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Survey of Neutron Generators for Active Interrogation

Introduction

Portable neutron generators contain compact linear accelerators that produce neutrons from the following nuclear reactions:

Deuterons (D) or tritons (T) are accelerated onto a target that contains deuterium, tritium or a mixture of these isotopes. The accelerating voltages are typically in the range 80 to 200 kV. The deuterium-tritium (DT) reaction is used more often than the deuterium-deuterium (DD) reaction because the yield of the DT reaction is 50–100 times higher than that of the DD reaction. Neutrons produced from the DT reaction are emitted nearly isotropically, while neutrons from the DD reaction are peaked in the forward direction.

For portable systems, the accelerator is sealed in a vacuum enclosure called a neutron tube. The tube contains an ion source, a target, a gas reservoir (getter), and ion optical elements. The tube, in turn, is enclosed in a metal housing, called the accelerator head, which contains a high voltage transformer and other electronic control boards. The accelerator head is usually filled with a dielectric liquid (such as mineral oil or a fluorocarbon-based fluid) or gas (such as sulfur hexafluoride) to provide insulation for the high voltage transformer and neutron tube. The power supplies for the low-voltage input to the high voltage transformer and for the ion source and gas reservoir are located from 0.5 to 10 m away. The designs are simple and robust for portable use. The requirements for a portable neutron generator for interrogating SNM are given in Table 1. These specifications are for the P211 (discussed below), which is an old design and is no longer available.

Table 1. Portable Neutron Generator Specifications

Key Parameters	Requirements
Neutron Output	10^6 n/pulse
Energy	14 MeV
Sync Pulse Output	To veto neutron data collection during pulse
Intrapulse Output	Output Zero
Lifetime	500 h
Pulse Range	Up to 100 pulses/s
Pulse Width	$<10 \mu\text{s}$
Power	Low enough for battery operation
Size and Weight	Man transportable

The requirement that no neutrons be produced between pulses is needed because some of the active techniques for uranium look for die-away or beta-delayed neutrons between pulses. Many small

neutron generators are commercially available for special applications such as borehole operations, bulk materials analysis, explosive detection, and chemical weapons. Some of these generators meet this requirement but some don't. Older-design portable neutron generators often used an analog transformer to activate the ion-source in the neutron tube; these systems were notorious for having a slow turn-off ramp, due to the presence of an effective resistor-capacitor (RC) circuit to bleed off voltage to the ion source. To compensate for this characteristic, neutron generators used in applications that required a 'zero-neutron-output' specification in between pulses also employed a high-voltage pulse transformer, so that any ions leaking from the ion source after the 'end' of a pulse did not experience a high-voltage gradient to permit neutron production. Newer generators, in contrast, often employ solid-state pulse transformers for controlling ion source performance; these generators have been shown to have inter-pulse turn-off times of less than 0.5 microseconds, with zero neutron production between pulses. For any candidate neutron generator being evaluated for the emergency response mission, tests will be required to determine if a neutron generator meets the zero-neutron requirement.

The following list of generators includes models that do not meet one or more of the above requirements but are included because there is a possibility that some of them could be modified to meet the requirements.

Vendors

Note: In nearly all cases specifying a DT neutron energy (14.1 MeV), a DD gas fill is also possible, which will produce 2.5 MeV neutrons. Neutron yields in these cases can be expected to be between 50-100 times less than the quoted DT neutron yields.

Thermo Fisher Scientific Inc

Website: <https://www.thermofisher.com/search/browse/results?customGroup=Neutron+Generators>

Models

P 211 (dual ion source – high-voltage pulse transformers, fluoroinert insulator)

Specifications:

Neutron Yield	1.0×10^6 neutrons/s
Neutron Energy	14 MeV
Pulsing	10 Hz, 50 Hz, 100 Hz, single shot
Minimum Pulse Width	10 μ s
Lifetime	500 h
Power	110 V, 1.3 A

B 211 (updated version of P 211, fluoroinert or SF₆ insulating gas)

Specifications: similar to P 211 specifications

MP 320 (lightweight, portable, SF₆ insulating gas)

Specifications:

