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Towards Optimized Use of Research Reactors in Europe
Project Number: 945 269

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Recommendations for planning refurbishment of existing research reactors or construction of new ones

Lead Beneficiary: CIEMAT

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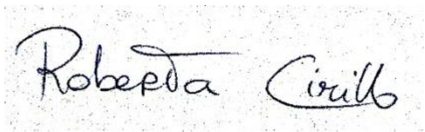
Vicente Bécares 	**Roberta CIRILLO** 	**G. Pavel** 

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EXECUTIVE SUMMARY

Nuclear research reactors are a type of scientific infrastructure with applications in many fields of science and technology. These applications include not only supporting the development of nuclear power programs, but also applications unrelated to nuclear energy, mainly neutron research for material science and the production of radioisotopes for nuclear medicine. Currently, there is a shortage of capacity to cover the demand for these applications (especially in neutron scattering) and the demand is expected to increase in the future (especially in medical isotope production).

Europe has traditionally enjoyed a varied research reactor fleet that has made Europe a world leader in most of these fields. However, this reactor fleet is aging and a strategy for the long-term maintenance and/or replacement of the facilities is necessary. On the other hand, new alternative technologies to research reactors are being pursued, and their possibilities should also be taken into account in this strategy. These new technologies include spallation and other accelerator-based sources.

Overall, the tendency in Europe in the last years has been the closure of many small and medium power research reactors and the concentration of the capacity in a few large facilities: HFR-ILL and FRM-II for neutron beam research, and HFR-Petten and BR2 for nuclear material testing and medical isotope production. While FRM-II is relatively new and its replacement is not considered yet, the other three facilities have planned successors in different stages of development (the ESS spallation source for the HFR-ILL, the PALLAS reactor for HFR-Petten and the MYRRHA facility for the BR2) and are expected to be kept in operation until these successors enter in operation. Furthermore, another large research reactor, the JHR, is being built and will allow restoring the capabilities (material testing and medical isotope production) lost by the recent closure of the OSIRIS reactor.

Although all these facilities have a very high performance and will be the most capable, or among the most capable, of the world in their respective fields of application, the complexity of their designs has resulted in major delays and/or cost overruns that are causing, or have the risk to cause, capacity gaps and have forced to extend the lives of existing research reactors. Furthermore, the concentration of the capacity in a reduced number of facilities also has adverse effects, the most relevant one being the risk of major capacity losses because of a single failure. This is particularly critical in the case of the production of short-lived medical isotopes.

Therefore, medium-size reactor facilities play an important role in complementing larger facilities. The number of these medium facilities in Europe has dwindled after several closures in recent years: Orphée, BER-II, and JEEP-II. The remaining facilities in this category in Europe are BRR, MARIA, LVR-15, and the TRIGA reactor at Pitesti. No new-build project in this category is currently envisaged in Europe. Hence, the future European research reactor strategy should include maintaining at least some of such facilities (either as a major refurbishment or as a new build). The number of medium-size reactor facilities to be considered in this strategy will be determined by the success in the development of alternative technologies, namely Compact Accelerator Neutron Sources (CANS) and accelerator-based isotope production.

Furthermore, low and zero-power reactor facilities also play an important role in particular in the field of nuclear education and training. Also, despite some recent closures, Europe still has a relevant number of such facilities, but unlike the larger facilities mentioned above, underuse is a concern. Hence, the priority here should be developing a strategy to make full use of the existing facility network, rather than considering building new facilities. Finally, another important application of these zero-power facilities is the production of integral data for the validation of computer codes and nuclear data libraries, which is of vital importance for the development of the advanced nuclear systems (SMR, Generation IV, ADS) being pursued in an increasing number of EU countries. Only two facilities in this category remain in operation in Europe (LR-0 and VENUS). Hence, maintaining these facilities or building a new one is also recommended to be included in a comprehensive European research reactor strategy.

CONTENT

LIST OF ACRONYMS

ACPR	Annular Core Pulsed Reactor
ADS	Accelerator Driven System
AKR	*Ausbildungskernreaktor* – Teaching Nuclear Reactor
ANL	Argonne National Laboratory (USA)
ATF	Accident Tolerant Fuel
ATR	Advanced Test Reactor
BER-II	*Berliner Experimentier-Reaktor* (Berlin Experimental Reactor)
BME	Budapest University of Technology and Economics
BNC	Budapest Neutron Centre
BOR	*Bystryi Opytnyi Reaktor* – Fast Experimental Reactor
BR	Belgian Reactor
BRR	Budapest Research Reactor
BWR	Boiling Water Reactor
c.a.	carrier-added
CANDU	CANada Deuterium Uranium (Canadian-designed pressurized heavy-water reactor)
CANS	Compact Accelerator-based Neutron Sources
CARR	China Advanced Research Reactor
CEA	*Commissariat à l'énergie atomique et aux énergies alternatives* – Nuclear and Alternative Energies Commission (France)
CEFR	China Experimental Fast Reactor
CERN	*Conseil Européen pour la Recherche Nucléaire* - European Organization for Nuclear Research
CIEMAT	*Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas* - Energy, Environment and Technology Research Certer (Spain)
CMRR	China Mianyang Research Reactor
CSNS	China Spallation Neutron Source
CTU	Czech Technical University
CVR	*Centrum Výzkumu Řež* – Research Centre Řež (Czech Rep.)
DOE	Department Of Energy (USA)
DT	Deuterium-tritium
EC	European Commission
ENEA	*Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile* – National Agency for New Technologies, Energy and Sustainable Economic Development (Italy)
ENEEP	European Nuclear Experimental Educational Platform
ENSA	European Neutron Scattering Association

EPFL	*École Polytechnique Fédérale de Lausanne* – Swiss Federal Institute of Technology in Lausanne
ESFRI	European Strategy Forum on Research Infrastructures
ESNII	European Sustainable Nuclear Industrial Initiative
ESS	European Spallation Source
E&T	Education and Training
ETRR	Experimental Training Research Reactor
FBTR	Fast Breeder Test Reactor
FDA	Food and Drug Administration (USA)
FRM	*Forschungsreaktor München* – Research Reactor Munich
HALEU	High-Assay Low Enriched Uranium
HANARO	High-Flux Advanced Neutron Application Reactor
HBS	High Brilliance neutron Source
HEU	Highly Enriched Uranium
HFIR	High Flux Isotope Reactor
HFR	High Flux Reactor
HLW	High-Level Radioactive Waste
HOR	*Hoger Onderwijs Reactor* (High Education Reactor)
HS	*Hochschule* – High school
IBR	*Impulsnyi Bystryi Reaktor* – Pulsed Fast Reactor
IFE	Institute for Energy Technology (Norway)
ILL	Institut Laue-Langevin
INL	Idaho National Laboratory (USA)
ITN	*Instituto Technologico e Nuclear* – Technological and Nuclear Institute (Portugal)
JAEA	Japan Atomic Energy Agency
JGU	*Johannes Gutenberg-Universität* – Johannes Gutenberg University
JHR	Jules Horowitz Reactor
JMTR	Japan Materials Testing Reactor
J-PARC	Japan Proton Accelerator Research Complex
JRR	Japan Research Reactor
JSI	Jožef Stefan Institute (Slovenia)
KINR	Kiev Institute for Nuclear Research (Ukraine)
KIPT	Kharkov Institute of Physics and Technology (Ukraine)
KJRR	Ki-Jang Research Reactor
LANL	Los Alamos National Laboratory (USA)
LANSCE	Los Alamos Neutron Science Center (USA)

LBE	Lead-Bismuth Eutectic
LENS	League of advanced European Neutron Sources
LET	Linear Energy Transfer
LEU	Low enriched Uranium
LINAC	LINear ACcelerator
LLB	Laboratoire Léon Brillouin (France)
LWR	Light Water Reactor
MBIR	*Mnogotselevoi Bystryi Issledovatelskii Reaktor* – Multipurpose Fast Research Reactor
MTR	Materials Test Reactor
MURR	Missouri University Research Reactor
MYRRHA	Multi-purpose hYbrid Research Reactor for High-tech Applications
n.c.a.	no-carrier-added
NCBJ	*Narodowe Centrum Badań Jądrowych* – National Centre for Nuclear Research (Poland)
NCERC	National Criticality Experiments Research Center (USA)
NEA	Nuclear energy Agency (OECD)
NET	Neuroendocrine tumours
NIDC	National Isotope Development Center (USA)
NIST	National Institute of Standards and Technology (USA)
NNSA	National Nuclear Security Administration (USA)
NPP	Nuclear Power Plant
NRG	Nuclear Research and Consultancy Group (The Netherlands)
NRIC	National Reactor Innovation Center (USA)
NRU	National Research Universal (a Canadian Research Reactor)
OFFERR	European platform for accessing nuclear R&D facilities
O&M	Operation and Maintenance
OPAL	Open Pool Australian Light water reactor
ORNL	Oak Ridge National Laboratory (USA)
PET	Positron Emission Tomography
PRISMAP	Production of high purity isotopes by mass separation
PSI	Paul Scherrer Institut (Switzerland)
PSMA	Prostate Specific Membrane Antigen
PWR	Pressurized Water Reactor
RA	*Reactor Argentino* – Argentinian Reactor
RATEN	*Regia Autonomă Tehnologii pentru Energia Nucleară* – Technologies for Nuclear Energy State Owned Company (Romania)

RBMK	*Reaktor Bolshoi Moshchnostyi Kanalnyi* – High-Power Channel-type Reactor (Soviet reactor design)
RIAR	Research Institute of Atomic Reactors (Russia)
RMB	*Reator Multipropósito Brasileiro* – Brazilian Multipurpose Reactor
RR	Research Reactor
RSG-GAS	*Reaktor Serba Guna–Gerrit Augustinus Siwabessy* – Multipurpose reactor Gerrit Augustinus Siwabessy
RSV	Radiosynovectomy
SCK CEN	*Studiecentrum voor Kernenergie – Centre d'Étude de l'énergie Nucléaire* – Belgian Nuclear Research Centre
SFR	Sodium-cooled Fast Reactor
SINQ	*Schweizerische Spallations-Neutronenquelle* – Swiss Spallation Neutron Source
SMR	Small Modular Reactor
SNS	Spallation Neutron Source
SNUNEI	Sevastopol National University of Nuclear Energy and Industry (Ukraine)
SUR	*Siemens Unterrichtsreaktor* – Siemens Educational Reactor
TH	*Technische Hochschule* – Technical high school
TOF	(Neutron) Time-Of-Flight
TRIGA	Training, Research, Isotopes, General Atomics
TRT	Targeted Radionuclide Therapy
TU	Technical University
UREX	Uranium EXtraction
VTR	Versatile Test Reactor
VTT	*Valtion Teknillinen Tutkimuskeskus* – Technical Research Centre of Finland
VVER	*Vodo-Vodyanoi Enyergeticheskyi Reaktor* – Water-Water Energetic Reactor (Soviet/Russian-designed pressurized water reactor)
ZEPHYR	Zero power Experimental PHYsics Reactor
ZPR	Zero Power Reactor

1 INTRODUCTION

The purpose of this document is fulfilling the requirements of task 3.3 “Refurbishment and construction support” of the TOURR project. As written in TOURR project grant agreement:

> *“The main purpose of this task is to support the planning of refurbishment of existing research reactors or construction of new ones. Assessment to what extent existing and new reactors will fulfil the future needs and identification of crucial time gaps in the transfer between existing and future reactors and neutron sources will be performed. The projected characteristics of new installations and the capability of current installations (both qualitatively as well as quantitatively) must be compared to the projected demand in the timeframe of remaining lifetime of current installations and projected availability of new installations. The task will include initial inventory of the actual situation in this field in Europe, invitation of the most developed projects to join TOURR network (PALLAS representative has already been involved in the preparatory phase as nominated Advisory Group member), comparison of the planned capacities to the needs identified in task 3.1 (also providing this information to the bodies involved in planning and implementation of the construction and refurbishment projects). It will also include identification of potential refurbishment/construction including barriers/obstacles and provide recommendations how to tackle them. CIEMAT will draft the recommendations with contributions from all RR operators”.*

Following the three major axes defined in TOURR D3.1, this report has been structured into three major chapters, each one assessing the current and foreseen situation in one of the major fields of application of research reactors, namely:

(a) *Science and technology*. This chapter has been subdivided in turn into neutron beam facilities and facilities for supporting nuclear power reactor programs.

(b) *Medical applications (isotope production)*. This chapter has been subdivided in turn in sections analysing the production of ^{99}Mo, β-emitters and α-emitters.

(c) *Education and training*. This chapter includes zero and low-power reactors used for training, but which also have other applications, albeit less demanding than the ones covered in the other chapters.

Finally, in section 5 a summary of the major findings of this analysis as well as the recommendations on the strategy for maintaining a comprehensive and adequate research reactor fleet in Europe into the 2030s and beyond are presented.

2 SCIENCE AND TECHNOLOGY

The many scientific and technical applications of research reactors (or, more generally, neutrons) have been extensively reviewed in TOURR D3.1 and elsewhere [IAEA 2001]. For the purposes of this report, it is useful to classify these applications into two broad groups. On the one hand, there are some neutron applications (e.g. geochronology, neutron activation, neutron radiography, radiation hardness assurance (RHA) of electronics) that require relatively low neutron fluxes and/or irradiation volumes. Therefore, they can be carried out in many types of facilities, including low-flux research reactors (treated in section 4), as a secondary application in higher-flux reactors, or even in smaller facilities, such as neutron generators. Hence, they do not require specialized reactor facilities and we will not discuss them in this section. On the other hand, other neutron applications are much more demanding in terms of neutron flux or have other requirements that result in the need of specialized research reactor facilities. More specifically, these specialized research reactors can be further classified into two broad categories:

1. Neutron beam facilities for neutron scattering techniques.
2. Facilities for supporting nuclear power reactor programs.

In this section, we will treat these two types of research reactor facilities separately.

2.1 Neutron beam facilities

As described in TOURR D3.1 one of the most relevant scientific applications of neutrons is determining the structure and composition of materials. Several neutron techniques are used for these purposes, among them, as stated above, neutron scattering techniques are the more demanding in terms of neutron flux intensity and hence they can only be performed in a reduced number of reactors, often built specifically for this purpose. In these reactors, neutrons are extracted from the reactor core through a number of neutron guides (neutron beam lines) and transported to instruments (diffractometers, spectrometers, reflectometers, interferometers) placed outside the reactor where the samples are analysed, hence the name of “neutron beam facilities” (Figure 1).

It must be remarked that in the last decades, there has been a shift towards spallation and other accelerator-based neutron sources as they offer some advantages for scattering purposes. The main advantage of accelerator-driven sources for neutron scattering is that they can operate in pulsed mode, which allows the efficient application of time-of-flight (TOF) techniques. In addition they are usually easier to license and do not produce high-level radioactive waste (irradiated fuel). Economically, however, there is not a clear advantage of spallation sources over nuclear reactors in operation and maintenance (O&M) costs (see Table 1 and Table 2) and research reactors are still widely used as neutron sources for scattering, imaging and composition analysis experiments, including several recently built ones (FRM-II in Germany, OPAL in Australia, PIK in Russia, CARR and CMRR in China).

It is worth remarking that Europe has been traditionally a leader in this field. Several related organizations already exist at the European level, such as the European Neutron Scattering Association (ENSA), which represents neutron users, and the League of advanced European Neutron Sources (LENS), formed by all major neutron competence centres. European capacities and needs in this field have been extensively assessed in several recent reports [ESFRI 2016, BrightnESS 2018, Velichko 2020, LENS 2022], and hence in this section, we will limit to stress the most relevant facts for the TOURR project. In any case, it is important to note that since these neutron-based research activities are not directly related to nuclear energy, funding the research in this field does not have to be necessarily covered by Euratom.

Figure 1. Reactor hall of Budapest Research reactor (BRR) with several neutron beam lines (Image courtesy of Budapest Neutron Center).

Reactors for neutron beam applications extend over a wide range of neutron fluxes. A possible classification is:

1. High-flux reactors, reaching fluxes up to ~1×10^{15} n/cm^2/s. They are highly optimized, high power (up to 100 MW_{th}) facilities, typically using highly enriched uranium (HEU) fuel and operating a large number of instruments (up to ~40). These facilities are very expensive to build and operate (~100 M€/year) and only major economic powers (Europe, USA, China, Russia, and Japan) can afford them. European and worldwide facilities in this category are listed in Table 1 and Table 4, respectively.
2. Medium flux reactors, with fluxes in the ~10^{14} n/cm^2/s range and power in the 10-100 MW_{th} range. They can be dedicated scattering facilities with a large number of instruments or multi-role reactors, usually with a reduced number of scattering instruments. They usually use low enriched uranium (LEU), material testing reactor (MTR) fuel. European and worldwide facilities in this category are listed in Table 2 and Table 5, respectively.
3. Low flux reactors, with fluxes about ~10^{13} n/cm^2/s range. These fluxes are in the lower allowable limit for neutron scattering and are close to the reactors described in the education and training (E&T) category, see section 4.

As it can be seen in the tables, the most prominent neutron scattering facility in the EU is the High Flux Reactor (HFR) at the Institut Laue-Langevin (ILL) in Grenoble (France)[1]. This reactor reached its first criticality in 1971 as a joint French-German project, later joined by the UK [Jacrot 2018]. Another 11 European countries have the status of "Scientific Members" of ILL. On 15th September 2021, the agreement between France, Germany, and the UK to operate the HFR-ILL was extended

[1] Not to be confused with the HFR in Petten (The Netherlands).

until 2033 [ILL 2021]. The EC has been supporting HFR-ILL upgrades through the ILL20/20 and FILL2030 projects.

This facility will be complemented or replaced by the European Spallation Source (ESS) being built in Lund (Sweden) [Peggs 2013, Garoby 2018, Andersen 2020]. This flagship facility should be able to attain peak neutron fluxes about ten times more intense than HFR-ILL. At the moment of this writing, the latest ESS schedule is achieving the first beam on target by mid-2025, starting the user program in 2026, and starting the sustained operation in 2028 [ESS 2023]. However, the initial instrument suite [Andersen 2020] will be limited to 15 instruments, with another 7 included in the ESS construction budget. Hence, an important reduction in the number of instrument-days in Europe will occur if HFR-ILL is shut down before ESS is fully operational. Furthermore, the other two major spallation sources in currently in operation in the world, namely the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory (ORNL) in the USA and the spallation source at J-PARC in Japan, have required several years and design changes to reliably operate at the intended power levels [Takada 2020, Winder 2021]. Hence, in order not to suffer a major loss of neutron scattering capacity, it is critical that the HFR-ILL is operated at least until the ESS becomes fully operational [Nature 2017].

The second major neutron scattering facility in the EU is the FRM-II (*Forschungsreaktor München II*, or Munich Research Reactor II) in Garching near Munich (Germany), also known as MLZ (*Forschungs-Neutronenquelle Heinz Maier-Leibnitz* or Research Neutron Source Heinz Maier-Leibnitz). It reached its first criticality in 2004. Since 2019 it has operated only one cycle because of a chain of problems: legal issues with the transport of fresh fuel, excessive C-14 emissions, issues with the cold neutron source, and a leakage in a major element (central channel), which had to be replaced. As of May 2023, the reactor was expected to resume operations by 2024 [FRM 2019, FRM 2020a, FRM 2021, FRM 2022a].

A major threat for both HFR-ILL and FRM-II is the availability of fuel. Both HFR-ILL and FRM-II run on HEU (93% enrichment). Since Europe does not produce HEU, HEU for research reactor fuel has been sourced from the USA, which is increasingly reluctant to export HEU. It is important to remark here that conversion from HEU to LEU without loss of performance is particularly challenging in reactors used for neutron beam applications since they require the highest possible fluxes. The supply of fuel for the European research reactor fleet is an issue that affect all research reactor applications and is treated in Annex 1.

