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IAEA NUCLEAR ENERGY SERIES No. NP-T-5.8

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2017

Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
http://www.iaea.org/books

Printed by the IAEA in Austria
September 2017
STI/PUB/1728

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Research reactors for the development of materials and fuels for innovative nuclear energy systems / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2017. | Series: IAEA nuclear energy series, ISSN 1995–7807 ; no. NP-T-5.8 | Includes bibliographical references.
Identifiers: IAEAL 17-01107 | ISBN 978–92–0–100816–9 (paperback : alk. paper)
Subjects: LCSH: Materials testing reactors. | Nuclear reactors — Materials — Testing. | Nuclear energy — Research.
Classification: UDC 621.039.57 | STI/PUB/1728

FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

There are 266 research reactors worldwide which are planned, under construction, operational or temporarily shut down. This publication provides an overview of the most important materials testing reactors and their capabilities and capacities, including the power level, mode of operation, current status and history of their utilization. A summary of this overview, together with reactor availability for materials and fuels testing, is also presented in the tables on the CD-ROM accompanying this publication. The main component of this publication comprises 30 profiles, which provide a technical description of the research reactors, including their specific features for utilization. The profiles can be found on the CD-ROM and are an integral part of the publication.

This publication and the corresponding update to the Research Reactor Database are expected to foster wider access to information on research reactors and thus ensure their increased utilization. The publication can serve as a supporting tool for the establishment of regional and international networking through research reactor coalitions and centres such as the IAEA-designated International Centre based on Research Reactor. The publication's development was supported during the meeting of the IAEA Technical Working Group on Research Reactors in April 2013.

The IAEA is grateful for the assistance of all the experts who contributed to the development of this publication, in particular W. Wiesenack (Norway) and A. Izhutov (Russian Federation). The IAEA officers responsible for this publication were M. Khoroshev of the Division of Nuclear Power and A. Borio di Tigliole of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Research reactors are indispensable tools used to support the nuclear power industry in material characterization and testing for life extension of operating plants, and in the qualification of structures, systems and components for the new generation of nuclear power plants. Research reactors are also of paramount importance for R&D, fission and fusion technologies, isotope production, neutron radiography, neutron beam research, education and training. The capacities of research reactors in IAEA Member States are often not fully exploited due to many reasons, including: a lack of funding; barriers to access; insufficient exchanges of information; a lack of strategic planning; insufficient ageing management; and intellectual property rights. The IAEA therefore strives to foster regional and international efforts in ensuring a wide access to existing research reactors in order to increase their viability and utilization.

In 2006, the IAEA started to investigate the research reactor support needed for innovative nuclear power reactors and fuel cycles with the following objectives:

(a) To identify innovative nuclear R&D activities that require research reactor support;
(b) To identify existing (or soon to be operational) research reactor facilities capable of supporting innovative nuclear development;
(c) To quantify the capabilities of the identified facilities within the context of the required research support;
(d) To promote the experience and available resources of the identified facilities;
(e) To list significant challenges and constraints potentially limiting a facility's ability to provide support;
(f) To quantify technical capability gaps between identified facilities and research requirements;
(g) To recommend measures to address the capability gaps identified.

The IAEA publication Utilization Related Design Features of Research Reactors: A Compendium [1] contains information on the design, construction and operation of research reactor facilities and their associated devices, and it explores the range of services available at research reactors in operation at that time. In the IAEA publication Applications of Research Reactors [2], a variety of applications is comprehensively presented — from those that are possible at any power level of research reactor, such as training, to those that require higher power and more specialized reactors with expensive experimental facilities. However, neither publication focuses specifically on innovative research and the research reactors capable of conducting it. This publication therefore explores the capacities and capabilities of the most important materials testing reactors (MTRs) in Member States for potential users and customers in need of innovative nuclear energy research.

One opportunity to increase the utilization of research reactors lies in enhancing and expanding the IAEA Research Reactor Database (RRDB).[1] The RRDB contains data on 774 reactors in 71 Member States. Data can be located using search categories such as the name of the research reactor, the location, and its operational status, power, utilization profile and applications. The RRDB has recently been expanded to include newly prepared and documented information and additional navigation options. It serves as a tool for planning R&D programmes and other activities at research reactor facilities in Member States on a regional and international basis.

There are also possibilities to establish more topical coalitions of research reactors: currently, there are seven coalitions based on geography and three based on joint activities.[2] Furthermore, the IAEA-designated International Centre based on Research Reactor (ICERR) scheme, which was officially launched in 2014 and has been developed in consultation with international experts, aims to provide nuclear education programmes that offer direct experience of working at nuclear facilities and provide training opportunities.

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[1] See http://nucleus.iaea.org/RRDB/
[2] For further information, see www.iaea.org/OurWork/ST/NE/NEFW/Technical_Areas/RRS/Utilization-Applications.html

1.2. OBJECTIVE

This publication provides an overview of the most important MTRs in Member States and provides 30 profiles on the CD-ROM. The publication focuses on the contributions that these research reactors and associated facilities can provide to major areas of R&D for advanced materials and fuels. However, since many MTRs are multipurpose facilities, this publication also includes some information relating to other research reactor applications.

1.3. SCOPE

In this publication, the term innovative nuclear energy system (NES) will be used in a narrow sense, and is more comparable to its use in the Generation IV International Forum (GIF). It is thus limited to innovative reactors and their components, materials and fuels. Within the IAEA, innovative NESs are defined within the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) as encompassing all elements of the broader system, including innovative reactors, associated fuel cycle facilities (including ultimate front and back end facilities) and all related nuclear infrastructure over the full life cycle.

1.4. STRUCTURE

Section 2 explores the role of MTRs in R&D and provides details on some of the more powerful MTRs in use. Section 3 describes research reactors supporting innovative NESs and categorizes the different types of reactor. Section 4 highlights the new challenges facing innovative NESs, and Section 5 reports on access to research reactors. The main component is the 30 profiles on the CD-ROM accompanying this publication, which provide a technical description of the research reactors, including their specific features for utilization (see Table 1). The profiles describe research reactors according to the template which was agreed among a broad group of international experts contributing to this publication. Most of the profiles were provided to the IAEA by Member State institutions in response to requests to complete the template. Although some profiles do not follow exactly the requested contents and format, they have been included for completeness.

TABLE 1. RESEARCH REACTORS INCLUDED IN THE PROFILES ON THE CD-ROM

Profile No.	Country	Research reactor	Readiness[a]	Table[b]
1	Argentina	Argentine multipurpose reactor (RA-10)	Planned	A–2
2	Belgium	Belgium Reactor 2 (BR-2)	Operational	A–1
3	China	China Experimental Fast Reactor (CEFR)	Operational	A–1
4	China	China Advanced Research Reactor (CARR)	Operational	A–1
5	Egypt	Experimental Training Research Reactor 2 (ETRR-2)	Potential	A–3
6	France	Jules Horowitz Reactor (JHR)	Planned	A–2
7	Hungary	Budapest Research Reactor (BRR)	Potential	A–3
8	India	DHRUVA	Operational	A–1
9	India	High Flux Research Reactor (HFRR)	Potential	A–2
10	Indonesia	Reaktor Serba Guna G.A. Siwabessy (RSG-GAS)	Operational	A–3

TABLE 1. RESEARCH REACTORS INCLUDED IN THE PROFILES ON THE CD-ROM (cont.)