Neutron Yield	1×10^8 neutrons/s
Neutron Energy	14 MeV
Pulsing	Continuous or 250 Hz to 20 kHz continuous
Minimum Pulse Width	5 μ s
Lifetime	1200 h @ 1×10^8 n/s
Power	< 50 W, may be operated from battery
Total Weight	12 kg (26.5 lbs)
Control	Digital control

B 320 (borehole tool, SF₆ insulating gas)

Specifications:

Neutron Yield	1×10^8 neutrons/s
Neutron Energy	14 MeV
Duty cycle	10%
Diameter	1.69 in

P 385 (middle weight, portable, SF₆ insulating gas)

Specifications:

Neutron Yield	Nominal 3.0×10^8 n/s, Max 5.0×10^8 n/s
Neutron Energy	14 MeV
Pulsing	Continuous or 250 Hz to 20 kHz
Minimum Pulse Width	5 μ s
Lifetime	1500 h at 3.0×10^8 n/s, 4500 h at 10^8 n/s
Duty Cycle	5% to 100%
Head Dimensions	102 mm dia. $\times$ 686 mm length
Head Weight	17 kg (37.4 lb)
Power	~ 75 W

API 120 (portable, associated particle imaging, SF₆ insulating gas)

Specifications:

Neutron Yield	2.0×10^7 n/s
Neutron Energy	14 MeV
Pulsing	Continuous only
Lifetime	1200 h at 1×10^7 n/s
Total Weight	15 kg (33 lb)
Power	< 50 W

D 711 (maximum flux, SF₆ insulating gas, Fluorinert insulator and coolant, water coolant)

Specifications:	
Neutron Yield	2.0×10^{10} n/s max
Neutron Energy	14 MeV
Pulsing	Continuous only
Lifetime	1000 h at 1×10^{10} n/s
Total Weight	1000 kg
Control	Digital control

SODERN

Website: <http://www.sodern.fr>

Models

Genie 16 (Portable, SF₆ insulating gas)

Specifications:	
Neutron Yield	up to 2×10^8 neutrons/s
Neutron Energy	14 MeV
Pulsing	up to 5 kHz or continuous
Minimum Pulse Width	< 5 μ s
Lifetime	4000 h at 1×10^8 n/s, 8000 h at 5×10^7 n/s
Head Dimensions	< 104 mm dia. $\times$ < 740 mm length
Head Weight	8 kg
Control Rack Weight	10 kg
Power Supply Weight	10 kg
Power	230 VAC/50 Hz (16 A) or 115 VAC/60 Hz

Genie 35 (Fixed system, oil insulator)

Specifications:	
Neutron Yield	up to 10^{10} neutrons/s
Neutron Energy	14 MeV
Pulsing	up to 5 kHz or continuous
Minimum Pulse Width	10 μ s
Lifetime	2000 h at 2×10^9 n/s
Head Dimensions	< 150 mm dia. $\times$ < 900 mm length
Power	230 VAC/50 Hz (16 A)

Phoenix Nuclear Labs

Website: <http://phoenixnuclearlabs.com/product/low-yield-neutron-generator/>

Models

Ultra Compact Generator

Specifications:

Neutron Yield	1×10^9 to 5×10^{10} neutrons/s
Neutron Energy	2.5 MeV
Pulsing	Pulsed or continuous
Lifetime	10,000 h
Maximum Beam Current	50 mA
Maximum Accelerating Voltage	300kV
Head Dimensions	100 × 35 × 35 cm
Head Weight	150 kg
Supporting Equipment Dims.	50 × 80 cm
Supporting Equipment Weight	100 kg
Power	480 VAC

Starfire Industries

Website: starfireindustries.com

Models

nGen-300C (battery powered)

Specifications:

Neutron Yield	10^7 n/s @ 4% duty factor
Neutron Energy	2.5 MeV
Ion Source Type	Electrodeless RF
Pulse Rate	Single shot to 200 kHz
Pulse Width	5-1000 μ s
Pulse Rise/Fall Time	< 5 μ s
Nominal Duty Factor	5%
Dark Current between Pulses	None
Operating Voltage	up to 140 kV
Power Requirements	400 W
Neutron Source Dimensions	3" OD × 18" L
Neutron Source Weight	10 lbs
Supporting Hardware Dims.	12" W × 12" H × 12" L
Supporting Hardware Weight	20 lbs with battery

Schlumberger

Website: www.slb.com/oilfield

Models

RSTPro (well logging tool)

Specifications:

DT Neutron Yield	3×10^8 neutrons/sec
Dimensions	Slim Tool: 1.710 in dia × 23.1 ft length Focused Tool: 2.505 in dia × 22.2 ft length Flasked Tool: 2.125 in dia × 33.7 ft length

Adelphi Technology, Inc.

