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CHARACTERIZATION OF LARGE LIQUID SCINTILLATION DETECTORS

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ABSTRACT

This report presents the results of the characterization of 11 large liquid scintillators. The neutron energy threshold and maximum detection efficiency were determined as a function of voltage and constant fraction discriminator threshold. Fits to the response of each detector were found. The results can be used to select the experimental settings in the operation of the detectors to ensure consistent response and repeatability.

CHARACTERIZATION OF LARGE LIQUID SCINTILLATION DETECTORS

1. INTRODUCTION

A series of measurements was performed with 11 liquid scintillation detectors having dimensions 25 by 25 by 8.2 cm (manufactured by Scionix, equivalent to Saint Gobain BC 501). In the measurements, the Nuclear Materials Identification System (NMIS) [1] was used to acquire the time of flight of neutrons and gamma rays from a Cf-252 source placed at a distance of 100 cm from the front face of the scintillators. The voltage on the detectors and the constant fraction discriminator (CFD) threshold were varied, and the effect of these variations on the neutron detection efficiency as a function of energy between ~0.5 and 6 MeV was analyzed. The present detector characterization will allow the user to operate the detectors with the same detection efficiency.

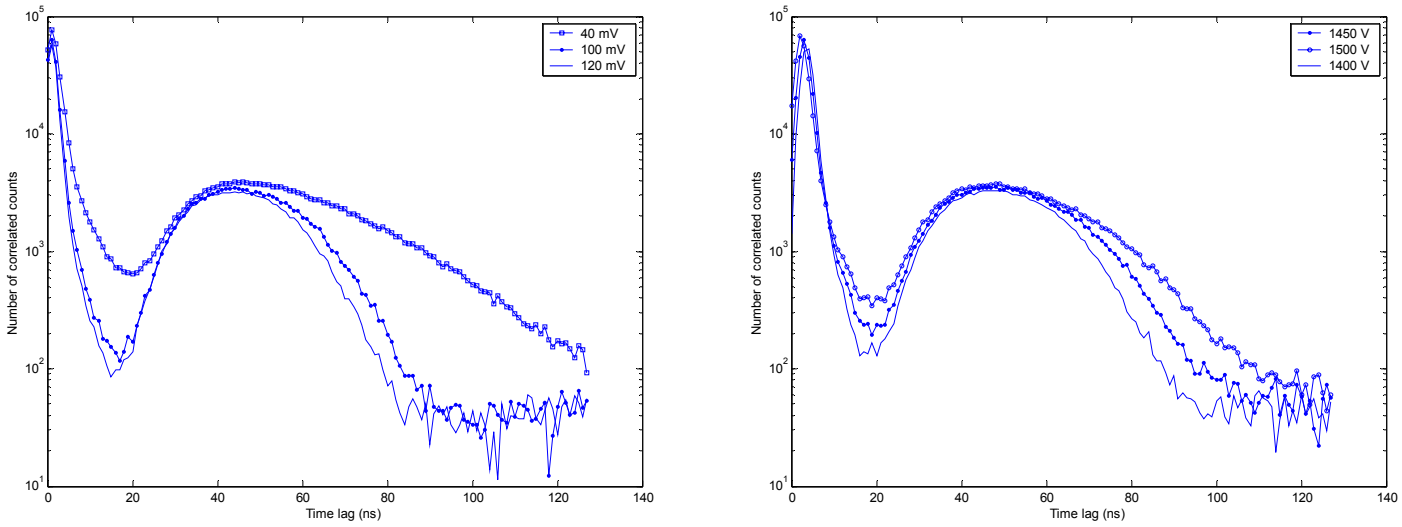
2. EXPERIMENTAL SETUP

The detectors are liquid scintillators having dimensions 25 by 25 by 8.2 cm. Each detector has one photomultiplier tube, attached to one side. The anode output was input to a CFD for discrimination. For the measurements, the same base and power supply were used for all 11 detectors.

In the measurements, NMIS was used to acquire the time of flight of neutrons and gamma rays from a Cf-252 source placed at a distance of 100 cm from the front face of the scintillator. The CFD threshold was varied, keeping the voltage on the detector constant. Then, the CFD threshold was kept constant, and the voltage was varied. Typical time-of-flight measurements are shown in Fig. 1. The neutron time of flight was converted into neutron efficiency by considering the solid angle subtended by the detector from the source and the known spectrum of neutron emission of the Cf-252.

3. DISPERSION OF TIME RESOLUTION DUE TO DETECTOR SIZE

The time spread of the gamma peak in a source-detector time-of-flight measurement depends on detector size. The measured gamma peak of a Bicron liquid scintillator having dimensions 11.75 cm in diameter by 10.2 cm thickness mounted on a XP4312 photomultiplier tube is shown in Fig. 2, together with the gamma peak for the 25 by 25 by 8.2 cm liquid cell. The total width of the gamma peak at 1/10 maximum is 6 ns for the large detector and 2.5 ns for the smaller detector.



(a) (b)

Fig. 1. Time of flight for (a) constant voltage and varying CFD threshold and (b) constant CFD threshold and varying detector voltage.

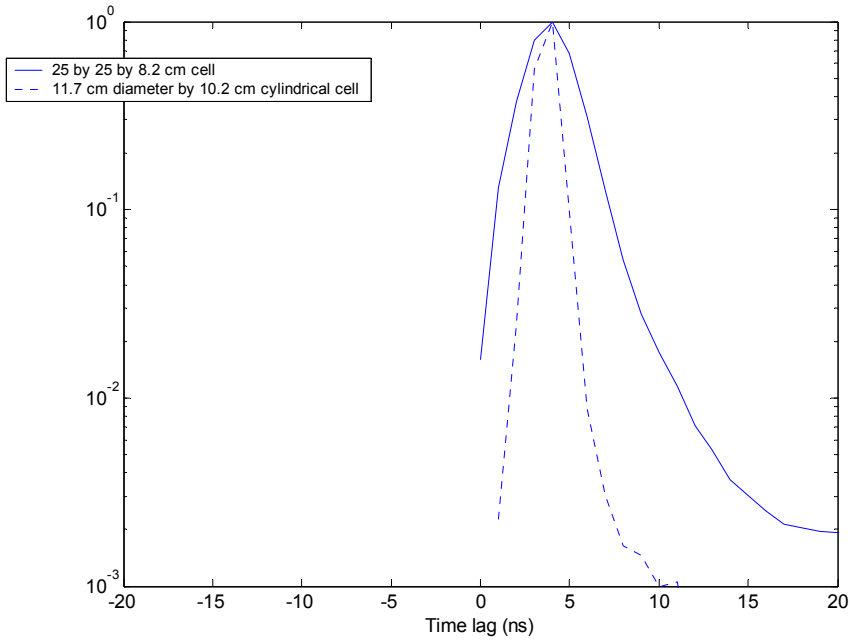


Fig. 2. Gamma peak from a time-of-flight measurement with a large liquid scintillator (25 by 25 by 8.2 cm) and a smaller cylindrical cell (11.75 cm diameter and 10.2 cm thickness).