A third large neutron scattering facility in Europe (but not in the EU) is the ISIS spallation neutron source in the UK, which was the most intense pulsed neutron source in the world until the Spallation Neutron Source (SNS) at ORNL entered into service. These large facilities are complemented by a number of less intense neutron sources. In decreasing order of performance, are the SINQ neutron source at the PSI (Switzerland), also based on a spallation source but in this case continuous mode; the Budapest Research Reactor (BRR) of the Budapest Neutron Centre (BNC) and the HOR reactor of the University of Delft. These are all dedicated neutron research facilities. Finally, the MARIA, LVR-15 and TRIGA-Pitesti multi-purpose research reactors also offer some scattering instruments. MARIA is currently increasing its capability in this field using instruments from the decommissioned BER-II reactor. One last research reactor facility in Europe capable of providing neutron beams is the 10-MW_{th} WWR-M multipurpose research reactor of the Kiev Institute for Nuclear Research (KINR) [Diakov 2019].

It is important to note, as it can be observed in Table 1 and Table 2, that the share of local users in most facilities is very large, so these “medium range” facilities play an important role in developing a local neutron scientist community, even if they have a smaller number of users overall. However, the number of these “medium range” scattering facilities has been largely reduced by the closure of three facilities in 2019: the Orphée reactor at the CEA/CNRS Laboratoire Léon Brillouin (LLB) in Saclay (France), the BER-II reactor at the Helmholtz-Zentrum Berlin (HZB) (Germany) and the smaller JEEP-II reactor at IFE in Kjeller (Norway). In the case of the BRR, the current plan is to operate it until 2027-2030, until the fresh fuel stocks are used up and replace it with a high-intensity compact accelerator-driven neutron source [BNC 2019, Mezei 2021].

An alternative to solve the problem posed by the abovementioned closures are the Compact Accelerator-based Neutron Sources (CANS) [Anderson 2016, Carpenter 2020, LENS 2020, UCANS 2023]. These facilities are centred on low energy (up to a few tens of MeV), high intensity (up to 100 mA) proton (or deuteron) accelerators, based on the first stages of higher energy accelerators, such as that of the ESS. In addition to the above-mentioned facility in Hungary, at least four other facilities are currently being pursued in Europe: LvB in Martonvásár (Hungary), the High Brilliance neutron Source (HBS) in Jülich (Germany), SONATE in Saclay (France) and ARGITU in Bilbao (Spain). Reportedly, these facilities could be able to offer performance similar to those of medium-flux reactors for many beamline instruments, but none of these facilities has surpassed the early design stage and their construction has not been approved yet. The main figures for these facilities are summarized in Table 3. The accelerator-driven neutron sources, however, cannot replace the reactor-based neutron sources in all aspects. The inherently lower neutron fluence makes them unable to perform activation, material aging or large-scale medical radioisotope production. Furthermore, it may be worth remarking that lab-scale D-T neutron generators with yields of 10^{13} n/s (in 4π) are commercially available nowadays. This is sufficient flux for some applications, as well as for training purposes.

A brief survey of the World's situation outside Europe follows:

- The major US neutron facilities are located at the Oak Ridge National Laboratory (ORNL) and are the High Flux Isotope Reactor (HFIR) and Spallation Neutron Source (SNS). Plans to power up the SNS to 2.8 MW and to build a second target station are underway. As of 2011, the joint operating budget of both facilities was about 250 M$/year [Rush 2011]. The NIST (National Institute of Standards and Technology) Center for Neutron Research also has a 20 MW_{th} research reactor dedicated to neutron experiments. Its annual budget by 2017 was 50 M$ [NAS 2018b]. This reactor has been shut down since February 2021 because of an improperly loaded fuel element that suffered damage. Restart authorization by NRC was granted in March 2023 [NIST 2023]. Other smaller neutron scattering facilities in the USA are the 10 MW_{th} MURR reactor with 4 instruments and the Lujan Neutron Scattering Center at Los Alamos Neutron Science Center (LANSCE), based on an 800 MeV spallation source, with another 4 instruments.
- Although primarily used for medical isotope production, the NRU reactor in Canada also had some neutron scattering instruments. This reactor is remarkable because it played a major role in the early development of neutron scattering techniques. After the closure of this facility in 2018, the McMaster University reactor is now the sole remaining neutron scattering facility in Canada, with only 2 instruments.
- Russia has two major neutron facilities, the IBR-2 pulsed reactor at the Joint Institute for Nuclear Research (JINR) in Dubna and the PIK reactor at the St. Petersburg Nuclear Physics Institute (PNPI) in Gatchina. The IBR-2 is a rather unique facility, being a PuO_2-fuelled, pulsed fast reactor. It was commissioned in 1984 and extensively modernized in 2007-2010 in order to remain in service for at least 20-25 years. The project of the PIK reactor, for its part, started in the 1960s, but construction was stopped after the Chornobyl accident in 1986. Work was resumed in 1999 and the first criticality was achieved in 2011. Nevertheless, ramping up has been slow and as of March 2022, the reactor was operating at 7 MW with 5 instruments in operation. When the PIK reactor reaches full capability, it will offer the largest number of neutron instruments (50) in the World. Another smaller facility, the WWR-M reactor, is also in operation at PNPI. The IVV-2M reactor of the Institute of Reactor Materials in Beloyarsk, which is primarily used for nuclear material research, is also fitted with neutron scattering facilities.
- China is rapidly developing neutron research capabilities, with three large neutron facilities having been put in service in the last ~10 years: the China Spallation Neutron Source (CSNS),

the China Advanced Research Reactor (CARR) and the smaller China Mianyang Research Reactor (CMRR). The development of Chinese facilities has also been plagued by delays. Concerning CSNS, the project was started in 2005 and it was originally expected to be commissioned in 2009, but the first beam was achieved in September 2017, 100 kW operation was reached in March 2020 and the first instrument was not completed until 2021. The construction of CARR, for its part, started in 2002 and the reactor reached its first criticality in 2010, but development has been slow thereafter [WNN 2018, NEI 2023b].

- Japan has two major neutron centres: a spallation source in the J-PARC complex and the JRR-3 reactor, both in Tokai. The JRR-3 was built in 1962 and extensively refurbished by 1990. It has been out of operation since 2010, however, because of the need to adapt it to the new regulations after the Fukushima nuclear accident, but resumed operation in February 2021. A 10 MW_{th} research reactor is in the planning stage at the Monju site, largely to replace the 5 MW_{th} Kyoto University Research Reactor, which also offers some neutron scattering capacities [Takehara 2023, JAEA 2023b].

Other research reactors around the world offer some neutron instruments, but these are multi-role facilities, not specialized in operating neutron beamline facilities. Most of them are located in the Asia-Pacific area: the OPAL reactor in Australia, the HANARO reactor in South Korea, the Dhruva reactor in India and the RSG-GAS reactor in Indonesia. The ETRR-2 reactor in Egypt is also reported to provide some scattering facilities. Finally, the RA-10 reactor being built in Argentina is also planned to include scattering facilities, initially with eight instruments. The HANARO reactor was shut down between 2014 and 2017 to improve earthquake resistance [Kim 2021].

Table 1. Top-class neutron sources in Europe. Sources: [BrightnESS 2018], [ESFRI 2016] for operating costs, [Peggs 2013] for ESS.

	Power (MW_{th})	**Max. therm. flux ($n/cm^2/s$)**	**No. of neutron instr.**	**Op. cost (M€/year)**	**Users / year**	**% of national PIs**
ESS	5 (spallation)	4×10^{16} (peak)	15 (initial) Up to 44	140[2]	N/A	N/A
HFR-ILL	58.3	1.5×10^{15}	~40	107.76[3]	1433	66%
ISIS	0.2 (spallation)	4.5×10^{15} (peak)	~30	62	1580	62%
FRM-II	20	8×10^{14}	26 (+6 being built)[4]	55	965	73%

[2] Source: [ESFRI 2021]
[3] Source: [ILL 2022]
[4] Source: [FRM 2020b]

Table 2. Other significant medium-class neutron sources in Europe. Recently shutdown facilities are shaded in gray. Sources: [BrightnESS 2018], [ESFRI 2016] for operating costs, [Barbos 2016] for TRIGA-Pitesti, [Diakov 2019] for KINR WWR-M.

	Institution	Power (MW_{th})	Max. therm. flux ($n/cm^2/s$)	No. of neutron instr.	Op. cost (M€/year)	Users / year	% of national PIs
SINQ	PSI (Switzerland)	1 (spallation)	4×10^{14}	~20	30	477	33%
Orphée†	LLB (France)	14	3×10^{14}	~20	30	637	66%
BRR	BNC (Hungary)	10	2.2×10^{14}	16	5	145	8%
BER-II†	HZB (Germany)	10	2×10^{14}	~15	22	302	61%
HOR	TU Delft (Netherlands)	2.3	4.6×10^{13}	9	4.7	N/A	N/A
WWR-M	KINR (Ukraine)	10	2×10^{14}	9[5]	N/A	N/A	N/A
LVR-15	CVR (Czech Rep.)	10	1×10^{14}	8	---	54	67%
MARIA	NCBJ (Poland)	30	1×10^{14}	6	---	13	77%
JEEP-II†	IFE (Norway)	2	3×10^{13}	5	7.5	43	52%
TRIGA-Pitesti	RATEN (Romania)	14	2.5×10^{14}	2	N/A	N/A	N/A

Table 3. Proposed CANS and HiCANS facilities in Europe.

	Accelerator parameters	Instruments	Cost	Sources
ESS (Lund, Sweden)	1.5 GeV protons W target (1) 5 MW av. power	15 initially 22 on constr. budget Up to ~40	3009 M€ build. cost 140 M€/yr op. cost	[Peggs 2013] [Andersen 2020] [ESFRI 2021]
HBS (Jülich, Germany)	70 MeV protons W or Ta targets (3) 420 kW av. power	Up to 15-20	370 M€ build. cost	[Brückel 2020] [Gutberlet 2020]
SONATE (Saclay, France)	20 MeV protons Be targets (2) 80 kW av. power	~10	~50 M€ build. cost ~4 M€/yr op. cost	[Ott 2018] [Ott 2019]
ARGITU (Bilbao, Spain)	30 MeV protons Be target 45 kW av. power	~7 (initially)	N/A	[Pérez 2020]
LvB (Martonvásár, Hungary)	2.5 MeV protons, 20 mA peak, solid Li target	up to ~7 (initially 3)	~8 M€ build. cost	F. Mezei personal communication

[5] Number of horizontal experimental channels.

Table 4. Major neutron centres outside Europe. Source: IAEA Reseach Reactor database [IAEA 2023] in addition to the ones listed in the table.

	Start. Op.	Power (MW_{th})	Max. therm. Flux ($n/cm^2/s$)	No. of neutron instr.	Sources
HFIR (Oak Ridge, USA)	1965 (modernized 2007)	85	2.5×10^{15}	~15	[ORNL 2023]
SNS (Oak Ridge, USA)	2006	1.55 (2023) Up to 2.8 (spallation)	N/A	~20 2nd target planned	[ORNL 2023] [Boisvert 2023]
IBR-2 (Dubna, Russia)	1984 (modernized 2010)	2	1×10^{16} (peak)	~15	[JINR 2020]
PIK (Gatchina, Russia)	2011	100	5×10^{15}	5 in Dec. 2020 Up to 50	[Kovalchuk 2021] [Kovalchuk 2022]
CARR (Beijing, China)	2010	60	8×10^{14}	11 (+6 being built)	[Yu 2020]
CSNS (Dongguan, China)	2018	0.1 (spallation)	N/A	~20 (planned)	[Wei 2009] [Chen 2016] [IHEP-CAS 2023]
J-PARC (Tokai, Japan)	2008	Up to 1 (spallation)	N/A	~20	[J-PARC 2023]

Table 5. Other notable neutron facilities in the World. Facilities currently non-operating are shaded in gray. Source: IAEA Reseach Reactor database [IAEA 2023] in addition to the ones listed in the table.

	Start. Op.	Power (MW_{th})	Φ_{th} max. ($n/cm^2/s$)	No. of neutron instr.	Sources
NIST (Gaithersburg, USA)	1967	20	4×10^{14}	~25	[Rush 2011] [NAS 2018b]
LANSCE (Los Alamos, USA)	1972	0.08-0.1 (spallation)	N/A	4	[Garnett 2018] [LANSCE 2023]
MURR (U. of Missouri, USA)	1966	10	6×10^{14}	5	[MURR 2023]
NRU† (Chalk River, Canada)	1957 (shutdown 2018)	135	4×10^{14}	6	[Banks 2018] [Holden 2021]
Mc. Master RR (Hamilton, Canada)	1959	3	1×10^{14}	2	[McMaster 2023]
WWR-M (Gatchina, Russia)	1959	18	4×10^{14}	~15	[PNPI 2023]
IVV-2M (Beloyarsk, Russia)	1966 (mod. 1976)	15	5×10^{14}	?	[Russkikh 2017]
CMRR (Mianyang, China)	2013	20	2.4×10^{14}	8 (+3 being build)	[Sun 2016]
JRR-3 (Tokai, Japan)	1962 (mod. 1990)	20	2.7×10^{14}	31	[Tsumura 2021] [JAEA 2023a]
HANARO (Daejeon, S. Korea)	1995	30	4.5×10^{14}	12	[Park 2013] [Choo 2014]
Dhruva (Mumbay, India)	1985	100	1.8×10^{14}	8	[Dasannacharya 2021]
RSG-GAS (Serpong, Indonesia)	1987	30	2.52×10^{14}	8	[Fajar 2007] [BRIN 2022]
OPAL (Sidney, Australia)	2006	20	2×10^{14}	Up to 18	[Kennedy 2006] [Kim 2006]
ETRR-2 (El Cairo, Egypt)	1997	22	2.8×10^{14}	5	[Fayek 2000]
RA-10 (Ezeiza, Argentina)	2025 (planned)	30	$\sim 4 \times 10^{14}$	8 (initially)	[Santisteban 2019]

2.2 Facilities for supporting nuclear power reactor programs

Despite the improvement of data (nuclear, material, thermal-hydraulic…) and computing capabilities, the development of advanced nuclear systems (SMRs, Generation IV reactors, ADS) will still require experimental support, as it is recognized for instance in 2021 ESNII Vision Paper [Schyns 2021]. Alongside other types of facilities (e.g. thermal-hydraulic test loops), some types of research reactors are also intended for supporting the development of new reactor technologies. Research reactors for this purpose can be classified into these three categories:

1. *Zero power reactors or critical assemblies.* They are very low ("zero") power reactors used to obtain integral reactor data to validate neutron transport codes and nuclear data libraries. Although sometimes these reactors are designed to test a specific core configuration and dismantled after the experiments are performed, they are also usually designed as permanent facilities where many different core configurations can be implemented.
2. *Prototypes/demonstrators of intermediate power*. They are essentially scaled-down versions of power reactors. They are specific to every design and are intended to operate for a few years, enough to gather experience to build larger reactors. For this reason, we will not consider them in this report. Note that reactors in this category may overlap in terms of power with Small Modular Reactor (SMRs) or micro-reactors, but these last ones are intended as commercial, permanent facilities.
3. *Material Irradiation facilities*. These reactors are intended to irradiate materials (both fuel and structural materials) in neutron fluxes higher than in power reactors to accelerate radiation damage. They have very different characteristics depending on whether they are thermal or fast spectrum facilities, and hence we have considered separately thermal (for which the name *Material Testing Reactors*, or MTRs, is reserved) and fast irradiation facilities.

2.2.1 Zero-power facilities for integral experiments.

In integral experiments, mock-ups of the cores of larger (e.g., power) reactors are assembled and a series of integral reactor parameters are measured (criticality constant, neutron flux distributions, kinetic parameters…) at very low power (*"zero"*) levels. By *"integral"* parameter or data is understood here that the measured parameters are particular to the whole reactor system, and depend on the geometry of the entire system and all materials present in it, in opposition to *"differential"* data, which usually refer to nuclear properties of selected nuclides at specific incident neutron energies, the most typical example being neutron cross sections.

These kinds of zero-power facilities were very common in the past, being built at the national or laboratory level as a first step of a reactor development program, for training and to obtain data for the design of larger facilities. Therefore, zero-power reactor mock-ups played a critical role in the development of reactor technology and many of the results have been compiled in databases. The most relevant ones are the International Criticality Safety Benchmark Evaluation Project Handbook (ICSBEP) [OECD 2020a] and the International Reactor Physics Evaluation Project Handbook (IRPhE) [OECD 2020b], both maintained by the OECD/NEA, which remain basic tools to validate nuclear transport codes and nuclear data libraries. Some famous examples of reactors that have played a major role in the development of reactor physics include the series of critical experiments performed at Los Alamos National Laboratory (Godiva, Jezebel, Topsy, Popsy, Big Ten…) and the ZPR series of reactors in Argonne National Laboratory (ANL).

The lack of interest in new reactor developments, the availability of results for already performed experiments, as well as the improvement of the quality differential data and computing capabilities have resulted in the closure of most of these facilities. In Europe, the recent closure of the Eole, Minerve, and MASURCA facilities in CEA-Cadarache (France) [Bignan 2010] coupled with the uncertain status of their planned successor ZEPHYR (Zero power Experimental PHYsics Reactor)

[Blaise 2019] has represented a major loss of capacity in this field. Only two flexible zero-power facilities suitable to integral experiments are left in the EU:

- The LR-0 reactor in CVR-Rez is a tank-type light water-moderated reactor with a fuel geometry characteristic of VVER reactors (with shortened fuel rods). Its main purpose was to perform integral experiments for the development of VVER reactors [Kostal 2022], but it has also been used for radiation resistance tests of electronic devices [Kostal 2013] and integral cross-section measurements [Kostal 2020].
- The VENUS-F belongs to SCK CEN and is located in Mol (Belgium). It was originally a tank-type light-water reactor but under the EUROTRANS project was converted into a zero-power mock-up of a lead fast reactor, and has been operated in this way since 2011. It has been used for a series of integral experiments in support of the MYRRHA and ALFRED programs under the Eurotrans, FREYA, and MYRTE projects [Kochetkov 2021]. Critical and subcritical configurations, the latest coupled to the GENEPI DT neutron source developed by French CNRS are possible.

Also in Europe, but outside the EU, the CROCUS light-water reactor at the EPF Lausanne (Switzerland) [Lamirand 2016], mainly used for education (see section 4), offers a certain flexibility in the core configuration and can be also been classed in this category. Note that all these zero-power reactors are also adequate for training, so this category overlaps with training reactors treated in section 4, but training reactors usually have fixed configurations with little flexibility for modification.

Despite this reduced number of facilities, and possibly for the reasons listed above, its level of utilization is low and it is difficult to justify keeping them in operation, even if their operating costs are low. The situation in other parts of the world (see below) is not much better. In relation to this, the OECD/NEA has also launched within the Working Party on Scientific Issues and Uncertainty Analysis of Reactor Systems of the Nuclear Science Committee (NSC/WPRS), a Task Force on Zero Power reactors to address the issue of the decreasing number of facilities [OECD 2023a].

A suggested solution to address this issue may be a transition from an operating model where these facilities were used by their owner countries or institutions to obtain proprietary data for their reactor projects to a model where the facility is open to other institutions through multinational projects and the produced data are shared by all participating institutions. The option to carry out proprietary programs can also be maintained. This can be similar to international programs in the field of nuclear material research that have been running for many years, such as the Halden Reactor Project [OECD 2023b] or FIDES [OECD 2023c]. In this sense, the inclusion of both LR-0 and VENUS-F in the OFFERR European User's facilities network may be a first step in this line. In a longer timeframe, the creation of a European Partnership in this field may also be an option to give more long-term stability to the programs.

In this sense, in the USA the National Reactor Innovation Center (NRIC) has recently been created at Idaho National Laboratory (INL) and is currently building two reactor testbeds by refurbishing the buildings of decommissioned research reactors. They have been named the LOTUS testbed, in the building of the former Zero-Power Physics Reactor (ZPRR) reactor, capable of holding reactor mock-ups of up to 500 kW_{th}, and the DOME testbed, in the building of the Experimental Breeder Reactor-II (EBR-II), capable of holding reactor mock-ups of up to 20 MW_{th}, greatly exceeding the range of a zero-power reactor. The current plan is to start operating the first facility by 2027/28 and the second by 2026 [Balsmeier 2020a, Balsmeier 2020b, Tommer 2023]. It must be remarked that the ability to test their designs in a relatively fast and straightforward way, without having to design and license a facility from the ground up, can result in an important competitive advantage for the US companies developing advanced reactors over the European ones.