Website: www.adelphitech.com

Models

DT109-DT110 (neutron generator)

Specifications:

DT Neutron Yield	1×10^{10} neutrons/sec maximum
Neutron Energy	14.1 MeV
Pulsing	$\geq 100 \mu\text{s}$ to continuous, requires TTL for pulsing
Power	500 W, 110V AC, battery power feasible
Lifetime	Several thousand hours

DT108API (associated particle imaging)

Specifications:

Neutron Energy	14 MeV
Pulsing	Continuous
Power	120 VAC, 20 A circuit
Lifetime	2000 h
Head Weight	50 lbs
Control & Power Rack Weight	100 lbs
Heat Exchanger Weight	30 lbs
Total Weight	180 lbs

All-Russia Research Institute of Automatics (VNIIA)

Website: <http://vniia.ru/eng/ng/element.html>

Models

ING-013 (vacuum neutron tube)

Specifications:

Neutron Yield	up to 5×10^9 neutrons/s
Neutron Energy	14 MeV
Pulse Width	0.8 to 1.2 μ s
Pulsing Frequency	1 to 50 Hz
Lifetime	1600 h at 10^8 neutrons/s
Power	220 V, 50 Hz, 500 W max
Head Dimensions	130 mm dia $\times$ 1000 mm length
Control	PC

ING-03 (vacuum neutron tube)

Specifications:	
Neutron Yield	up to 3×10^9 neutrons/s
Neutron Energy	14 MeV
Pulse Width	1.2 μ s
Pulsing Frequency	1 to 30 Hz
Lifetime	1600 h at 10^8 neutrons/s
Power	220 V, 50 Hz, 100 W max
Head Dimensions	130 mm dia $\times$ 950 mm length
Control	PC

ING-031 (vacuum neutron tube)

Specifications:	
Neutron Yield	up to 2×10^{10} neutrons/s
Neutron Energy	14 MeV
Pulse Width	1.2 μ s
Pulsing Frequency	1 to 100 Hz
Lifetime	1600 h at 10^8 neutrons/s
Power	220 V, 50 Hz, 700 W max
Head Dimensions	130 mm dia $\times$ 950 mm length
Control	PC

ING-07 (gas-filled neutron tube)

Specifications:	
Neutron Yield	up to 10^9 neutrons/s
Neutron Energy	14 MeV
Pulse Width	20 to 100 μ s
Pulsing Frequency	400 to 10000 Hz or continuous
Lifetime	500 h
Power	110/220 V, 50/60 Hz, 200 W max
Head Dimensions	190 mm dia $\times$ 440 mm length
Control	PC

ING-17 (gas-filled neutron tube)

Specifications:

Neutron Yield	up to 3×10^8 neutrons/s
Neutron Energy	14 MeV
Pulse Width	20 to 100 μ s
Pulsing Frequency	400 to 10000 Hz or continuous
Lifetime	300 h
Power	110/220 V, 50/60 Hz, 120 W max
Head Dimensions	70 mm dia $\times$ 480 mm length
Control	PC

ING-27 (gas-filled neutron tube, associated particle imaging)

Specifications:

Neutron Yield	up to 10^8 neutrons/s
Neutron Energy	14 MeV
Pulsing Frequency	Continuous
Number of pixels	at least 9
Lifetime	100 h @ 5×10^7 neutrons/s
Head Dimensions (mm)	220 $\times$ 130 $\times$ 179
PS and Control Dimensions (mm)	279 $\times$ 193 $\times$ 94
Head Weight	7.0 kg
PS and Control Weight	3.0 kg

ING-14 (gas-filled neutron tube)

Specifications:

Neutron Yield	up to 2×10^{10} neutrons/s
Neutron Energy	14 MeV
Pulsing Frequency	Continuous
Lifetime	300 h
Power	110/220 V, 50/60 Hz, 600 W max
Head Dimensions	290 mm dia $\times$ 840 mm length
Head Weight	60 kg
Control	PC

Xi'an Petroleum Exploration Instrument Complex

Borehole neutron generators

Reference: Peng Hu, Ke Xianda, and Lu Jishen, "Applications of Neutron Generators in Well Logging and Other Fields," Nuclear Electronics and Detection Technology **13**, 137 (1993) in Chinese.

