INL/RPT-24-80056-Revision-0

Survey of neutron flux sensors for monitoring advanced reactor concepts operating with low neutron fluence rate and extended uninterrupted lifespans

August 2024

Changing the World's Energy Future

Kevin Tsai

Idaho National Laboratory

INL/RPT-24-80056-Revision-0

Survey of neutron flux sensors for monitoring advanced reactor concepts operating with low neutron fluence rate and extended uninterrupted lifespans

Kevin Tsai

August 2024

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

INL/RPT-24-80056

Survey of Neutron Flux Sensors for Monitoring Advanced Reactor Concepts Operating with Low Neutron Fluence Rate and Extended Uninterrupted Lifespans

Milestone Report—M4CT-24IN0702014

Advanced Sensors and Instrumentation

JULY 2024

Kevin Tsai

Idaho National Laboratory

Idaho National Laboratory

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy

INL/RPT-24-80056

Survey of Neutron Flux Sensors for Monitoring Advanced Reactor Concepts Operating with Low Neutron Fluence Rate and Extended Uninterrupted Lifespans

Milestone Report—M4CT-24IN0702014

Kevin Tsai
Idaho National Laboratory

July 2024

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

Page intentionally left blank

CONTENTS

FIGURES

TABLES

Page intentionally left blank

ACRONYMS

BWR	boiling water reactor
CIC	compensated ion chamber
cps	counts per second
FC	fission chamber
MSV	mean square voltage
PC	proportional counter
SMR	small modular reactor
SPND	self-powered neutron detector
UIC	uncompensated ion chamber

Page intentionally left blank

Survey of Neutron Flux Sensors for Monitoring Advanced Reactor Concepts Operating with Low Neutron Fluence Rate and Extended Uninterrupted Lifespans

1. INTRODUCTION

Several advanced reactor concepts focused on compact and modular designs are under development, with support from the U.S. Department of Energy's Advanced Reactor Demonstration Program. [1]. These small modular reactors (SMRs) and microreactors are designed to enable flexibility and scalability for deployment. Additionally, depending on the application, extended uninterrupted operational lifetimes with minimal external intervention are desired. Given these design requirements, microreactors operate in the power range of 1–20 MWe, and SMRs in the power range of 20–300 MWe. The purpose of this report is to provide a survey of neutron sensors applicable to the low power levels (low neutron fluence rate) for reactor monitoring and controls. A survey of detectors for reactor power monitoring and controls from various commercial vendors—Reuter-Stokes, Framatome, Exosens, and Mirion—is presented in the following sections based on application of reactor power ranges. Detector specifications are provided where available per each of the vendor's catalogues and specification sheets found on their websites. While this is not an all-encompassing list, it provides an example of detector options. Fission chambers and self-powered neutron detectors (SPNDs) for in-core application with changes to the neutron-sensitive materials—fissile depots for fission chambers and emitters for SPNDs—for regenerative capabilities will be discussed in the latter sections.

The typical power monitoring ranges are source, intermediate, and startup to above 100% and around 12 decades of neutron flux, depending on design. A typical spread of monitoring ranges for ex-core detectors is given in Figure 1. [2] Additional spreads of monitoring ranges for comparison can be found in Appendix A. It should be noted that the expected flux levels from two similarly power-rated reactors can vary significantly due to differences in design, and the power-to-flux ratio cannot be determined without intimate knowledge of the reactor configuration. However, this does not detract from the typical application of detector types per reactor monitoring range. This is due to the importance of detector types rather than sensitivity, which can be altered by varying the mass of the neutron reactive material or the detector volume.

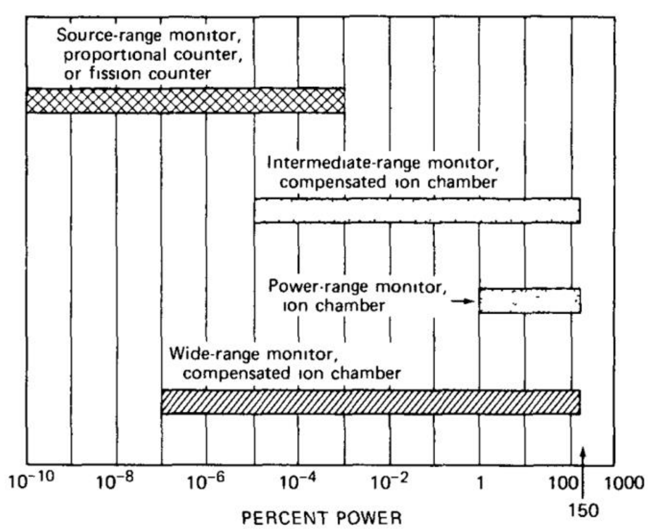

Figure 1. Typical power range separation and ex-core detector types. [2]

2. SOURCE RANGE DETECTORS

Source range detectors are typically proportional counters (PC) or fission chambers (FC). In both cases, the measurement is performed by measuring the pulses related to a neutron interaction through the detector and outputs in counts per second (cps). Operation in pulse mode is necessary due to low neutron flux levels and a high gamma background. Typical proportional counters use B-10 lining or BF_3 gas that interacts with a neutron and emits an alpha in an (n, α) reaction. Likewise, for fission chambers, the neutron reactive lining is U-235 that undergoes a neutron-induced fission (n, f) reaction. In both cases, the alpha-particle or fission product has the higher ionizing energy in the fill-gas compared to the background gamma, thus allowing for background rejection through a pulse-height discriminator. A list of commercially-available source range detectors is provided in Table 1.

Table 1. List of commercially-available source range detectors.