It must be stressed here that, although for some systems widely investigated in the past, such as Light Water Reactors (LWRs) or Sodium Fast Reactors (SFRs), there may be a large amount of past experimental information, this information is unlike to be enough for the design of advanced reactors or even conventional LWRs with novel characteristics, e.g. SMR cores and LWRs loaded with High-Assay Low Enriched Uranium (HALEU) or Accident Tolerant Fuels (ATFs). As an example of the need for new integral experiments, activities performed under the EU-funded H2020 SANDA project have shown that the uncertainties in the nuclear data cause the majority of calculated neutronic parameters of advanced systems to exceed target accuracy requirements [Romojaro 2022]. As another example of the relevance uncertainties still existing in the nuclear data libraries and neutron transport codes even for relatively conventional designs, the twin MAPLE research reactors in Canada, built between 1997 and 2000, could not be put into operation because they were found to have a positive reactivity coefficient, instead of negative, as designed [NEI 2008].

Concerning the situation in the rest of the world, zero-power reactors for integral experiments are in operation in Belarus, Brazil, Canada, China, India, Russia and the USA. In the USA, in addition to the projects at NRIC mentioned above, there are two zero-power reactor facilities in operation: the light water moderated SPR-CX in Sandia [Ames 2021], installed in the building of the Sandia Pulsed Reactor (SPR) and the National Criticality Experiments Research Center (NCERC) in Nevada and operated by Los Alamos National Laboratory (LANL), focused in fast or intermediate systems, which holds several critical (Godiva-IV, Flattop, Comet and Planet) and subcritical assemblies. This facility started operations in 2011 and was built by relocating and rebuilding facilities previously held at the Critical Experiments Facility at Los Alamos [Thompson 2019].

Japan currently has only two zero-power reactor facilities suitable for integral experiments, namely the Kyoto University Critical Assembly (KUCA) and JAEA's STAtic experiment Critical facilitY (STACY) reactor at Tokai, after having closed several zero-power reactor facilities after the Fukushima accident, including JAEA's Tank Critical Assembly (TCA) and Fast Critical Assembly (FCA).

The KUCA facility [Pyeon 2021] actually consists of three zero-power cores, one of the tank type, moderated by light water, and the other two solid-moderator cores. These two use highly enriched uranium fuel, a project is ongoing to convert them to LEU [Morman 2019]. One of these cores can also be operated as an accelerator-driven subcritical system (ADS). STACY, for its part, is in the process of being converted from a uranyl-solution fuel system to a solid-fuel, tank-type system [Sono 2015]. Its purpose is to simulate reactor core configurations containing fuel debris to assist in the decommissioning of Fukushima nuclear reactors.

A project called Transmutation Experimental Facility (TEF) was also pursued in Japan a few years ago. The facility would have included a critical assembly (built using FCA components) capable of operating both in critical and subcritical configurations, coupled to a spallation source driven by the J-PARC accelerator complex (the same accelerator that the Japanese spallation neutron source) [Sasa 2008]. This facility would have had the capability to be able to be loaded with minor actinide (MA) fuel through a remote handling system, which would have allowed to extend the integral experiments to a much larger range of fuel compositions. However, the project was abandoned after the Fukushima accident.

2.2.2 Material Testing Reactors (MTRs)

A type of research reactor that plays a major role in supporting the development of nuclear power plants is Material Testing Reactors (MTRs). MTRs are relatively large research reactors (usually in the 10-100 MW_{th} range) that can reach very high neutron fluxes (10^{14}-10^{15} n/cm^2/s). These fluxes are about 1-2 orders of magnitude larger than in commercial power reactors (~10^{13} n/cm^2/s), which accelerates radiation damage in fuels and materials, thus providing experimental results in much shorter times than would be required in commercial reactors.

It is worth mentioning that the medical isotope-producing reactors described in section 3 are actually MTRs; in fact, the initial purpose of most of them (HFR-Petten, BR2, MARIA, LVR-15, JHR) was material testing for LWRs.

Despite two recent closures (CEA's 70 MW_{th} OSIRIS reactor in France and IFE's 25 MW_{th} Halden reactor in Norway), Europe still maintains an important fleet of MTRs (Table 6). The two largest ones are the BR2 reactor in Mol (Belgium) and the High Flux Reactor (HFR) in Petten (The Netherlands). BR2s is owned by SCK CEN and HFR-Petten is owned by the European Commission, but operated by NRG. Three other somewhat smaller MTRs are the MARIA reactor in Poland, the LVR-15 reactor, and the 14 MW_{th} TRIGA reactor in Pitesti (Romania). This last one has the peculiarity of using TRIGA-type fuel [Barbos 2016], being the most powerful TRIGA reactor in the world.

Another large MTR, the 100 MW_{th} Jules Horowitz Reactor (JHR) is under construction in Cadarache (France) [Dupuy 2005]. Intended as a replacement for the OSIRIS reactor, this reactor is being built by an international consortium led by France, but with the participation of Belgium, the Czech Republic, Finland, Spain, Sweden, China, India, Israel, and the UK, plus the European Commission. The European Commission has acquired 6% access rights to this reactor, the management of these access rights has been the goal of the H2020 JHOP2040 project [JHOP2040 2023]. However, the construction of this reactor has been much delayed. Initially intended for 2014, it is not expected to enter operation until after 2030.

The replacement reactor for HFR-Petten is the PALLAS reactor. Although primarily focused on isotope production, this reactor will likely offer some capabilities for material testing. The intended replacement for BR2 is the MYRRHA reactor, which is a facility with a fast-spectrum (see section 2.2.3). Regarding the other three MTRs in operation in Europe, although no replacement is planned, they are expected to remain in operation at least into the 2030s. More specifically:

- The operator of LVR-15 expects to extend its operation until 2035, but this will depend on the provision of fuel (originally of Russian design) and the implementation of aging management.
- TRIGA-Pitesti reactor is currently licensed until 30/11/2024 and the operator plans to extend its license for at least another 10 years.
- MARIA is currently expected to remain in operation for a long time (until maybe 2060), providing a proper modernizations are carried out in the future.

Regarding the situation in the rest of the world, the most powerful MTR in operation is the 250 MW_{th} Advanced Test Reactor (ATR) at INL (USA). Japan also operated until recently a specialized facility for nuclear material testing, the 50 MW_{th} Japan Material Test Reactor (JMTR), but this facility was shut down due to the high cost of adapting it to new requirements after the Fukushima accident. A replacement reactor is being planned [Kaminaga 2021]. Russia also operates two large, specialized MTRs in RIAR institute in Dimitrovgrad, both of 100 MW_{th} power: MIR [Izhutov 2017, Tuzov 2019a] and the SM-3 reactor [Tuzov 2019b, Tuzov 2021], this last featuring a higher-energy spectrum. In addition to these two facilities, Russia operates a number of smaller MTRs, including the RBT-6 (6 MW_{th}) and RBT-10 (10 MW_{th}) in RIAR [Burukin 2015] and the IVV-2M in Beloyarsk mentioned above [Markov 2018]. Many other multi-purpose research reactors mentioned in this document are also used (or can be used) for the purpose of nuclear material testing.

Finally, in addition to MTRs, another specialized type of research reactors used for nuclear material research are pulsed reactors used to study the fuel behaviour under reactor transients, in particular Reactivity-Initiated Accidents (RIAs). These reactors are capable to produce very short, but very intense power bursts. In Europe, there exist two such facilities: the CABRI reactor at CEA-Cadarache (France) [Biard 2020] and the TRIGA Annular Core Pulsed Reactor (ACPR) in Pitesti (Romania), which shares the same pool with the 14 MW_{th} TRIGA mentioned above. Other pulsed reactor facilities in the world used for the same purposes are the Transient Reactor Test Facility (TREAT) reactor in INL [Pope 2019] (operated 1959-1994 and refurbished and brought back to operation in 2017) and the Nuclear Safety Research Reactor (NSRR) in Tokai (Japan), also a TRIGA ACPR [Nakamura 2002].

2.2.3 Fast spectrum irradiation facilities

In this category, we include fast spectrum research reactors that are neither prototypes nor demonstrators of specific designs but that are intended as more or less multi-purpose, permanent research facilities. The main purpose of these facilities is testing materials in a fast neutron environment, hence playing a similar role to thermal MTRs but with a fast instead of a thermal spectrum. An important difference with thermal MTRs is that fast reactors cannot be designed to reach higher fluxes than power (commercial) fast reactors to accelerate material damage. Neutron flux levels in fast spectrum irradiation facilities are similar to or lower than large, commercial fast reactors. Hence, from the point of view of the neutron flux and damage rate, material testing for fast reactors can be performed in commercial fast reactors in similar conditions than in smaller irradiation facilities but other aspects such as instrumentation requirements, accessibility or operation disruptions have to be taken into account.

It is worth noticing that a fraction of the neutrons in thermal MTRs are fast neutrons, and therefore fast neutron fluxes can be obtained in thermal MTRs e.g. through the use of thermal neutron absorbers. This is difficult to achieve without relevant reductions in the flux level, however. Furthermore, it is difficult to achieve neutron spectra characteristic of fast systems in this way. In this sense, since the spectrum also changes between different types of fast reactors (e.g. lead-cooled or sodium-cooled), fast spectrum irradiation facilities are usually built with the double purpose of material testing and serving as prototypes for industrial-scale fast reactors. Finally, fast reactors are not usable for scattering or isotope production (with some exceptions discussed in section 3).

Currently, since the shutdown of the Joyo reactor in Japan in 2007 and the closures of the Phénix reactor in France (2009) and the Monju reactor in Japan (2016), no fast spectrum irradiation facility is in operation in Europe or in any other Western country. However, Japan has plans to restart its Joyo reactor by 2024, which would put an end to this situation. This reactor was temporarily shut down in 2007 for repairs and the shutdown has been extended because of the need to adapt it to the new regulations after the Fukushima accident [NEI 2023d]. In 2019 the USA also launched the so-called Versatile Test Reactor (VTR) project to build a large (300 MW_{th}) SFR prototype whit material testing capabilities [Roglans-Ribas 2022, Unikewicz 2022], but the future of this project is unclear. In Europe, SCK CEN is pursuing the MYRRHA facility, which will be centred on a fast spectrum irradiation facility and is currently planned to enter in service in 2036 (see below).

The situation in the Western block contrast with the situation in other parts of the world. In particular, Russia operates the BOR-60 reactor. Irradiations of interest for the development of the MYRRHA reactor have been carried out in BOR-60, with support EU FP7 GETMAT project [Stergar 2014]. This reactor is due for closure by 2025 but it will be replaced by the larger MBIR, which is scheduled to enter in operation by 2027 [Novikov 2021, Zagornov 2021, WNN 2023a]. India also has a fast MTR, the Fast Breeder Test Reactor (FBTR) in Kalpakkam, in operation since 1985, and China also started operation of the China Experimental Fast Reactor (CEFR) in 2010. Some of the main features of these facilities are summarized in Table 7.

MYRRHA [SCK CEN 2022b, MYRRHA 2023] will be centred on a Lead-Bismuth Eutectic (LBE) cooled fast reactor. Although its design has not yet been frozen, it is planned to have a maximum power of 100 MW_{th}. It is intended to be capable of both critical and subcritical modes of operation, in the last case it will be coupled to a proton linear accelerator (600 MeV, 4 mA). It is intended to be used as a fast spectrum MTR and to serve as a prototype for an industrial scale reactor/ADS system for the transmutation of High-Level Radioactive Waste (HLW). It is also expected to contain thermal spectrum zones suitable for radioisotope production or other applications such as silicon transmutation doping, replacing the BR2 reactor in these roles.

The MYRRHA facility will be built in three phases:

- The first phase (to be completed by 2026) will consist of the initial phase of the proton accelerator (up to 100 MeV), alongside target facilities for the production of radioisotopes, material irradiation (for fusion research) and fundamental research. This facility is called MINERVA.

- The second phase will consist of the extension of the accelerator to 600 MeV, to be completed by 2033.
- The third phase will consist of the reactor itself, to be completed by 2036.

The total construction costs of the MYRRHA facility are estimated at 1.6 b€. On 7 September 2018, the Belgian Government approved an initial budget of 558 M€, distributed as follows:

- 287 M€ for the construction of the MINERVA facility (2019-2026).
- 156 M€ for the operation of MINERVA between 2027 and 2038.
- 115 M€ between 2019 and 2026 for preparation of phases 2 and 3.

Preparatory works for the construction of the facility started at SCK CEN Mol site in the spring of 2023 [SCK CEN 2023b].

Table 6. Major parameters of some material testing reactors. Sources IAEA Research Reactor Database and [De Raedt 2000].

	Op. start	**Reactor power (MW_{th})**	**Peak thermal flux ($n/cm^2/s$)**	**Peak fast flux ($n/cm^2/s$)**
BR2 (Mol, Belgium)	1961	50-70	$2\text{-}4\times10^{14}$ (core) $2\text{-}9\times10^{14}$ (reflector)	$4\text{-}7\times10^{14}$
HFR-Petten (Petten, Netherlands)	1961	45	2.7×10^{14}	N/A
MARIA (Otwock, Poland)	1974	30	3.5×10^{14}	1.0×10^{14}
TRIGA-Pitesti (Pitesti, Romania)	1980	14	2.5×10^{14}	1.8×10^{14}
LVR-15 (Rez, Czech Rep.)	1957	10	1.5×10^{14}	3.0×10^{14}
JHR (Cadarache, France)	2030s	100	5.5×10^{14}	5.0×10^{14}
ATR (INL, USA)	1967	250	8.5×10^{14}	1.8×10^{14}
MIR (Dimitrovgrad, Russia)	1966	100	5.0×10^{14}	1.0×10^{14}
SM-3 (Dimitrovgrad, Russia)	1961	100	5.0×10^{15}	2.0×10^{15}

Table 7. Major parameters of some fast spectrum reactors. Sources IAEA Research Reactor Database, [Hu 2018], [Unikewicz 2022].

	Op. start	**Reactor power (MW_{th})**	**Max. fast flux ($n/cm^2/s$)**
MYRRHA (Mol, Belgium)	2036 (planned)	<100	1.0×10^{15}
VTR (USA)	N/A	300	$>4.0 \times 10^{15}$
BOR-60 (Dimitrovgrad, Russia)	1968 (op. end 2025)	60	3.7×10^{15}
MBIR (Dimitrovgrad, Russia)	2027 (scheduled)	150	5.3×10^{15}
CEFR (Beijing, China)	2010	65	2.5×10^{15}
FBTR (Kalpakkam, India)	1985	40	3.3×10^{15}
Joyo (Oarai, Japan)	1977 (restart 2024?)	140	3.0×10^{15}

3 MEDICAL APPLICATIONS

The production of medical radioisotopes is likely the most relevant task from the social point of view performed by research reactors and therefore a great part of the TOURR project has been devoted to this role.

From the point of view of their production technology, medical radioisotopes can be classified into accelerator-produced and reactor produced. The first group consists mostly of proton-rich isotopes whose production is accomplished in relatively small-size accelerators (cyclotrons) that can be based in hospitals themselves and their supply is not a source of major concerns. The accelerator-produced isotope in most widespread use is ^{18}F ($t_{1/2}$ = 109.8 min), used for Positron Emission Tomography (PET) imaging.

On the other hand, reactor-produced isotopes are usually neutron-rich isotopes and they are mostly produced in a few large research reactors. A list of the most relevant reactor-produced isotopes for medical applications is provided in Table 8. By far, the most relevant reactor-produced isotope is ^{99}Mo, used in many medical imaging procedures. It is worth remarking that while diagnostic isotopes can be either reactor or accelerator-produced, therapeutic radionuclides are mostly reactor-produced. Since for most medical applications short-lived radioisotopes are required to minimize the exposure times of patients stocks cannot be accumulated and this means that shutdowns of a single reactor can result in major disruptions of the supply. This problem is compounded by the high age of these facilities, which results in increasing downtime due to maintenance issues. These issues were brought to widespread attention in 2009-2010 when a series of unplanned shutdowns in the NRU and HFR-Petten reactors caused a major shortage of medical isotopes [Webster 2009, Gould 2009, Van Noorden 2013].

The 2009-2010 isotope shortage prompted several responses by governments and intergovernmental agencies. In particular, the Nuclear Energy Agency of the OECD (OECD/NEA) created a High-Level Group on the security of the supply of Medical Radioisotopes (HLG-MR), which worked between 2009 and 2018. The work of this group has mostly focused on the policy and economy of the entire medical isotope supply chain [OECD 2019a]. This group worked out a number of principles to guarantee the supply of radioisotopes (among them, the need to guarantee full-cost recovery by isotope producers and the need to keep an adequate production reserve capacity) that crystalized in the 2014 Joint Declaration on the Security of Supply of Medical Radioisotopes [OECD 2022], that was signed by a total of 14 countries, including four EU member states (Germany, the Netherlands, Poland, and Spain).

Within Europe, a European Observatory on the Supply of Medical Radioisotopes was created in 2012 by Euratom's Supply Agency and Nuclear Medicine Europe (NM-EU, former AIPES) [Euratom 2023]. It is worth mentioning that it is NM-EU, through its Security of Supply Working Group, that coordinates the downtimes of major isotope producer reactors, both European and non-European, to guarantee the continuity of the supply of short-lived isotopes [NM-EU 2023]. Nevertheless, all these initiatives have focused on management, economics, and coordination of the current reactor fleet. No European or international joint initiative has been launched to deal with the issue of the ageing research reactor infrastructure or to jointly tackle the refurbishment of these reactors or the building of new ones.

More recently, in 2021 the European Commission launched a *Strategic Agenda for Medical Ionising Radiation Applications* (SAMIRA). One of its priorities is securing the supply of radioisotopes, through the so-called European Radioisotope Valley Initiative (ERVI). This initiative is mostly focused on the supply chain for medical isotope production (highly enriched uranium, high-assay low enriched uranium (HALEU), and other isotopically-enriched materials), including supporting the development of European suppliers for these materials [EC 2021]. Also in 2021, the PRISMAP project [PRISMAP 2023] was launched to create a coordinated network of European facilities (including reactors and accelerators) to provide rare isotopes for medical research. A similar initiative, called the National Isotope Development Center (NIDC) has also been launched in the USA [NIDC 2023b].

Many reports have been recently produced dealing with the issue of medical isotope supply in Europe [Kolmayer 2018, Mario 2021, Ligtvoet 2021, Mario 2022]. Also, Work Package 2 of the TOURR project has also been devoted to these issues. Hence, in this document, we focus on the aspects directly related with the research reactor infrastructure, particularly with the most recent developments in this field. For this purpose, focusing mostly on their production technology, reactor-produced isotopes have been classified into three major groups:

1. ^{99}Mo and other fission products. They are obtained as fission products from the irradiation of HEU or LEU targets and comprise ^{99}Mo/^{99m}Tc, which represents the vast majority of the reactor-isotope market, and other isotopes that can be obtained as by-products of ^{99}Mo production (^{131}I and ^{133}Xe). They are used mostly for imaging, but ^{131}I is also used for therapy. Another fission product in widespread use is ^{90}Y, but it is produced in ^{90}Sr generators and, therefore, in practice it is not directly linked to research reactors.
2. β-emitters. They represent a family of isotopes used in cancer therapy. They are mostly produced in neutron capture reactions. Currently, the most widespread one is ^{177}Lu. It was approved for routine usage by the US FDA in 2013 and it has also been granted Marketing Authorization in Europe, both in the carrier-added (c.a.) and no-carrier-added (n.c.a.) forms. Other isotopes in this category include ^{89}Sr, ^{166}Ho, ^{153}Sm, ^{47}Sc, ^{169}Er, ^{186}Re and ^{188}Re. Although the demand for these isotopes is currently much smaller than for ^{99}Mo, it is rapidly increasing and is expected to continue so in the coming years. In addition to these isotopes, ^{90}Sr/^{90}Y and ^{131}I are also β-emitters used in cancer therapy, but from the point of view of their production, they can be obtained as by-products of ^{99}Mo production, and are discussed alongside with ^{99}Mo in section 3.1[6].
3. α-emitters. These isotopes offer potential benefits over β-emitters for targeted radionuclide therapy (TRT), given the shorter range and higher linear energy transfer (LET) of α-particles in matter. Up to now, however, their use has been largely hampered by small availability, and their production is a matter of active research. The only α-emitter currently approved by US FDA and in Europe for routine usage is ^{223}Ra. Furthermore, there is a strong interest in ^{225}Ac (and its daughter ^{213}Bi), with much research ongoing to increase its production. Other α-emitters of interest are ^{149}Tb, ^{211}At and ^{212}Pb/^{212}Bi. These isotopes are produced either in radioisotope generators (^{223}Ra, ^{225}Ac, ^{212}Pb/^{212}Bi) or in accelerators (^{149}Tb, ^{211}At and likely ^{225}Ac), and hence the role of research reactors in their production is less evident, but given the high interest in them, options for their production have also been examined.
4. Others. In this category are included gamma emitters that are not contained in radiopharmaceuticals but are used in brachytherapy, external radiation therapy or other uses (^{192}Ir, ^{125}I, ^{60}Co and ^{14}C).