China Institute of Atomic Energy

Generator for well logging

Reference: Xiao Kunxiang, Ai Jun, Shi Guijuan, Xiang Chuan, and Mei Lin, "Development of Small Neutron Generators for Well Logging," Nuclear Physics Review **29**, 81 (2012) in Chinese.

Northeast Normal University

References:

Gang Li, Zhong-Shuai Zhang, Qian Chi, and Lin-Mao Liu, "50 m Diameter Digital DC/pulse Neutron Generator for Subcritical Reactor Test," Nucl. Instr. Meth. B **290**, 64 (2012).

Dong Aiping, Li Wenjie, Wang Qiang, and Chen Baojiu, "A Sealed Tube Neutron Generator with Neutron Yield $> 1.5 \times 10^{10}$ n/s," http://en.cnki.com.cn/Article_en/CJFDTOTAL-HJSU506.003.htm.

Lanzhou University

Engineering Research Center for Neutron Application Technology

Website: <http://en.lzu.edu.cn/content/88.html>

China Academy of Engineering Physics

Compact Pulsed Neutron Generator

Reference: Zhen Yang, "Performance Improvement of a Compact Pulsed Neutron Generator with a Vacuum Arc Ion Source," IEEE Power Modulator and High Voltage Conference, San Francisco, 5-9 July 2016.

Discussion and Conclusions

Some of these commercially available generators meet all of the requirements in Table 1, but there are other concerns. Most generators containing SF_6 will be required to have the SF_6 gas removed for shipping because of DOT regulations. However, Thermo Fisher has a DOT exemption. The P211 and B211 from Thermo Fisher meet the requirements listed in Table 1, but they are old designs and are no longer offered for sale. Also, they require 15 minutes or more of warmup before neutron output is available, and they lack a modern digital control. The nGen-300C from Starfire Industries is interesting because it is a portable system, but it uses the DD reaction for 2.5 MeV neutrons, which are not as penetrating as the 14 MeV neutrons from the DT reaction. The MP 320 from Thermo Fisher is another portable system, but the minimum pulse rate is 250 Hz, which is too fast for measurement of delayed neutrons and re-interrogation by delayed neutrons between pulses. The Genie 16 from Sodern (from France) probably meets the requirements, but the required power is probably too high for battery operation. The generators from Russia and China may be difficult to purchase, and service may not be available.

The power required by some of these generators is low enough that batteries can be used. The portable units, nGen-300C and the MP320, could easily be operated with batteries. Other generators with low power requirements, as specified in the above vendors list, could possibly be operated with reason size batteries. The batteries do not need to be internal to the generator, but can be in a separate package. The availability of high capacity lithium batteries with sophisticated safety circuits makes battery operation more possible now than when lead acid batteries were used.

The best path forward probably requires working with vendors of the existing systems. If Starfire Industries could be persuaded to put tritium in their nGen-300C generator, possibly in collaboration with a national laboratory, this would provide the 14-MeV neutrons needed. Another possibility is a modification of the Thermo Fisher MP 320 to run at 50 to 100 Hz. More discussions with these vendors, and possibly others, are required to determine their interest and possible costs.

Appendix. Other Considerations for Emergency Response

- Start-up time, from storage to being ready for operation
- Recommended regular operating frequency
- Temperature operating range
- Humidity operating range
- Vibration limits for shipping, etc.
- Dust susceptibility
- Associated x-ray production
- Electromagnetic emissions
- Electromagnetic susceptibility
- Electronic grounding
- Orientation limitations (mostly only relevant for the liquid filled systems, where the presence of a bubble in the liquid can be a problem)
- Maximum single-use on time (found in systems with poor cooling, where they tend to heat up)