Detector Model	Detector Type	Sensitivity	Range (nv)		Max Temperature (°C)	Max Dimensions (cm)	
			Min	Max		Diameter	Length
Reuter-Stokes							
RS-P6-1608-110	FC	0.95 cps/nv	--	10^{10} nv	300	5.16	30.66
Framatome							
Proportional counter	PC	--	--	--	200	2.54–7.65	39.4–7.61
Exosens							
CPNB28	PC	5 cps/nv	2×10^{-1}	4×10^{5}	200	2.54	36.8
CPNB48	PC	10 cps/nv	10^{-1}	2×10^{5}	200	2.54	56.0
CPNB44	PC	8 cps/nv	10^{-1}	2×10^{5}	200	4.8	76.1
CPNB65	PC	25 cps/nv	5×10^{-2}	5×10^{4}	200	7.65	72.7
CPNB64	PC	25 cps/nv	5×10^{-2}	5×10^{4}	200	7.65	74.15
CPNB84	PC	42 cps/nv	5×10^{-2}	3×10^{4}	200	8.2	74.15
Mirion							
CPNB25	PC	4 cps/nv	5×10^{-1}	3×10^{5}	200	2.54	39.4
CPNB45	PC	8 cps/nv	10^{-1}	2×10^{5}	200	2.54	67.8
CPNB48	PC	10 cps/nv	10^{-1}	10^{5}	200	2.54	56.0
CPNB35	PC	12 cps/nv	10^{-1}	10^{5}	200	7.65	44.3
CPNB65	PC	20 cps/nv	5×10^{-2}	5×10^{4}	200	7.65	72.7
CPNB44	PC	8 cps/nv	10^{-1}	2×10^{5}	200	4.80	76.1
CPNB34	PC	12 cps/nv	10^{-1}	10^{5}	200	7.65	45.75
CPNB64	PC	20 cps/nv	5×10^{-2}	5×10^{4}	200	7.65	74.15

The operating range for pulse mode is limited by the detector type and the electronic system. This is to avoid pulse pileup from high-frequency pulses without sufficient decay time, and to have an electronic system that can track up to 10^7 cps (seven decades). [3] After the reactor reaches the upper operational range of the source range detector, power monitoring is passed on to the intermediate range detectors. The source range detectors are turned off and usually retracted or shielded to prolong their lifespan. [4]

3. INTERMEDIATE RANGE DETECTORS

Intermediate range detectors are typically compensated ion chambers (CIC) or fission chambers. In the intermediate power range, the neutron flux is high enough that it is more practical to measure the neutron flux through integrated electrical current instead of pulses. However, a straightforward electrical current measurement includes all radiation contribution (regardless of pulse height). As such, compensation techniques need to be employed to reduce the background gamma contribution. In the case of the CIC, gamma compensation is employed by using two ionization chambers. The primary chamber is lined with B-10 to measure the total radiation (neutron and gamma), and the other chamber compensates for the gamma contribution by omitting the B-10 lining. The difference between the two chambers provides the neutron-contributed current. For the fission chamber, gamma contribution reduction can be performed by operating in mean square voltage (MSV) mode. [3] This is done through the electronics signal processing system by measuring the time averaged squared amplitude of the electric current fluctuation. This method gives greater weight to neutron-related events with a higher charge contribution, such as fission fragment ionization, than smaller charge contributions such as gamma ionization.

The lower limitation of these detectors is provided by the leakage current of the detector system, but the detection range can span the remaining reactor power range to beyond full power. A list of commercially-available source range detectors is provided in Table 2. However, due to advantages such as simplicity of operation, the power range detectors are used for full power operations.

Table 2. List of commercially-available intermediate range detectors.

Detector Model	Detector Type	Sensitivity (A/nv)	Range (nv)		Max Temp. (°C)	Max Dimensions (cm)	
			Min	Max		Diameter	Length
Reuter-Stokes							
RS-C1B-2514-115	CIC	9.4×10^{-14}	2.5×10^{2}	2.5×10^{10}	200	8.02	60.17
RS-C1B-1210-135	CIC	3.6×10^{-14}	10^{4}	10^{11}	200	3.89	34.45
Framatome							
CC-80	CIC	--	--	--	120	8.0	57.3
CC-83 VV	CIC	--	--	--	120	8.4	30.25
Mirion							
KNK 50 SAC	CIC	4.2×10^{-14}	10^{2}	10^{10}	130	5.0	66.5

4. POWER RANGE DETECTORS

Power range detectors are generally uncompensated ion chambers (UIC) or fission chambers. Power range detectors are chosen over intermediate detectors with similar operational ranges for their inherent simplicity. At full power, the neutron-to-gamma ratio is high enough that gamma compensation or reduction methods are not necessary. Therefore, the detector design can be simplified into an uncompensated design, such as the UIC, or can operate fission chambers in current mode instead of MSV mode. Simplifying the detector design or operational mode reduces the potential for failure or error. A list of commercially-available power range detectors is provided in Table 3.

Table 3. List of commercially-available power range detectors.

Detector Model	Detector Type	Sensitivity (A/nv)	Range (nv)		Max Temp. (°C)	Max Dimensions (cm)	
			Min	Max		Diameter	Length
Reuter-Stokes							
RS-C2B-0808-129	UIC	1.7×10^{-14}	10^{4}	10^{11}	200	2.62	23.09
RS-C6-1100	FC	1×10^{-17}	1.4×10^{12}	1.4×10^{14}	315	--	--
Framatome							
CNC-50	UIC	--	--	--	120	4.9	47.6
Mirion							
KNK 50-1 ACH … KNK 50-6 ACH	CIC	0.7×10^{-14} … 4.4×10^{-14}	10^{2}	10^{10}	200	5.0	25.5 … 70.5
KNU 50-1 ACH … KNU 50-6 ACH	UIC	0.7×10^{-14} … 4.4×10^{-14}	10^{2}	10^{10}	200	5.0	25.5 … 70.5

5. WIDE RANGE DETECTORS

It can be observed that the fission chambers are available for in-core use in all power ranges. As such, fission chambers can also be used as wide range detectors. This is achievable due to a controllable fissile deposit and electronic systems that can switch between operational modes. Wide range detectors are typically added for supplemental data acquisition. They provide additional data for power distribution monitoring and information for source, intermediate, and power range detector recalibration. A list of commercially-available wide range ex-core detectors is provided in Table 4.