[6] Both ^{131}Y and ^{90}Y can also be produced in neutron capture reactions, as described in section 3.1.

Table 8. Most relevant reactor-produced medical radioisotopes.

Isotope	Half-life	Production	EU demand [Ligtvoet 2021]	Procedures per year in EU [Mario 2021]	Procedures per year in NL [Roobol 2017]	Major applications
^{99}Mo/ ^{99m}Tc	2.75 d / 6.00 h	Fission product	---	>10 million	430,000	Imaging (many organs)
^{131}I	8.02 d	Fission product $^{130}Te(n,\gamma)^{131}Te$	240 TBq	10,000 - 50,000	1846	Thyroid imaging, thyroid cancer, hyperthyroidism.
^{177}Lu	6.65 d	$^{176}Lu(n,\gamma)^{177}Lu$ $^{176}Yb(n,\gamma)^{177}Yb$	160 TBq	5,000 – 10,000	270 (prostate cancer) 400 (NET)	Neuroendocrine tumours (NET), prostate cancer.
^{90}Sr/ ^{90}Y	28.8 y / 2.67 d	Isotope generator $^{89}Y(n,\gamma)^{90}Y$	40 TBq	10,000-50,000 (RSV) >10,000 (TRT)	225	Radiosynovectomy (RSV) in joint diseases, liver cancer (radioem-bolization)
^{153}Sm	1.93 d	$^{152}Sm\ (n,\gamma)^{153}Sm$	5 TBq	---	120	Pain palliation in bone cancer.
^{166}Ho	1.12 d	$^{165}Ho(n,\gamma)^{166}Ho$ $^{164}Dy(2n,\gamma)^{166}Dy$	540 GBq	---	40	Liver cancer (radioembolization).
^{188}W/ ^{188}Re	69.8 d / 17 h	$^{186}W(2n,\gamma)^{188}W$	260 GBq	---	100	Pain palliation in bone cancer.
^{186}Re	3.75 d	$^{185}Re(n,\gamma)^{186}Re$	205 GBq	---	10-15	RSV in joint diseases.
^{169}Er	9.38 d	$^{168}Er(n,\gamma)^{169}Er$	160 GBq	---	---	RSV in joint diseases.
^{223}Ra	11.4 d	Ioisotope generator	80 GBq	20,000 -40,000	1,100	Pain palliation in bone cancer.
^{89}Sr	50.6 d	$^{88}Sr(n,\gamma)^{89}Sr$	40 GBq	---	22	Pain palliation in bone cancer.
^{32}P	14.3 d	$^{31}P(n,\gamma)^{32}P$ $^{32}S(n,p)^{32}P$	30 GBq	---	22	Blood cancer.
^{225}Ac/ ^{213}Bi	10 d / 46 min	Isotope generator Spallation in ^{232}Th $^{226}Ra(\gamma,n)^{225}Ra$	5 GBq	---	---	Research.
^{212}Pb/ ^{212}Bi	10.64 h / 1.0 h	Isotope generator	---	---	---	Research.
^{125}I	59.4 d	$^{124}Xe(n,\gamma)^{125}Xe$	---	---	>1,000	Brachytherapy.
^{192}Ir	73.8 d	$^{191}Ir(n,\gamma)^{192}Ir$	---	---	1,724	Brachytherapy.
^{47}Sc	3.35 d		---	---	---	Research.
^{161}Tb	6.89 d	$^{160}Gd(n,\gamma)^{161}Gd$	---	---	---	Research.
^{14}C	5700 y	$^{14}N(n,p)^{14}C$	---	---	---	Urea breath test, radiolabelling.
^{133}Xe	5.25 d	Fission product	---	---	---	Lung ventilation studies.

3.1 ^{99}Mo and other fission products

The most used reactor-produced medical isotope is ^{99m}Tc, used for imaging a number of organs. It can be produced in portable radiochemical generators from the decay of its parent ^{99}Mo, itself a fission product of ^{235}U ($\sigma_{0.0253eV}$ = 585 b, thermal fission yield 6.14%). ^{99}Mo is produced by the irradiation of purpose build HEU[7] or LEU targets (see below for further details) in research reactors.

Given the importance of this isotope, the current and future demand of ^{99}Mo has been assessed and periodically upgraded by OECD/NEA's HLG-MR since 2011. In their 2019 report [OECD 2019b], the estimation was a global demand of 9500 6-day Ci/week at the beginning of 2019, with a yearly increase of 0.5% for developed countries (81.5% of the global demand in 2018) and 5% for developing countries (18.5% of the global demand in 2018).

It is worth remarking that since the 2009-2011 isotope crisis there has been a downward tendency in the use of ^{99}Mo. Thus, NEA HLG-MR estimated global demand in 12,000 6-day Ci/week in 2011, 10,000 in 2012 and 9,000 in 2015, before increasing its estimate to 9,500 in 2019. A noticeable decline in the USA is also reported in the 2006-2015 period [NAS 2018a]. Within Europe, a decrease has been also reported in Germany between 2009 and 2015 [Hellwig 2017, Kolmayer 2018, Mario 2022]. The reasons behind this tendency are not fully understood. Reasons may include increased use of alternative diagnostic techniques, more efficient use of the isotope, and an increased price as a consequence of the shortages. In [NAS 2018a] it is reported, however, that the downward trend actually started at least in 2006, before the 2009-2010 supply shortages. Furthermore, there exist major differences in medical isotope usage between different countries, including between EU countries [Ligtvoet 2021, Kolmayer 2018, Mario 2022].

Other fission products in medical usage that can be obtained as by-products of ^{99}Mo production are ^{131}I (thermal fission yield 2.92%), ^{90}Sr/^{90}Y (5.68%) and ^{133}Xe (6.65%)[8]. Since ^{131}I and ^{133}Xe are short-lived fission products, they are affected by the same issues regarding shortages and supply disruptions as ^{99}Mo. The exception is ^{90}Y, which is also a short-lived fission product but it is extracted from the much longer-lived ($t_{1/2}$ = 28.8 year) ^{90}Sr. However, contrary to ^{99}Mo/^{99m}Tc, portable ^{90}Y generators for hospitals are not commercially available, although attempts have been made to develop them, and production is performed in industrial-scale facilities [IAEA 2009].

It must be remarked that in addition to the fission production route, ^{131}I can be also produced through the reaction ^{130}Te(n,γ)^{131}Te ($\sigma_{0.0253eV}$ = 0.20 b) [Haffner 2019] and ^{90}Y through the reaction ^{89}Y(n,γ)^{90}Y ($\sigma_{0.0253eV}$ = 1.28 b) [NRG 2023b]. Notice that with these routes, the supply of ^{131}I and ^{90}Y will be disrupted by reactor outages. Furthermore, while the ^{90}Y from radioisotope generators is no-carrier-added and hence suitable for radiolabelling of peptides for therapy of neuroendocrine tumors, or for labelling of prostate specific membrane antigen (PSMA) inhibitors for prostate cancer treatment, the ^{89}Y(n,γ)^{90}Y produced ^{90}Y is carrier-added and is not suitable for radiolabeling of biomolecules, hence it is only used for radiosynovectomy or for liver cancer radioembolization (in the form of glass spheres).

From the production side, ^{99}Mo production is currently concentrated in six reactors, as listed in Table 9: HFR-Petten (The Netherlands), BR2 (Belgium), MARIA (Poland), LVR-15 (Czech Republic), OPAL (Australia) and SAFARI (South Africa). It is worth remarking that four of these reactors are in the EU, so the European dominance in this field is remarkable. Other research reactors also supply smaller quantities of ^{99}Mo (see below). Finally, the HFR-ILL reactor in Grenoble (France) has also been used for the production of some medical isotopes (^{177}Lu, ^{161}Tb, ^{47}Sc), but not ^{99}Mo [ILL 2023].

As stated above, the major concern regarding the future supply of ^{99}Mo is the ageing of this reactor fleet (all except OPAL are more than 40 years old and three are more than 60 years old). In the last decade, two major reactor-producing isotopes have closed: NRU in Canada (2016), which was the largest ^{99}Mo producer for many years, and OSIRIS in France (2015). Although these closures have

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[7] HEU targets are not anymore used in Europe, as will be discussed below.
[8] ^{133}Xe is used in the USA but not in Europe.

been offset by the increase of ^{99}Mo production capacity in other reactors, most notably BR2, and by new reactors that have been made available for the production of this isotope, namely OPAL, LVR-15 and MARIA, the situation in 2023 is not much different than that of 2010: the bulk of isotope production is still carried out by a small number of facilities and periodic isotope shortages continue to occur. For instance, during 2022 two disruptions occurred: in January, due to a leakage in the HFR-Petten reactor [NM-EU 2022a] and in November due to a mechanical failure at BR2 [NM-EU 2022b]. If a simultaneous outage of two main producers (HFR-Petten and BR2) takes place, a crisis similar to the 2009-2010 one is likely to happen again.

In spite of the age of these facilities, it is worth remarking that typically they get license extensions in 10-year periods and hence the end of their current operating license should not be taken as their end of operation date. HFR-Petten reactor, whose current operation license ends in 2025, is planned to get additional license extensions until the new PALLAS reactor enters into operation [WNN 2023d, WNN 2023g]. Similarly, the BR2 reactor, which is currently licensed until 2026, will likely get further license extensions, at least until its planned replacement, the MYRRHA facility, enters into operation in 2036. Nevertheless, as stated before, MYRRHA (a fast reactor) is a very different kind of facility than BR2 and its design has not yet been frozen, so there is high uncertainty regarding the completion date and the capacity of ^{99}Mo production in this facility. On the other hand, it is worth mentioning that MYRRHA will open the possibility to use fast-neutron reactions to produce isotopes and will also have the capacity to produce isotopes through accelerator-based routes. In any case, by 2036, the JHR reactor, which should have a ^{99}Mo production capacity similar to BR2, should be already in operation.

The other two major European isotope-producing reactors (MARIA and LVR-15) also have their operation licenses renewed every 10-years and currently are also expected to remain in operation until at least 2035, with further life extensions possible. Finally, the FRM-II and the Triga-Pitesti reactors have also power and capability to become major ^{99}Mo producers. FRM-II was licensed in July 2022 to build a ^{99}Mo production facility [Müller 2015, FRM 2022a, FRM 2022b]. The TRIGA reactor at Pitesti also produces some isotopes (^{131}I, ^{125}I, ^{192}Ir) and the possibility to produce ^{99}Mo [Barbos 2016] has been mentioned, but at this moment it has no plans to start ^{99}Mo production in the short-term future.

One of the major developments in recent years regarding ^{99}Mo production is the replacement of HEU targets for LEU targets, thus reducing proliferation concerns. By 2023, all major ^{99}Mo producers have switched to LEU targets [WNN 2023e]. In 2021, the USA discontinued HEU exports for ^{99}Mo production [WNN 2021c]. It must be noted that with this conversion, one of the major motivations for searching alternative (i.e. without reactors) production routes for ^{99}Mo production (see below) has disappeared.

Concerning the situation in the rest of the world, the developments in the USA in the last decade are particularly remarkable and may considerably affect the global ^{99}Mo supply. Although the USA is the largest consumer of ^{99}Mo and a major supplier of HEU targets for its production, they have largely depended on other countries for reactor irradiation. However, as a reaction to the 2009-2010 medical isotope crisis, the USA approved the America Medical Isotopes Production Act (AMIPA) in 2012. As a consequence of this law, the DOE's National Nuclear Security Administration (NNSA) launched an R&D program to create a domestic supply of medical isotopes, with the additional requirement of not using HEU in the process. This program has been based on agreements (50% cost share) with commercial companies; overall, 256 M$ have been awarded by DOE in the period 2012-22 to several companies, in addition to 152 M$ to National Laboratories [Nuclear News 2019, Kramer 2022]. In addition to reactor-based ^{99}Mo production by the company NWMI discussed below, three different companies have developed alternative technologies:

a) The company SHINE aims to produce ^{99}Mo in small accelerator-driven subcritical systems (ADS) [Van Abel 2016, Radel 2019, SHINE 2019a]. The subcritical systems consist of tanks containing an aqueous solution of LEU (19.75% enriched uranyl sulphate), while the external neutron source is a high-intensity deuterium-tritium (DT) generator. The ^{99}Mo is produced in the LEU solution (instead of in dedicated targets) that is continuously extracted for processing. Presently, the first production plant in Janesville (Wisconsin, USA) is expected to be producing 1500 6-day Ci per week by the end of 2023, with a full production capacity of 3000 6-day Ci per week [Nuclear Newswire 2021]. This plant consists of eight such ADS units, which allows for continuous production in the event of a single-unit outage. SHINE also plans to start building a similar facility in Veendam (The Netherlands) in 2023, with financial support from the Groningen province and the Dutch government. Commercial production is expected for 2025 [WNN 2022b].

Although this technology presents some advantages with respect to conventional reactors (use of subcritical systems and hence increased safety margins and simplified licensing procedures, redundancy of systems), it also presents some important challenges. Although during the TOURR project we have lacked information to make a detailed assessment of this technology, we have identified some possible issues. These include, at least: complexity of the on-site production and processing of the fuel solution (including the consequences of gas generation and possible leakages involving this irradiated fuel solution) and the formation of uranyl peroxide during the operation, which must be carefully controlled to avoid risks of criticality accidents related to its precipitation. The reliability of the neutron source may also be a source of concern, although in this respect very high reliability figures have been reported [SHINE 2019b]. Finally, the level of criticality of the subcritical systems has not been disclosed, and therefore is not possible to assess the advantages from the point of view of safety or licensing.

It is worth mentioning, however, that the use of similar homogeneous aqueous solution nuclear reactors for ^{99}Mo production has been considered in the past, although considering critical instead of subcritical facilities. Experiments were performed in the Argus nuclear reactor (20 kW_{th}, 90% enriched uranyl sulphate) at the Kurchatov Institute in Russia and conceptual designs include the SR-RN reactor (50 kW_{th}, 90% enriched uranyl sulfate) designed at IPPE (Russia), the MIPR (or MIPS) reactor (200 kW_{th}, <20% uranyl nitrate, 1100 6-day Ci/week) designed by BWXS (USA) and the also-denoted MIPR designed by National Power Institute of China (NPIC) (200 kW_{th}, 90% enriched uranyl nitrate). [IAEA 1999, IAEA 2008, IAEA 2013a]. More recently, the National Nuclear Energy Agency (BATAN) of Indonesia is also pursuing an ADS very similar to SHINE's, but with uranyl nitrate fuel, instead of a uranyl sulfate [Syarip 2018].

b) The Niowave company proposes a technology also based on an ADS, but it has a liquid lead-bismuth eutectic photoneutron source driven by a 40 MeV (when fully developed) electron LINACs (instead of a DT source) and an array of solid, low enriched U_3O_8 fuel rods, water moderated and cooled (instead of an aqueous solution). The development of the subcritical assembly (or Uranium Target Assembly in Niowave's nomenclature) is being carried out in three phases: UTA-1 ($k_{eff} \leq 0.43$ and 2.3 W fission power), operating since 2018, UTA-2 ($k_{eff} \cong 0.75$ and 230 W fission power) which was ongoing as of 2020 and the final UTA-3 (k_{eff} =0.95 and 230 kW fission power) which was intended for 2025 and should be capable of provide 1500 6-day Ci/week by 2025 [Grimm 2019b, Whalen 2020]. The subcritical assembly will be irradiated in 7-day periods, processed using a variant of the UREX method to extract the ^{99}Mo and other fission products and recover the U and Pu to refabricate the U_3O_8 fuel again [Johnson 2020, Brown 2021].

c) The NorthStar company is producing ^{99}Mo through the neutron capture $^{98}Mo(n,\gamma)^{99}Mo$ reaction. Highly-enriched ^{98}Mo targets are irradiated in the MURR reactor of the University of Missouri and then are shipped to the company facilities for chemical processing. NorthStar started producing ^{99}Mo using this technology in 2018 and it is reportedly satisfying 20% of the US's needs with this technology. Interestingly enough, this technology has been also applied in Russia (see below), but the amounts of ^{99}Mo produced are small. NorthStar is also exploring an alternative route for ^{99}Mo production, without reactors, through the $^{100}Mo(\gamma,n)^{99}Mo$ reaction. Enriched ^{100}Mo (>95%) targets are irradiated with electron beams from commercial electron accelerators, the targets themselves acting as Bremsstrahlung converters. A facility was completed in December 2022 and the first production of ^{99}Mo was announced in January 2023. The company plans to double its production capacity with this new technology [Tkac 2011, Nuclear Newswire 2022b, Nuclear Newswire 2023].

In Europe, the Belgian IRE and Dutch ASML Companies ran a similar project (SMART), with the support of the Belgian authorities, to produce ^{99}Mo from ^{100}Mo with 75 MeV electron accelerators. The aim was to build a factory in Fleurus (Belgium) and start production in 2028 [IRE 2023]. However, the project was cancelled in spring 2023, as it was estimated too complex and leading to excessive costs to be profitable [De Tijd 2023].

Furthermore, in addition to these innovative technologies, the production of ^{99}Mo using the conventional fission route in nuclear reactors (with LEU targets) is also being explored by Northwest Medical Isotopes (NWMI) [NWMI 2023]. This company plans to manufacture LEU targets, send them for irradiation in existing university research reactors (MURR and Oregon State University TRIGA Reactor) and then have the targets shipped back and processed to extract ^{99}Mo. The planned production capacity is 3000 6-day Ci/week and production should start in 2023. Another US company, Coquí Pharma, also planned to build a reactor facility for ^{99}Mo production in Oak Ridge. In 2019, the US DoE transferred land for the facility, but we haven't found any upgraded information since then [Coquí 2019]. Finally, more recently, the University of Missouri has announced plans to build a new reactor, named NextGen MURR, to replace the currently operating MURR and focused on medical isotope production [University of Missouri 2023].

Other countries (Canada, Russia, Argentina and South Korea) are also building new facilities or expanding existing ones that can substantially contribute to the world's supply of medical isotopes. Canada, which has been a major player in the isotope market until the closure of the NRU reactor in 2018, had been pursuing since the late 1980s a dedicated isotope producer reactor named MAPLE (actually, they were two 10 MW_{th} reactors working in alternation to cover up for each other shutdown periods) to replace NRU, but this project was cancelled in 2008 because of a positive reactivity coefficient that was never resolved [Magnus 2008, WNN 2008]. Currently, the Darlington NPP in Canada (CANDU type) is also planning to produce ^{99}Mo [WNN 2023c]. CANDU-type power reactors are better suited for short-lived isotope production than other types of power reactors (PWR, BWR, VVER) because of their on-line refuelling capability. In Europe, the only plant with this technology that could be potentially used for ^{99}Mo production is the 5-unit Cernavodă power plant in Romania. However, it must be noticed that the production of isotopes in power reactors has the disadvantage of the lower fluxes (~10^{13} n/cm^2/s vs. ~10^{14}-10^{15} n/cm^2/s) in these reactors with respect to research reactors, and hence it requires irradiating and processing larger amounts of target materials for obtaining the same amount of isotope.