Profile No.	Country	Research reactor	Readiness[a]	Table[b]
11	Japan	Japan Materials Testing Reactor (JMTR)	Operational	A–1
12	Japan	Experimental Fast Reactor (JOYO)	Potential	A–3
13	Kazakhstan	Impulse Graphite Reactor (IGR)	Operational[c]	A–4
14	Republic of Korea	High-flux Advanced Neutron Application Reactor (HANARO)	Operational	A–1
15	Netherlands	High Flux Reactor (HFR)	Operational	A–1
16	Norway	Halden Boiling Water Reactor (HBWR)	Operational	A–1
17	Poland	MARIA	Potential	A–3
18	Romania	TRIGA II Piteşti	Operational[c]	A–1, A–4
19	Russian Federation	Fast Pulse Graphite Reactor (BIGR)	Operational[c]	A–4
20	Russian Federation	IR-8	Operational	A–1
21	Russian Federation	IVV-2M	Potential	A–1
22	Russian Federation	MIR.M1	Operational	A–1
23	Russian Federation	SM-3	Operational	A–1
24	Russian Federation	BOR-60	Operational	A–1
25	Russian Federation	RBT-6	Operational	A–1
26	Slovenia	TRIGA Mark II	Operational	A–5
27	USA	Advanced Test Reactor (ATR)	Operational	A–1
28	USA	High Flux Isotope Reactor (HFIR)	Operational	A–1
29	USA	Massachusetts Institute of Technology Reactor (MITR)	Operational	A–1
30	Italy Italy Russian Federation	TRIGA RC-1 TAPIRO BFS-1, BFS-2 (Fast Critical Assembly)	Operational Planned Operational	A–5 A–5 A–5

Note: The research reactors CABRI (France), Nuclear Safety Research Reactor (NSRR, Japan) and Transient Reactor Test Facility (TREAT, United States of America) did not provide information. However, it should be noted that they are important and powerful facilities, in particular for reactivity insertion accident tests. The research reactors ASTRID (France), MBIR (Russian Federation) and MYRRHA (Belgium) are projects to provide additional fast spectrum research capabilities, but they did not provide information. LVR-15 (Czech Republic) and OSIRIS (France) are not included in the profiles because the research reactors did not provide information. SS — steady state; TRIGA — training, research, isotopes, General Atomics.

[a] The readiness for materials testing research falls under three categories of research reactor: operational; planned or under construction; and those with the potential for materials testing research.

[b] Tables A–1 to A–5 can be found on the CD-ROM accompanying this publication.

[c] Operational pulsed research reactor.

A summary of the capabilities and capacities of MTRs and their readiness for materials and fuels testing is provided in five tables on the CD-ROM accompanying this publication:

— Table A–1. Operational Research Reactors: Overview of current capabilities and capacities for materials testing research.
— Table A–2. Planned Research Reactors: Overview of future capabilities and capacities for materials testing research.
— Table A–3. Research Reactors with the Potential for Materials Testing Research: Overview of current capabilities and capacities.
— Table A–4. Pulsed Research Reactors: Overview of current capabilities and capacities for materials testing research.
— Table A–5. Low Power Research Reactors: Some examples of roles complementary to materials testing research.

1.5. USERS

This publication is aimed at national and international organizations directly involved in the development of materials and fuels for the nuclear energy industry, and includes public and private sector organizations responsible for the development and lifetime extension of reactors already in operation and the development and deployment of innovative NESs, such as designers, manufacturers, vendors, research institutions, safety authorities, technical support organizations and academia.

2. ROLE OF MATERIALS TESTING REACTORS IN R&D

With the advent of commercial nuclear power in the 1950s, not much was known about the effects of radiation on the materials, fuels and core components used in nuclear reactors. Since then, MTRs have performed applied research on structure and fuel materials for commercial power reactors. The total number of research reactors in operation peaked at 400 in the 1970s but decreased to around 270 by 2007 [3, 4]. Fewer than 30 of them are MTRs currently capable for use in materials testing and related research.

MTRs have proved to be an essential tool for fundamental research, providing representative conditions in nuclear power reactors, such as strong radiation, high temperature and pressure, and resistance of fuels and structural materials [5]. Many powerful MTRs are still in use today, even though they started their operation in the late 1950s and 1960s (see Table 2) [5]. Reactors built in the 1970s include some specialized reactors such as: CABRI; NSRR; IGR; TREAT; and BIGR for power pulse reactivity insertion accident (RIA) mode of testing.

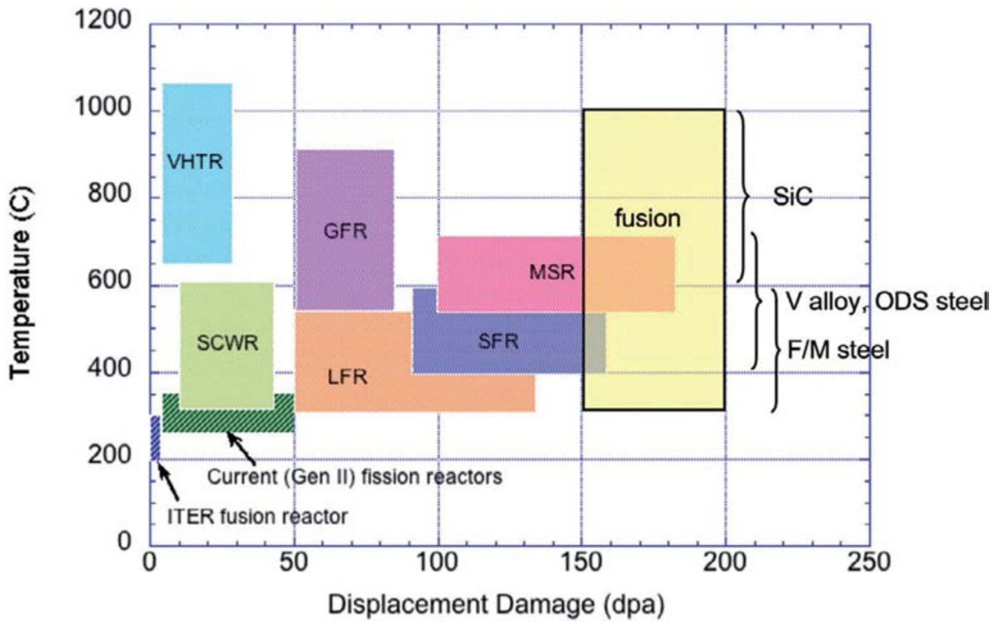
Considerable experience with materials and fuels testing has been gained since the first MTR commenced its services, and a wealth of knowledge on materials and fuels behaviour has been documented through ever more sophisticated experiments [6]. Research has helped to answer many questions, but new ones continue to emerge. Growing safety criteria and new regulatory safety requirements place greater demands on materials and fuels, which in turn places evolving demands on safety regulation. Innovative NESs, such as Generation IV systems, bring new requirements and conditions not yet experienced on an industrial scale.

The innovative NESs currently being designed and developed worldwide pose even greater challenges than present day light water reactors once did. Their operation conditions are much more demanding and require new materials and fuels to be developed (see Fig. 1).

