Filling the Neutron Gap at the Canadian Nuclear Laboratories after Shutdown of the National Research Universal (NRU) Reactor

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Abstract. The National Research Universal (NRU) reactor, commissioned in 1957, has served three primary purposes: to be a supplier of industrial and medical radioisotopes used for the diagnosis and treatment of life-threatening diseases; to be a major Canadian facility for neutron physics research, and to provide engineering research and development support for CANDU® power reactors. Present uses for the NRU reactor include experimental irradiation programs in support of current and advanced reactors and isotope production. It also hosts the Canadian Neutron Beam Centre, where materials science research is carried out.

On March 31, 2018, the NRU reactor will be permanently shut down. Canadian Nuclear Laboratories (CNL), as Canada's national nuclear laboratory, needs access to neutron irradiation sources to realize its long-term strategy, and is considering multiple options to fill the neutron gap.

CNL has developed a list of requirements based on current and projected work, and is leveraging studies that have been done both inside and outside CNL. The requirements for nuclear fuels testing, for example, are quite different than the requirements for materials research or isotope production. There are multiple options for filling the neutron gap, and each is being considered with respect to factors such as timeline, capabilities, cost (including transportation costs), available space, and feasibility. Options include utilizing multiple test reactors as needed, setting up long-term agreements for reserved space with one or more research reactors, leveraging the IAEA International Centre based on Research Reactors (ICERR) framework, and participation in the development of a new test reactor. The optimal solution may be a combination of these options.

This paper discusses the options under consideration and progress towards identification of the best way to fill the neutron gap at CNL.

INTRODUCTION

Canadian Nuclear Laboratories (CNL) has a long and rich history in nuclear innovation. For over 70 years, the company has pioneered ground-breaking applications in nuclear science and technology that have impacted the lives of people all over the world, ranging from nuclear medicine to diagnose and fight cancer, to nuclear energy that powers our way of life. Today, nuclear power supplies 18% of Canada's electricity generation from electric utilities, and drives a $6 billion domestic industry providing 30,000 direct and another 30,000 indirect jobs.

CNL's expertise in physics, metallurgy, chemistry, biology, ecology and engineering is underpinned by more than 50 unique facilities and laboratories at Canada's largest science and technology complex in Chalk River, Ontario. A signature feature in this infrastructure is the National Research Universal (NRU) reactor.

At the time it was commissioned in 1957, the NRU reactor was the most powerful research reactor in the world. Over its lifetime, it has been used to produce over 500 million patient treatments, principally technetium-99m from molybdenum-99; perform research to develop the Canada Deuterium Uranium (CANDU) reactor; and develop neutron spectroscopy, an achievement recognized with a Nobel Prize in Physics for Bertram Brockhouse. For much of its life, the reactor operated at power levels up to 135 megawatts (thermal) with maximum thermal flux of $4.0\text{x}10^{14}$ n/cm^2/s (E<0.625 eV) and included experimental facilities with a maximum fast flux not exceeding $1.0\text{x}10^{14}$ n/cm^2/s (E>1MeV). The NRU reactor was notable for its large test volumes and ability to irradiate full-size CANDU (Pressurized Heavy Water Reactor-type) fuel bundles under representative conditions.

After 60 years enabling scientific innovation, the NRU reactor will cease operation in 2018 March. CNL's Zero-Energy Deuterium (ZED-2) reactor will continue to operate, providing an excellent training platform and enabling reactor and fuel design studies, instrument calibrations and commercial projects; however, its use for materials irradiations is limited. As such, CNL is developing a strategy to address the neutron gap created when the NRU reactor shuts down. This has been carried out within the broader landscape of nuclear science infrastructure in Canada. While there is benefit to CNL and Canada in having a multipurpose reactor on site – as evidenced by the achievements that the NRU reactor has enabled over the past 60 years – the scope of this report focuses on fuels and materials irradiations over the near-to-mid-term to support federal and commercial priorities.