Russia produces relatively small quantities of ^{99}Mo in several reactors [Pozdeev 2014, Zhuikov 2014, NAS 2018a]. The main Russian ^{99}Mo production facility is the 15 MW_{th} WWR-TS reactor in Obninsk, where ^{99}Mo is produced by the conventional fission technique by irradiating HEU targets. Several reactors at RIAR in Dimitrovgrad (SM-3, RBT-6/10) also produce or have produced ^{99}Mo with this technique. As stated above, the neutron capture $^{98}Mo(n,\gamma)^{99}Mo$ reaction has also been applied by several Russian reactors, including the 6 MW_{th} IRT-T reactor at Tomsk Polytechnic University, the 18 MW_{th} WWR-M at Gatchina and a commercial RBMK reactor at the Leningrad-4 power plant, but the amounts produced in this way seem to be very small (~10 6-day Ci per week). Two more power plants using RBMK reactors (Smolensk and Kursk) plan to start producing ^{99}Mo by 2026 with this technique [NEI 2023c]. As a final comment on medical isotope production in Russia, the construction of a large isotope-manufacturing plant in Obninsk, including ^{99}Mo, started in January 2023 and is scheduled to be completed by 2025 [WNN 2023b].

Argentina currently can produce small quantities of ^{99}Mo in its 10 MW_{th} RA-3 reactor and is building a larger multipurpose reactor, RA-10 (30 MW_{th}) with ^{99}Mo production among their main applications [Blaumann 2019]. Building started in 2016 and operation start is currently scheduled for 2024 [Alonso 2022]. A similar reactor is projected in Brazil (RMB), but it is in a less advanced stage

[Camusso 2019]. South Korea can also produce small quantities at its 25 MW_{th} HANARO reactor and has been designing another reactor for the specific purpose of isotope production since 2012, the 15 MW_{th} Ki-Jang Research Reactor (KJRR) [Park 2014]. The construction permit was granted in 2019 [Ryu 2019], construction start took place in 2023 and completion is scheduled by 2026 [WNN 2023f]. South Africa also plans to replace its SAFARI-I reactor in the long term [WNN 2022d]. Finally, very recently, the Welsh Government in the UK has launched a project to build a reactor-based medical isotope facility under project ARTHUR [Welsh Government 2023], with the goal of securing the long-term radioisotope supply in the UK.

As a final comment, direct cyclotron production of ^{99m}Tc using the $^{100}Mo(p,2n)^{99m}Tc$ reaction has also been investigated and other nuclear reactions for cyclotron-based production of either ^{99}Mo or ^{99m}Tc are also available [IAEA 2017]. Hence, as far as we know, commercial production of ^{99}Mo or ^{99m}Tc with cyclotrons is not foreseeable in the short-term future.

A summary of the new planned ^{99}Mo production capability, both in Europe and the rest of the world, is presented in Table 10.

Table 9. Largest ^{99}Mo producers and production capacity. Sources: [Kolmayer 2018], [Thro 2018], [Roobol 2018], [OECD 2019a] and reactor operators.

Reactor	**Current operation licence expiration**	**Is further life extension possible?**	**^{99}Mo production capacity (6-day Ci per week)**
BR2 (Mol, Belgium)	June 2026 (10-year extension planned)	Yes, no time limited operation licence, but PSR (Periodic Safety Review) every 10 years	7500
HFR-Petten (Petten, The Neterlands)	2025 (10-year extension planned)	Yes, planned to be extended until PALLAS is operational	6200
MARIA (Otwock, Poland)	2025 (10-year extension planned)	Yes, providing proper modernizations are carried out in the future.	1900
LVR-15 (Rez, Czech Republic)	2026 (10-year extension planned)	Yes, no time limited operation licence, but PSR every 10 years	3000
OPAL (Sidney, Australia)	N/A	PSSR (Periodic Safety & Security Review) every 10 years [Vittorio 2020]	3500
SAFARI (Pelindaba, South Africa)	Expected decommission in 2030, planned replacement by a new MTR	N/A	3000

Table 10. Planned new ^{99}Mo production capacity in Europe. Sources: [Kolmayer 2018], [Thro 2018], [Roobol 2018], [OECD 2019a] and references given in the text.

Reactor	Expected production start	^{99}Mo production capacity (6-day Ci per week)	Comments
FRM-II (Garching, Germany)	License to build facility received in July 2022, production foreseen after 2025	2100	Upgrade of existing neutron-beam reactor (20 MW_{th})
PALLAS (Petten, Neterlands)	Construction start 2023, commissioning by 2028	7280	New MTR (25 MW_{th}), replacement of HFR-Petten
JHR (Cadarache, France)	2030s	4800[9]	New MTR (100 MW_{th})
MYRRHA (Mol, Belgium)	2036 (expected completion date)	4550	New, multi-role fast irradiation facility (<100 MW_{th})
Darlington NPP (Canada)	2023	>3000	CANDU-type power reactor
NWMI (Columbia, Missouri, USA)	2023	>3000	Irradiation of LEU targets in existing university reactors: MURR (10 MW_{th}) and OSTR (1.1 MW_{th})
SHINE (Janesville, Wisconsin, USA) (Veendam, Netherlands)	2023 (USA) 2025 (Netherlands)	>3000	Liquid fuel (uranyl sulfate) subcritical assemblies driven by high-intensity DT neutron generators
Niowave (Lansing, Michigan, USA)	2025	1500	Solid (U_3O_8) fuel, water-moderated subcritical assembly driven by electron LINAC
NorthStar (Beloit, Wiscosin, USA)	2023	>3000	Irradiation of ^{98}Mo targets in MURR reactor and ^{100}Mo targets with electron accelerators
IRE (Fleurus, Belgium)	2028 (?)	N/A	Irradiation of ^{100}Mo targets with electron accelerators
RA-10 (Ezeiza, Argentina)	2024 (planned)	>2000	New multi-role MTR (30 MW_{th})
KJRR (Busan, South Korea)	2026 (planned) Construction start in 2023	>2000	New MTR (15 MW_{th})
SAFARI-2 (Pelindaba, South Africa)	After 2030 Project launched in 2023	N/A	New MTR, replacement of SAFARI
NextGen MURR (Columbia, Missouri, USA)	N/A Project launched in 2023	N/A	New MTR, replacement of MURR
ARTHUR (North West Wales, UK)	N/A Project launched in 2023	N/A	New MTR

[9] This figure is based on expected demand, JHR maximum ^{99}Mo production capacity should be similar to BR2 or PALLAS (Marion Libessart, private communication).

3.2 β-emitters

β-emitters represent a family of isotopes used in cancer therapy and since they are neutron-rich nuclei, they are usually produced through neutron irradiation in nuclear reactors, although some accelerator production routes also exist. They include in particular several radiolanthanides (e.g. ^{153}Sm, ^{161}Tb, ^{166}Ho, ^{169}Er and ^{177}Lu) but also other isotopes (e.g. ^{32}P, ^{47}Sc, ^{89}Sr, ^{186}Re and ^{188}Re) [Van de Voorde 2019]. Some of these isotopes are currently being produced commercially and other are being researched. Although they are mainly therapeutic nuclides, they can sometimes be used to perform imaging simultaneously with therapy ("theragnostic" techniques), either using their own gamma emission (e.g. ^{153}Sm) or through the combination with γ or β^+ emitters (e.g. ^{47}Sc with ^{43}Sc or ^{44}Sc). Notice that fission products described in the previous section are also β-emitters.

Although they can be produced in the same reactors as fission products, and hence the same recommendations in the previous section regarding the current and future research reactor fleet also hold for these isotopes, some specific comments apply to this family of isotopes.

First, it must be taken into account that although these isotopes are usually produced through neutron capture (n,γ) nuclear reactions, which usually have $1/\sqrt{E}$ dependencies with the neutron energy and hence thermal fluxes are required for their production, other reactions, such as (n,xn), (n,p) or (n,α) can be preferable in some cases. These reactions are usually threshold reactions that require a fast neutron spectrum. Hence, the JHR reactor (and, in the longer term, the MYRRHA fast spectrum facility), which has a very intense and relatively fast neutron spectrum in the core can be particularly well suited to produce some of these isotopes. It must be also taken into account that production routes involving low cross sections or requiring double captures require very high fluxes, which cannot be achieved in medium flux reactors like LVR-15 or MARIA. On the other hand, the HFR-ILL reactor in Grenoble would be well suited to the production of these isotopes.

Another factor to take into account is that for targeted radionuclide therapy high specific activities are required. This means high purity (i.e. non-carried added) isotopes, which may condition the production route and/or require additional chemical separation or even isotope mass separation, such as in the CERN-MEDICIS facility or in the planned MINERVA facility at SCK CEN. Notice that while mass separation can be viable for producing small quantities of isotopically pure isotopes for research, the viability of this technique to mass-produce isotopes for clinical usage remains to be proven[10]. Furthermore, highly enriched targets in some (stable) isotopes are usually required, which in some cases are not produced in Europe and need to be imported from other countries (USA, Russia).

As a final comment, the ongoing Horizon Europe SECURE project is related to guaranteeing the supply of β- and α-emitters [CORDIS 2023, ENEN 2023].

^{177}Lu

^{177}Lu is the most used β-emitter for cancer therapy (apart from ^{131}I). Currently, it is approved in Europe and the USA for some types of neuroendocrine tumours and prostate cancer, and other applications are being researched. In [Ligtvoet 2021], total EU demand (excluding Denmark) was estimated to be 160 TBq. Another estimate [Vogel 2021] is of 10,000-15,000 doses of 7.4 GBq (0.2 Ci) per year, or a total of 2,000-3,000 Ci per year (74-111 TBq) for the whole world, although these authors considered that these figures were likely to be underestimated and a rapid increase was expected. For instance, in [Mario 2021] it was estimated a need of 100,000 extra doses for every newly approved radiopharmaceutical.

Concerning the production of this isotope, two routes are available [Dash 2015, Vogel 2021]. The first one is through the reaction ^{176}Lu(n,γ)^{177}Lu ($\sigma_{0.0253eV}$ = 2032 b) using either natural Lu targets (2.6% ^{176}Lu) or targets enriched in ^{176}Lu. This technique has the disadvantage of the low specific

[10] One of the goals of the PRISMAP project mentioned above is to provide evidence that mass separation can be utilized efficiently for producing n.c.a. radioisotopes.

activities achievable due to the presence of ^{175}Lu and ^{176}Lu carriers and the contamination with the relatively long-lived ^{177m}Lu ($t_{1/2}$ = 160 d). The second route, that allows producing non-carrier added ^{177}Lu is:

$$^{176}\text{Yb}(n,\gamma)^{177}\text{Yb} \xrightarrow{1.91\text{ h}} {}^{177}\text{Lu}$$

This route has the additional advantage that it produces no ^{177m}Lu contamination. The disadvantages are the requirement of chemical separation from Yb after the irradiation and the small thermal cross-section of the ^{176}Yb(n,γ)^{177}Yb reaction ($\sigma_{0.0253eV}$ = 2.83 b). Enriched ^{176}Yb targets are also in short supply as they are only produced in Russia and the USA [NIDC 2022].

The high demand for this isotope is prompting the development of new production methods, in addition to research reactors. As a first alternative, as it was the case of ^{99}Mo, CANDU power reactors can also be used for the production of ^{177}Lu thanks to their online refuelling capability. In particular, unit 7 of Bruce NPP in Canada started production of ^{177}Lu in 2022, using the non-carrier added route [WNN 2022c].

As a second alternative, the SHINE Company of the USA is also offering ^{177}Lu, reportedly produced by the no-carrier-added route using a separation process developed in the Institute of Organic Chemistry and Biochemistry (IOCB) of the Czech Academy of Sciences, with plans to supply 300,000 ^{177}Lu doses (activity per dose not specified) per year [WNN 2019a, SHINE 2020]. In August 2022, the company submitted a drug master file with the US FDA [Nuclear Newswire 2022a]. However, since its subcritical reactor facility was not operating at this time, it remains unclear the technology used for irradiation (possibly neutron generators without subcritical multiplicative systems).

^{153}Sm

^{153}Sm is produced in the reaction ^{152}Sm(n,γ)^{153}Sm ($\sigma_{0.0253eV}$ = 206 b). Its usage is limited by its short half-life ($t_{1/2}$ = 1.93 d), the difficulty of separating it from the ^{152}Sm carrier, and the contamination with ^{194}Eu ($t_{1/2}$ = 8.6 yr) also produced during irradiation. Currently, only carrier-added ^{153}Sm is approved for clinical use. It is commercially produced under the name QUADRAMET® and it is broadly used as a palliation agent in patients with painful bone metastases from prostate cancer.

Recently, successful mass separation of ^{153}Sm from ^{152}Sm samples irradiated at BR2 has been reported at CERN's MEDICIS facility [Van de Voorde 2021] and no-carrier-added ^{153}Sm is available for research through the PRISMAP network. Pharmaceuticals based on n.c.a ^{153}Sm are not approved for clinical use, however, and the ability to produce ^{153}Sm in large quantities with this mass separation technique remains to be proven.

^{166}Ho

^{166}Ho is being investigated for the treatment of different types of cancer, most notably as an alternative or complement to ^{90}Y for radioembolization therapy of some types of liver cancer. It has the advantage that it can be monitored either through its gamma emission or through MRI (holmium is a paramagnetic element that can act contrast agent). Its short life ($t_{1/2}$ = 1.12 days), however, limits its use to the proximity of the producing reactors.

^{166}Ho can be produced in nuclear reactors by two routes [Klaasen 2019]:

$$^{165}\text{Ho}(n,\gamma)^{166}\text{Ho} \ (\sigma_{0.0253eV} = 64.7\text{ b})$$

$$^{164}\text{Dy}(n,\gamma)^{165}\text{Dy} \rightarrow {}^{165}\text{Dy}(n,\gamma)^{166}\text{Dy} \xrightarrow{81.6\text{ h}} {}^{166}\text{Ho}$$

$$\sigma_{0.0253eV} = 2650\text{ b} \qquad \sigma_{0.0253eV} = 3582\text{ b}$$

The second route produces carrier-free ^{166}Ho, but it requires double neutron capture, including one in the short-lived ^{165}Dy ($t_{1/2}$ = 2.33 h). We are not aware of what route is currently applied for the production of this isotope. It is currently produced commercially in BR2 and HFR-Petten reactors

[SCK CEN 2021, NRG 2023a]. The MacMaster nuclear reactor in Canada has also produced some quantities for clinical trials in North America [Armstrong 2019] using the $^{165}Ho(n,\gamma)^{166}Ho$ route.

Another advantage of the second route is that it can allow for the production of ^{166}Ho in ^{166}Dy radiochemical generators, which can help alleviate the distribution problems due to the very short life of ^{166}Ho. No commercial $^{166}Dy/^{166}Ho$ generator is currently available to our knowledge, however. As a final comment, the possibility of using ^{166}Dy in in-vivo ^{166}Ho generators has also been suggested [Smith 1995, Edem 2016, Cho 2018, Villarreal 2022].

^{186}Re and ^{188}W/^{188}Re

There are two isotopes of rhenium of medical interest, namely ^{186}Re and ^{188}Re. The use of ^{188}Re ($t_{1/2}$ = 17 h) is facilitated thanks to the commercial availability of portable ^{188}W generators ($t_{1/2}$ = 69.8 d) that allow its on-site production in hospitals [Knapp 1998, Pillai 2012, Argyrou 2013, Lepareur 2019]. ^{188}W is produced from ^{186}W in the reaction chain:

$$^{186}W(n,\gamma)^{187}W \rightarrow {}^{187}W(n,\gamma)^{188}W$$

$$\sigma_{0.0253eV} = 38.3 \text{ b} \quad \sigma_{0.0253eV} = 6.5 \text{ b}$$ [11]

This double capture route and the short life of ^{187}W ($t_{1/2}$ = 23.85 h) requires very high neutron fluxes ($>5\times10^{14}$ n/cm^2/s) for efficient production of ^{188}W, which limits the number of reactors available for their production [Pillai 2012]. ^{188}W has been routinely produced at HFIR (ORNL, USA) since 1986. In 2001, the BR2 (SCK CEN, Belgium) started to provide backup production capacity during HFIR outages [Ponsard 2003, Pillai 2012]. The SM3 reactor (RIAR, Russia) can also produce this isotope and the ATR reactor (INL, USA) has also been reported to have plans to produce ^{188}W [Pillai 2012], but no recent reference about it has been found.

^{186}Re is also produced in reactors through the $^{185}Re(n,\gamma)^{186}Re$ reaction ($\sigma_{0.0253eV}$ = 112 b). However, its short life ($t_{1/2}$ = 3.75 days) and the low specific activities achievable through this route, due to the presence of ^{185}Re carrier, constitute limits for expanding their applications. For this reason, accelerator production of ^{186}Re is also being investigated, through the reactions $^{186}W(p,n)^{186}Re$, $^{186}W(d,2n)^{186}Re$, $^{189}Os(p,\alpha)^{186}Re$ and $^{192}Os(p,\alpha 3n)^{186}Re$ [Uccelli 2022].

^{169}Er

^{169}Er ($t_{1/2}$ = 9.38 d) is produced in the $^{168}Er(n,\gamma)^{169}Er$ reaction ($\sigma_{0.0253eV}$ = 2.76 b). Limits for extended usage of this isotope are the difficulty to separate it from the ^{168}Er carrier and from the longer-lived ^{169}Yb ($t_{1/2}$ = 32 d) that is also produced during irradiation via the $^{168}Yb(n,\gamma)^{169}Yb$ reaction ($\sigma_{0.0253eV}$ = 2309 b) in ^{168}Yb impurities [Chakravarty 2014, Formento-Cavaier 2020, Talip 2021].

^{89}Sr

^{89}Sr ($t_{1/2}$ = 50.6 d) is one of the first isotopes used for pain management in bone cancer [Dickinson 1993], but its use is declining as it is replaced by other nuclides. It is produced in research reactors through the $^{88}Sr(n,\gamma)^{89}Sr$ reaction ($\sigma_{0.0253eV}$ = 5.8 mb) with highly enriched ^{88}Sr targets [Knapp 1998, IAEA 2003], although the cross-section is very small. It can also be produced in fast reactors through the reaction $^{89}Y(n,p)^{89}Sr$ [Karelin 2000, Saha 2013, Hu 2018, Risovanyi 2020] and might also be recovered as a fission product of ^{235}U (fission yield 4.73%) if it is separated from other Sr isotopes [Chuvilin 2007], but we are not aware of any of these techniques having been applied in commercial scale.

^{32}P

^{32}P ($t_{1/2}$ = 14.3 d) was the first isotope used for bone cancer pain management, but currently, it is not used in this role due to its radiotoxicity to the bone marrow, having been replaced by other isotopes.

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[11] The cross section of the reaction $^{187}W(n,\gamma)^{188}W$ is not well known. It is not included in major nuclear data libraries and the experimental values included in the EXFOR library range between 6.5 and 64 b. The value of 6.5 b corresponds to the most recent measurement [Ersöz 2019].

It has some limited use, however, for the treatment of some types of blood cancer and more applications may appear in the future. It can be produced through the $^{31}P(n,\gamma)^{32}P$ reaction with thermal neutrons ($\sigma_{0.0253eV}$ = 165 mb) or the $^{32}S(n,p)^{32}P$ with fast neutrons, but cross sections in both cases are rather small [Vimalnath 2014].

^{47}Sc

The interest in ^{47}Sc ($t_{1/2}$ = 14.3 d) is largely due to the fact that it can be combined with β^+-emitters ^{43}Sc, ^{44}Sc (accelerator produced) for simultaneous imaging during the treatment (theragnostics).