4. RESULTS AND ANALYSIS

A linear regression was performed to fit the neutron detection efficiency as a function of energy using the expression

$$eff = a_1 + a_2 e^{-E} + a_3 E \cdot e^{-E} + a_4 E^2 e^{-E} \quad (1)$$

where E is the neutron energy (MeV) and *eff* is the neutron detection efficiency. This fit is empirical and was selected because it provided a good approximation of the neutron efficiency.

The resulting fit was used to characterize the energy dependence of the efficiency by use of three features: the neutron energy threshold, the maximum neutron detection efficiency, and the energy at which the maximum neutron detection efficiency occurs.

The neutron detection efficiency and the fit given by Eq. (1) are shown for a few sample cases in Fig. 3.

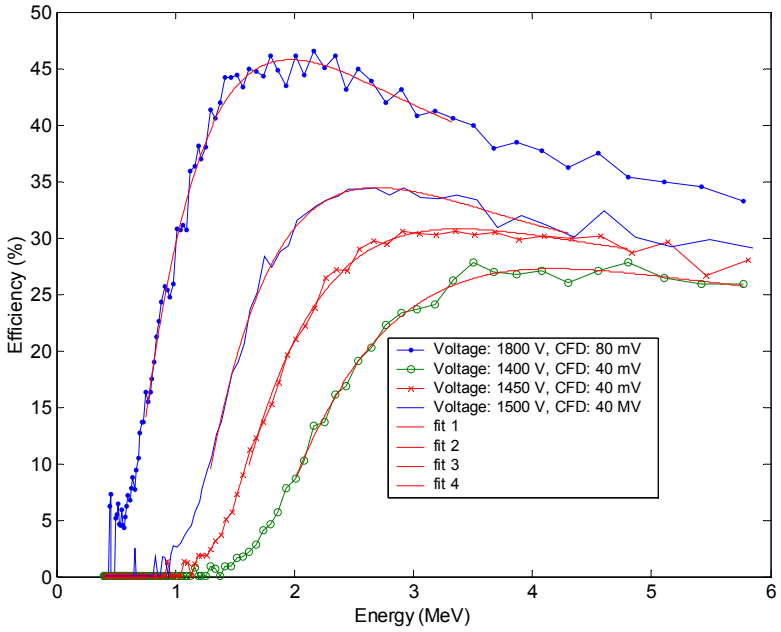


Fig. 3. Neutron detection efficiency for varying voltages and CFD thresholds for one of the detectors analyzed. Fit given by Eq. (1) is shown with the red lines.

The experimental results are given in Figs. 4-25. The neutron energy threshold and the maximum neutron detection efficiency are given as a function of detector voltage in the even-numbered figures for all detectors. The odd-numbered figures show the neutron energy threshold and the maximum neutron detection efficiency as a function of CFD threshold for fixed voltage. The neutron energy threshold as a function of detector voltage [Fig. 4 (a) and similar] was fit with a second-order polynomial:

$$t = a_1 V^2 + a_2 V + a_3 \tag{2}$$

where t is the neutron energy threshold and V is the detector voltage. The values of the coefficients $a_1, a_2, \ and \ \ a_3$ are given in Table 1 for all detectors[1].

The maximum detection efficiency was found to have a linear dependence on detector voltage [Fig. 4 (b) and similar]:

$$eff = a_1 V + a_2 \tag{3}$$

where *eff* is the maximum neutron detection efficiency and V is the detector voltage.

The values of the coefficients $a_1 \ \ and \ \ a_2$ are given in Table 2 for all detectors.

The neutron energy threshold as a function of the CFD threshold was fit to a quadratic polynomial [Fig. 5 (a) and similar]:

$$t = a_1 \tau^2 + a_2 \tau + a_3 \tag{4}$$

where t is the neutron energy threshold and τ is the CFD threshold. The values of the coefficients $a_1, a_2, \ and \ \ a_3$ are given in Table 3 for all detectors.

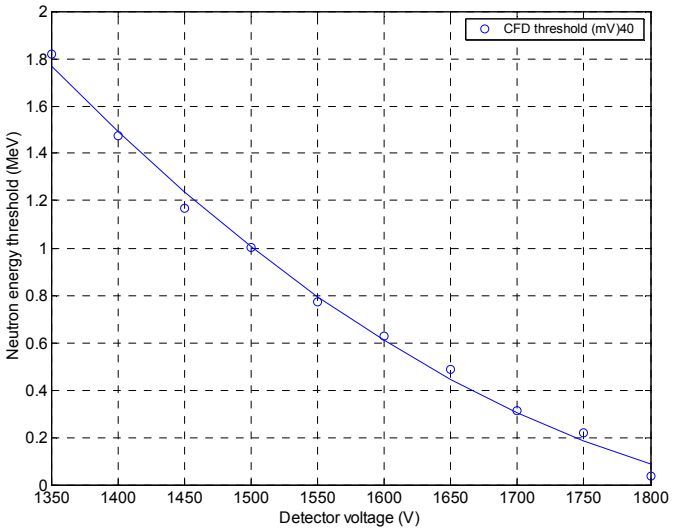
The maximum neutron detection efficiency as a function of CFD threshold was fit to a quadratic polynomial [Fig. 5 (b) and similar]:

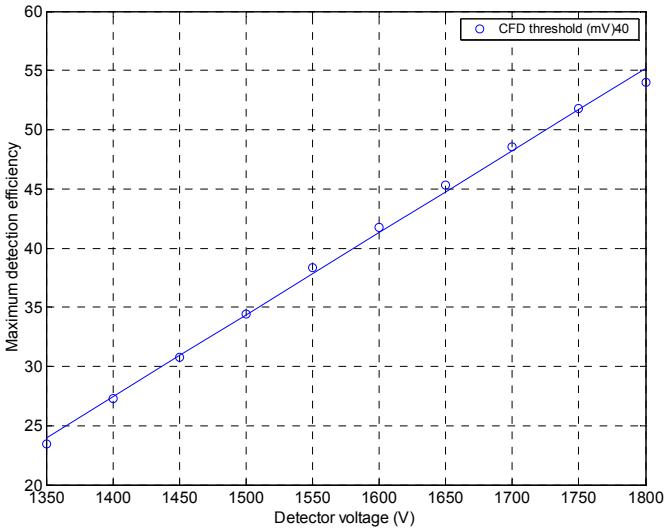
$$eff = a_1 \tau^2 + a_2 \tau + a_3 \tag{5}$$

where *eff* is the maximum neutron detection efficiency and τ is the CFD threshold.