SUSTAINING CNL'S VALUE PROPOSITION

CNL's objectives are to remain a one-stop-shop for nuclear R&D and Canada's national nuclear laboratory. This will be achieved by accessing external irradiation capabilities and managing work in those reactors in such a way that CNL's strategic science and technology capabilities – particularly advanced nuclear fuels and materials research – seamlessly transition to exclusively off-site irradiations following the shutdown of the NRU reactor. In the past, CNL has used third-party irradiation facilities for commercial and federal experimental programs when its own facilities did not have the necessary characteristics. The intent is to leverage and build on CNL's own experience as well as surveys of irradiation facilities conducted internationally, notably within the International Atomic Energy Agency (IAEA)[1,2] and the United States[3].

CNL's advanced nuclear fuels and materials research capability is founded on broad expertise and facilities that enable the full lifecycle of experimental programs: from experiment design and irradiation test assembly development, to irradiation oversight, post-irradiation examination (PIE), data analysis and long-term performance predictions (Figure 1).

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[1] International Atomic Energy Agency, *Utilization Related Design Features of Research Reactors: A Compendium*, Technical Report Series No. 455, 2007.

[2] International Atomic Energy Agency, Research Reactor Database, http://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx?rf=1, last accessed 2017 September 22.

[3] United States Office of Nuclear Energy, Nuclear Energy Advisory Committee, *Assessment of Missions and Requirements for a New U.S. Test Reactor*, 2017.

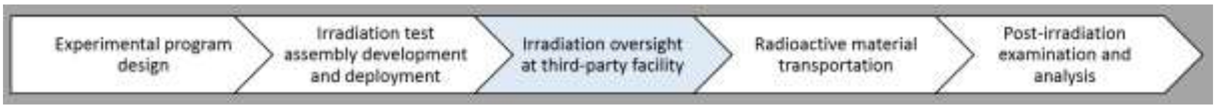

Figure 1: Sustaining the value chain by maximizing use of CNL's expertise and nuclear facilities

Following the shutdown of the NRU reactor, CNL will sustain its value chain by continuing to self-perform the majority of these steps while accessing third-party irradiation facilities. Preference will be given to engaging research reactors where CNL can continue to design experiments and perform the majority of planning, sample preparation, shipping and post-irradiation activities, sustaining technical expertise and maximizing use of CNL nuclear facilities. As described in CNL's Long-Term Strategy[4], the Government of Canada is investing $1.2 billion over 10 years to revitalize the Chalk River site. This includes a new Advanced Nuclear Materials Research Centre featuring state-of-the-art hot cells, fuel fabrication facilities, and fuel and materials research laboratories.

APPROACH

This report represents the culmination of the analysis and planning phase of a multi-year exercise to prepare for the neutron gap, and rests on prior studies of workforce, infrastructure, federal needs and commercial markets. The objective is to maintain the flexibility that allows CNL to adjust to changing federal priorities and commercial market shifts, while providing sufficient clarity to enable establishing partnerships, engaging customers, and planning experimental programs.

CNL's approach includes projecting irradiation demands, capturing key parameters, consolidating requirements, evaluating options, and identifying risks and mitigating actions (Figure 2). The intended outcome of this process is a list of reactors that meet the technical requirements for a broad set of irradiation work streams, as well as a smaller number of reactors that appear to fulfill very specific needs of one or more work streams. While the objective is to establish long-term partnerships where they best serve CNL, it is recognized that each experimental program may have unique requirements that further constrain reactor options. Reactor availability, cost and schedule will also be important considerations.