Existing and planned MTRs are indispensable for the design and deployment of innovative NESs and their fuel cycles. There are currently 15 MTRs in operation that are capable of supporting materials testing for innovative NESs and technologies, some of which are listed in Table 1. Some of these reactors have unique systems and capabilities to address some of the most difficult problems facing current and future materials and fuels research. Maintaining them and developing further sophisticated and up to date experimental capabilities are crucial.

TABLE 2. SELECTION OF THE MORE POWERFUL MTRs IN USE

Startup	Country	Reactor	Power (MW)
1957	Czech Republic	LVR-15	10
1959	Norway	HBWR	20
1961	Belgium	BR-2	100
1961	Russian Federation	SM-3	100
1963	Netherlands	HFR	45
1965	United States of America	HFIR	85
1967	United States of America	ATR	250
1967	Russian Federation	MIR.M1	100
1968	Japan	JMTR	50
1968	Russian Federation	BOR-60	60



Note: F/M — ferritic/martensitic; GFR — gas cooled fast reactor; ITER — International Thermonuclear Experimental Reactor; LFR — lead cooled fast reactor; MSR — molten salt reactor; ODS — oxide dispersion strengthened; SCWR — supercritical water cooled reactor; SFR — sodium cooled fast reactor; VHTR — very high temperature reactor.

FIG. 1. Requirements on materials in future NESs (reproduced from Ref. [7] with permission courtesy of Elsevier).

NES R&D is generally focused on advanced materials research, which includes the testing of advanced fuels and structural materials (e.g. liquid metal as a coolant or molten salt as a fuel), studying minor actinides and long lived fission products burnout as well as exploring the extension of fuel resources using thorium fuel cycle options or fusion technologies. Existing and planned MTRs have, or will have, capacities to perform a broad spectrum of R&D aimed at developing innovative reactors like those being developed through the GIF, in Member State national programmes and in the concepts of future NESs considered in INPRO.[3]

3. RESEARCH REACTORS SUPPORTING INNOVATIVE NUCLEAR ENERGY SYSTEMS

With regard to materials testing capabilities, the MTRs in this publication are categorized according to the following (the tables are to be found on the CD-ROM accompanying this publication):

- Current status:
  - Operational (see Table A–1);
  - Planned (see Table A–2);
  - Potential (see Table A–3).
- Power level:
  - High (see Tables A–1 to A–4);
  - Medium (see Tables A–1 to A–4);
  - Low (see Table A–5).
- Mode of operation:
  - Steady state (see Tables A–1 to A–3);
  - Pulsed (see Table A–4).
- Neutron spectrum (thermal and fast presented in all Tables A–1 to A–5).

With regard to emerging challenges and the ability to respond to new requirements in materials and fuels testing research for innovative nuclear technologies, the following features of MTRs are considered:

- Unique features provided (e.g. experimental volume combined with neutron flux);
- Ability to handle molten metals or salts or supercritical water;
- In situ instrumentation;
- Post-irradiation examination (PIE) capabilities;
- Method of access.

With regard to lifetime, the MTRs in this publication can be categorized according to age:

- Oldest (possibly with expected lifetime extension);
- Newest;
- Planned or under construction;
- Potentially able to contribute to materials testing research.

[3] For more information, see www.iaea.org/INPRO/publications/INPRO_Brochure_2012.pdf

3.1. RESEARCH REACTOR POWER LEVELS

The MTRs in this publication (with the exception of pulsed reactors, which are categorized differently) are categorized as follows (see Table 3):

— High power (≥20 MW);
— Medium power (5–20 MW);
— Low power (<5 MW).

TABLE 3. RESEARCH REACTOR POWER LEVELS

Country	Reactor
High power (≥20 MW)	
Argentina	RA-10
Belgium	BR-2
China	CEFR CARR
Egypt	ETRR-2
France	JHR
India	DHRUVA HFRR
Indonesia	RSG-GAS
Japan	JMTR JOYO
Republic of Korea	HANARO
Netherlands	HFR
Norway	HBWR
Poland	MARIA
Russian Federation	MIR.M1 SM-3 BOR-60
USA	ATR HFIR
Medium power (5–20 MW)	
Hungary	BRR
Romania	TRIGA II Piteşti
Russian Federation	IVV-2M IR-8 RBT-6
USA	MITR

TABLE 3. RESEARCH REACTOR POWER LEVELS (cont.)

Country	Reactor
Low power (<5 MW)	
Italy	TAPIRO (zero power) TRIGA RC-1 (1 MW)
Slovenia	TRIGA Mark II (250 kW)
Russian Federation	BFS (Fast Critical Assembly) Zero power critical facility at SM-3 Zero power critical facility at MIR.M1

3.2. PRINCIPAL MODES OF OPERATION

With regard to operating mode, the MTRs in this publication can be categorized as steady state and pulsed reactors.

3.2.1. Steady state operation

Most research reactors are designed for operation in steady state. Some of them have capabilities to implement relatively fast power transients, for example as required for ramp testing of fuels, and to subject fuels to simulated accident conditions, for example loss of coolant accident (LOCA) or RIA. These transients only affect the experiment and not the entire reactor, which is protected by its safety system against detrimental developments. If transients limited to an experimental system can be implemented, the feature is mentioned in the descriptions of the individual reactors (see the CD-ROM accompanying this publication).

3.2.2. Pulsed operation

Fewer than 10 MTRs are pulsed systems. Pulsed reactors have unique capabilities to support fuels testing by addressing very fast transient accident scenarios, in particular RIA. The three pulsed reactors included in this publication can be utilized for testing the behaviour of reactor fuel in design extension conditions (DECs) in order to define the safety limits for the design basis accident. Pulsed research reactors ensure a controllable, predefined energy release to simulate accidents on fuels and thus demonstrate safety parameters of new nuclear fuels designed for existing commercial reactors and for innovative NESs.

Testing the nuclear fuel in DEC conditions is not yet a requirement, but the industry anticipates a trend towards adopting such a standard. Design basis and DEC testing will continue to be coupled with engineering judgement, utilization of computer simulation codes and demonstrated operational experience. The testing programmes, including irradiation and post-irradiation activities, will produce data which should enable justified judgements on the safety as well as economic efficiency of future NESs.

For the scope of this publication, information on three pulsed research reactors (BIGR, IGR and TRIGA II Piteşti)[4] suitable for fuels testing is included, considering the past experience on fuels testing and performances of facilities:

(a) BIGR has a solid compact core with graphite and ceramic fuel. In the steady state mode, power is less than 500 kW; in the quasi-pulse mode on delayed neutrons, power is less than 1.5 GW, 280 MJ at pulse half width of less than 0.5 s; in the pulse mode on prompt neutrons, power is less than 75 GW, 280 MJ at pulse half width of less than 2 ms.

[4] The research reactors CABRI, NSRR and TREAT did not provide information. However, it should be noted that they are important and powerful facilities, in particular for RIA tests.

(b) IGR is a pulsed core research reactor with a solid, compact, graphite moderated core and uranium carbide fuel. The pulse energy release in an uncontrolled mode of 10 GW is 1.5 GJ during 0.12 s; in a controlled mode, the maximal power release is 5.2 GJ during 1–10^6 s.

(c) TRIGA II Piteşti has an annular core with low enriched uranium–zirconium hydride fuel, graphite and water reflector, and a water cooling system. In the steady state mode, power is less than 500 kW; in the pulse mode, power is less than 20 GW in a 1.7 ms half width pulse.