Two reactor routes for the production of ^{47}Sc are available. The first one is the $^{47}Ti(n,p)^{47}Sc$ reaction with fast neutrons. Apart from the requirement of a fast neutron flux, this route has the inconvenient of the coproduction of the long-lived ^{46}Sc ($t_{1/2}$ = 83.8 d) through the $^{47}Ti(n,np)^{46}Sc$ reaction, which makes this production route unfeasible according to some authors [Domnanich 2017][12]. This route has been applied at HFIR ($\Phi_{E>1MeV} = 1.5 \times 10^{14}$ n/cm^2/s) [Kolsky 1998], Tehran Research Reactor ($\Phi_{fast(?)} = 3\times10^{13}$ n/cm^2/s) [Deilami-nezhad 2016], BR2 ($\Phi_{E>1MeV} = 5.7 \times 10^{13}$ n/cm^2/s) and SINQ ($\Phi_{E>1MeV}$ = 3.3-3.5 $\times 10^{11}$ n/cm^2/s) spallation source [Domnanich 2017].

The second route for reactor production of ^{47}Sc, which makes use of thermal neutrons, is:

$$^{46}Ca(n,\gamma)^{47}Ca \xrightarrow{4.5\ d} {}^{47}Sc$$

$$\sigma_{0.0253eV} = 0.74\ b$$

This route has the advantage of no production of ^{46}Sc, but has the disadvantages of the small cross-section of the $^{46}Ca(n,\gamma)^{47}Ca$ and the low abundance of ^{46}Ca (0.004%), which makes this technique *“prohibitively expensive”* [Bartós 2012]. In spite of this, this production route has been applied at BR2, HFR-ILL [Domnanich 2017], MARIA [Pawlak 2019] and OPAL [WNN 2020]. The possibility of developing ^{47}Ca generators has also been pointed out as an advantage of this route, but given the relatively long life of ^{47}Sc, this possibility is not as critical as for other isotopes.

Finally, a number of routes for accelerator production of ^{47}Sc have also been studied, including $^{48}Ti(p,2p)^{47}Sc$, $^{44}Ca(\alpha,p)^{47}Sc$, $^{48}Ti(\gamma,p)^{47}Sc$ and $^{48}Ca(\gamma,n)^{47}Ca \rightarrow {}^{47}Sc$ [Mikolajczak 2021, Müller 2018]. Spallation in titanium or vanadium targets irradiated with 100 MeV protons was also investigated in Los Alamos LANSCE facility [DeLorme 2014].

^{161}Tb

Currently, none of the four terbium isotopes of medical interest (^{149}Tb, ^{152}Tb, ^{155}Tb, and ^{161}Tb) is produced commercially and their use has been limited to clinical or pre-clinical research [Naskar 2021]. The most investigated isotope of these four is ^{161}Tb, which is a β-emitter suitable for therapy that may offer advantages over ^{177}Lu. ^{161}Tb is the only neutron-rich isotope of these four and hence it can be produced in reactors via the $^{160}Gd(n,\gamma)^{161}Gd$ reaction. Some ^{161}Tb has been produced at the HFR-ILL and SAFARI reactors, as well as the SINQ spallation source at PSI [Gracheva 2019, Müller 2019].

The other three terbium isotopes are neutron-deficient and can be produced in accelerators. While ^{149}Tb is an α-emitter suitable for therapy, ^{152}Tb and ^{155}Tb can be used for diagnostics, possibly in combination with either ^{149}Tb/^{161}Tb. They have been produced since 2017 at CERN’s MEDICIS facility [Duchemin 2020, Duchemin 2021] through spallation reactions induced by the 1.4 GeV proton beam from CERN’s Proton Synchrotron Booster (PSB). Nevertheless, as stated above, the quantities produced are small, and up to now their use has been limited to research.

[12] In any case, the production of ^{46}Sc is highly depedendent on neutron spectrum. Since the reaction has a threshold of 10 MeV, ^{46}Sc production increases largely as the neutron spectrum becomes harder.

3.3 α-emitters

The use of α-emitters use is limited as far as now because of limited availability [Ferrier 2019, Nelson 2021]. They are usually produced in isotope generators from the decay of long-lived parents rather than in reactors, although reactor irradiations are required in some cases to produce these long-lived parents. Because of the long-life of these parents, however, their production will not be affected by short reactor outages, as it is the case of other short-lived medical isotopes.

^{223}Ra

The only currently approved α-emitter both in the USA and Europe (under the name of XOFIGO®) is ^{223}Ra. ^{223}Ra is produced from ^{226}Ra (obtained from legacy medical radioactive sources) through the chain:

$$^{226}\text{Ra}(n,\gamma)^{227}\text{Ra} \xrightarrow{42.2\text{ min}} {}^{227}\text{Ac} \xrightarrow{21.8\text{ y}} {}^{227}\text{Th} \xrightarrow{18.7\text{ d}} {}^{223}\text{Ra}.$$

EU demand of ^{223}Ra was estimated to be 80 GBq [Ligtvoet 2021]. Currently, the only reactor where irradiation ^{226}Ra is performed is HFIR at Oak Ridge (USA) and then shipped to Bayer (formerly Algeta) facilities at IFE in Kjeller (Norway) for extracting ^{223}Ra [ORNL 2018]. As a final comment, the parent of ^{223}Ra, ^{227}Th, is also being investigated for TAT [Hagemann 2020]. ITU at Karlsruhe also offers small quantities of this isotope for research [PRISMAP 2023].

^{225}Ac/^{213}Bi

Another very promising α-emitters are ^{225}Ac and its daughter ^{213}Bi [Bruchertseifer 2019, Morgenstern 2020]. These isotopes have been routinely produced since the 1990s using ^{229}Th ($t_{1/2}$=7340 years) generators, ^{229}Th extracted in turn from the ^{233}U stocks produced in past thorium-cycle nuclear energy projects. Currently, ^{225}Ac generators based on this principle are in operation at ITU (1.7 GBq of ^{229}Th, 13 GBq/year), ORNL (5.55 GBq of ^{229}Th, 22.2-33 GBq/year, depending on the source), IPPE (5.55 GBq of ^{229}Th, up to 26.6 GBq/year) and CNL (50 mg of ^{229}Th, 3.7 GBq/year) [IAEA 2013b, Makvandi 2018, Morgenstern 2018, Robertson 2018, Perron 2020, Radchenko 2021], for a total production capacity estimate of 63-74 GBq/year. This production is insufficient to satisfy current world demand, which is estimated to be about 200 GBq/year (5-6 Ci/year) [Cutler 2020, Robertson 2018]. Furthermore, an additional 200-400 GBq/year is estimated to be required for every new treatment approved [Robertson 2018]. Hence, a clear production shortage exists, which has prompted the search for alternative sources.

The most straightforward one is the extraction of an additional ^{229}Th from ^{233}U stocks. In 2014, the TerraPower company in the USA signed an agreement to purchase ^{229}Th extracted during the disposal process of US stocks of ^{233}U [WNN 2019b, Yan 2020, WNN 2021a]. The total amount of ^{229}Th expected to be recovered is 45 g [Radchenko 2021], which, according to the company, should be enough to increase by 50-100-fold current production levels. However, the recovered material contains large amounts of other thorium isotopes, ^{228}Th in particular, whose decay chain results in high levels of radioactivity. Notice that since the US is disposing of its ^{233}U stocks, the extraction of additional ^{229}Th will not be possible in the future, if required. In the same line, Russia is also reportedly increasing its ^{225}Ac production capacity [NEI 2023a].

Apart from ^{229}Th generators, the only alternative for ^{225}Ac that is currently exploited commercially is the spallation reaction in ^{232}Th targets [Engle 2018]. This technique has been applied since 2019 in the USA at LANL Isotope Production Facility (IPF), using a 100 MeV proton beam, and Brookhaven LINAC Isotope Producer (BLIP), using proton beams between 66 and 202 MeV. This is the result of a coordinated program between ORNL, LANL and BNL, designated as Tri-Lab Effort, started in 2015. Initial production was 50-100 mCi (1.85-3.7 GBq) per batch, to expand it to 100-1000 mCi per batch (3.7-37 GBq) in 4 years [NIDC 2023a][13].

[13] No information about how many batches per year will be produced is provided in the reference, but ORNL is currently shipping ^{225}Ac in monthly batches.

In Canada, TRIUMF is also producing ^{225}Ac using the spallation technique with its 480 MeV cyclotron and is working towards increasing its production [Robertson 2019, Augusto 2022]. In Europe, the CERN MEDECIS facility has also produced ^{225}Ac through spallation in ^{232}Th with 1.4 GeV proton beams and plans to become a supplier as well [Dockx 2019]. One issue with the spallation technique, however, is the contamination with ^{227}Ac. On the other hand, it is worth remarking that presently these facilities only divert a small fraction of the beam for ^{225}Ac production, and hence there exists a large margin to increase production by deploying higher beam intensities to the targets.

A third route that can become available in the short term for production ^{225}Ac is the reaction:

$$^{226}Ra(\gamma,n)^{225}Ra \xrightarrow{14.8\ d} {}^{225}Ac$$

This reaction can be applied using Bremsstrahlung γ-rays produced in relatively inexpensive electron accelerators. In April 2019, the Niowave Company of the USA [Grimm 2019a] reported the production of 10 mCi (0.37 GBq) batches of ^{225}Ac with this technology. The company expected to be able to produce 10 Ci/week (370 GBq/week) of ^{225}Ac, or over 500 Ci/year (18.5 TBq/year) with a full-scale facility, but there is no upgraded information on its production capability since 2019. Another US company, NorthStar, is also pursuing the production of ^{225}Ac with electron accelerators[14], with a production start expected in late 2023 [IBA 2022, NorthStar 2022]. More recently (2022), in Europe SCK-CEN and IBA have established a partnership dubbed PANTERA to produce ^{225}Ac using this route [SCK CEN 2022b, Leysen 2022].

Finally, reactions with low-energy protons (15-20 MeV) and α particles have been also investigated [Engle 2018, Higashi 2022]:

$$^{226}Ra(p,2n)^{225}Ac$$

$$^{226}Ra(p,pn)^{225}Ra \xrightarrow{14.8\ d} {}^{225}Ac$$

$$^{226}Ra(\alpha,n)^{229}Th$$

These techniques have the advantage that they can be applied with small cyclotrons that are widespread but have the inconvenience of the scarcity of ^{226}Ra, which, as stated above, is currently obtained solely from old medical sources. In any case, some companies in the US (IONETIX, SpectronRx) have reportedly produced, or are planning to produce, some quantities of ^{225}Ac using cyclotrons [IONETIX 2022, ContractPharma 2023].

Concerning reactor production of ^{225}Ac, a distinction can be made between *"direct routes"* where ^{225}Ac is directly produced, and *"indirect routes"* where the parent ^{229}Th is produced instead [Engle 2018]. The most investigated route for ^{225}Ac production in nuclear reactors is an indirect one, in which ^{229}Th through the dominant reaction chain:

$$^{226}Ra(n,\gamma)^{227}Ra \xrightarrow{42.2\ min} {}^{227}Ac\ ;\ {}^{227}Ac(n,\gamma)^{228}Ac \xrightarrow{6.15\ h} {}^{228}Th\ ;\ {}^{228}Th(n,\gamma)^{229}Th$$

This technique can be applied with thermal neutron fluxes and has been experimentally tested at the SM reactor in Dimitrovgrad [Kuznetsov 2012] and the HFIR reactor at ORNL [Hogle 2016]. In [Hogle 2016] it is reported production of up to 400-500 MBq of ^{229}Th per gram of ^{226}Ra in 100 days of irradiation at HFIR. A disadvantage of this technique is that, since the process requires three neutron captures, very high neutron fluxes are required. Another disadvantage of this technique is the co-production of large amounts of ^{228}Th and ^{227}Ac.

Another proposed indirect route for ^{225}Ac production in nuclear reactors is the $^{230}Th(n,2n)^{229}Th$ reaction with fast neutrons. This route has the advantage of removing the need for scarce ^{226}Ra targets. According to [Iwahashi 2022] about 6.5 GBq/year of ^{225}Ac could be produced from 50g of ^{230}Th irradiated during 5-years in the Joyo reactor. Finally, a final possible indirect reactor route for ^{225}Ac production is through the production of ^{233}U from ^{232}Th irradiation. Although this is the source of all

[14] NorthStar has been also involved in other technologies for ^{225}Ac production [Harvey 2018, Harvey 2019].

^{229}Th used in current ^{225}Ac generators, this route has the drawback of the long times required to build up enough ^{229}Th, in addition to the proliferation issues related to the ^{233}U.

A direct reactor route for ^{225}Ac production is via the (n,2n) reaction with fast neutrons:

$$^{226}\text{Ra(n,2n)}^{225}\text{Ra} \xrightarrow{14.8\ \text{d}} {}^{225}\text{Ac}$$

This technique has been studied for the Joyo fast reactor in Japan [Iwahashi 2022]. It is reported that 15.7 GBq of high-purity ^{225}Ac could be produced from 60-day irradiation of 1g of ^{226}Ra. Other authors have also investigated the potential of applying this reaction in thermal reactors [Melville 2013].

Recently, the Serva Energy company of the USA has announced the production of ^{225}Ac from ^{226}Ra at the 250 kW_{th} TRIGA reactor of the University of California-Irvine [Serva 2023], but the route used for production has not been reported. Westinghouse has also announced the production of ^{225}Ac in a 1 MW_{th} TRIGA reactor at Pennsylvania State University, also without reporting the route [Westinghouse 2023]. According to Westinghouse, their technology can be applied to produce ^{225}Ac in power reactors.

^{212}Pb/^{212}Bi

^{212}Pb ($t_{1/2}$ = 10.64 h) is in fact a β-emitter, but it is administered instead of its shorter-lived, α-emitter daughter ^{212}Bi ($t_{1/2}$ = 1 h), which is generated within the patient's body. These isotopes are produced in ^{228}Th or ^{224}Ra generators, themselves extracted from the decay chain of ^{232}U:

$$^{232}\text{U} \xrightarrow{69.8\ \text{y}} {}^{228}\text{Th} \xrightarrow{1.91\ \text{y}} {}^{224}\text{Ra} \xrightarrow{3.63\ \text{d}} {}^{220}\text{Rn} \xrightarrow{18\ \text{ms}} {}^{216}\text{Po} \xrightarrow{148\ \text{ms}} {}^{212}\text{Pb}$$

Currently, the major actor developing ^{212}Pb pharmaceuticals is the French company OranoMed. Its production is based on an 11 GBq ^{232}U source supplied by ORNL (another by-product of past thorium fuel-cycle programs). This source is in the Laboratoire Maurice Tubiana (LMT) in Bessines-sur-Gartempe (France), where ^{224}Ra (and/or ^{228}Th?) is extracted. Production of ^{212}Pb is then performed in this facility and in another one in Plano (Texas, USA) for the US market. The first facility for producing radiopharmaceuticals containing ^{212}Pb is in construction in Brownsburg (Indiana, USA). According to the company, it is to start production in 2024 [Yong 2015, Makvandi 2018, Kokov 2022, OranoMed 2023]. US NIDC can also supply ^{224}Ra and ^{212}Pb. On the other hand, portable ^{212}Pb generators are not currently available as far as we know.

3.4 Other reactor-produced isotopes

Another important family of medical isotopes are γ-emitters, which can be further divided into short-lived and long-lived. Short-lived γ-emitters are used in brachytherapy, and they include reactor produced ^{192}Ir and ^{125}I. ^{192}Ir ($t_{1/2}$ = 74 d) is produced through the reaction ^{191}Ir(n,γ)^{192}Ir using targets of natural iridium or iridium enriched in ^{191}Ir. Given its relatively short life, it can be also affected by long reactor outages, although not so critically as shorter-lived isotopes. Concerning ^{125}I ($t_{1/2}$ = 59 d), it is produced through neutron capture in ^{124}Xe. Currently, a major producer is McMaster University Nuclear Reactor (MNR) in Canada, a 5 MW_{th} research reactor. An agreement was signed in 2019 with NRG to become an alternative supplier of this isotope during MNR shutdowns [NRG 2019, Frketich 2019]. SHINE also aims to produce ^{125}I [WNN 2019a].

Among the long-lived γ-emitters, the most widely used is ^{60}Co ($t_{1/2}$ = 5.27 y), also used in brachytherapy, as well as in gamma sources for external radiation therapy, medical instrument sterilization and many other scientific and industrial applications. The world's demand is estimated at 60 MCi/year (2.22 Ebq/year) [Westinghouse 2020]. ^{60}Co is produced by irradiation of natural cobalt (100% ^{59}Co) in power reactors, mainly of the CANDU or RBMK types [Rosatom 2019, WNN 2022a], which feature online refuelling. It is also produced in the BN-600 and BN-800 fast rectors in Russia [Risovanyi 2020] and the ATR reactor at INL (USA) [Reichenberger 2022]. Furthermore, at least two PWRs in the USA (Clinton and Hope Creek NPPs) are producing or have produced ^{60}Co and EDF is reportedly investigating the possibility of producing it in French PWRs [WNN 2021b]. Given the long life of this isotope, however, stocks can be accumulated and its supply is not affected by short-term reactor shutdowns.

Concerning ^{14}C, it is obtained through neutron irradiation of aluminium nitride targets. After NRU stopped production of this isotope in 2009, the only remaining ^{14}C production facility is Rosatom's Mayak facility in Russia [Kitson 2012]. Nevertheless, given the very long half-life of this isotope ($t_{1/2}$ = 5700 y), stocks can be accumulated and its supply is not affected by reactor shutdowns.

4 EDUCATION AND TRAINING

In this section are included low-power reactor facilities (<1 MW_{th}) that have not been included in previous sections Note that although education and training (E&T) is usually the main application of many of these low-power reactors, they also have other applications (see below). On the other hand, E&T activities can also be performed in larger facilities, although at a higher cost, and therefore E&T is not the main application of the large facilities discussed in the previous sections.

The facilities in Europe that can fit within this category are listed in Table 11. Zero-power reactors discussed in section 2.2.1 have also been included in the table, as they can also be used for training. It is important to remark, anyway, that among these facilities the range of power levels (i.e. neutron fluxes) is very large and, consequently, their range of applications is also very large. A possible classification of these facilities is:

1. *Zero power reactors for training.* To this category belong reactors with a power level low enough to limit their applications to E&T and a few other applications such as instrument calibration. Many of these reactors correspond to standardized designs developed in the 1950-1960s that were purchased by many universities as turnkey facilities. These designs include the SUR-100 (*Siemens Unterrichtsreaktor*) type, developed by the German company Siemens [Jüttemann 2022], and the AGN-201 [Tomarchio 2011], developed by U.S. company Aerojet-General. Other reactors in this category, such as VR-1 [Frybortova 2020] or CROCUS [Lamirand 2016], have been designed by the user institution and may be closer to the next category.
2. *Zero power reactors for integral reactor experiments.* As stated above, the primary application of these reactors is to obtain integral experimental data, as described in section 2.2.1. However, since they have very low power levels, like the reactors in the previous category, they are also well suited for E&T. The difference with the reactors in the previous category is that they have a flexible core configuration, which is the feature that make them useful for integral reactor experiments. These reactors do not have a standardized design, but they usually have been designed by the owner institution. Furthermore, these institutions are usually not universities, but research centres, that developed these reactors to obtain integral experimental data in support of nuclear reactor development programs. The VENUS, LR-0 and, to a certain extent, CROCUS reactors would fall within this category.
3. *Low-power reactors*. In this category are included reactors with a power level in the ~100 kW_{th} to ~1 MW_{th} range. While they are still adequate for E&T, the higher fluxes achievable (~10^{13} n/cm^2/s) allow use for a much wider range of applications, such as neutron imaging, neutron activation analyses, testing of electronic devices under irradiation, production of small quantities of isotopes or BNCT. They can even be used for some of the applications described in the previous sections of this document (neutron scattering, isotope production), but to a limited extent since these applications usually require higher neutron fluxes (~10^{14} n/cm^2/s). TRIGA-type reactors, a standardized design by U.S. Company General Atomics, are the most widespread reactors in this category [IAEA 2016]. The training reactor of the Budapest University of Technology and Economics (BME) [BME 2023] and the IR-100 reactor of the Sevastopol National University of Nuclear Energy and Industry (SNUNEI) in Ukraine [Shepitchak 2014, Shepitchak 2017] would also fall within this category.
4. Finally, there exist some research reactors that do not fit into any of these categories, such as TAPIRO or BR1. The TAPIRO reactor of ENEA (Italy) is used as a fast neutron source with a well-characterized spectrum for instrument calibration and integral cross-section measurements [Fabrizio 2020]. Instrument calibration, in this case with a thermal spectrum, is also an important application of the BR1 reactor of SCK CEN, which is a large graphite-moderated reactor [SCK CEN 2023a].