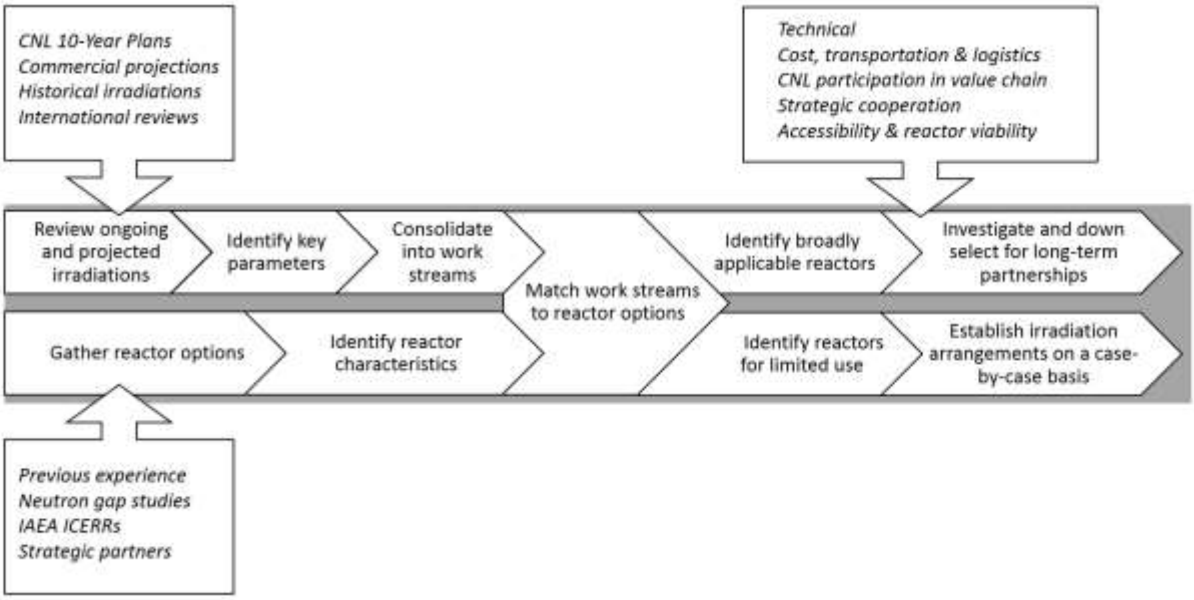

Figure 2: Approach to developing CNL's strategy for accessing irradiation capabilities

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[4] Canadian Nuclear Laboratories, *2016-2026 10-Year Integrated Plan Summary,* CRL-502000-PLA-001, 2017.

IRRADIATION DEMAND

With $25 billion over the next 15 years being invested in the refurbishment of CANDU reactors in Ontario, nuclear energy will remain a primary source of clean and reliable energy in Canada for many decades to come. In this context, CNL requires access to high-flux research reactors to enable ongoing fuel, materials and safety research; supporting reliable, low-cost, low-carbon electricity to power Canada and its economy.

This will also support emerging opportunities, including the development of the next generation of nuclear energy technologies, such as:

- Deployment of advanced and small modular reactors (SMR) to support meeting global demand for on-grid power, decarbonizing industrial processes, and supplying energy to remote locations[5]
- Use of fissile material recycled from spent fuel from other reactors
- Transition from uranium to plutonium mixed-oxide and thorium-based fuels in CANDU and advanced reactors
- Demonstration of fusion reactors[6]

CNL has considered irradiation requirements across three time horizons: historical, ongoing, and future. While the context and nature of CNL's science and technology mission has changed significantly, the historical perspective is useful as a means of understanding requirements for qualifying new fuels. Projections are informed by a broad range of inputs, such as ongoing and near-term federal and commercial projects, CNL's Long-Term Strategy, the Generation IV International Forum roadmap for advanced reactor designs[7], and the IAEA deployment forecast for SMR technologies[8]. Future experimental programs are expected to:

- Support the development of various reactor designs by assessing the impact of prolonged irradiations on materials and fuels, which may include specific small modular reactor fuels for qualification, and next generation fuel development
- Underpin studies and experiments related to the aging, safety and life-extension of CANDU and light-water reactors
- Support the training and skills development of Canada's future nuclear workforce
- Preserve and advance strategically important CNL facilities and expertise, including those associated with post-irradiation examination, fuel fabrication and development, fuel and reactor modelling, reactor physics as well as design and fabrication of test assemblies for irradiating fuels and materials
- Provide radioisotopes for medical research and other applications
- Sustain a forensic capability to identify the origins of irradiated material
- Leverage existing irradiated material inventory and nuclear data while addressing knowledge gaps related to the development of fuels of interest to Canada and commercial fuel vendors

Small Modular Reactors

As part of its Long-Term Strategy, CNL established the ambitious goal of siting a new SMR on a CNL site by 2026. With a domestic need for this technology, mature and robust regulatory programs, and fully-equipped laboratories to support such a project, CNL is uniquely positioned to support an SMR from concept to deployment. The SMR initiative has the potential to significantly impact CNL's irradiation strategy because it represents a big demand for neutrons and broadens the scope of irradiation programs needed to support deployment of new reactor types.