These pulsed reactors are inherently safe by their design. Pulse quenching is achieved through the nuclear properties of the core materials without operator or safety system intervention when the temperature increases as a consequence of the power pulse energy release.

3.3. THERMAL SPECTRUM AND FAST SPECTRUM RESEARCH REACTORS

With regard to neutron spectrum, the MTRs in this publication can be categorized as thermal spectrum and fast spectrum.

3.3.1. Thermal spectrum research reactors

Most commercial reactors currently operating use light or heavy water as the coolant and the moderator is based on light water reactor (LWR) or heavy water reactor (HWR) technology, which defines their thermal neutron spectrum. The same is true for a majority of MTRs. Therefore, existing facilities can serve current materials testing needs of thermal spectrum reactors as well as Generation III/III+ reactors, which are based on present LWR technology.

Although some current and planned research reactors with high power density cores are able to provide locally a high fast neutron flux, their natural neutron spectrum differs from those foreseen in the context of Generation IV development, with the exception of the supercritical water cooled reactor and the high temperature reactor. Flux tailoring and trapping can be applied to come closer to the spectrum of metal cooled and molten salt reactor types, and JHR is designed with an under moderated core in order to support a high level of fast flux and less thermal spectrum in the core itself.

Eventually, research reactors specifically designed to serve the needs of next generation reactors will have to be considered, and prototype reactors need to be designed to include ancillary systems for materials and fuels testing. In the meantime, existing MTRs are a necessary and acceptable compromise. They can be made suitable for many types of investigation with the installation of appropriate experimental devices and systems.

3.3.2. Fast spectrum research reactors

There are very few options for fast reactor research: BOR-60 and CEFR are currently operating; JOYO is planned to restart.[5] Some major Generation IV reactor designs plan to use non-water coolants (e.g. liquid metal and gas). These designs create technical demands concerning materials and fuels qualification leading to some very challenging R&D. In particular, the damage to material is quite high compared to thermal reactors, and consequently it requires research reactors with fast spectrum and high displacement per atom (dpa) rates (15–50 dpa/year). Worldwide, there is limited experimental capacity with the ability to deliver the required spectrum and corresponding dpa levels.

The accumulated material damage, measured in dpa, is proportional to the product of fast flux and irradiation time. BOR-60 currently provides the highest dpa (up to 25 dpa/year) and has many available cells with a very high flux and fast spectrum. Therefore, it is possible to provide massive testing of core materials and fuels in this reactor. CEFR has recently started its operation, and JOYO will provide similar capabilities when restarted.

Thermal spectrum reactors can also provide high dpa (up to 10–25 dpa/year): SM-3, HFIR and HFR (with JHR in the future). However, the available volume and cells with highest flux in these reactors are limited, and

[5] The research reactors ASTRID, MBIR and MYRRHA are projects to provide additional fast spectrum research capabilities, but they did not provide information.

these are typically accompanied by high gamma heating rates, which can pose challenges to sample temperatures. The JHR core has a design that permits an under moderated spectrum with some in-core location of hard neutron spectrum. In such a location, it will be possible to investigate GEN IV type fuel and materials behaviour in some dedicated loops (targeting a maximum of 16 dpa/year in some core positions). It is possible to achieve 14 dpa/year in HFIR and 25 dpa/year in SM-3 for the capsule type irradiation experiments.

3.4. LOW POWER RESEARCH REACTORS

Low power research reactors (<5 MW) can provide certain support for high flux irradiation facilities in a number of related applications. This feature can alleviate the general current underutilization of such low power facilities. Some complementary roles include the following [2]:

(a) Instrument testing and calibration: Neutron and gamma detection instruments need to be tested and calibrated in well controlled and characterized neutron and gamma fields to ensure that they function appropriately. Examples of such detectors are fission chambers, self-powered neutron detectors, nuclear heating calorimeters and radiological protection instruments. Some low power facilities can be a standard neutron reference field for calibration purposes.
(b) Neutron irradiation testing: Low power research reactors, although characterized by a low intensity neutron irradiation field, can provide some basic damage information in well defined neutron spectrum conditions, such as almost pure fission spectrum, on materials of interest for fission and on innovative nuclear fusion technologies.
(c) Nuclear data: Low power research reactors are historically one of the primary sources of basic information on nuclear data through utilization of their inherent capabilities for cross-section measurements, integral experiments, benchmarking and code validation analyses.
(d) Non-destructive analysis: Neutron radiography and other neutron beam techniques such as small angle neutron scattering and neutron diffraction are powerful tools for the non-destructive testing of materials. In particular, degradation phenomena in fissile and structural materials following high level neutron fluence irradiation in high power research facilities can also be investigated in low power research reactors (as well as in high power research reactors) using this technique, and theoretical models can be improved on the basis of the experimental results.

4. NEW CHALLENGES FACING INNOVATIVE NUCLEAR ENERGY SYSTEMS

Many research reactors face issues and challenges such as ageing management (50% of the facilities are older than 40 years), ageing of personnel, underutilization (50% of the facilities are operated for less than four full power equivalent weeks per year), a lack of clear purpose and mission, limited budgets, and the need to address reactor safety and security. Underutilization does not affect most MTRs, which usually have a higher utilization factor of up to approximately 70% (250 full power days per year).[6]

As Fig. 2 shows, the total number of research reactors will continue to decrease. New powerful (and therefore expensive) research reactors will need to be considered in a cooperative and consolidated manner, and should be proposed as shared user facilities among interested international partners. HBWR and JHR are perhaps the best such examples of MTRs in operation and under construction, respectively. The future of existing and planned MTRs will strongly depend on international cooperation and willingness of Member States to open these facilities to international use. In this context, the ICERR scheme is a promising possibility to address the challenges of present and future MTRs.

[6] For more information, see www.iaea.org/INPRO/publications/INPRO_Brochure_2012.pdf

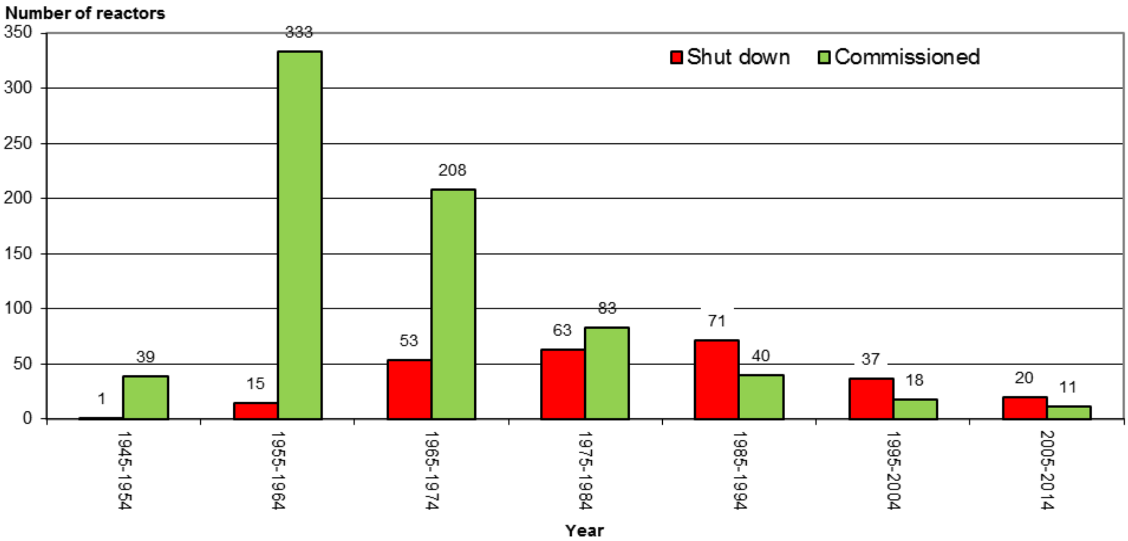


FIG. 2. Number of research reactors commissioned (green) and shut down (red).