The values of the coefficients $a_1, a_2, \ and \ \ a_3$ are given in Table 4 for all detectors.

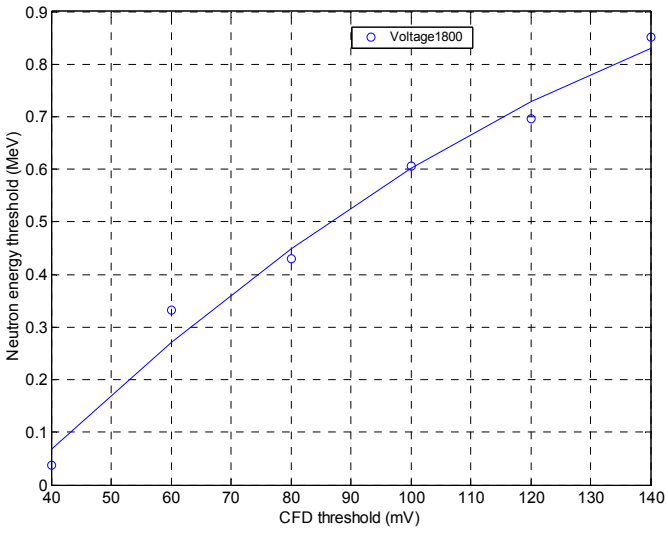
[1] In this and in the subsequent fits, the coefficients have the appropriate dimensions to make the expression meaningful.

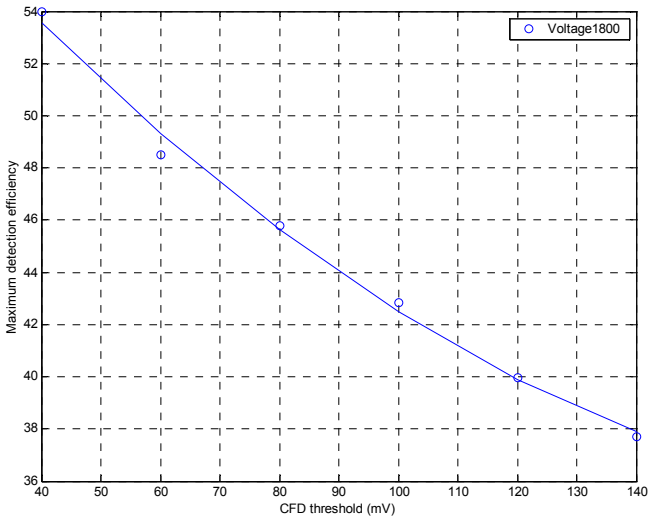




(a) (b)

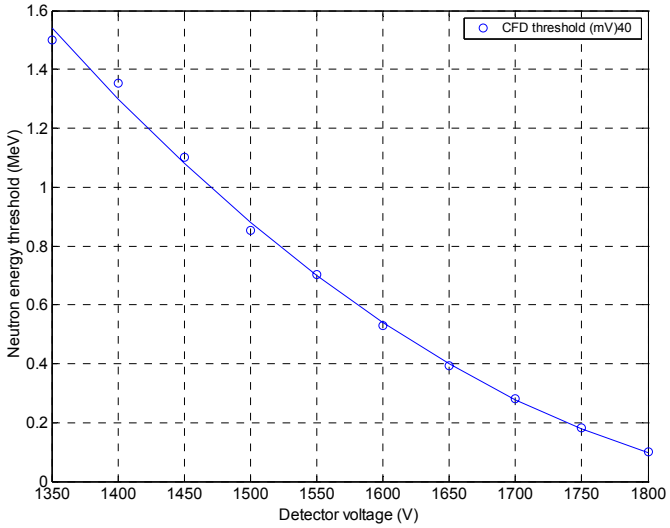
Fig. 4. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of detector voltage for fixed CFD threshold for detector 503.



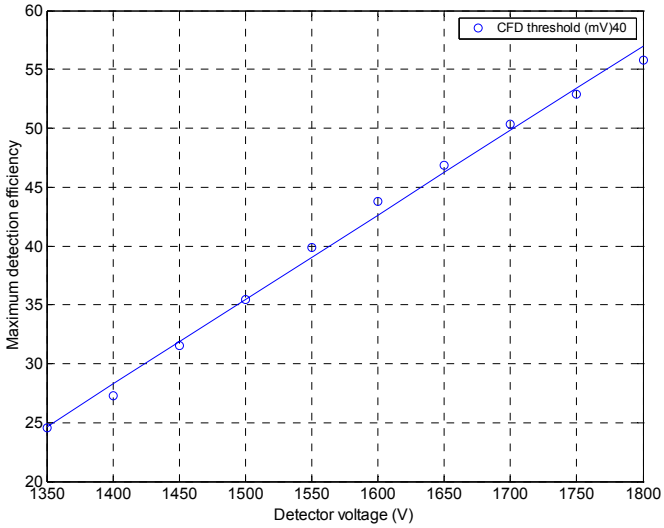


(a) (b)

Fig. 5. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of CFD threshold for fixed detector voltage for detector 503.

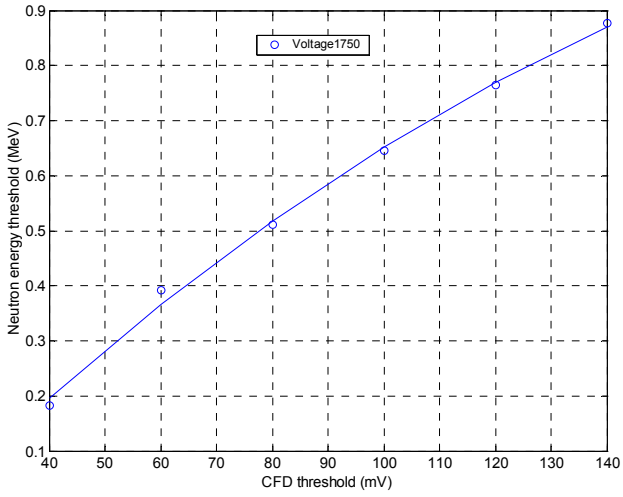


(a)

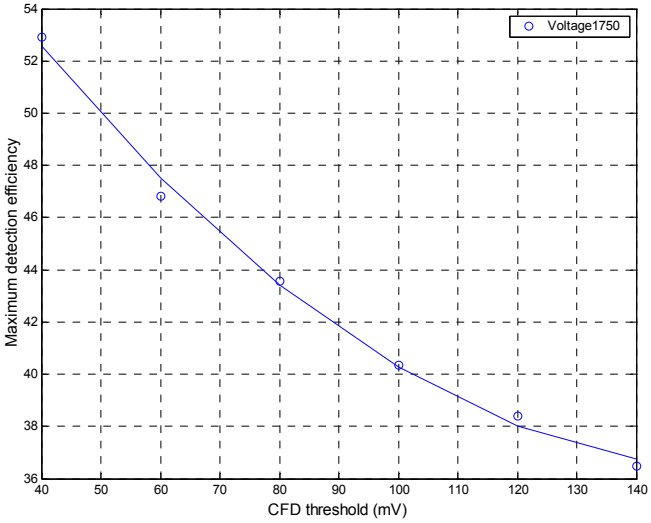


(b)

Fig. 6. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of detector voltage for fixed CFD threshold for detector 504.