Table 4. List of commercially-available wide range detectors.

Detector	Sensitivity	Range (nv)		Max Temp. (°C)	Max Dimensions (cm)	
		Min	Max		Diameter	Length
Reuter-Stokes						
RS-C3-2510-114	(current) $>1.2\times10^{-13}$ A/nv	--	(counting) 10^{10}	300	8.02	33.18
	(MSV) $>1\times10^{-10}$ V^2/nv	(MSV) 10^{4}	(MSV) 10^{10}			
Framatome						
FC range	--	--	--	140–550	0.62–8.9	4.55–70.0
Exosens						
CFUM11	1×10^{-1} cps/nv	10	10^{7}	250	2.54	22.7
	1×10^{-14} A/nv	10^{7}	10^{11}			
CFUM18	1×10^{-1} cps/nv	10	10^{7}	250	2.54	26.3
	1×10^{-14} A/nv	10^{7}	10^{11}			

		Range (nv)		Max Temp. (°C)	Max Dimensions (cm)	
Detector	Sensitivity	Min	Max		Diameter	Length
CFUM21	1×10^{-2} cps/nv	10^{2}	10^{8}	250	2.54	22.7
	1×10^{-15} A/nv	10^{8}	10^{12}			
CFUM19	0.6 cps/nv	2	2×10^{6}	250	4.8	42.1
	1.2×10^{-13} A/nv	2×10^{4}	2×10^{10}			
CFUP08	0.7 cps/nv	1	10^{6}	250	7.65	38.9
	1.4×10^{-13} A/nv	10^{4}	10^{10}			
CFUC06	1 cps/nv	1	10^{5}	600	4.8	41.2
	2×10^{-13} A/nv	10^{4}	10^{10}			
CFUL01	1 cps/nv	1	10^{6}	250	4.8	33.7
	2×10^{-13} A/nv	10^{4}	10^{10}			
CFUL08	1 cps/nv	1	10^{6}	250	4.8	38.45
	2×10^{-13} A/nv	10^{4}	10^{10}			
CFUK09	3 cps/nv	0.3	3×10^{5}	250	6.0	38.5
	6×10^{-13} A/nv	10^{5}	10^{10}			
CFUG08	4 cps/nv	0.2	2×10^{5}	250	8.0	41.9
	8×10^{-13} A/nv	10^{5}	7×10^{10}			
Mirion						
CFUG08	4 cps/nv	2×10^{-1}	2×10^{5}	250	8.0	41.9
	1.6×10^{-25} A^2Hz^{-1}/nv	2×10^{3}	7×10^{10}			
	8×10^{-13} A/nv	1×10^{5}	7×10^{10}			
CFUL08	1 cps/nv	1	1×10^{6}	250	4.8	38.45
	4×10^{-26} A^2Hz^{-1}/nv	8×10^{4}	2×10^{9}			
	2×10^{-13} A/nv	1×10^{4}	1×10^{10}			
CFUM18	1×10^{-1} cps/nv	10	1×10^{7}	250	2.54	26.3
NY-11016	0.7 cps/nv	2	2×10^{10}	150	7.62	58.0
	2×10^{-13} A/nv					
WL-6376A	0.7 cps/nv	1.4	1.4×10^{10}	--	--	--
	1.4×10^{-13} A/nv					

6. IN-CORE DETECTORS

In-core detectors can generally be split into two categories: fission chambers and SPNDs. This does not include activation detectors and systems that monitor materials that traverse the core, which can take the form of solids, liquids, or gases (i.e., activation foils, coolant activation monitoring, etc.). [2] In-core detectors are most commonly used with boiling water reactors (BWRs), where the two-phase flow of water coolant necessitates large numbers of in-core detectors for local and average power monitoring. [5] However, for most reactors, having a form of periodic or continuous in-core monitoring has been found to be advantageous in terms of improving reactor utility—increasing power margins, maintaining balanced fuel burnup, etc. A list of commercially-available in-core fission chambers used for supplemental data acquisition such as flux mapping is provided in Table 5.

Table 5. List of commercially-available in-core fission chambers.

Detector	Sensitivity	Range (nv)		Max Temp. (°C)	Max Dimensions (cm)	
		Min	Max		Diameter	Length
Reuter-Stokes						
RS-C6-0201-231	8.5×10^{-18} A/nv	10^{11}	2×10^{14}	--	0.48	5.51
Framatome						
Movable incore probe	1×10^{-17} A/nv	10^{10}	1.4×10^{14}	--	0.47	6.6
Exosens						
CFUE24	1×10^{-2} cps/nv	10^{2}	10^{8}	400	0.7	15.0
	1×10^{-15} A/nv	10^{8}	10^{12}			
CFUE32	1×10^{-3} cps/nv	10^{3}	10^{8}	600	0.7	15.0
	1×10^{-16} A/nv	10^{9}	10^{13}			
CFUF43	1×10^{-17} A/nv	10^{10}	10^{14}	350	0.47	8.6
CFUR43	3×10^{-18} A/nv	10^{11}	1.5×10^{14}	350	0.3	4.2
CFUZ53	5×10^{-18} A/nv	2×10^{11}	10^{14}	350	0.15	4.9
CFUR64	8×10^{-6} cps/nv	10^{6}	10^{11}	400	0.3	4.2
	9.2×10^{-19} A/nv	10^{12}	10^{15}			
	4×10^{-27} A^2Hz^{-1}/nv	1×10^{5}	3×10^{10}			
	1×10^{-14} A/nv	1×10^{7}	1×10^{11}			
Mirion						
WL-24132	5.6×10^{-18} A/nv	10^{10}	1.4×10^{14}	400	0.47	6.6
NY-10026	1×10^{-17} A/nv	--	--	343	--	--