4.1. UNIQUE EXPERIMENTAL CAPABILITIES DUE TO CORE DESIGN

Virtually all of the reactors discussed in this publication have unique capabilities with regard to core designs. Throughout the reactor lifetime, many of these facilities have changed or modified their configurations in order to develop new testing capabilities. These reactors typically use plate type fuel. However, there are several variations on the plate fuel composition, and some also use rod fuels.

4.1.1. Advanced Test Reactor

The ATR core geometry is shaped like a four leaf clover. This enables ATR to be operated as four separate core regions (lobes) in a single operating cycle to accommodate multiple experiment parameter specifications.

4.1.2. Belgium Reactor 2

The BR-2 core is composed of hexagonal beryllium blocks with central channels. The channels form a twisted hyperboloidal bundle and hence are close together at the midplane but further apart at the lower and upper ends. With this array, a high fuel density and neutron flux are achieved in the middle part of the core. The standard BR-2 fuel element comprises up to six concentric tubular shells, which provide a central channel for locating irradiation experiments and isotope irradiation.

4.1.3. Halden Boiling Water Reactor

HBWR was initially designed and built to be a prototype boiling water reactor, and then the mission changed to become a research reactor. Because the reactor was initially licensed for a fully fuelled core with more than 300 fuel element positions, it is possible to irradiate up to 30 fuelled experiments in the reactor core region simultaneously.

4.1.4. High Flux Isotope Reactor

The HFIR fuel core comprises 569 involute shaped plates arranged in two concentric fuel elements. This particular geometry, with a very high concentration of fuel in the centre of the core region and heavy water as the moderator, results in the extremely high thermal fluxes necessary for some types of isotope production. By design, it also provides high fast flux in the central trap, which can provide materials testing in a reasonable time compared to other MTRs.

4.1.5. MIR

MIR.M1 has a channel type design and is placed in the water pool. The frame of the core comprises hexagonal beryllium blocks 148.5 mm wide located in a triangle grid with a 1.5 mm gap between them. Channel bodies are installed in the central axial holes of the blocks, and up to 50 driver fuel elements and up to 11 experimental channels for loop facilities are installed. The driver fuel comprises four tube type elements with 34 mm central holes for irradiation purposes. The maximal diameter of the experimental channels is 148.5 mm, which have a relatively high thermal neutron flux of 5×10^{14} $n\cdot cm^{-2}\cdot s^{-1}$.

4.1.6. SM-3

SM-3 has a compact core of square cross-section (420 mm × 420 mm) and a height of 350 mm, with a square shape trap in the centre of the core. Due to the high concentration of fuel surrounding this space, the flux is extremely high and can be up to 5×10^{15} $n\cdot cm^{-2}\cdot s^{-1}$. There are 28 driver fuel assemblies, which comprise up to 188 fuel rods in the formation of a cross. The reactor core is surrounded by a metal beryllium side reflector. In the reflector, there are 30 vertical cylindrical holes located at different distances from the core to house experimental channels and irradiation rigs.

4.2. BALANCING EXPERIMENT VOLUME AND NEUTRON FLUX

Generally speaking, research reactors are compact machines compared to power producing reactors. This compactness can make experiment design very challenging, particularly for MTR type fuels and non-pin style targets, where full scale geometries may be necessary to test adequately fuel swelling and fuel–clad interactions. Because MTRs are so physically small and have such high power densities, they also tend to have a higher variation of neutron flux across their cores. The result is a non-uniform flux distribution in the radial and axial direction. These flux profiles can cause difficulty when designing experiments, in particular for controlling sample temperatures and irradiation geometries. There are often times that experiments would benefit from a large volume channel coupled with a consistent high flux, but since flux and power density are directly proportional, larger reactors tend to have lower fluxes.

For sealed capsule experiments on materials, specimens can be easily packed into small capsules and placed at the optimal location in most reactors. Particularly with the advent of very small tensile specimen sizes, this has become a relatively routine task. For experiments requiring flow loops, irradiation rigs or larger sample sizes, the flux distribution becomes more important to the design of the experiment and may be a limiting factor for certain test samples.

4.3. QUALIFYING UNIQUE COOLANTS FOR NEXT GENERATION REACTORS

Innovative NESs are designed to make better use of the fuel by high conversion or breeding ratios to achieve high thermal efficiency and to improve safety and reliability. To reach these goals, the reactor core needs to have favourable neutronic, thermophysical, chemical and economic properties and to be capable of withstanding high radiation doses. However, no structural material or coolant in nature ideally satisfies all requirements, and research in MTRs is required to optimize the reactor materials, with special attention to prospective coolants (e.g. molten metals, salts or supercritical water) and their interaction with in-core and primary circuit materials.

Several current MTRs offer loops to create the thermohydraulic conditions of various types of nuclear power reactor (see Table 4). There are plans to install such loops at other research reactors, for example JHR and CARR. However, limited data on the coolants of next generation reactors are available. Plans exist for supercritical water loops whose design can rely on proven technologies known from LWRs and supercritical water fossil plants. These loops will be first commissioned for out-of-core use (e.g. at HBWR). Their application will be to identify and test materials that are resistant to corrosion and stress corrosion cracking in supercritical water conditions.

TABLE 4. MATERIALS TESTING REACTOR TEST CONFIGURATIONS

Reactor name	Test configuration
BR-2	Water loops PWR, liquid metal
BRR	Gas cooled irradiation rig
JHR (planned)	Water loops PWR, BWR, WWER, sodium (planned)
DHRUVA	Water loops 1.6 MW, LWR
HBWR	Water loops 200 kW, BWR, PWR, WWER, CANDU
TRIGA II Pitești	High temperature water loops 100 kW, fuels testing
SM-3	High and low temperature water loops
MIR.M1	Water loops 1.5–2.0 MW, WWER, RBMK, PWR, vapour loops, gas loops
ATR	High temperature water loops

Note: BWR — boiling water reactor; CANDU — Canada deuterium–uranium; LWR — light water reactor; PWR — pressurized water reactor; RBMK — high power, channel type reactor; WWER — water cooled, water moderated power reactor.

Currently, there are not any research reactors in operation which include in-core loops for molten salts or liquid metals. The operation of such loops will face the same problems that the research intends to solve. For example, the MIR.M1 lead–bismuth facility was in operation in the past, but currently it is in standby.

A solution that is easier to implement, but which does not allow control of the chemistry, is the use of capsules with only internal circulation of the coolant. A number of MTRs have experience with such irradiation devices and loop experiments, although not necessarily with molten salts or metals in them: JMTR (water), JOYO (sodium), HANARO (water), HFR (water), TRIGA II Pitești (gas), BOR-60 (lead, lead–bismuth, sodium), RBT-6 (water, supercritical water) and ATR (gas). MYRRHA (lead–bismuth) is planned to be operational by 2024.