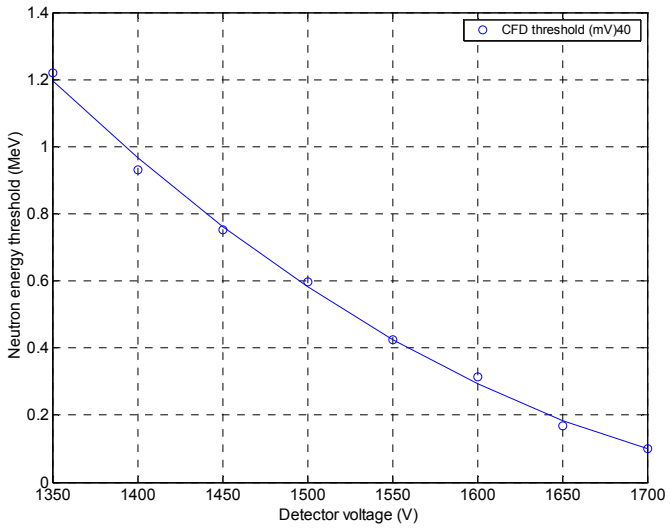


(a)

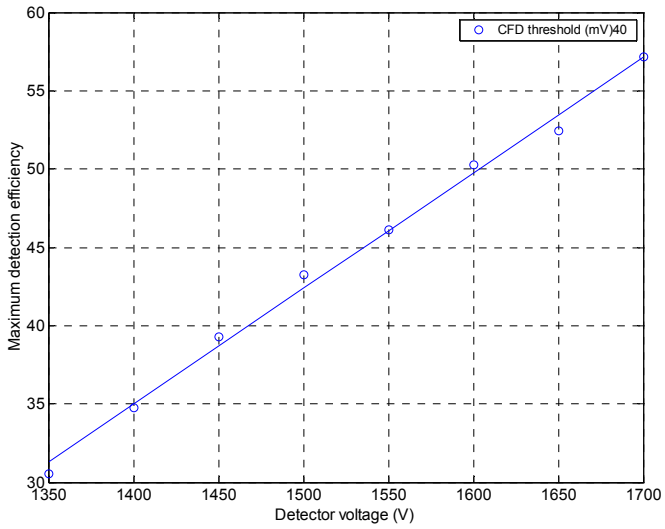


(b)

Fig. 7. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of CFD threshold for fixed detector voltage for detector 504.

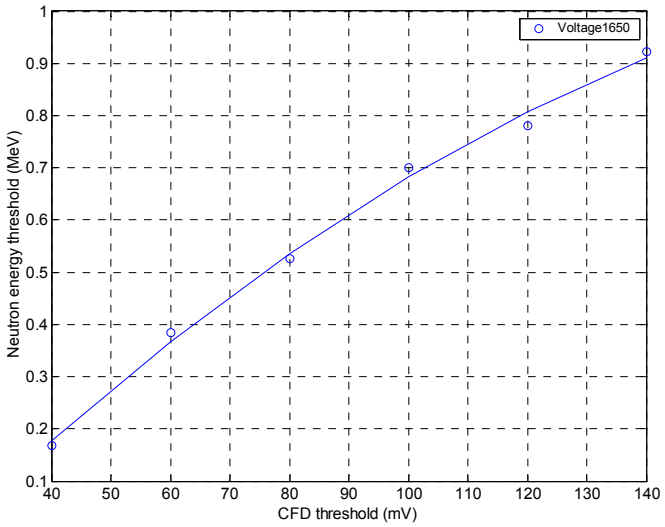


(a)

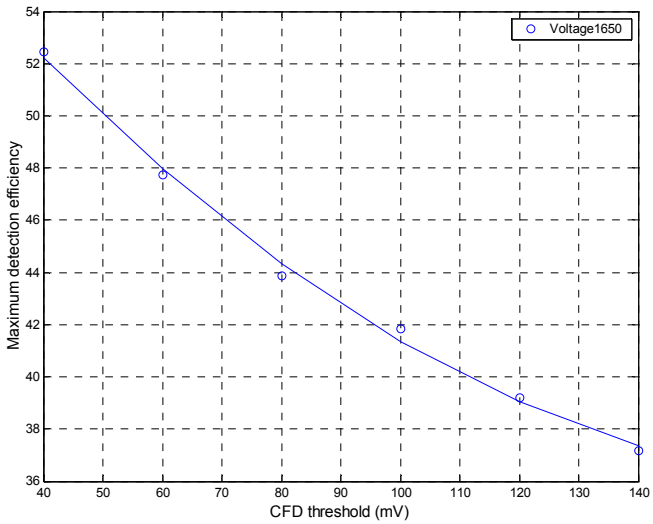


(b)

Fig. 8. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of detector voltage for fixed CFD threshold for detector 505.

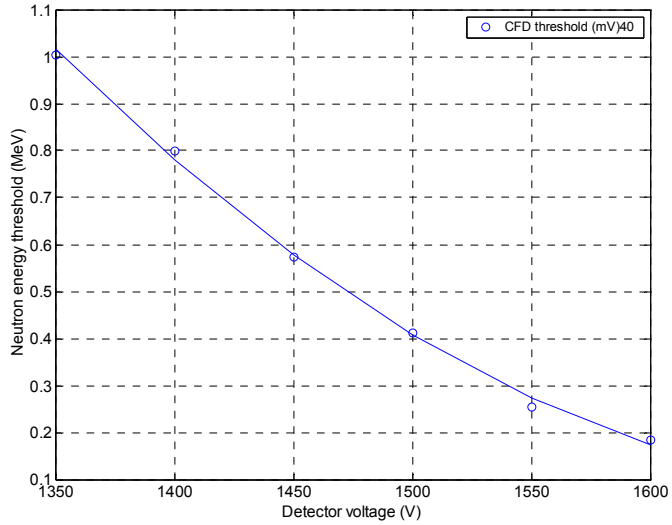


(a)