Photographs of some of these reactors are shown in Figure 2 and Figure 3. In addition to these critical reactors, some subcritical assemblies (Table 12) are also in operation in the EU (GR-B and SM-1 at the University of Pavia) including some recently built or being built (Delphi, VR-2). Furthermore, a larger, accelerator-driven subcritical assembly has been built recently at the Kharkov Institute for Physics and Technology (KIPT) of Ukraine, in collaboration the ANL of the USA [Gohar 2022]. This subcritical facility is much more powerful than the other ones mentioned and can offer a performance in the class of a TRIGA reactor, with neutron fluxes up to 2.5×10^{13} n/cm^2/s.

There have been some shutdowns in recent years: the ISIS reactor at CEA-Saclay and the TRIGA Mk. II reactors at ITN (Portugal, 2016) and FiR-1 at VTT (Finland, 2015). On the positive side, no facility closure is foreseen in the short-term future. Finally, Poland is currently considering the possibility to build a reactor in this class as a refurbishment of a shutdown facility (AGATA or ANNA).

It must be stressed here that, although most reactors listed in Table 11 are about 60 years old, the simplicity of their designs and the low neutron fluxes (and hence radiation damage) that are attained in them make their operational lives virtually unlimited. Furthermore, because of their very low power levels, fuel burn-up in these reactors is very low. SUR-100 and similar systems virtually use no fuel and are designed to operate for their entire life without refuelling. Even for the highest-power systems, the fuel consumption of a typical 250 kW_{th} TRIGA reactor (with about 60-80 fuel elements in the core) can be 1 fuel element (containing 38 g of ^{235}U) every 2 years [Villa 2004].

Hence, from the point of view of the infrastructure no major obstacle to extend their operation to 2030 and beyond has been identified. This is consistent with the findings presented in TOURR Deliverable 3.1, where existing facilities indicated a ‘lack of personnel’, ‘lack of time’ or ‘lack of interest’ (i.e., students) as the main obstacles to expanding their activities. Paradoxically maybe, most of these low-power reactors are in countries not using or phasing out nuclear power (Germany, Italy, Austria). Possible actions to tackle these issues have been discussed in D3.1. The recommendation we can make here is that these activities (e.g. the ENEEP project [ENEEP 2023] or the online centralized platform developed within the TOURR project) should be continued as long-term actions. This means that they should become a structural part of the Euratom programme (including permanent funding if possible) instead of being considered time-limited projects. This also applies to initiatives to facilitate the access of external users to reactor facilities. An example is the currently ongoing OFFERR project, which financially compensates nuclear facilities for accepting external users. This can increase the revenues of the facilities which in turn will facilitate their refurbishment or the hiring of new personnel.

Nevertheless, some challenges to extending the life of the European low-power research reactor fleet have been identified during the TOURR project:

1. The dwindling number of research reactors is increasing the cost of supplies.
2. US decision regarding not taking back irradiated TRIGA fuel is a major issue regarding the future of the European TRIGA fleet [IAEA 2016].
3. The local, European nuclear competence and industrial background are being eroded, making lifetime prolongation efforts of research reactors more difficult and the supply chain more complex.

Finally, regarding the use of research reactors for E&T, it should be stressed that although they can be in principle replaced by simulators (in particular, for NPP operator training) or neutron generators (for teaching neutron physics and as low-intensity neutron sources for research), research reactors remain the only possible tool for teaching experimental reactor physics and many experimental techniques (e.g., reactivity measurements, neutron noise techniques). There is an increasing number of future nuclear scientists and engineers that have never had practical experience with a real research reactor and with the increasing need for future engineers this number will only grow larger. More specifically, the results from E&T projects (e.g. the ENEEP project mentioned above) and teaching experience obtained throughout the years at JSI TRIGA reactor show the importance of having a low-power research reactor for educational and training experiments with the possibility to upgrade and introduce new experiments (e.g. higher power reactors enable the teaching of fuel temperature feedback effects, important in nuclear reactor operation). It should also be expressed that in order to advance the quality of E&T obtained from research reactors, new types of research reactors (e.g. micro-reactors capable of electricity and hydrogen co-generation, small modular reactors with Gen IV technologies) will have to be built to educate the future generations.

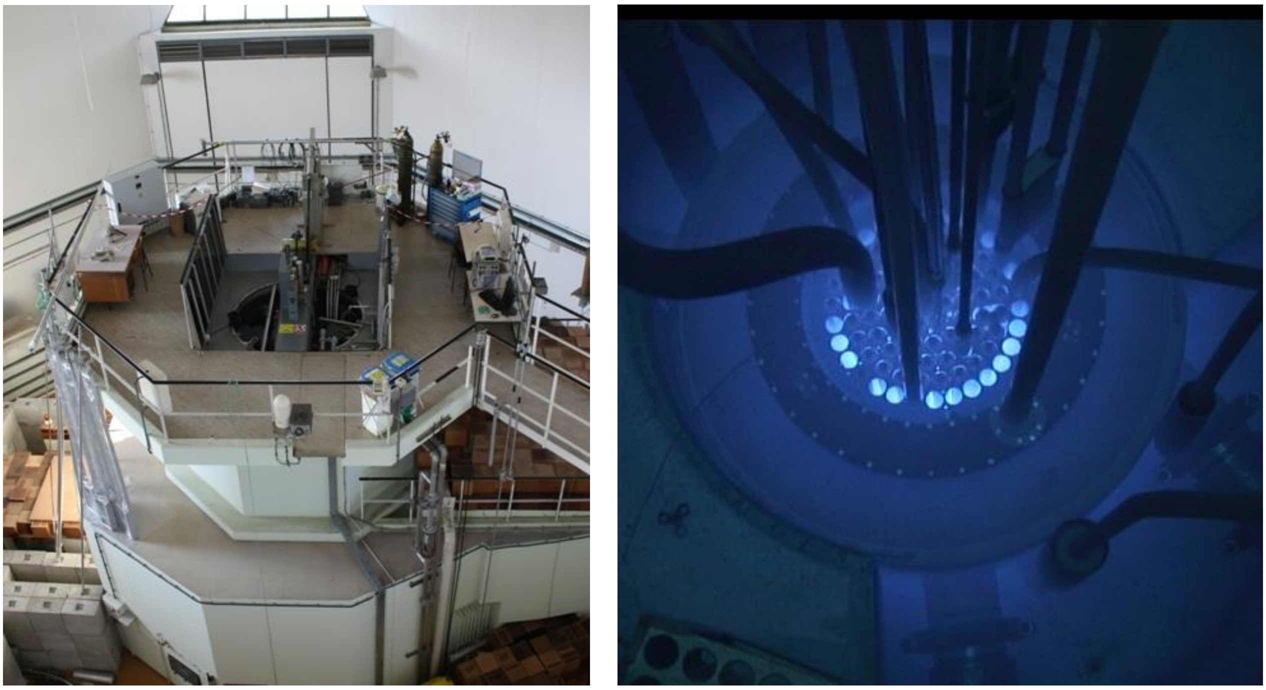
Table 11. Zero and low power reactors used for E&T in Europe, ordered by incrreasing power level (facilities in Europe but not in the EU are shaded in gray).

Facility name or type	Op. start	Max. power (continuous)	Institution (country)	Comments
SUR-100	1966	100 mW_{th}	U. Stuttgart (Germany)	U_3O_8 (<20%) powder dispersed in polyethylene with graphite reflector. Up to 1 W_{th} for a short time.
SUR-100	1965	100 mW_{th}	TH Ulm (Germany)	Up to 1 W_{th} for a short time.
SUR-100	1973	100 mW_{th}	HS Furtwangen (Germany)	
AKR-2	1978 (2005)	2 W_{th}	TU Dresden (Germany)	Based on the SUR-100 design, refurbished in 2005.
AGN-201 "Costanza"	1960	20 W_{th}	U. Palermo (Italy)	UO_2 (20%) plate fuel, polyethylene moderator. Up to 200 W_{th} for a short time.
CROCUS	1983	100 W_{th}	EPFL (Switzerland)	UO_2 fuel rods (0.9-18%) in water tank.
VR-1	1990	100 W_{th}	CTU in Prague (Czech Rep.)	UO_2 (19.7%) – Al plate fuel (IRT-4M) and water moderator. Up to 500 W_{th} for a short time.
VENUS	1964	500 W_{th}	SCK CEN Mol (Belgium)	Since 2011 it is operated as a LFR mock-up (VENUS-F) with U_{MET} fuel (30%) and Pb, Bi coolant mock-ups.
LR-0	1983	1 kW_{th}	CVR Rez (Czech Rep.)	UO_2 (1.6-4.4%) fuel (shortened VVER FAs), water moderator.
TAPIRO	1971	5 kW_{th}	ENEA Casaccia (Italy)	Fast reactor. U (98.5 %) – Mo fuel and copper reflector.
Training reactor	1969	100 kW_{th}	BME (Hungary)	UO_2 (10 %) – Mg (EK-10) fuel, water moderator and graphite reflector.
IR-100	1967	200 kW_{th}	SNUNEI (Ukraine)	UO_2 (10 %) fuel, light water moderator.
TRIGA Mk. II	1962	250 kW_{th}	TU Vienna (Austria)	U (20%) – ZrH fuel and water moderator. Pulsed operation is possible.
TRIGA Mk. II (LENA)	1965	250 kW_{th}	U. Pavia (Italy)	
TRIGA Mk. II (FRMZ)	1965	250 kW_{th}	J. G. U. Mainz (Germany)	Pulsed operation is possible.
TRIGA Mk. II	1966	250 kW_{th}	JSI (Slovenia)	U (20%) - ZrH fuel and water moderator. Pulsed operation is possible.
TRIGA Mk. II (RC-1)	1960	1 MW_{th}	ENEA Cassaccia (Italy)	
BR-1	1956	1 MW_{th}	SCK CEN Mol (Belgium)	U_{MET} (natural), graphite moderator. Oldest reactor reactor in operation in Europe.

Table 12. List of existing subcritical facilities for E&T in Europe (facilities in Europe but not in the EU are shaded in gray).

Facility name or type	Op. start	k_{eff}	Institution (country)	Comments
SM-1	1962	0.88	U. Pavia (Italy)	Light-water moderated natural uranium fuel rods with Pu-Be source [Alloni 2014]
Delphi	2004	0.92	TU Delft (Netherlands)	Light-water moderated 3.8% UO_2 fuel rods with ^{252}Cf source [Kloosterman 2004]
KIPT neutron source	2021 (construction completed)	0.98	KIPT (Ukraine)	19.7% UO_2 + Al fuel assemblies (WWR-M2), light-water moderator/coolant, Be and graphite reflectors. Driven by a 100 MeV, 100 kW electron linear accelerator [Gohar 2022]
VR-2	2023 (planned)	0.97	CTU in Prague (Czech Rep.)	Light-water moderated natural metallic and 10% UO_2 fuel with DD neutron generator [Rataj 2022]

Figure 2. University of Stuttgart SUR-100 reactor (© IKE Universität Stuttgart).



(a) **(b)**

Figure 3. TRIGA Mark II research reactor at Jožef Stefan Institute in Slovenia. (a) Picture of the reactor platform with reactor pool surrounded with concrete. (b) Picture of the reactor core during operation at maximum steady-state power of 250 kW. The reactor has the possibility to perform in pulse mode (Images courtesy of Jožef Stefan Institute).

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and conclusions

Regarding neutron beam applications, the following conclusions can be reached:

1. There is a high demand for beam time for neutron science, clearly exceeding capacity. EU capacity in this area is concentrated in two high-flux neutron reactors: the HFR-ILL in Grenoble (France) and the FRM-II in Garching (Germany). While the first one is a multi-national facility, the second is rather a national-level German venture. Other two major neutron scattering facilities in Europe are ISIS (UK) and SINQ (Switzerland), both based on accelerators.
2. The HFR-ILL is currently expected to remain in operation until 2033. By this time, the European Spallation Source (ESS) currently under construction in Lund (Sweden) should be in operation (currently entry in service is expected by 2026). About the other three facilities (FRM-II, ISIS and SINQ) there are no plans for closure at this moment.
3. However, the initial instrument suite of ESS will be much smaller than that of HFR-ILL (15 instruments vs. 40). Furthermore, there is a risk of further delays and early commissioning problems in the ESS. Hence, if HFR-ILL closes before the ESS is proven and fully operational there will be a major loss of neutron beam time in Europe.
4. On the other hand, the closure of several medium flux facilities in recent years (Orphée, BER-II, JEEP-II) has resulted in the loss of a large number of neutron instruments, even if of more modest capacity. The concentration of neutron beam time in a reduced number of facilities also amplifies the risk of a large loss of capacity in case of unexpected shutdowns. Furthermore, a network of distributed facilities is also important to create national or regional neutron scientist communities.
5. Compact Accelerator-based Neutron Sources (CANS) are the preferred option for replacing medium flux reactors for neutron scattering applications, however, all such facilities in Europe are still in the design stage, with none being operative or even under construction.
6. Keeping in operation the HFR-ILL until ESS and other alternative neutron sources are fully operational seems the more straightforward way to maintain neutron experimental capacity in Europe. The cost of operating simultaneously HFR-ILL and ESS may be prohibitive, however. This strategy would be similar to the strategy applied by other countries (USA, China, Russia, Japan) that have also opted to operate simultaneously a steady-state neutron source (nuclear reactor) and a pulsed source (pulsed reactor or spallation source). The other alternative is keeping only the ESS and complementing it with a network of medium-flux facilities (either accelerator-based or reactor-based).
7. Finally, given the very long timespan between conceiving an idea and the successful construction of a facility, it is worth mentioning that there are contemplations to start designing an eventual post-ESS neutron source [Andersen 2016].

Regarding reactor facilities for supporting nuclear power programs:

1. There are only two zero-power reactors suitable for integral experiments remaining in Europe (LR-0 and VENUS-F). In spite of the improvements in nuclear data and computational capabilities and the experience gathered in previous zero-power experiments, the development of new reactor types will require new integral experiments with characteristic configurations of these new reactors. Hence, it is important to keep these facilities in operation, to fully exploit their capabilities and to consider their replacement in a longer term.
2. Despite some recent closures, Europe still has a respectable fleet of Material Testing Reactors: BR2, HFR-Petten, MARIA, TRIGA-Pitesti and LVR-15. No further closure is foreseen this decade, and two new facilities are being built to enter into service in the 2030s: JHR and PALLAS.

3. No fast irradiation facility is currently operating in Europe or any other Western country. The planned restart of the Joyo reactor in Japan in 2024 can alleviate this situation and may be accessible to European researchers. In a longer timeframe (2036), the MYRRHA facility can fulfil this role.

Regarding the production of medical isotopes:

1. Regarding the production of ^{99}Mo, the two largest producing reactors (HFR-Petten and BR2) are now expected to remain in operation until after 2030. This should give time for replacement reactors (PALLAS, JHR and, in a longer term, MYRRHA) to be completed by the time of their shutdown. However, an unexpected earlier shutdown of HFR-Petten or BR2, or delays in the completion of their successors, may lead to a major ^{99}Mo shortage.
2. In the same way, all other major ^{99}Mo-producing reactors (MARIA, LVR-15, SAFARI-I and OPAL) are expected to remain in operation until after 2030. Although all these reactors, except for the OPAL, are also over 40 years old, it seems to be enough replacement capacity to enter into service during this decade (FRM-II, RA-10, KJRR) or in the longer term (SAFARI replacement, RMB, ARTHUR, NextGen MURR). Again, if no unexpected earlier shutdowns or construction delays take place, ^{99}Mo production capacity should remain stable or even increase. Although these new facilities can help alleviate periodic ^{99}Mo shortages and meet the expected increasing isotope demand, there is a risk of ^{99}Mo overproduction at some times and hence low prices and problems for producers.
3. In addition to the conventional reactor-based facilities, novel ^{99}Mo production methods are in an advanced stage of development, mainly in the USA, and are stated to start commercial production in the next few years, during this decade in any case. Although they have the potential to change the ^{99}Mo market and lead to a more distributed and less disruption-prone supply of ^{99}Mo, their ability to reliably and economically produce ^{99}Mo remains to be proven.
4. In any case, additional radioisotope production capacity is expected to be needed to meet the expected increasing demand for β-emitters for cancer therapy. Furthermore, some isotopes require special production routes that make use of fast neutron spectra or very high neutron fluxes that cannot be obtained in most isotope-producing reactors mentioned above. Hence, HFR-ILL, JHR and MYRRHA can be particularly well suited for the production of some of these isotopes.
5. Regarding the second family of emerging isotopes for cancer therapy, α-emitters, ^{225}Ac and ^{212}Pb are currently produced in ^{229}Th and ^{232}U generators extracted from wastes from past thorium nuclear fuel cycle projects. Research for alternative sources is focused on accelerator-production routes, and hence research reactors are not expected to play a major role in its production in the short term. However, research reactors are used to irradiate ^{226}Ra for ^{223}Ra production and may also be applied to produce these isotopes if alternative routes are not sufficient.

Regarding the use of research reactors for education and training:

1. In spite of recent closures, there is still a considerable number of low-power facilities in Europe that are suitable for E&T. Underuse is actually a major issue. Strategies for optimizing the use of these facilities are presented in TOURR project deliverables D3.1 and D3.2. These strategies will likely also apply in the longer-term future, which is the object of this deliverable.
2. Low- or zero-power reactors can operate for a long time (low or virtually no fuel consumption, very low irradiation damage). Hence, no major obstacle has been identified to extend the operation of the current fleet of E&T reactors into the 2030s.

5.2 Recommendations

From the conclusions above, it can be observed that there is a tendency in Europe to concentrate all the capability in a few large facilities (ESS, JHR, PALLAS and MYRRHA). This strategy brings some advantages and inconveniences. The major identified advantages are:

1. These facilities complement well each other: the ESS for neutron science; JHR for material testing (with a secondary isotope production capacity); PALLAS for medical isotope production (with a secondary material testing capacity), and MYRRHA for fast spectrum irradiation.
2. All these facilities will be the most capable, or among the most capable, facilities of the world in their respective area of application.
3. ESS and JHR are being conducted as European projects, with many European countries and the EC involved. A similar consortium is being pursued for MYRRHA, although it is not yet established. The exception is PALLAS, which is largely a National Dutch project.

However, this strategy also brings some important risks:

1. Cutting-edge facilities have large associated technological risks. These can be partially mitigated by using state-of-the-art computer simulations and advanced design software tools. However, the design, the construction and the commissioning of all these facilities have been affected by very significant delays and cost overruns, and further delays and overcosts may occur in the future.
2. Concentrating a large fraction of the European capacity in a single facility has the obvious risk that a single failure, or a maintenance break, will result in a sudden and substantial loss of capacity in Europe. This is very critical in the case of medical isotope production.
3. Not all applications require very high-performance facilities. In the case of neutron science, the tendency is for a significant reduction of the number of available neutron instruments, even if the remaining ones are very high-performing.
4. Small and medium facilities also play a role in developing scientific communities at the national or regional level, as it is very apparent in the case of neutron research.

With these considerations, the view of the TOURR project is that in the long term (2030s) these large facilities should be complemented by some small and medium ones. More specifically, we propose that the two following facilities should be considered to be integrated into a European research reactor strategy.