4.4. IN-CORE INSTRUMENTATION

In-core instrumentation is essential for performance studies of materials and fuels, since it provides direct insight into phenomena as they develop and cross-correlations between them [5]. The basic instrumentation for fuel behaviour studies, for example as applied in HBWR, encompasses fuel thermocouples, rod pressure transducers for fission gas release assessment, fuel stack elongation detectors for measuring densification and swelling, and clad elongation detectors for axial pellet–clad mechanical interactions [5]. Typical materials performance studies require the ability to measure crack initiation, crack growth and time to failure.

The conditions in the core of a research reactor are not conducive to instrument performance and the ability to survive for a long period of time [5]. Instrument performance issues will be accentuated in MTRs simulating next generation reactor conditions with even higher gamma fluxes (up to 15 W/g), higher neutron fluxes ($>5 \times 10^{14}$ $n \cdot cm^{-2} \cdot s^{-1}$), higher temperatures (>600°C) and higher pressures (>25 MPa), which can all contribute to instrument failure [5]. Only robust instruments will endure in-core conditions for longer times, and this requires the development of more reliable instrumentation [7]. Similar considerations apply to instrumentation in the coolant.

Instrument performance is an important topic for future experiments in MTR, as end users (e.g. fuel physicists and material scientists) require ever more on-line information for simulation of physics phenomena based on related computer codes. This requirement can be associated with the following:

(a) The need to have a better management of the irradiation conditions to improve the analysis of the experiments, and especially for key parameters such as:
  - Temperature;
  - Pressure;
  - Fast and thermal neutron flux.

(b) The need to have on-line information of physical parameters of primary importance for the follow-up and analysis of the experiments, such as:
  - Neutron flux;
  - Temperature;
  - Gamma heating;
  - Fission gas release;
  - Conductivity;
  - Material elongation in mono- and bi-axes;
  - Coolant pressure;
  - Flow rate and chemistry.

This leads to some important R&D collaboration between research institutions, and on projects, in different countries, for example: the Halden Reactor Project; the Belgian Nuclear Research Centre (SCK•CEN); the Idaho National Laboratory (INL); the French Alternative Energies and Atomic Energy Commission (CEA); and the Research Institute of Atomic Reactors (RIAR). Eventually, it will also lead to the arrival of new instrumentation for the next generation of experiments in MTRs, for example: sensors; thermocouple devices; enhanced linear voltage differential transformers; neutron fission chambers; radiation and temperature resistance video scopes; and ultrasonic transducers.

4.5. PRE- AND POST-IRRADIATION FACILITIES

Pre- and post-irradiation facilities are critical partners to current research reactors. Ideally, a research reactor site should provide laboratories to prepare and perform experimental research, and workshops for designing and manufacturing experimental devices and installations and for refabrication of experimental samples from irradiated materials and fuels. Hot cells and glove boxes for non-destructive and destructive PIEs of irradiated materials and fuels should also be provided. The main types of non-destructive analysis include:

- Measurements of geometrical characteristics;
- Visual examinations;
- Gamma scanning;
- Eddy current testing;
- Ultrasonic;
- Neutron radiography;
- X ray radiography.

The destructive analysis includes:

- Metallography and ceramography;
- Microhardness;
- Density and porosity;
- Burnup measurements;

— Fission products release;
— Thermal conductivity and electric resistance;
— X ray analysis;
— Transmission electron microscopy (TEM);
— Scanning electron microscopy (SEM);
— Electron probe microanalysis (EPMA);
— Auger electron spectroscopy (AES);
— Secondary ion mass spectrometry (SIMS);
— Mechanical testing (e.g. tensile, compression, bending and impact).[7]

Some examples of specific experimental capabilities are described in the following subsections.

4.5.1. Research Institute of Atomic Reactors

Situated in the Russian Federation, the RIAR materials testing complex (including SM-3, BOR-60, MIR.M1 and RBT-6) is located in three adjacent buildings, which house more than 110 devices and facilities. There is the capability to perform all experiment assembly and post-irradiation non-destructive and destructive examinations of core elements and a wide range of irradiated materials. There are 7 special, large hot cells for investigation of full size irradiated fuel assemblies from nuclear power plants, and more than 40 hot cells for destructive examinations, equipped with modern equipment for mechanical testing, examination and analysis of structural and fuel materials. Non-destructive analysis of full scale fuel rods and assemblies includes the following:

— Measurements of geometrical characteristics;
— Visual examinations;
— Gamma scanning;
— Eddy current testing;
— Ultrasonic.

Destructive analysis includes the following:

— Burnup measurements;
— Fission products release;
— Metallography and ceramography;
— Microhardness;
— Density and porosity;
— Thermal conductivity and electric resistance;
— X ray analysis;
— TEM;
— SEM;
— EPMA;
— AES;
— SIMS;
— Mechanical testing (e.g. tensile, compression, bending and impact).

4.5.2. Advanced Test Reactor

All experiments to be inserted into ATR, at INL, can be assembled on site, but there are no PIE facilities directly adjacent to the reactor facility. There is, however, a wide variety of destructive and non-destructive examination capabilities available at the materials and fuels complex, also part of INL. Transport between the two facilities uses approved shipping containers. Multiple hot cells and laboratories examine irradiated fuel with destructive and non-destructive techniques. Neutron radiography is performed using the neutron radiography

[7] For detailed information on PIE techniques used and hot characteristics, see https://infcis.iaea.org/PIE/About.cshtml

reactor in the basement of the primary fuel hot cell in the Hot Fuel Examination Facility. Types of analysis include the following:

— Gamma scanning;
— Profilometry;
— SEM;
— TEM;
— Atom probe (which can detect single atoms);
— EPMA;
— Inductively coupled plasma mass spectrometry;
— Thermal ionization mass spectrometry;
— Fission gas analysis;
— Plenum pressure analysis;
— Crack growth measurement.

Through the ATR National Scientific User Facility, researchers can access additional facilities at other locations that have different examination capability, such as light sources and accelerators for examining irradiated material.

4.5.3. Halden Boiling Water Reactor

The HBWR research capabilities comprise several facilities that can design, fabricate, irradiate and examine materials and fuels. It also possesses transport facilities and interim storage. All irradiation test rigs and measurement devices can be developed, designed and manufactured on site, including fabrication of uranium dioxide fuel pellets. HBWR specializes in fuel research and has several hot cell facilities for irradiated fuel examinations to perform the following:

— Visual inspections;
— Photography;
— Dimensional measurements;
— Isotopic analysis;
— Gamma scanning;
— Fission gas analysis;
— Pressure measurements;
— Locating leakage in case of fuel failure;
— Burst tests of irradiated canning tubes;
— Metallography;
— Neutron radiography.

The hot laboratory has auxiliary installations such as an unloading bay for shipping flasks, storage pits, and decontamination and maintenance rooms for active components. The laboratory is furnished with partly shielded equipment for tensile testing (ring shaped samples), hardness measurements, and active and inactive SEM with an energy dispersive X ray spectroscopy (EDS) analyser.