Separately, SPNDs are also an acceptable replacement to fission chambers at sufficient power levels. These detectors are more commonly used for Canada Deuterium Uranium reactors. [6] SPNDs have the benefits of simple construction, ruggedness, and a small footprint, and they don't require a high-voltage power supply, but these benefits come at a cost of lower sensitivity and gamma rejection. As such, SPNDs are most often used for power range detectors or supplemental data acquisition sensors similar to wide range detectors. Two categories of SPNDs exist based on their emitter material: prompt-response, which utilizes the two-interaction process of (n, γ, e), and delayed-response, which utilizes the single-interaction process of (n, β). Prompt-response SPNDs typically use platinum, Inconel, or cobalt emitters, and can be used for power range detectors tied to reactor controls and safety. However, their sensitivity is limited, often to an order of magnitude below delayed-response SPNDs. Delayed-response SPNDs typically use rhodium or vanadium emitters and have good neutron-to-gamma signal ratio at most power levels, but are limited by the decay half-life of the activated emitter material; thus, they are only used for flux distribution measurements. Given the simplicity of their design and fabrication, many SPNDs can be purchased based on customer specifications (from vendors such as Framatome and Thermocoax) and are thus not advertised beyond availability and emitter types. However, for comparison, a list of SPNDs with specifications from Mirion is provided in Table 6.

Table 6. List of SPNDs available from Mirion with specifications.

Detector	Emitter	Sensitivity (A/nv)	Range (nv)		Probe Dimension (cm)	
			Min	Max	Diameter	Length
Mirion						
WL-23215	Rhodium	1.0×10^{-20}	10^{9}	10^{15}	0.16	7.6
WL-23226	Vanadium	1.1×10^{-20}	10^{9}	10^{15}	0.16	132.1
WL-23283	Cobalt	1.4×10^{-21}	10^{10}	10^{15}	0.16	86.4

In general, fission chambers can be fabricated with enough fissile material, coupled with flexibility in operational modes—pulse, MSV, and current mode—to operate in low-power reactors such as SMRs and microreactors. Since SPNDs can only operate in current mode, they are limited to power range operations. Additionally, increasing the sensitivity of an SPND involves making compromises with detector burnup and local flux depression by selecting stronger neutron-absorbing emitters or increasing its size.

6.1. Extending Detector Lifespan

All neutron sensors listed in this report are subject to signal degradation. A major component of signal degradation is burnup of the neutron-reactive materials responsible for providing sensor signals in response to a neutron flux, as shown in Figure 2. As such, neutron detectors often need to be recalibrated or replaced over time. However, for microreactors and SMRs, minimizing external intervention is desirable. Detector longevity is thus an important factor in sensor design. To address detector burnup and extend the detector's lifespan within a reactor, regenerative neutron-sensitive materials that can sustain a strong detector signal for a higher neutron fluence are considered.

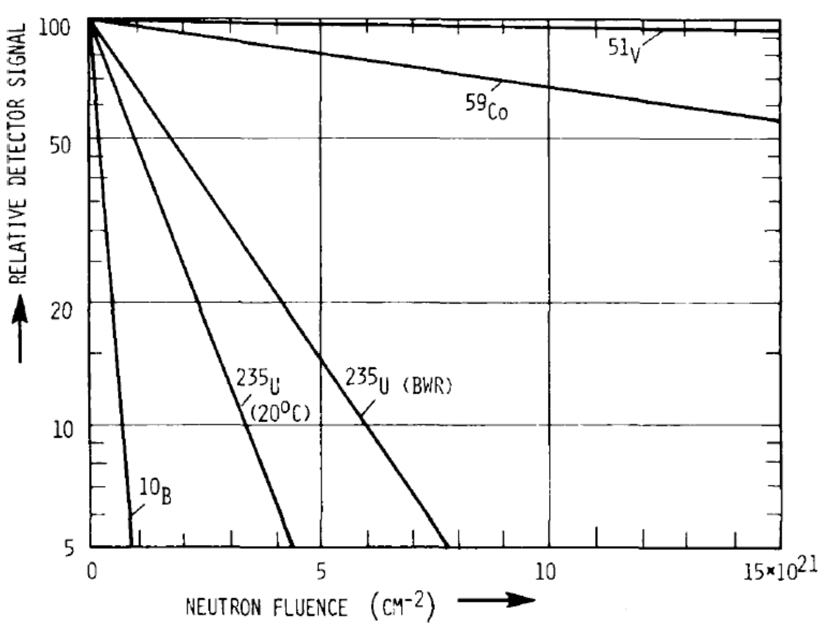

Figure 2. Detector signal degradation as a function of neutron fluence. [7]

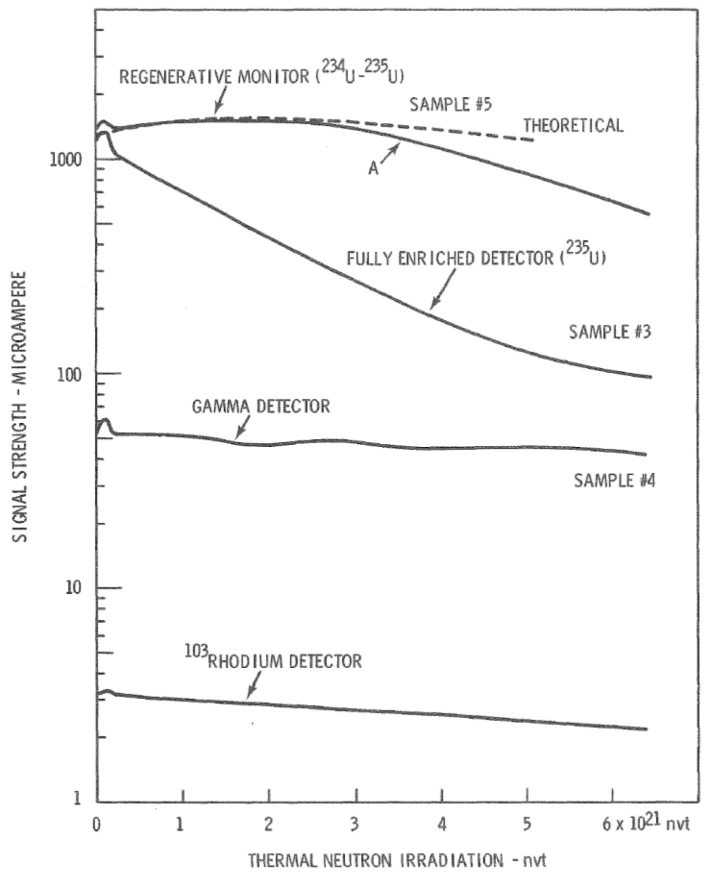

Figure 3. Detector signal for regenerative fission chamber compared to typical in-core detectors. [8]