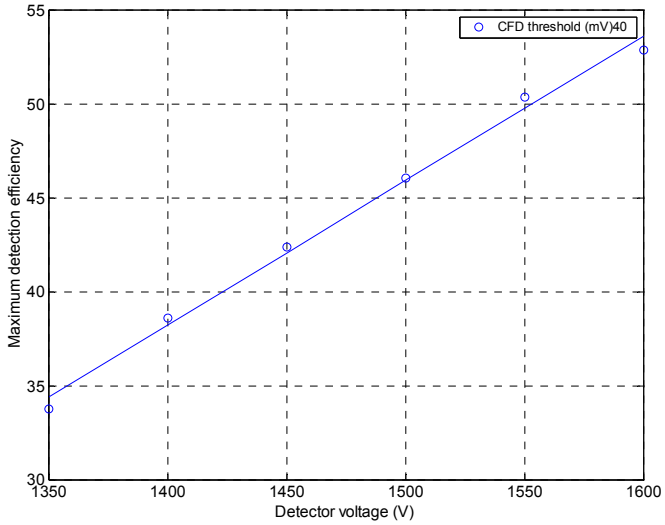


(b)

Fig. 9. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of CFD threshold for fixed detector voltage for detector 505.

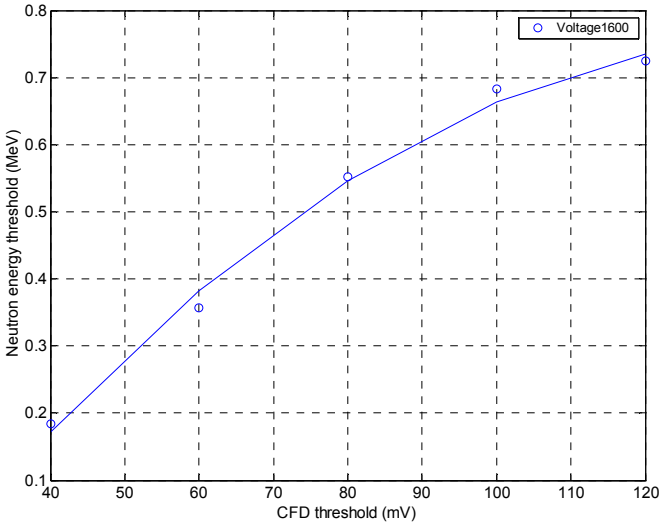


(a)

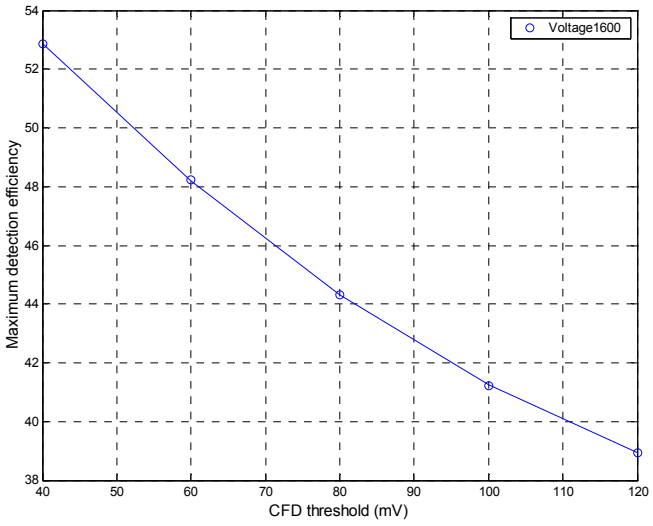


(b)

Fig. 10. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of detector voltage for fixed CFD threshold for detector 506.

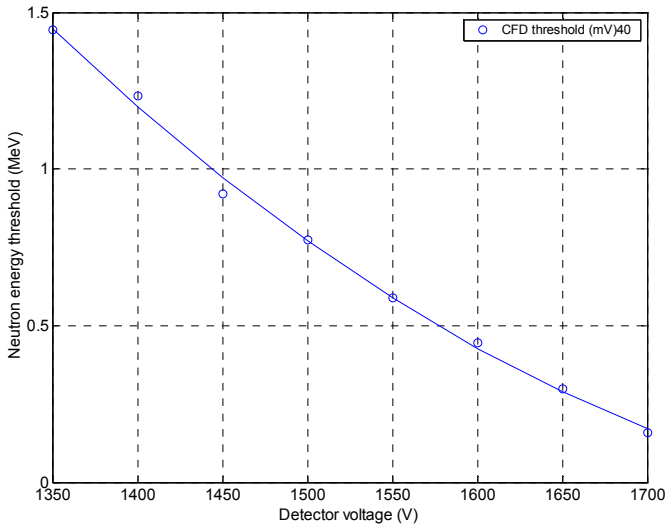


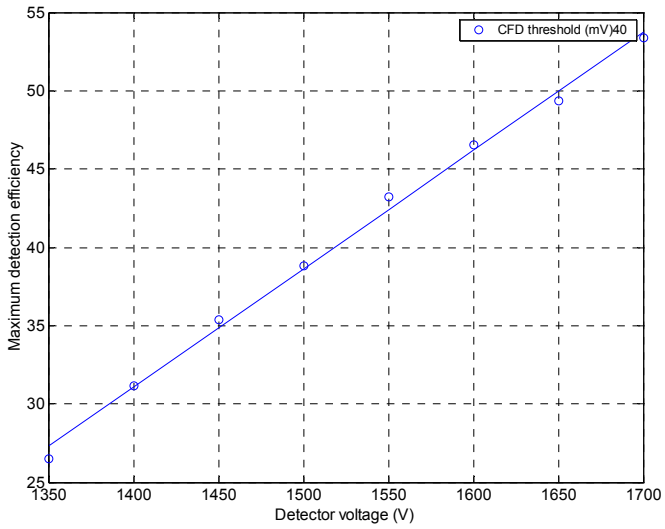
(a)



(b)

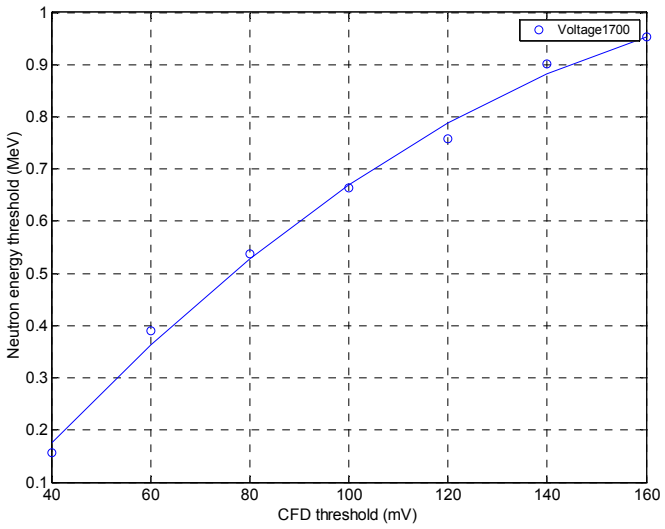
Fig. 11. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of CFD threshold for fixed detector voltage for detector 506.