4.5.4. High Flux Isotope Reactor

HFIR, at Oak Ridge National Laboratory, has several hot cell facilities for the examination of irradiated materials and fuels. Capabilities for materials testing include the following:

— Furnace annealing;
— Automated welding;
— Ultrasonic cleaning;
— High temperature and high vacuum testing;

- Tensile testing, with a high vacuum chamber option;
- Impact testing;
- Fatigue and fracture toughness testing of standard and subsize impact specimens;
- Automated microhardness testing;
- Profilometry;
- SEM.

Fuels testing capabilities include the following:

- Full length LWR fuel examinations;
- Spent fuel repackaging;
- Metrology;
- Metallography;
- Grinding and polishing;
- Optical and electron microscopy;
- Gamma spectrometry;
- Fission gas sampling and analysis;
- Thermal imaging;
- SEM and microprobes;
- Microsphere gamma analysers for individual fuel particle analysis.

4.5.5. High-flux Advanced Neutron Application Reactor

The HANARO facility, at the Korea Atomic Energy Research Institute, houses hot cells in the reactor complex that can perform materials and fuels examinations. There are also facilities available to design and assemble all experiments inserted into HANARO reactor. PIE capabilities include the following:

- Gamma scanning dimension measurements;
- Mechanical testing (e.g. tensile, hardness and impact);
- Optical microscopy;
- Density measurements;
- SEM;
- Shielded EPMA;
- TEM;
- EDS;
- Thermal diffusivity;
- Fission gas diffusivity.

5. ACCESS TO RESEARCH REACTORS

Research reactor technology needs to match the requirements of the materials and fuels experiments. However, gaining access to an appropriate reactor can be difficult. While universities operate many of the smaller research reactors, larger ones are more often operated by government organizations which have established a primary mission for each reactor that may be incompatible with particular materials and fuels experiments, despite the technical compatibility. For example, HFIR might have experiment positions with the perfect characteristics for a particular material irradiation. However, the primary missions of this reactor are neutron scattering and radioisotope production, which requires consistent flux and reactor uptime. A particular experiment may involve a spectral filter to reduce the thermal flux on the sample, also reducing the HFIR operating cycle and possibly perturbing the beam tube fluxes. This may negatively affect the reactor’s primary mission, thus making the experiment impractical.

Other reactors, such as HFR, have the respective primary missions of neutron scattering and isotope production, which cannot be compromised and will always take priority.

Even if the technical capability and facility mission successfully match, another hurdle can be cost. Very few reactors perform materials and fuels experiments on a full cost recovery basis. Even if experiment fees are assessed in the form of labour and materials costs or neutron fees, there is almost always some subsidized component of the operation, be it maintenance, base infrastructure or eventual decommissioning and disposal. Costs vary widely among the research reactors, and while the technical compatibility between an experiment and a particular reactor might make the test feasible, the associated costs can make it impossible to perform the test. Materials and fuels experiments can be quite complex. There are no trivial cost estimations methods, and for most reactors there is no simple pricing guide to assist an experiment programme in determining the cost. The best path is good communication between the customer and the reactor operating organization. A very clear explanation of the proposed experiment is necessary, in combination with close collaboration.

Most proposals from another country will require a bilateral agreement between the facilities. However, some research reactors can only be accessed easily through membership in a consortium. For example, research at HBWR can be easily performed if proposed by a member of the Halden Reactor Project consortium, which comprises 19 sponsoring countries; it is harder for non-members (albeit still possible through a bilateral agreement). Other research reactors can be accessed at minimal cost through a scientific user facility. ATR may be accessed at little or no cost via the National Scientific User Facility peer reviewed proposal system or by bilateral agreement.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Utilization Related Design Features of Research Reactors: A Compendium, Technical Reports Series No. 455, IAEA, Vienna (2007).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Applications of Research Reactors, IAEA Nuclear Energy Series No. NP-T-5.3, IAEA, Vienna (2014).

[3] VON DER HARDT, P., RÖTTGER, H. (Eds.), Handbook of Materials Testing Reactors and Associated Hot Laboratories in the European Community, D. Reidel Publishing Company, London (1981).

[4] MANK, G., "Materials research: A challenge for fission, fusion and accelerator research", Characterization and Testing of Materials for Nuclear Reactors, IAEA-TECDOC-1545, IAEA, Vienna (2007) 135–139.

[5] WIESENACK, W., "Status and outlook for irradiation testing", Nuclear Power: A Sustainable Resource (Proc. Inter. Con. on the Physics of Reactors, PHYSOR'08, Interlaken, 2008), Paul Scherrer Institute, Villigen (2008) 78–88.

[6] ZINKLE, S.J., BUSBY, J.T., Structural materials for fission and fusion energy, Mater. Today **12** (2009) 12–19.

[7] VAN NIEUWENHOVE, R., "Development and testing of instruments for Generation-IV materials research at the Halden Reactor Project", In-pile Testing and Instrumentation for Development of Generation-IV Fuels and Materials (Proc. Tech. Mtg, Halden, 2012), IAEA-TECDOC-CD-1726, IAEA, Vienna (2013) 11–22.

Annex

CONTENTS OF CD-ROM

The CD-ROM accompanying this publication comprises 30 research reactor profiles, which provide technical descriptions and specific features for utilization. The profiles are an integral part of the publication (see Table 1, in Section 1). In addition, the CD-ROM contains Tables A–1 to A–5, which summarize the research reactors in this publication according to their readiness for materials and fuels testing research. Sections A–1 to A–5 provide a brief description of their content.

A–1. OPERATIONAL RESEARCH REACTORS: OVERVIEW OF CURRENT CAPABILITIES AND CAPACITIES FOR MATERIALS TESTING RESEARCH

Table A–1 provides information on current contributions of research reactors and associated facilities to major areas of R&D in advanced materials and fuels. In Table A–1, key parameters of 19 operating research reactors[1] are presented in alphabetical order by country. It provides a technical description of the research reactors, including their specific features for utilization. The capabilities of many of these research reactors are not only limited to materials testing reactors (MTRs). They are multipurpose research reactor facilities, and therefore some information on other research reactor applications is also included.

A–2. PLANNED RESEARCH REACTORS: OVERVIEW OF FUTURE CAPACITIES AND CAPACITIES FOR MATERIALS TESTING RESEARCH

This publication has been developed in support of innovation research activities, taking into account long term R&D needs in this area. Therefore, information on existing as well as future services for R&D on the development of innovative nuclear energy systems and technologies, which can be provided by planned research reactors and those under construction, is also included. A summary characterizing capabilities and capacities for future materials and fuels testing of four[2] planned, or already under construction, research reactors, is presented in Table A–2.

A–3. RESEARCH REACTORS WITH THE POTENTIAL FOR MATERIALS TESTING RESEARCH: OVERVIEW OF CAPABILITIES AND CAPACITIES

Currently, some research reactors are not utilized for materials testing research owing to their current operating status or scheduled utilization for other purposes. However, they are still capable of performing materials testing provided there is a need and resources to restore the MTR capabilities. A summary characterizing potential capabilities and capacities for materials and fuels testing of six research reactors[3] is presented in Table A–3.

A–4. PULSED RESEARCH REACTORS: OVERVIEW OF CURRENT CAPABILITIES AND CAPACITIES FOR MATERIALS TESTING RESEARCH

A summary characterizing capabilities and capacities for materials and fuels testing of four research reactors operating in a pulse mode is presented in Table A–4. As noted in Section 3.2.2, pulsed reactors have unique capabilities to support fuels testing by addressing very fast transient accident scenarios, in particular reactivity insertion accident tests. Inputs on some pulse research reactors were not provided in this publication. Taking into

[1] LVR-15 (Czech Republic) and OSIRIS (France) are not included in the profiles because the research reactors did not provide information.