A solution already exists for fission chambers. The preferred regenerative method for fission chambers is to use U-234 as the fertile isotope to generate the fissile isotope U-235. The ratio of U-234 to U-235 is used to maintain a balanced rate of generation-to-burnup of U-235. This can be calculated per reactor design. [8] This method is common practice for many commercial in-core fission chambers. An example regenerative fission chamber used in a commercial BWR contains a ratio of 18% U-235 to 78% U-234. [9]

Typical SPNDs have a low burnup compared to fission chambers due to significantly lower neutron capture cross-sections than U-235 (and corresponding lower neutron sensitivity). [7] However, historical mentions of emitters with prolonged life and some regenerative-like capabilities exists. These emitters are terbium, thulium, and tantalum. [10], [11] They are chosen as prompt-response emitters with a high neutron capture cross-section for higher sensitivity, which would generally result in higher burnup. However, the activation products generated also have a comparable or higher neutron capture cross-section that generates its own prompt signal through the (n, γ, e) reaction. Additionally, the activation products have a long decay half-life that would reduce the effects of a direct-current offset from long-term exposure.

For both the regenerative fission chamber and the SPND, additional analysis of the reactor design is needed to ensure that the regenerative nature of the fission chamber or SPND is within an acceptable tolerance for reactor monitoring over the detector lifespan. For the fission chamber, a proper mixture of U-234 to U-235 would result in a balanced generation-to-burnup ratio. However, for the SPND, an acceptability study on the progression of detector sensitivity over time would be needed since the isotopic compositions are unlikely to change.

7. SUMMARY

Reactor monitoring generally takes place under three ranges: source, intermediate, and power. Each range utilizes a detector that functions optimally for its intended purpose. Lists of commercially available detectors for each reactor range were provided as a guide to assess applicability based on reactor design requirements, such as sensitivity, size, and operational temperature. However, it should be noted that the sensitivities and geometries of the detectors presented are only typical values and can change based on reactor requirements. Separately, given the inclusion of in-core detectors utilizing fission chambers and SPNDs for wide range monitoring and power distribution measurements, methods of signal regeneration or retention were provided as a starting point for future assessments.

8. REFERENCES

[1] Office of Nuclear Energy. "Advanced Reactor Types Fact Sheet." 2019. https://www.energy.gov/sites/default/files/2020/05/f74/Advanced-Reactor-Types_Fact-Sheet_Draft_Hi-Res_R1.pdf Handbook vol. 1 ML14031A424

[2] Harrer, J. M. and J. G. Beckerley, "Nuclear Power Reactor Instrumentation Systems Handbook." vol. 1, U.S. Atomic Energy Commission. 1973. https://www.nrc.gov/docs/ML1403/ML14031A424.pdf

[3] Knoll, Glenn F. "Radiation Detection and Measurement." 4th ed. Hoboken, N.J: John Wiley, 2010. Print.

[4] U.S. Department of Energy. "DOE Fundamentals Handbook Instrumentation and Control." vol. 2. DOE-HDBK-1013/2-92. 1992. https://www.standards.doe.gov/standards-documents/1000/1013-bhdbk-1992-v2/@@images/file

[5] Harrer, J. M. and J. G. Beckerley, "Nuclear Power Reactor Instrumentation Systems Handbook." vol. 2, U.S. Atomic Energy Commission. 1973. https://www.nrc.gov/docs/ML1403/ML14031A391.pdf

[6] Allan, C. J. "Response Characteristics of Self-Powered Flux Detectors in CANDU Reactors." AECL-6171. International Symposium on Nuclear Power Plant Control and Instrumentation. Cannes, France. 1978. https://inis.iaea.org/collection/NCLCollectionStore/_Public/09/411/9411990.pdf

[7] Böck, H. "Miniature Detectors for Reactor Incore Neutron Flux Monitoring." *Atomic Energy Review*. 14(1): 87–132. 1976. https://inis.iaea.org/collection/NCLCollectionStore/_Public/53/072/53072397.pdf

[8] Bunch, W. L., W.G. Spear, and M.R. Wood. "In-core Regenerative Thermal Neutron Detectors for Nuclear Reactors." WHAN-FR-37. WADCO Corporation. 1970. https://doi.org/10.2172/4050544

[9] USNRC HRTD. "General Electric Systems Technology Manual Chapter 5.3 Local Power Range Monitoring System." Rev. 09/11. https://www.nrc.gov/docs/ML1125/ML11258A333.pdf

[10] Klar, E. "Long-Life Neutron Detector for Instrumentation of a Nuclear Reactor Core." United States Patent. Patent No. 3903420. 1975.

[11] Shields, R. B. "Neutron and Gamma Flux Detector." United States Patent. Patent No. 3787697. 1974.

Appendix A

Additional Power and Fluence Ranges

A-1. INTRODUCTION

While it is common to separate detector types into three monitoring ranges, the minimum and maximum spread of each range is not standardized (nor required to be) due to differences in reactor design. The main requirement is simply to monitor power, with appropriate range overlap, from startup to full power (and some percentage above for overpower protection). As such, the following figures present power coverage data obtained from reports and vendors based on reactor designs and vendor suggestions.