To understand the landscape of SMRs in Canada and globally, CNL carried out a SMR Request for Expressions of Interest. The 80 responses included 19 developers – representing seven different SMR technologies and 21 different fuel types – who expressed interest in building a prototype/demonstration reactor on a CNL site. The extent of research and development support that will be needed varies with maturity of the technologies, and

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[5] Canadian Nuclear Association, *Vision 2050 – Canada's Nuclear Advantage: Using Nuclear Energy to Deliver a Healthy, Low-Carbon Canadian and Global Future,* 2017.

[6] Ministry of Environment and Climate Change, *Canada's Mid-Century Long-Term Low-Greenhouse Gas Development Strategy,* 2016.

[7] Generation IV International Forum, *Technology Roadmap Update for Generation IV Nuclear Energy Systems,* 2014.

[8] International Atomic Energy Agency, *Advances in Small Modular Reactor Technology Developments – A Supplement to IAEA Advanced Reactors Information System (ARIS),* 2016.

ranges from incremental in-reactor qualification testing to partial and full-scale assembly irradiations in representative conditions.[9]

Technical Parameters

CNL's process for identifying key parameters and research reactors for consideration is based on the approach used by the U.S. Nuclear Energy Advisory Committee (NEAC) to assess missions and requirements for a new U.S. test reactor.[10] For each projected irradiation, the following key parameters and technical requirements are captured:

- Required power
- Required maximum thermal flux[11]
- Required maximum fast flux
- Irradiation arrangement and test conditions (e.g. experimental loop, in-core position/channel, reflector position, rabbit, beam port, gas-cooled, flows, pressure/temperature, instrumented)
- Required largest thermal flux test volume
- Required largest fast flux test volume
- Time frame
- Other requirements

Projected irradiations are then grouped into high-level work streams:

- Material irradiation
    - High neutron damage (displacements per atom), fast flux
    - High neutron damage, thermal flux
    - Corrosion loops
- Fuel irradiation
    - CANDU reactor
    - Light-water reactor
    - Research reactor
    - Advanced reactor
        - Super-critical water reactor
        - Molten salt reactor
        - Gas-cooled reactor
        - Lead-cooled reactor
        - Sodium-cooled reactor

Table 1 summarizes the high-level irradiation requirements for each work stream. Particularly for novel fuel concepts, the required irradiations, tests and evaluations will consider fabrication, licensing, normal operation and anticipated operational occurrences, postulated accidents and severe accidents as well as used fuel storage, transportation, disposition and potential for reprocessing. To support SMR development and deployment, projections cover the ranges of potential coolants, operating temperatures, materials, fuel types and neutron spectrum (fast and thermal). CNL continues to monitor the evolution of the SMR industry and adjust this strategy as specific SMR technologies or designs begin to emerge from the current large number of possibilities.

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[9] Canadian Nuclear Laboratories, *Perspectives on Canada's SMR Opportunity, Summary Report: Request for Expressions of Interest – CNL's Small Modular Reactor Strategy,* 2017.

[10] United States Office of Nuclear Energy, Nuclear Energy Advisory Committee, *Assessment of Missions and Requirements for a New U.S. Test Reactor*, 2017.

[11] For many fuel qualification tests, the enrichment of the fuel can be varied to produce the required fuel powers if the test reactor flux level is higher or lower than the proposed reactor conditions.