[2] MYRRHA, in Belgium, is not included in the profiles because the research reactor did not provide information.

[3] WWR-K, in Kazakhstan, is not included in the profiles because the research reactor did not provide information.

account the importance of these research reactors for R&D, however, Table A–4 also contains data on the CABRI facility, in France, for completeness.[4]

A–5. LOW POWER RESEARCH REACTORS: SOME EXAMPLES OF ROLES COMPLEMENTARY TO MATERIALS TESTING RESEARCH

As noted in Section 3.4, low power research reactors (<5 MW) can provide certain support for high flux irradiation facilities in a number of related applications. Low power research reactors are not the main subject of this publication. However, due to their complementary role to MTR missions, information on four research reactors is presented in Table A–5 (see Profile No. 30).

[4] CABRI is not included in the profiles because the research reactor did not provide information.

ABBREVIATIONS

AES	Auger electron spectroscopy
dpa	displacement per atom
EDS	energy dispersive X ray spectroscopy
EPMA	electron probe microanalysis
GIF	Generation IV International Forum
ICERR scheme	IAEA-designated International Centre based on Research Reactor scheme
INL	Idaho National Laboratory
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
LWR	light water reactor
MTR	materials testing reactor
NES	nuclear energy system
PIE	post-irradiation examination
RIA	reactivity insertion accident
SEM	scanning electron microscopy
SIMS	secondary ion mass spectrometry
TEM	transmission electron microscopy

CONTRIBUTORS TO DRAFTING AND REVIEW

Arkhangelskiy, N.	State Atomic Energy Corporation “Rosatom”, Russian Federation
Barbos, D.	Institute for Nuclear Research, Romania
Belgya, T.	Centre for Energy Research, Hungarian Academy of Sciences, Hungary
Bignan, G.	CEA Cadarache, French Alternative Energies and Atomic Energy Commission, France
Borio di Tigliole, A.	International Atomic Energy Agency
Bradley, E.	International Atomic Energy Agency
Bryan, C.	Oak Ridge National Laboratory, United States of America
Carta, M.	ENEA Casaccia Research Centre, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Italy
Cho Man Soon	Korea Atomic Energy Research Institute, Republic of Korea
Ciocanescu, M.	Institute for Nuclear Research, Romania
De Haas, G.-J.	Nuclear Research and Consultancy Group, Netherlands
Gougar, H.	Idaho National Laboratory, United States of America
Inozemtsev, V.	International Atomic Energy Agency
Izhutov, A.L.	Research Institute of Atomic Reactors, Russian Federation
Juricek, V.	Nuclear Research Institute Řež, Czech Republic
Khoroshev, M.	International Atomic Energy Agency
Kim Hyung Kyu	Korea Atomic Energy Research Institute, Republic of Korea
Liu Xingman	China Institute of Atomic Energy, China
Mammen, Sh.	Bhabha Atomic Research Centre, India
Marshall, F.	Idaho National Laboratory, United States of America
Ridikas, D.	International Atomic Energy Agency
Shikama, T.	Tohoku University, Japan
Wiesenack, W.	Institute for Energy Technology, Norway
Yang Yong	China Institute of Atomic Energy, China

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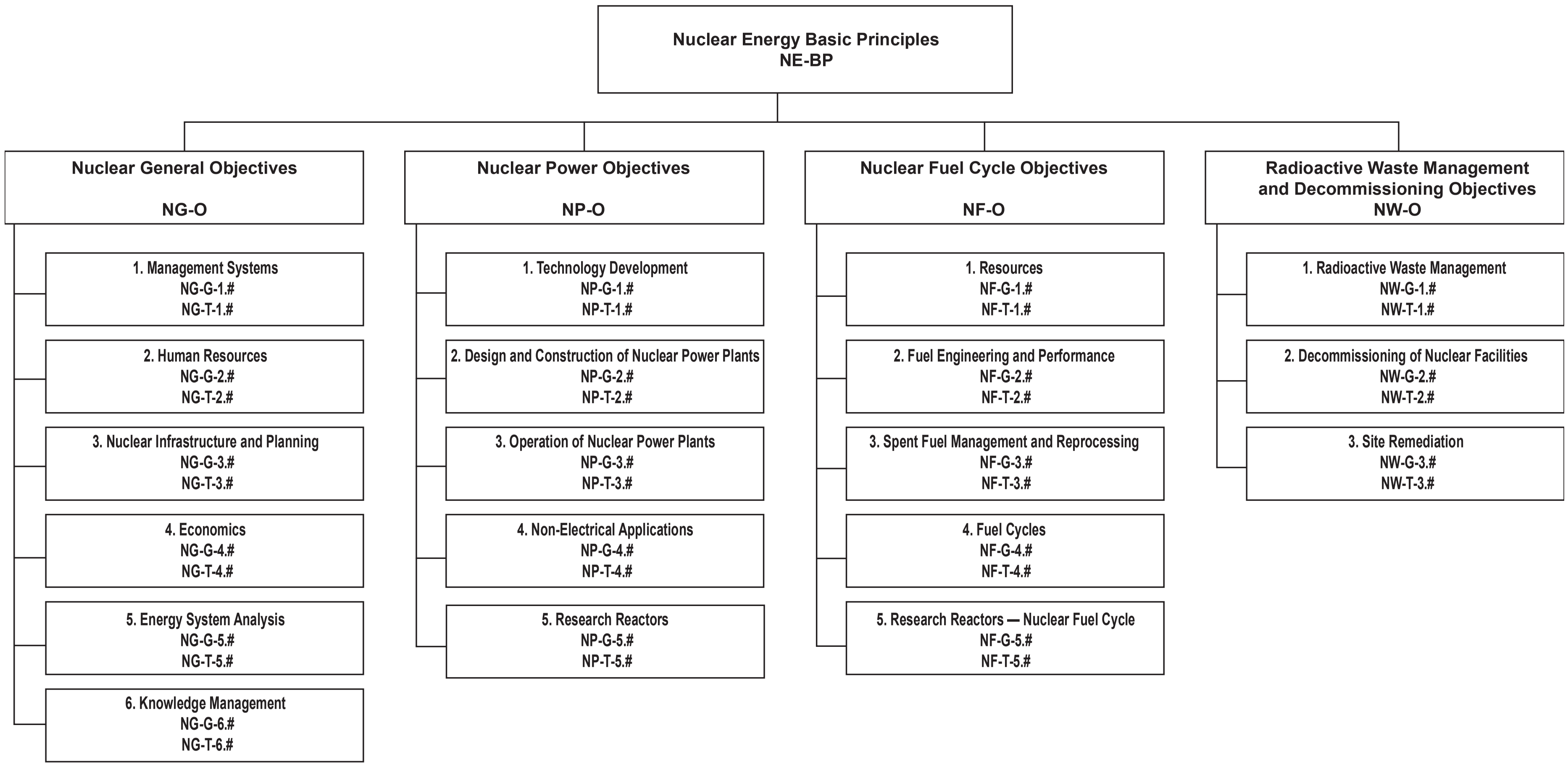

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ISBN 978–92–0–100816-9
ISSN 1995–7807