A-1.1 Pressurized Water Reactor

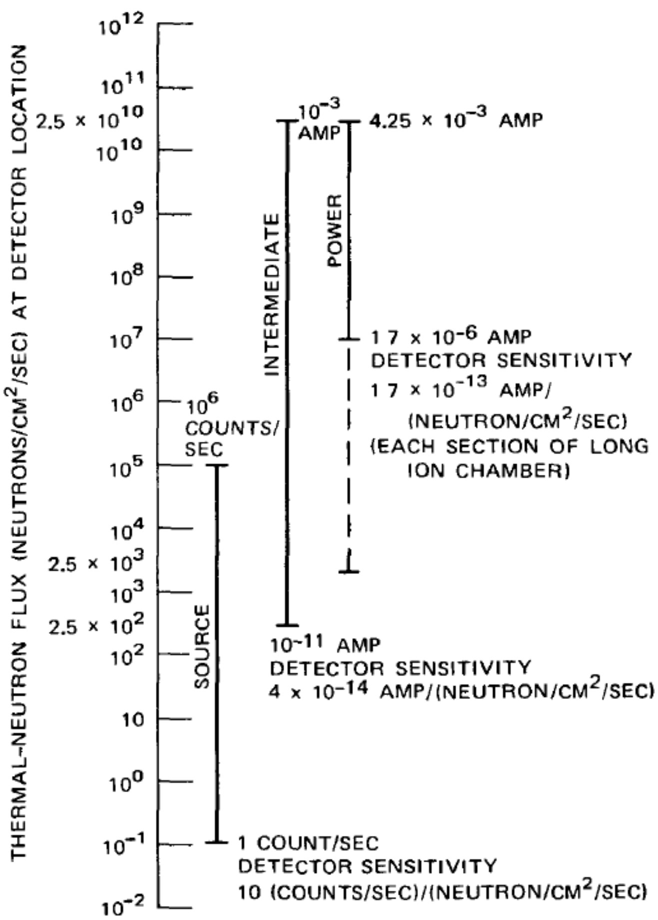

Figure A-1. Pressurized water reactor neutron flux monitoring spread.

Harrer, J. M. and J. G. Beckerley, "Nuclear Power Reactor Instrumentation Systems Handbook." vol. 2, U.S. Atomic Energy Commission. 1973. https://www.nrc.gov/docs/ML1403/ML14031A391.pdf

A-1.2 Sodium-Cooled Reactor

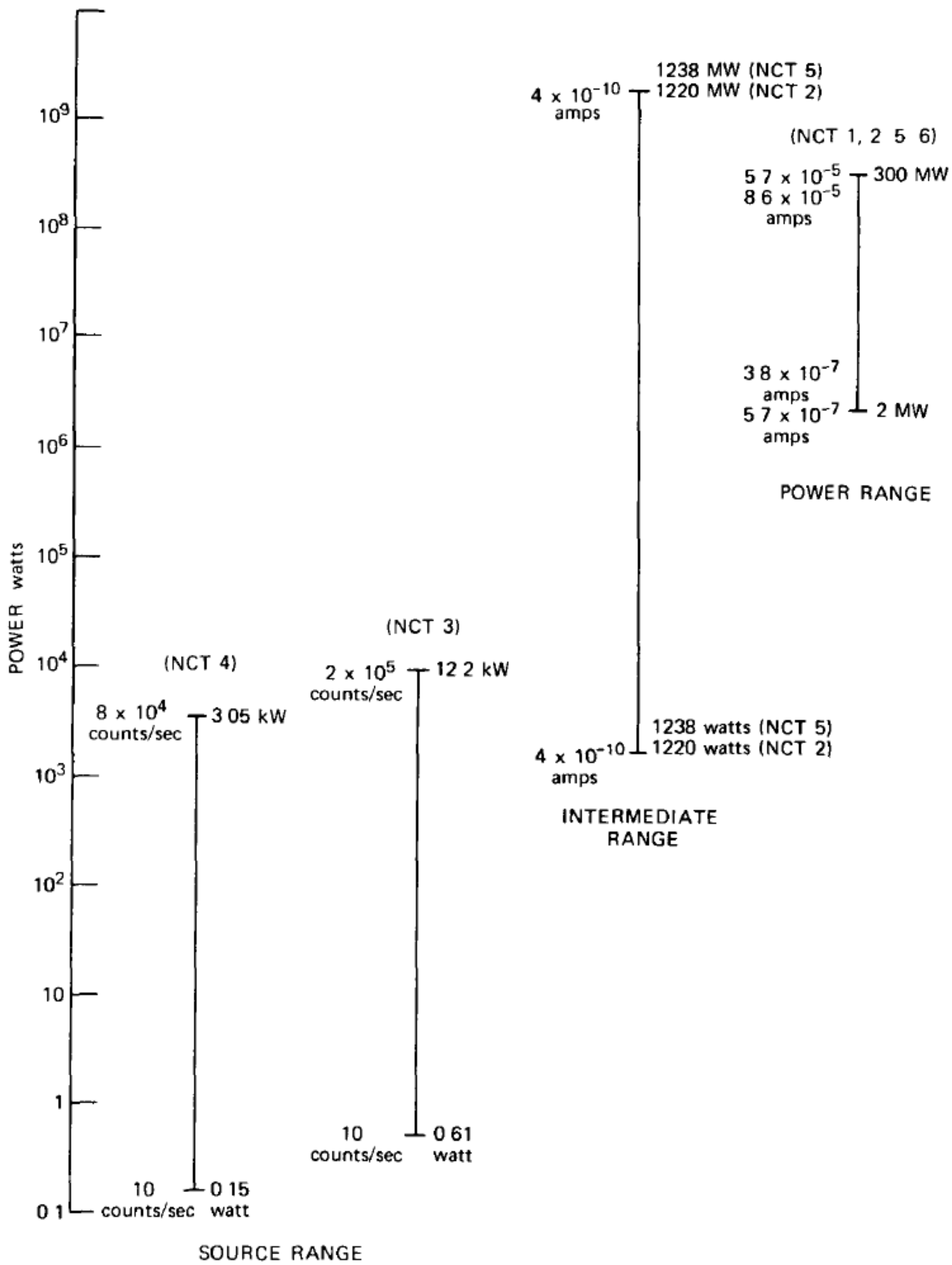

Figure A-2. Sodium-cooled reactor power monitoring spread.