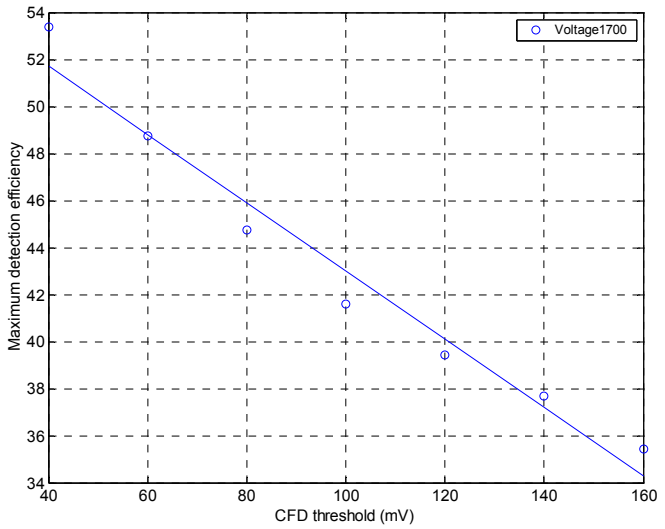




(a) (b)

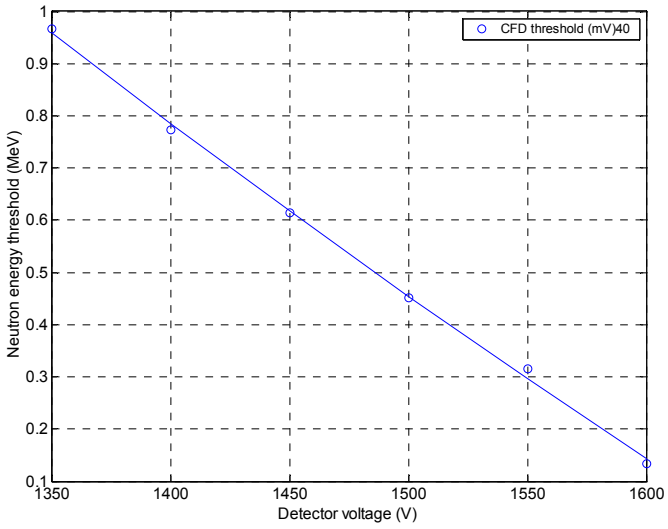
Fig. 12. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of detector voltage for fixed CFD threshold for detector 507.

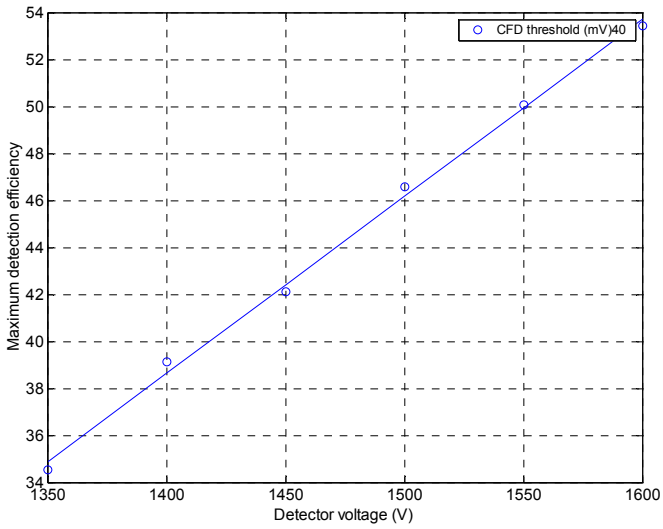




(a) (b)

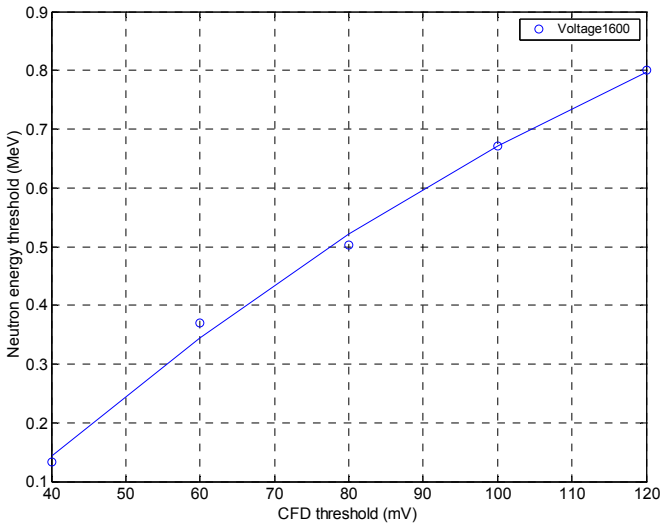
Fig. 13. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of CFD threshold for fixed detector voltage for detector 507.

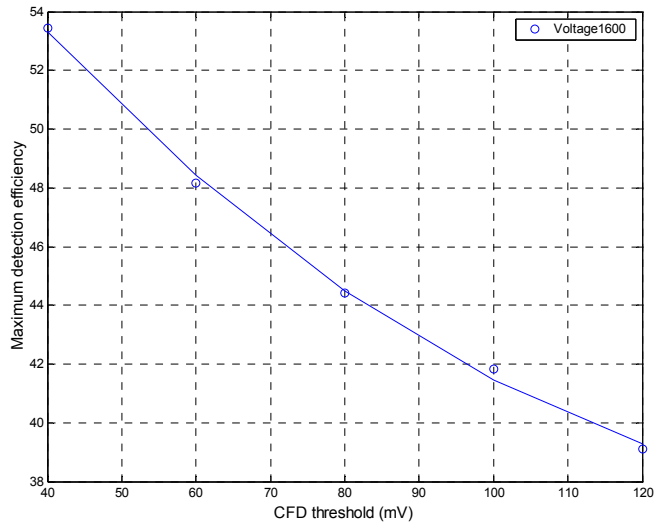




(a) (b)