Table 1: High-Level Irradiation Requirements

Work Stream	Thermal Neutron Flux Required (n/cm²/s)	Fast Neutron Flux Required (n/cm²/s)	Irradiation Environment Conditions Required
FUEL IRRADIATION			
CANDU Reactor	1.5 to 3.0 x 10^{14}	>1.0 x 10^{14}	Pressurized Heavy Water Reactor preferred (CANDU or Advanced CANDU Reactor)
Light Water Reactor	>1.0 x 10^{14}	>1.0 x 10^{14}	Light Water Reactor preferred
Research Reactor	>1.0 x 10^{14}	>1.0 x 10^{14}	Pool Reactor
Advanced Reactor (fast or thermal)	>2.0 x 10^{14}	>2.0 x 10^{14} (up to 7 x 10^{15})	Design-specific advanced reactor conditions
Advanced Reactor (SCWR)	To be determined	>2.6 x 10^{13}	Reactor-specific design conditions
MATERIAL IRRADIATION			
High Neutron Damage	>1.5 x 10^{14}	>1.0 x 10^{14}	Reactor-specific design conditions
Corrosion Loops	0.4 to 1.5 x 10^{14}	~5.0 x 10^{13}	Reactor-specific design conditions

EVALUATION OF OPTIONS

CNL continues to explore several options to address the technical irradiation requirements, including utilizing multiple research reactors, setting up long-term agreements for reserved space with one or more reactors, leveraging the IAEA International Centre based on Research Reactors (ICERR) framework, securing space in an operating power reactor, acquiring time on a new test reactor, and participating in the development of a new test reactor.[12]

As CNL partners with reactors, a one-size-fits-all solution is not expected or realistic. The intention is to identify possible technical options, with the expectation that specific experimental program requirements will drive the final selection process. To facilitate case-by-case project-specific negotiations, CNL will pursue agreements with a small number of reactors offering general suitability. The currently projected needs are varied, and do not substantiate reserving space on a long-term basis in a single reactor. As the SMR initiative advances and there is clarity around SMR technology and experimental program needs, long-term agreements may be beneficial.

Building on the IAEA research reactor database as well as data from the 2017 NEAC report, CNL has consolidated a preliminary list of reactors for consideration and their operating characteristics (Table 2). This list is expected to evolve with time, as experimental needs are clarified, facilities become more or less accessible, and new reactors are commissioned. In addition, others are listed that are not yet operational and therefore are not a viable solution in the next three to five years.

Cross-referencing the technical parameters of irradiation work streams with reactor characteristics has identified several reactors that satisfy CNL's technical requirements. Reactors are being further investigated and down-selected based on a number of considerations:

- Technical requirements
- Strategic partners and cooperation
- Cost, transportation and logistics
- Reactor accessibility and long-term availability

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[12] Beyond the high-energy high-flux material and fuel tests offered by research reactors, three irradiation source alternatives continue to be considered:

- Low-power reactors
- Power reactors
- Other irradiation systems

These alternatives principally address niche requirements, and are not considered suitable irradiation sources for CNL's core federal and commercial work. Although low-power reactors will not be a substantial part of the post-NRU solution, CNL will aim to exploit these reactors for specific projects; for example, to study low fluence, transient phenomena.

- CNL's ability to perform key activities as needed to sustain technical competencies

The IAEA has established a framework by which research reactors can be nominated as centres to increase their utilization, while facilitating access by other countries. The IAEA ICERR designation is intended to help member states gain timely access to relevant nuclear infrastructure based on research reactors and their ancillary facilities. This framework aids in highlighting reactors that are accessible and currently available for international cooperation. To the extent it is cost-effective, practical and appropriate, CNL intends to leverage the designated ICERRs.

Transportation

Once technical and partnering criteria are satisfied, schedule, cost and transportation-related logistics dominate decision making. The ability to transport radioactive materials in a timely, safe and cost-effective manner is vital, and CNL has decades of experience transporting radioactive and nuclear materials globally for government and commercial customers.