Harrer, J. M. and J. G. Beckerley, “Nuclear Power Reactor Instrumentation Systems Handbook.” vol. 2, U.S. Atomic Energy Commission. 1973. https://www.nrc.gov/docs/ML1403/ML14031A391.pdf

A-1.3 High-Temperature Gas Reactor

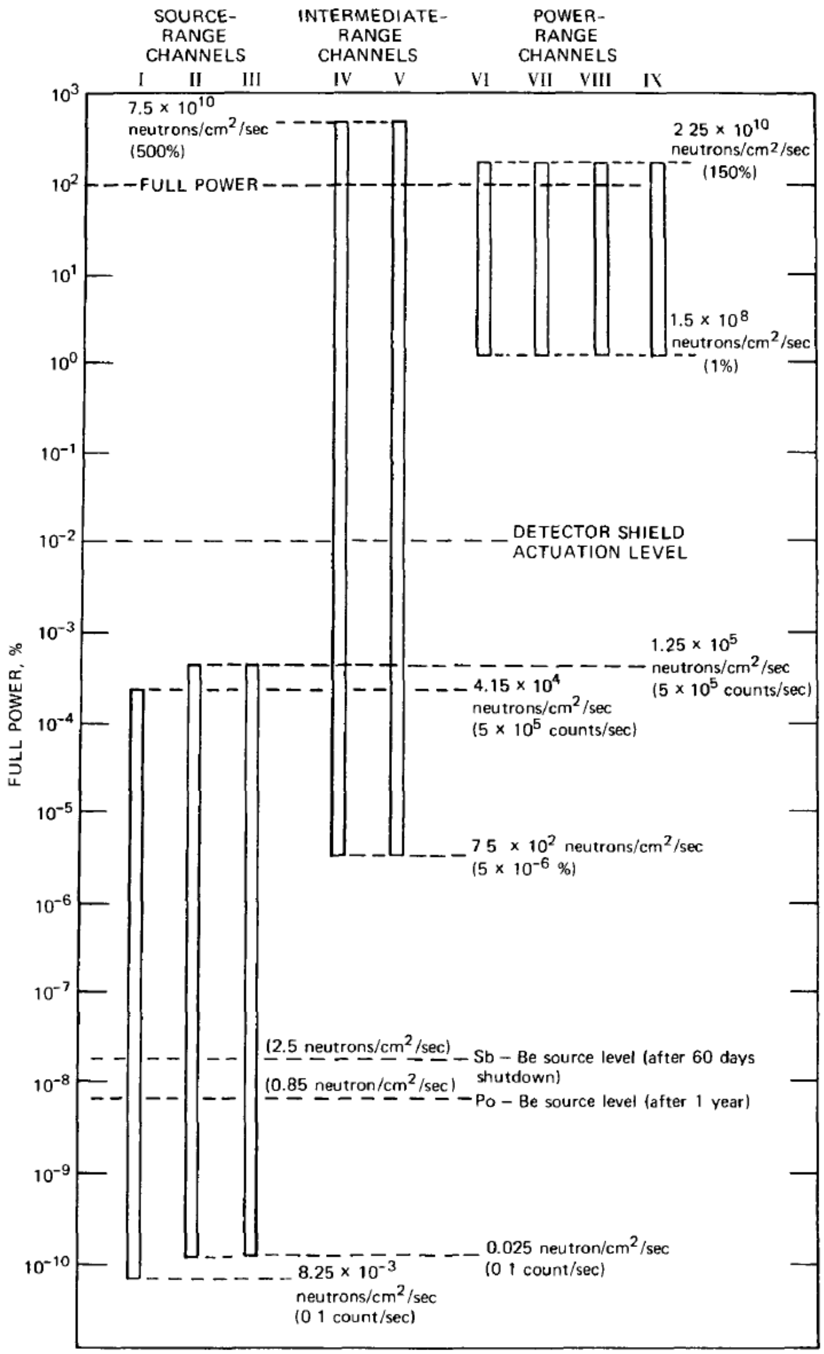

Figure A-3. High-temperature gas reactor (from Peach Bottom) power monitoring spread.

Harrer, J. M. and J. G. Beckerley, "Nuclear Power Reactor Instrumentation Systems Handbook." vol. 2, U.S. Atomic Energy Commission. 1973. https://www.nrc.gov/docs/ML1403/ML14031A391.pdf