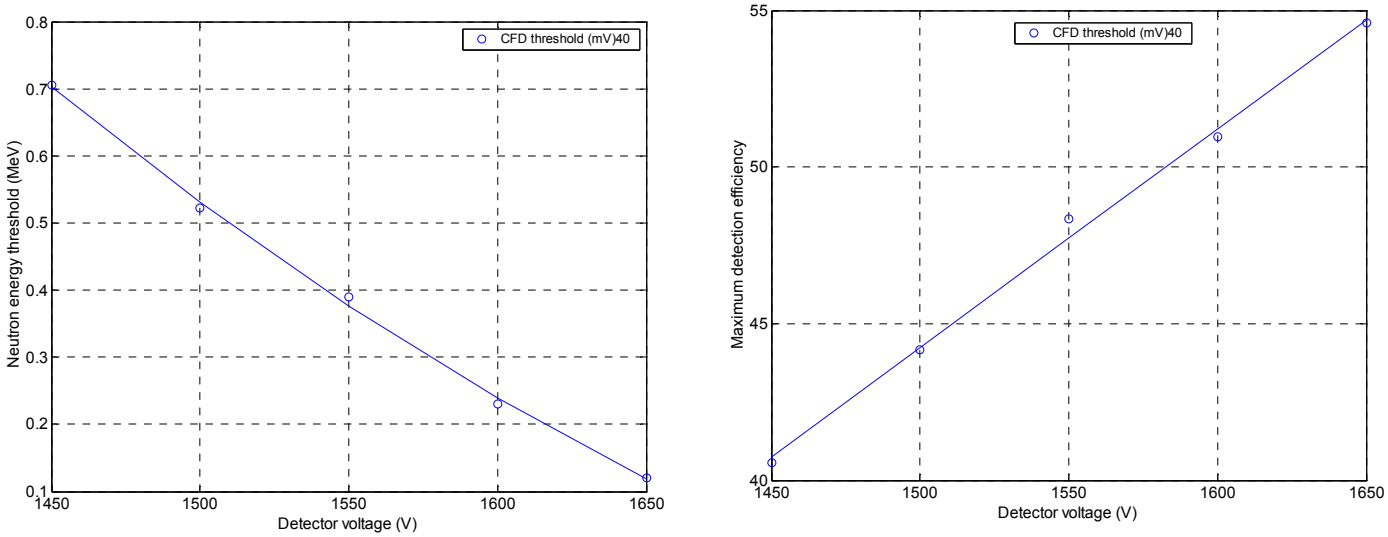
Fig. 14. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of detector voltage for fixed CFD threshold for detector 508.





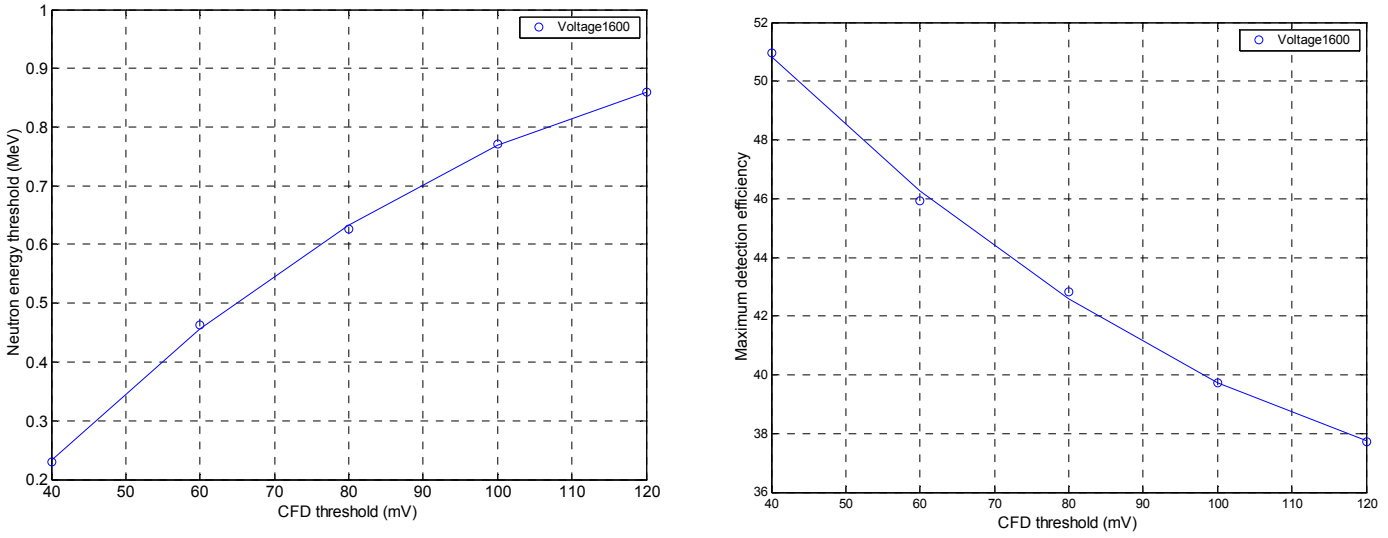
(a) (b)

Fig. 15. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of CFD threshold for fixed detector voltage for detector 508.



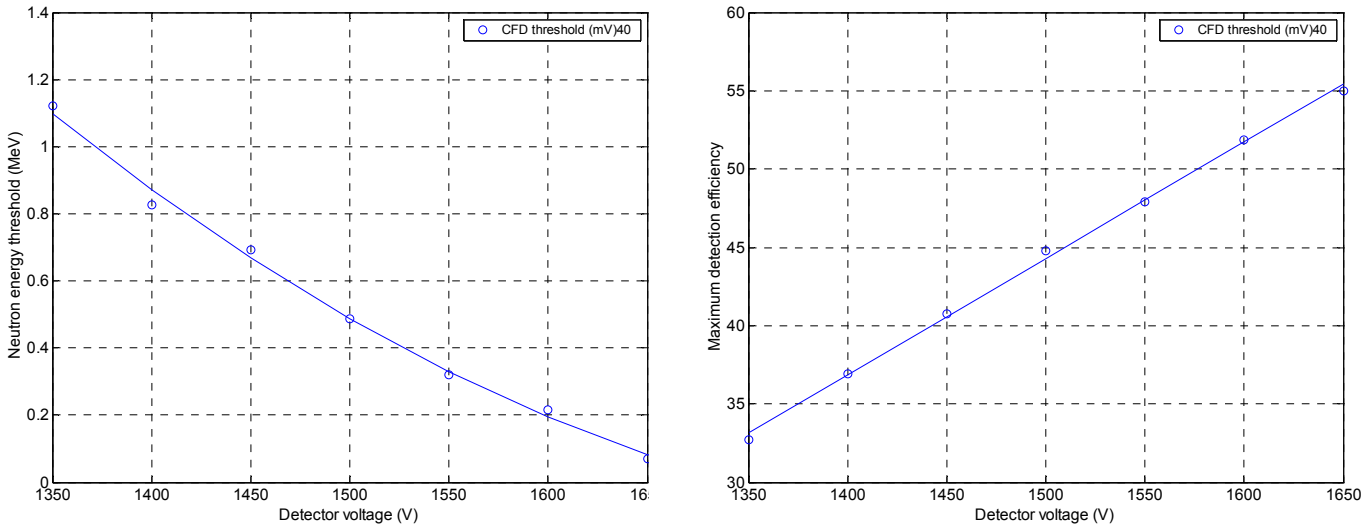
(a) (b)

Fig. 16. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of detector voltage for fixed CFD threshold for detector 509.