1. At least one multipurpose medium-flux reactor, likely in the 20-30 MW_{th} range. The required number of such reactors will largely depend on the success of other technologies currently under development (namely, the abovementioned CANS and alternative isotope-producing technologies), what should be much clearer than today by the end of this decade. This facility can be a fully newly built facility or a major refurbishment of an existing one (e.g. MARIA, LVR-15, TRIGA-Pitesti). Such a facility can provide 15-20 neutron scattering instruments, and will allow us to maintain the current four reactor strategies for isotope production (this new MTR + PALLAS, JHR, and upgraded FRM-II) and provide some extra material irradiation capability.

   Concerning the cost of such a facility, although it can vary substantially, according to the specific country, the regulatory environment, and other factors, some figures can be obtained from recent projects. Also notice that the costs can be lowered if a major refurbishment of an existing facility is undertaken, instead of building a new one from scratch.

   - The construction cost of the 20 MW_{th} FRM-II reactor was 435 million EUR in 2004 [FRM F&F]. Its estimated replacement value was 600 million EUR in 2016 [ESFRI 2016].
   - The construction cost of the 20 MW_{th} OPAL reactor was 345 million AUD plus 28 million AUD for the instruments (in 1999 AUD). By 2007 the replacement cost was estimated to be 474 million AUD, including provision for reactor decommissioning [Australian Senate 2008].

- The cost of the 30 MW_{th} RA-10 project was USD 330 million USD in 2021 [Doñate 2021].
- The smaller, 5 MW_{th} Jordan Research Reactor costed 161 million USD in 2016 [NEI 2016].
- The total cost of the 15 MW_{th} KJRR reactor project in South Korea was 765 billion KRW or 574 million USD in 2023 [WNN 2023f].
- The estimated cost of the ARTHUR project in the UK was 400 million GBP in 2023 [BBC 2023].
- In April 2023, the total cost of the 20 MW_{th} NextGen MURR reactor project in the USA was estimated at around 1 billion USD [Gallaway 2023].

These figures are to be compared with the 2 billion EUR replacement cost for ILL [ESFRI 2016], 3 billion EUR for ESS [ESFRI 2021], 1.8 billion EUR for JHR [ESFRI 2021], 1.6 billion EUR for MYRRHA [MYRRHA 2023] and 1.68 billion EUR for PALLAS [WNN 2023h].

2. A flexible, zero-power facility for integral reactor physics experiments, possibly a multi-core facility. This facility should replace or complement VENUS-F and LVR-0 reactors and should be designed to offer maximum flexibility to simulate as many different nuclear systems as possible. Such a facility can also fulfil an education and training role. An example of such a facility can be the zero-power reactor testbed being built by the NRIC in the USA. Given the very low power of such a facility, it should be relatively cheap to build and operate, although it is always difficult to provide cost estimates. For instance, the estimated construction cost of the ZEPHYR facility with a single reactor core was 80 M€ [Blaise 2019].

   Again, these costs can be lowered if the facility is built as a major refurbishment of an existing facility rather than as a new one from scratch. Furthermore, an important fact to take into account is that since they virtually spend no fuel, they can reuse the fuel from previous zero-power reactors. This is an important consideration to take into account when considering disposing of this fuel. On the other hand, other features such as the ability to be loaded with irradiated fuel would increase the cost. Finally, co-locating a zero-power facility together with higher-power research reactors allows sharing the costs of such a facility. In this sense, the JSI in Slovenia, in cooperation with the French CEA is in the early stages of the planning of a new research reactor facility, accessible at the EU level. The idea is to have a Versatile European Reactor fOr Neutron Irradiation and nuClear reseArch (VERONICA), consisting of two reactor cores. The first core will be a flexible and versatile zero power reactor for research (e.g. integral experiments), education and training. The second planned core is a 5 MW_{th} multi-purpose reactor, capable of isotope production, neutron scattering research and also E&T [Malec 2022].

A sketch of the current and future situation regarding research reactors in Europe, including an indication of how would fit these facilities within it is presented in Figure 4. As some final general recommendations:

1. Keeping the competencies in research reactor building is very important. Reactor building and major refurbishments should be planned so that a continuous effort can be maintained.
2. The decommissioning of current facilities will be a significant source of cost. This will be of particular relevance as many current facilities reach the end of their operational lives almost simultaneously in the 2030s.
3. Standardization of the maximum number of elements (e.g., fuel) between facilities can help reduce building and operating costs.

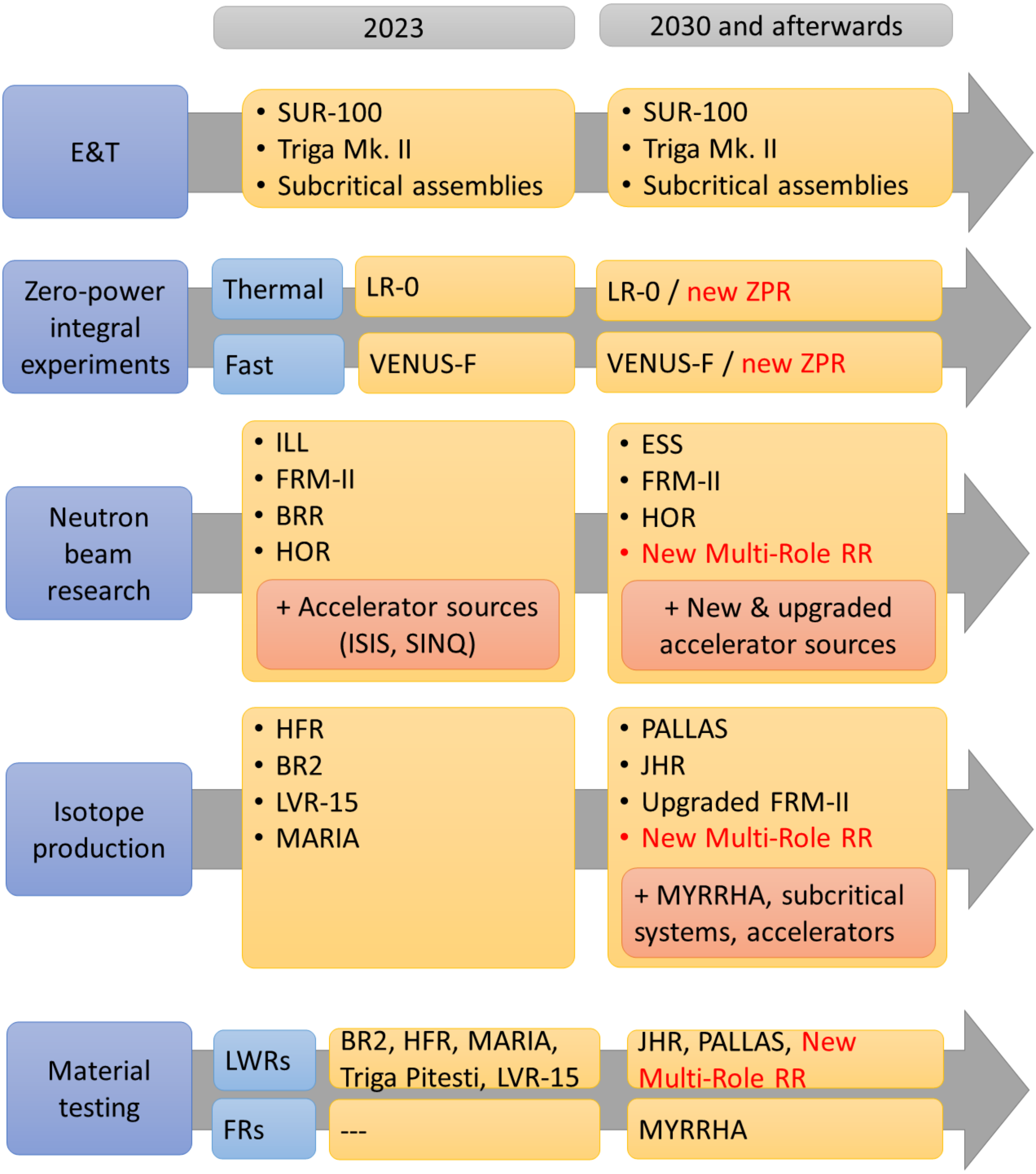


Figure 4. Current and future European research reactor landscape with the strategy proposed in section 5.2.

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ANNEX 1: FUEL TYPES USED BY EUROPEAN RESEARCH REACTORS

Guaranteeing the long-term supply of research reactor fuel is a major challenge for the European research reactor fleet and has been the subject of several EU-funded projects in H2020 programme (HERACLES-CP, LEU-FOREvER, EU-QUALIFY) [Valence 2020, Wight 2023].

The major issue is the fact that Europe does not have the capability to produce nuclear fuel at enrichment levels used by research reactors. This includes both highly-enriched uranium (HEU, >20% enrichment) and low-enriched uranium at levels used by research reactors (~20%), usually referred to as High-Assay Low-Enriched Uranium (HALEU). Therefore, fuel for European research reactors has been traditionally supplied by the USA or Russia. Given the increasing restrictions of the USA to export HEU fuel (due to proliferation concerns) and the situation after Russia's invasion of Ukraine, there exists an obvious risk of lack of supply.

Most European research reactors have converted to use LEU fuel and therefore they should be able to keep using US-supplied fuel. Only the HFR-ILL reactor in Grenoble, BR-2 and FRM-II are still using HEU fuel. BR-2 plans to transition to LEU fuel by 2026 [SCK CEN 2023]. FRM-II has also plans to switch to LEU fuel; currently, a process is ongoing to reduce the enrichment from 93% to 50% with the ultimate goal to reduce it to less than 20%. According to calculations, with new fuel types, this should be achievable with less than 10% loss in performance [FRM 2023, NEI 2023b, Reiter 2023]. These conversions would leave HFR-ILL as the only EU research reactor to use HEU fuel (plus the zero-power TAPIRO reactor that requires no fuel supply). Furthermore, at least initially JHR will use HEU (up to 27% enriched) fuel [Parrat 2015]. In any case, there are currently no plans in Europe to develop the capability to produce HALEU (nor HEU) fuel [ESA 2022].

Also, presently all TRIGA reactors have transitioned from HEU to LEU fuel. The TRIGA at Pitesti converted to a full-LEU core in 2006 [Barbos 2016]. The TRIGA reactor at the Technical University of Vienna, which had some HEU fuel elements, returned them to the USA in 2012 and currently only contains LEU fuel elements [Villa 2016].

Furthermore, several research reactors based on Soviet technology (MARIA, LVR-15 and BRR) keep using fuel supplied by Russian manufacturer TVEL. MARIA has been qualified for using fuel supplied by French manufacturer CERCA, but LVR-15 and BRR keep TVEL as the only qualified fuel supplier [Huet 2019]. Concerning BRR, as stated in section 2.1, the last fuel purchase in 2019 should be enough until 2027-2030, but the lack of fuel supply can be a major issue if it is decided to extend the life of this reactor. Budapest training reactor also depends on Russian fuel.

As a final comment, there is a lack of standardization among EU research reactors, every one of them using its own fuel type design. Table 13 contains a summary of the fuel types used by the research reactors in Europe.

Table 13. Fuel characteristics of European Research Reactors.

Reactor	Current fuel type	Total ^{235}U in core and consumption	References
HFR-ILL	93% UAl_x-Al (involute plate FE)	8.6 kg 43 kg/yr	[Bergeron 2010]
BR2	93% UAl_x-Al (SVG, SVIG)	10-13 kg	[De Raedt 2000], [Curnutt 2022]
HFR-Petten	19.75% U_3Si_2-Al	20.8 kg 3.2-3.8 kg/yr	[Thijssen 2006]
FRM-II	93% U_3Si_2-Al (involute plate FE)	7.5 kg 28 kg/yr	[Reiter 2023]
MARIA	19.7% UO_2-Al (MR) 19.75% UO_2-Al (MC)	15-20 FA/year	[Huet 2019], [Migdal 2014]
LVR-15	19.75% UO_2 –Al (IRT-4M)	N/A	[Huet 2019]
BRR	19.75% UO_2-Al (VVR-M2)	9.5 kg ~1.2 kg/year	[Huet 2019], [Toth 2014]
HOR	19.75% U_3Si_2-Al	5.43 kg	[NRG 2013]
TRIGA[15]	19.97% $UZrH_x$	60-80 FAs (38g ^{235}U/FA) 1 FA / 2 years	[Villa 2004]

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ANNEX 2: MONTE CARLO SIMULATIONS FOR PLANNING THE REFURBISHMENT OF EXISTING RESEARCH REACTORS

The radioisotopes production by neutron irradiation for medical, industrial purposes or for material composition analysis, accelerated material aging studies, the activation assessment of the structural component in a research reactor, the feasibility study and the engineering design of a technical upgrade to the reactor core or a beamline facility, all require the knowledge of the neutron field within and near the active zone, as well as a dose-rate estimation and almost quantitative inventories of neutron-induced radioisotopes. Through modern, high-performance computing solutions these questions can be successfully addressed, assisting in the lifetime prolongation of the existing neutron facilities, as well as in implementing technical and functional improvements for material irradiation studies, or in the eventual decommissioning of complete nuclear installations.

The combination of Monte Carlo simulation software [Metropolis 1949, Metropolis 1987] and deterministic inventory codes is a well-proven way to predict the amounts of radionuclides during and after neutron exposure. Detailed MCNP [Goorley 2015] models of several research reactor types operational within the EU are available in the literature, which, in combination with realistic material cards [Detwiler 2021], can deliver reliable estimates for the neutron field and its effects in the presently operational facilities or for future installations.

Introduction

Research reactors are used for decades as reliable and intense neutron sources to produce radioisotopes for medical and industrial applications [IAEA 2014], to study the elemental composition of samples (NAA) [Parry 2019], or the radiation-induced degradation of the mechanical properties (material ageing) [IAEA 2011] . These reactors were often built 50-60 years ago when computation techniques were less advanced and reliable than nowadays. However, presently, the daily operation, the design of any technical upgrade, the safety analysis of novel irradiation activities, the extension of service lifetime, or the decommissioning of these installations are unimaginable without the support of detailed calculations [IAEA 2022]. These are from one side requested by the authorities for licensing but have definite advantages for the operators as the calculations help to achieve the optimum design and reduce the related costs.

Nowadays, non-routine irradiation requests and applications are more abundant and increasingly well-specified. With the advent of novel target isotopes for radiopharmaceuticals, the target assemblies may contain previously unstudied isotopes, for which no hands-on experience may exist at all irradiation facilities. Experimentally, several trial-and-error test irradiations might be necessary to select the appropriate facility, irradiation channel and optimize the conditions. Further, the simplified predictions rely on the undisturbed neutron field, as determined by activation foils and the related activation equations [Basenko 2005], and do not necessarily consider the depression of the neutron field for bulky and/or highly-absorbent target materials, nor the effect of neutron resonance shielding [Romero-Barrientos 2016]. Therefore, a rigorous assessment of the irradiation conditions, the resulting reaction rates, neutron-induced activities [Blaauw 2017], and dose-rate levels have become essential for such irradiation applications. This calls for a generalized computational approach.

Coherent handling of the sample activation is possible by employing full-scale Monte Carlo computer simulations of the irradiation facility, where the complex interactions between the target and the impinging particles are all considered, coupled to isotope-inventory calculations via one of the well-established FISPACT [Fleming 2018], CINDER [England 1962], ACTYS [Tadepalli 2017], or ORIGEN [Parks 1992] codes [Hajdú 2020, Hajdú 2021]. These solve the Bateman-Rubinson differential equations numerically and keep track of the time-dependent growth and decay of all relevant radionuclides at any time instances.

MCNP reactor models

Just like in the case of power reactors [Montwedi 2014], MCNP is the “golden standard” software for reactor simulations. Geometries of several research reactor types operational within the EU are available in the open literature. This is especially true for standardized reactor types, such as the TRIGA. Some illustrative examples are shown below with references to the literature sources.

TRIGA reactors

Published simulation models exist for the widespread and standard reactor type TRIGA at JSI (Slovenia) [Snoj 2011, Henry 2014], Pavia [Alloni 2014], Pitesti [Budriman 2013], and also outside Europe [Shauddin 2021, El Maliki 2023].

Non-standard European reactor types

MCNP models of the FRM-II reactor [Röhrmoser 2010] and HFR-ILL have also been published [Bergeron 2014].

Post-Soviet research reactors of Eastern Europe

These uncommon core configurations require case by case geometry modelling, such as the LVR-15 reactor (Czech Republic) [Koleška 2015, Mikula 1997], the Budapest Technical University’s Training Reactor [Duong 2016], the Budapest Research Reactor [Harsányi 2022] and the MARIA reactor [Andrzejewski 2002].

Geometry implementation

MCNP and other simulation programs use basic geometrical structures, such as planes, cylinders and their unions, intersections, to specify the geometry. The construction of a full-scope reactor simulation model from scratch was cumbersome and prone to errors. Recently, the machine translation of the geometry from CAD file formats to MCNP became available [Wu 2014], which may help and accelerate the successful implementation of complicated geometries.

Calculation results

Spatial and energy-distribution of the neutron flux

The fluxes can be obtained for a specific volume within the radiation field, or full 3D mapping can also be printed out. The calculated fluxes have to be scaled with the reactor power to obtain realistic flux values as it has been done in [Žerovnik 2014]. The neutron flux specified by MCNP in the so-called F4 track length estimates per volume tally (Φ_{F4}) are normalized per source neutron. To get to the real flux intensity, this must be scaled up using Eq. (1):

$$\Phi = \frac{P \cdot \overline{\nu}}{1.622 \times 10^{-13} \cdot w_f} \frac{1}{k_{eff}} \Phi_{F4} \qquad (1)$$

where P is the reactor thermal power, $\overline{\nu}$ is the average number of neutrons produced per fission, w_f is the energy released per fission, k_{eff} the calculated reactor multiplication factor, and Φ_{F4} is the flux normalized per source neutron [cm^{-2}] from the MCNP output [Žerovnik 2014].

Activation inventory and decommissioning

Using the inputs above, activation inventory was established for the Morocco TRIGA reactor [El Maliki 2023]. Detailed decommissioning studies were completed for the Politecnico di Milano L-54 M nuclear research reactor [Parma 2018] and for the FRJ-2 reactor in Jülich [Abbasi 2016].

Experimental validation

Within the scope of this task, studies were made with the Budapest Research Reactor (BRR). It is a tank-type research reactor with thermal power of 10 MW, moderated and cooled by light water. Unlike common reactor types, the BRR has a unique core geometry, where the 190 pieces of 19.75% enriched VVR-M2 type (LEU) fuel elements are arranged in a hexagonal pattern. This core has been implemented within MCNP. We specifically focused on the characterization of the BRR's No. 17 vertical channel, where the irradiations for instrumental neutron activation analysis take place, and for which a vast amount of historical flux measurements are available.

Using the neutron field parameters and the composition of various targets, radioisotope inventories for any time instance during and following the irradiation can be obtained by using either the MCNP's built-in CINDER routines or in our case, by the FISPACT code. We used the FISPACT's TENDL-2017 nuclear data library for our calculations. The FISPACT activity calculations not only account for the major contributors to gamma dose rate but also for the decays to the ground state, that are without gamma emission, or decays emitting very low-energy gamma radiation that falls below the low-level discriminator of the gamma spectrometer. These are invisible to our experiments but still can contribute to the total activity of the samples.

We have demonstrated [Harsányi 2022] that if the material compositions are known or pre-determined, MCNP-based irradiation calculations, and FISPACT-based radioisotope inventory calculations are adequate computational tools to predict the activation of targets placed into a vertical channel of the Budapest Research Reactor. This approach is general enough to handle different target materials, shapes, and irradiation conditions, including target upscaling problems. The ratios of experimental and simulated activities agreed typically within 10%, while the uncertainty margin was about 5%-30%.

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CORRIGENDA TO TOURR PROJECT DELIVERABLE 3.4

19 November 2023

1. The nominal thermal power of the PALLAS reactor stated in the Safety Report [PALLAS 2022] is 25 MW_{th}, not 55 MW_{th} as stated in the deliverable.

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