A-1.4 Reuter-Stokes Selection Guide of Neutron Detectors for Reactor Control

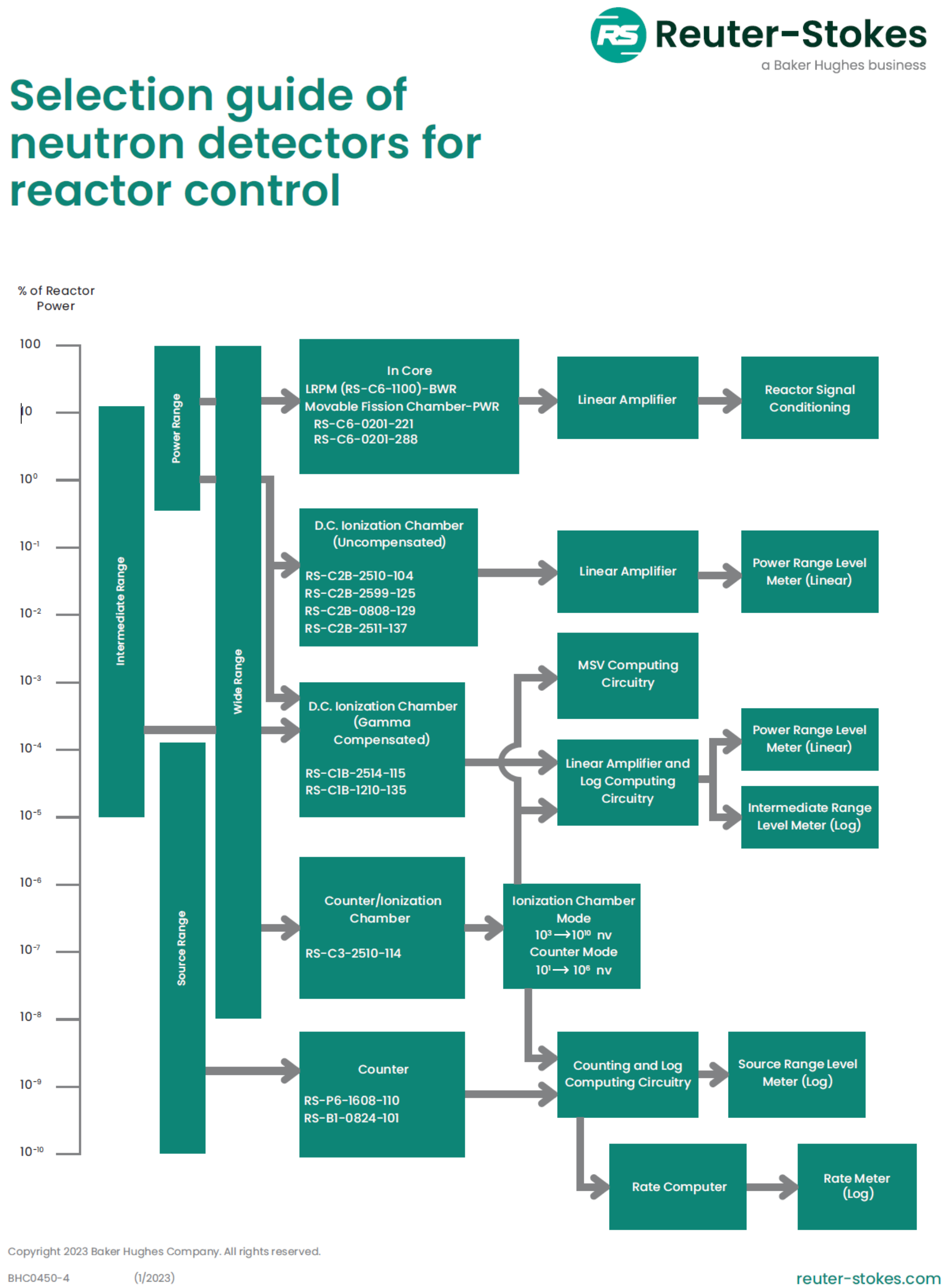

Figure A-4. Reactor power spread selection guide for Reuter-Stokes power monitoring detectors.

"Selection guide of neutron detectors for reactor control." Reuter-Stokes. 2023. https://dam.bakerhughes.com/m/7e8f96db7dda675b/original/0450-Selection-Guide-of-Neutron-Detectors-for-Reactor-Control-Data-Sheet.pdf

A-1.5 Framatome Flux Measurement Ranges

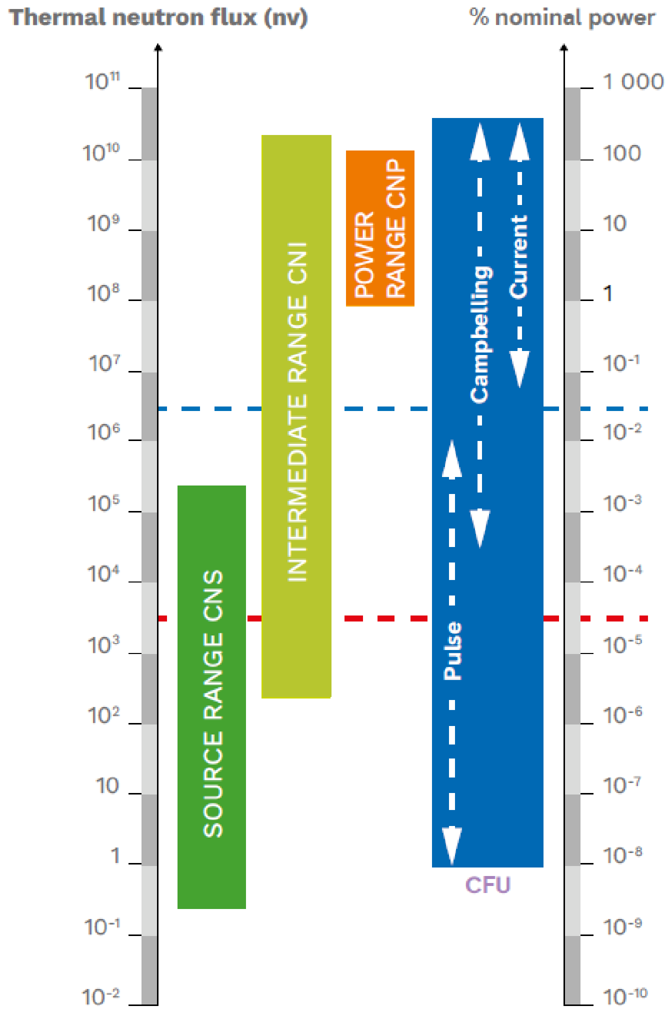

Figure A-5. Reactor power spread for power monitoring per Framatome.

“Excore Neutron Detectors for Nuclear Reactors.” Framatome. 2022. https://www.framatome.com/solutions-portfolio/docs/default-source/default-document-library/product-sheets/a3026-b-fr-g-en-1222-excoreneutrondetectors.pdf?Status=Master&sfvrsn=719b5f4a_2