To enable an increase in off-site irradiations and shipments of irradiated material to Chalk River, CNL's current radioactive material transportation capabilities and future needs were reviewed. Technical considerations included the radioisotopes, activity, physical form, contamination and radiation levels, weight and dimensions of the material being transported. Given that transport packages are expensive and time-consuming to design, fabricate, test, qualify and license, preference was given to using existing packages where possible. Package compatibility with CNL's hot cells was also considered. This exercise confirmed that radioactive material transport packaging solutions are currently available within Canada and/or internationally to support six applications: fuel research and development; non-fissile materials research and development; radioisotope research, development and processing; commercial fuel fabrication; tritium dispensing; radioactive waste management.

CNL has demonstrated the feasibility of transportation and is optimizing acquisition of new packages based on future needs, and turn-around times to ensure customer schedules are not compromised. Where CNL does not already own an appropriate package, transport packages are being secured through a combination of rentals and procurements with the necessary certifications and endorsements for the relevant countries. CNL also continues to monitor the development, design and licensing of new packages that offer additional benefits.

Key actions to de-risk and reduce schedules and cost estimates include confirming appropriate country-to-country nuclear cooperative agreements exist; identifying and securing shipment containers with the necessary certifications, registrations and endorsements; and settling terms and conditions with third-party irradiation facilities.

CONCLUSION

CNL plays a uniquely important role for Canada. It is expected to develop and maintain technical capabilities that can address existing national priorities and be responsive to emerging issues in a broad range of areas centering on nuclear science and technology, past, present and future. For 60 years, the NRU reactor has been a cornerstone of CNL's nuclear science infrastructure. To prepare for its closure in 2018, CNL is establishing a strategy to access other research reactors in a way that assures continuity of ongoing and near-to-mid-term federal and commercial projects, while sustaining the technical expertise and facilities needed to meet future challenges.

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Table 2: Preliminary List of Technical Characteristics of Existing Research Reactors

Reactor	**Type**	**Thermal Power** (MW)	**Maximum thermal flux** ($n/cm^2/s$) E<0.625eV	**Maximum fast flux** ($n/cm^2/s$) E>0.1MeV	**Initial criticality/ design life**	**Irradiation capabilities/ Test conditions**	**Largest thermal flux test volume** ($n/cm^2/s$) E<0.625eV	**Largest fast flux test volume** ($n/cm^2/s$) E>0.1MeV
Advanced Test Reactor (ATR) United States	Light water tank	250	1.0 x 10^{15}	5.0 x 10^{14} 2.0 x 10^{14} (E>1Mev)	1967/ ≥2040	6 loops 0 channels 47 in-core positions 24/36 reflector/pool positions 0 beam ports PWR loops	13.7 cm dia. 122 cm height (1.0 x 10^{15})	13.7 cm dia. 122 cm height (5.0 x 10^{14})
Belgium Reactor-2 (BR-2) Belgium	Light water tank	100	1.0 x 10^{15}	7.0 x 10^{14}	1961/ projected life is 2026 or beyond	1 loop 80 in-core channels 0 rabbits 0 beam port 15.7 MPa, 340°C PWR	90 cm height 8.0 cm dia. 20 cm dia.	-[13]
BOR-60 Russia	Fast Breeder, Na cooled	60	2.0 x 10^{14}	3.7 x 10^{15} 5.0 x 10^{14} (E>1Mev)	1968	0 loops 11 channels 15 in-core positions 10 reflector positions 0 beam ports SFR	-	4.4 cm width, 45 cm height 3.7 x 10^{15}
CABRI France	Light water pool	25	2.6 x 10^{13} Pulse: 2.12 x 10^{16}	7.34 x 10^{13} Pulse: 5.87 x 10^{16}	1963	1 loop 1 channel	-	-
China Advanced Research Reactor (CARR) China	Light water tank	60	8.0 x 10^{14}	6.0 x 10^{14}	2010	>1 loops 31 channels 4 in-core channels 9 beam ports	-	-
DHRUVA India	Heavy water	100	1.8 x 10^{14}	4.5 x 10^{13}	1985	1 loop 22 channels 5 in-core channels 2 MW pressurized water test loop	-	-
Halden Boiling Water Reactor Norway	Heavy water	20	1.5 x 10^{14}	0.8 x 10^{14}	1959/ expected to 2030 or beyond	11 loops 40 in-core positions 5 reflector positions 0 rabbits 0 beam ports PWR,BWR,GCR, HWR,VVER	7.0 cm dia. (open D_2O) 3.5 to 4.5 cm dia. (test capsule)	High power booster rigs (4 to 6 x 10^{13})
High Flux Advance Neutron Application Reactor (HANARO) Korea	Light water pool	30	4.5 x 10^{14}	2.0 x 10^{14}	1995	1 loop 39 channels 7 in-core channels 25 reflector channels 10 MPa, 290°C at outlet, 26.5 kg/s (CANDU mode)	7.4 cm dia. 1.95 x 10^{14}, E>0.82Me	7.4 cm dia. 4.30 x 10^{14}
High Flux Engineering Test Reactor (HFETR) China	Light water tank	125	6.2 x 10^{14}	1.7 x 10^{15}	1979	1 loop 11 channels 7 in-core channels >11 MPa, >300°C, ~8 kg/s	-	-
High Flux Isotope Reactor (HFIR) United States	Light water tank	85	2.5 x 10^{15}	1.0 x 10^{15} 6.0 x 10^{14} (E>1Mev)	1965/ ≥2050	0 loops 37 in-core positions 42 reflector positions 4 beam ports Irradiation temperature up to 1200 °C	7.2 cm dia. 61 cm height (4.3 x 10^{14})	7.2 cm dia. 61 cm height (1.3 x 10^{13})

