-6061, Cd, Be and Zircaloy-4	1. Literature survey of irradiation effects. 2. Pre irradiation tests results of martial specimen using Hot Cells equipment. 3. Compile materials properties and environment-al conditions to a Database.	• Outputs mentioned for the 1st year of activity. • Available irradiation position & hot cell.

TAB. 3 (cont.): **MS proposals for the establishment of a Material Properties DATABASE for irradiated CORE STRUCTURAL COMPONENTS**

CRP Participant						Research Programme Characteristics	Remarks
COMPANY	**RR ID (Database)**	**Type**	**Nominal Power**	**Year of 1st Critically**	**Materials**	**Expected Outputs**	
JAEA - Oarai	JMTR	Tank	50 MW	1968	Unspecified RR core components	1. Literature survey of irradiation effects. 2. Contribution to Database creation.	• Unspecified physical condition of JMTR & Hot cells • Outputs mentioned for the 3 years of activity.
KAERI	HANARO	MTR-pool	30 MW	1995	Zircaloy-4	1. Literature survey of irradiation effects on Zircaloy-4. 2. Irradiation tests results. (HANARO & Hot Cells). 3. Database on: swelling, microstructural observations, phys. & mech. properties.	• Study related to the design of the new KAERI RR. • Outputs mentioned for the 3 years of activity.
NECSA	SAFARI-1	MTR-pool	20MW	1966	RR Core structural materials	1. Review of relevant operating experience and existing exp. data. 2. Database, including own information and results from open literature.	• Outputs mentioned for the 4 years of activity.
NNC- RK	EWG-1	Tank	35MW	1972	SS 8Cr18Ni10Ti SS12Cr18Ni10Ti Al-5%Mg, Al-6%Mg Zr-1%Ni, Ti-9%Gd,TSHG-Beryllium	1. Data on the corrosion condition and irradiation effects of: stainless steel, aluminium-magnesium, zirconium-niobium, titanium-gadolinium alloys and beryllium. 2. Data on irradiation damages and corrosion of water-cooled fuel channel.	• Outputs mentioned for the 3 years of activity
NRG - Petten	HFR	Tank in pool	45 MW	1961	Al alloys (Al-5054-O)	1. Literature survey of irradiation effects on core materials & compilation of data from HFR ageing surveillance programme. (FT properties & SEM/TEM tests). 2. Comprehensive experimental result analysis. 3. Contribution to Database creation.	• Outputs mentioned for the 3 years of activity. • Hot cells fully equipped: FT & Fatigue measurements, SEM & TEM.

TAB. 3 (cont.): MS proposals for the establishment of a Material Properties DATABASE for irradiated CORE STRUCTURAL COMPONENTS

CRP Participant					Research Programme Characteristics		Remarks
COMPANY	RR ID (Database)	Type	Nominal Power	Year of 1st Critically	Materials	Expected Outputs	
ORNL (Y-12)	N/A	N/A	N/A	N/A	RR Core structural materials	1. Comprehensive advanced Database system. 2. Developing a NDT Electro-magnetic Corrosion Analysis by a non-contact Electronic Property Measurement system. 3. Developing a Resonance Ultrasound Spectro-copy method for testing tensile strength and yield stress of irradiated RR's Core Structural Materials in Hot Cells.	• Generic activity to provide tools for testing and assembling data of irradiated Core Structural Materials • Outputs mentioned for the 3 years of activity
RIAR	BOR-60	Na-cooled fast reactor	60MW	1968	SS-Cr9Ni10Ti SS-Cr19Ni9	Data on physical and mechanical properties of irradiated materials dependence on neutron dose & temperature. Emphasizing the effect of sample geometry on the properties and study the correlation between the increase of yield point and increase in micro-hardness.	• Outputs mentioned for the 3 years of activity. • Study related to the programme to justify the life extension of BOR-60 fast sodium cooled reactor.

5. Conclusions

Considering the pre-CRP Questionnaire, the results are highly valuable for the identification of items relevant for the establishment of a material properties Database for irradiated core structural components for continued safe operation and lifetime extension of ageing RR's.
The respondents considered the core basket and grid (plate support) structure, reactor vessel and some irradiation facilities as the most important components affected by ageing. As the major materials affected by ageing were identified stainless steel and aluminum alloys, followed by Beryllium, carbon steel, Zircaloy and boron carbide. The most important lacking information that the respondents indicate as needed, concerns irradiation effects on mechanical properties. The identified materials and components are in the listing of typical RR Core Components and structures. The measurement results of radiation embrittlement of structural alloys, swelling measurement of control rod materials, and development of appropriate ageing indicators are items that might be included in the data base useful for a much wider community. For what concern the Database form, the respondents' majority shows a preference for MS Excel environment.
Following the analysis of the pre-CRP Questionnaire, the call for participating in the CRP results into thirteen (13) approved research proposals, from different MSs. The proposals are a very welcomed mixture of contribution from organizations, owning high power ageing RRs, with sustainable programmes on age-management. Some of the proposals are considering existing young RR programmes, where some are interested in the Database to be used for advance designs of new RRs. Another motivation to participate in the CRP is the life extension licensing of old RRs. Finally, a part of the research proposals includes plans to irradiate materials, analyze and report the results during the CRP activity, the others will elaborate the existing information and compile it into the Database and one proposal is offering a very detailed and generic project to develop the format of the Database as well as to develop advanced experimental tools to carry on the typical tests needed in this IAEA programme. It should be noted that some clarifications resulting in slight modification of the programmes are expected, following the 1st Research Coordinated Meeting in Vienna on November 2013.

6. References

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