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[13] Indicates data to be determined.

Reactor	**Type**	**Thermal Power** (MW)	**Maximum thermal flux** ($n/cm^2/s$) E<0.625eV	**Maximum fast flux** ($n/cm^2/s$) E>0.1MeV	**Initial criticality/ design life**	**Irradiation capabilities/ Test conditions**	**Largest thermal flux test volume** ($n/cm^2/s$) E<0.625eV	**Largest fast flux test volume** ($n/cm^2/s$) E>0.1MeV
High Flux Reactor (HFR) Netherlands	Light water tank	45	2.7 x 10^{14}	5.1 x 10^{14} 2.2 x 10^{14} (E>1 Mev)	1961	0 loops 19 in-core positions 12 reflector positions 0 rabbits 12 beam ports PWR,BWR,GCR	60 cm height (2.9 x 10^{14})	60 cm height (1.8 x 10^{14})
High Flux Research Reactor (SM-3) Russia	Light water pressure vessel, trap-type	100	5.0 x 10^{15}	2.0 x 10^{15} 6.0 x 10^{14} (E>1Mev)	1961	2 loops 1 channel 6 in-core positions 30 reflector positions 0 beam ports	6.8 cm dia.	6.8 cm dia.
Japan Materials Test Reactor (JMTR) Japan	Light water tank	50	4.0 x 10^{14}	4.0 x 10^{14}	1968	2 loops 20 in-core positions 40 reflector positions 2 rabbits PWR,BWR,GCR	3.6 cm dia. 85 cm height (4.0 x 10^{14})	-
JOYO Japan	Fast, Na cooled	140	5.7 x 10^{15}	4.0 x 10^{15}	1977	0 loops 5 channels 21 in-core positions 1 reflector positions SFR	-	60 cm height Fuel bundle sized capsules (4.0 x 10^{15})
Jules Horowitz Reactor France	Tank in pool	100	5.5 x 10^{14}	1.0 x 10^{15} 5.5 x 10^{14} (E>1 Mev)	Expected in 2022 /50 years	1 corrosion loop 10 in-core positions 26 reflector positions 0 rabbits 0 beam ports PWR,BWR,GCR,SFR	10 cm in-core position 20 cm dia. reflector position	10 cm in-core position 20 cm dia. reflector position
LVR-15 REZ Czech Republic	Light water tank	10	1.5 x 10^{14}	3.0 x 10^{14}	1957	4 loops 16 channels 2 in-core channels 2 reflector channels	-	-
Massachusetts Institute of Technology Reactor – II (MITR-II) United States	Light water tank with heavy water outer tank	6	7.0 x 10^{13}	1.7 x 10^{14}	1975/ ≥2050	1 loop 3 in-core positions 9 reflector positions 9 beam ports In-core flow loops at PWR or BWR conditions, HTGR materials loop up to 1600 °C, gas-filled static capsule with instrumentation available	4.57 cm dia. 55.9 cm height (3.6 x 10^{13})	4.57 cm dia. 55.9 cm height (1.2 x 10^{14})
McMaster Nuclear Reactor (MNR) Canada	Pool	3	1.0 x 10^{14}	4.0 x 10^{13}	1959	0 loops 7 channels (4.0E+13 max flux)	-	-
MIR-M1 Russia	Light water cooled, Be moderated	100	5.0 x 10^{14}	1.0 x 10^{14}	1966/ >2020	7 loops 13 channels 11 in-core channels 20 MPa, 300°C, up to 27.8 kg/s	12 cm dia.	12 cm dia.
Multipurpose Fast Research Reactor (MBIR) Russia	Fast, power, Na cooled	150	-	5.3 x 10^{15}	Target date: 2020/ 50 years	3 loops (1 sodium loop) 14 channels 3 in-core channels Inlet: 330 to 600 °C Outlet up to 850 °C	7.2 cm width 12.0 cm dia. 55 cm height	7.2 cm width 12.0 cm dia. 5.0 x 10^{15}

Reactor	**Type**	**Thermal Power** (MW)	**Maximum thermal flux** ($n/cm^2/s$) E<0.625eV	**Maximum fast flux** ($n/cm^2/s$) E>0.1MeV	**Initial criticality/ design life**	**Irradiation capabilities/ Test conditions**	**Largest thermal flux test volume** ($n/cm^2/s$) E<0.625eV	**Largest fast flux test volume** ($n/cm^2/s$) E>0.1MeV
Open Pool Australian Lightwater (OPAL) reactor Australia	Light water pool	20	2.0×10^{14}	2.1×10^{14}	2006	10 horizontal channels 80 vertical channels 0 in-core irradiation channels 0 loops	-	-
PIK Russia	Light water tank, heavy water reflector	100	4.8×10^{15}	8.0×10^{14}	2011	2 loops 17 channels 1 in-core channel 6 reflector channels	10 cm dia. 4.8×10^{15}	4.1 cm dia. 8.0×10^{14}
RA-10 Argentina	Light water	30	3.0×10^{14}	$>3.0 \times 10^{14}$	Expected in 2020	-	8 x 8 cm section with 65 cm length $>1.0 \times 10^{14}$	5 cm dia. 12 cm length $>3.0 \times 10^{14}$
SLOWPOKE-2 (various) Canada	Pool	20 kW	1.0×10^{12}	$\geq 1.8 \times 10^{11}$	1976 and later	Up to 5 positions	-	-
Transient Reactor Test Facility (TREAT) United States	Graphite, Pulse	0.08	4.0×10^{11} Pulse: 1.0×10^{17}	-	1959	-	-	-
TRIGA-II Romania	Light water TRIGA dual cores	14	2.6×10^{14}	1.8×10^{14}	1980	1 loop 8 channels 6 in-core channels 2 reflector channels 15.5 MPa, 280 to 300°C	-	-
U.S. National Bureau of Standards Reactor (NBSR) United States	Heavy water tank	20	4.0×10^{14}	2.0×10^{14}	1967/ ≥2065	0 loops 10 in-core positions 7 reflector positions 18 beam ports Static capsules only	8.89 cm dia. 73.7 cm height (4.0×10^{14})	8.89 cm dia. 73.7 cm height (2.0×10^{14})
University of Missouri Research Reactor (MURR) United States	Light water tank	10	6.0×10^{14}	1.0×10^{14}	1966/ ≥2056	0 loops 3 in-core positions 12/3 reflector/pool positions 6 beam ports Static capsules only	13.6 cm dia. 61 cm height (6.0×10^{14})	13.6 cm dia. 61 cm height (6.0×10^{13})