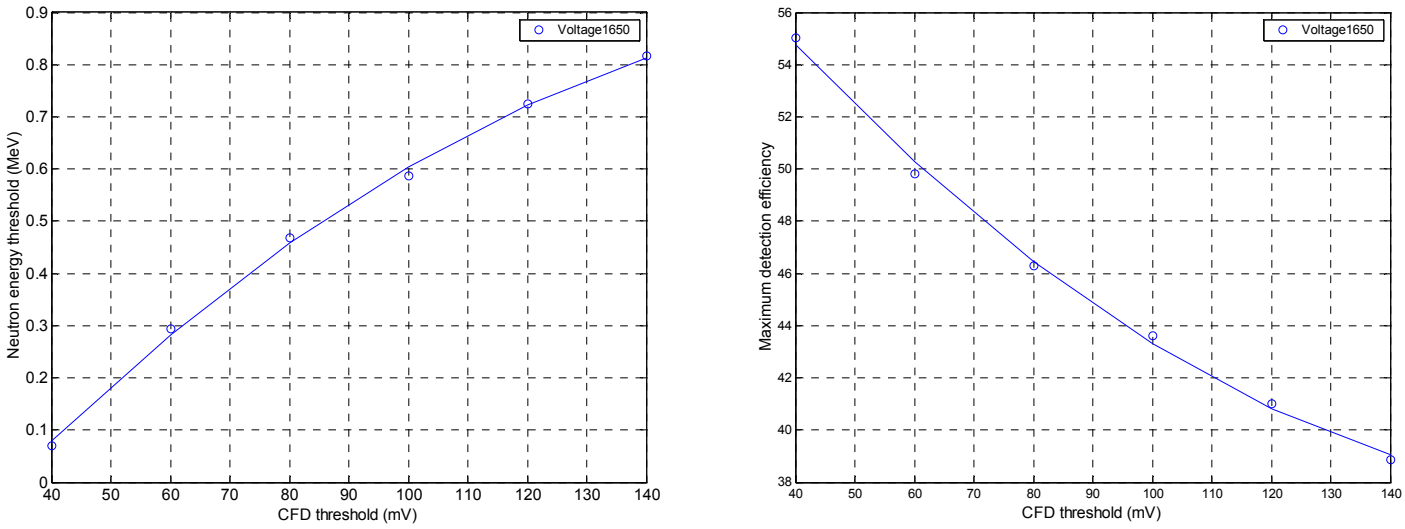
(a) (b)

Fig. 17. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of CFD threshold for fixed detector voltage for detector 509.



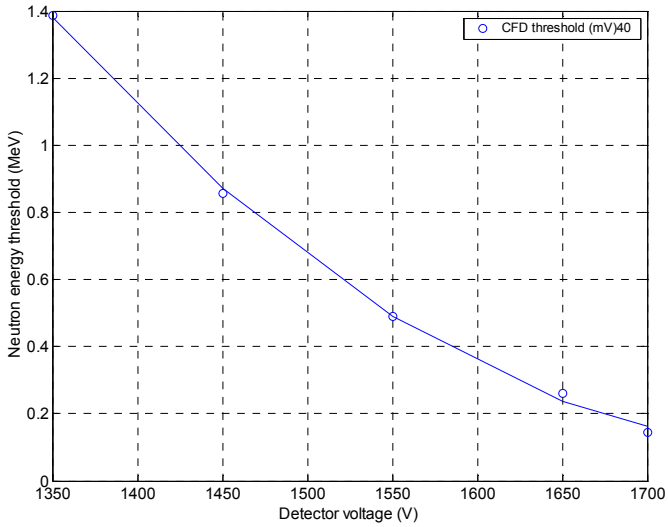
(a) (b)

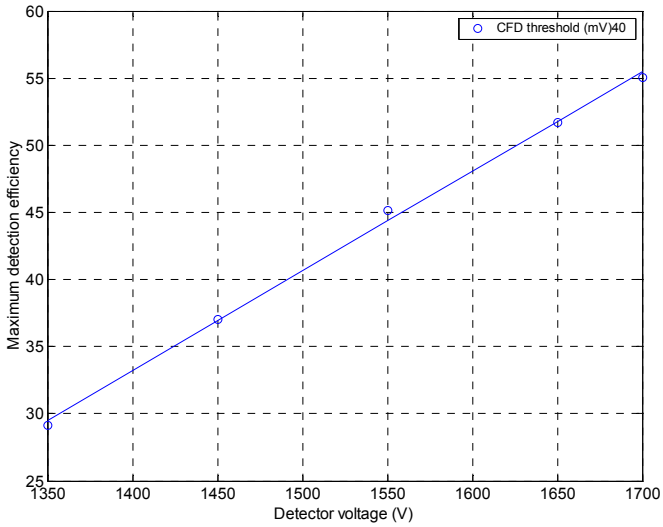
Fig. 18. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of detector voltage for fixed CFD threshold for detector 510.



(a) (b)

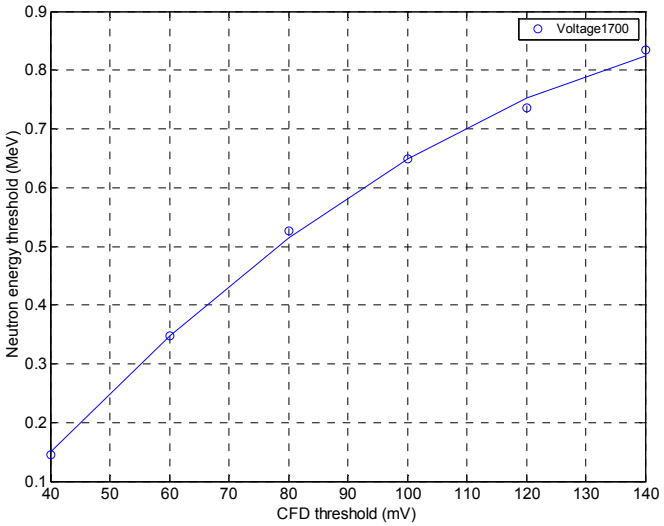
Fig. 19. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of CFD threshold for fixed detector voltage for detector 510.

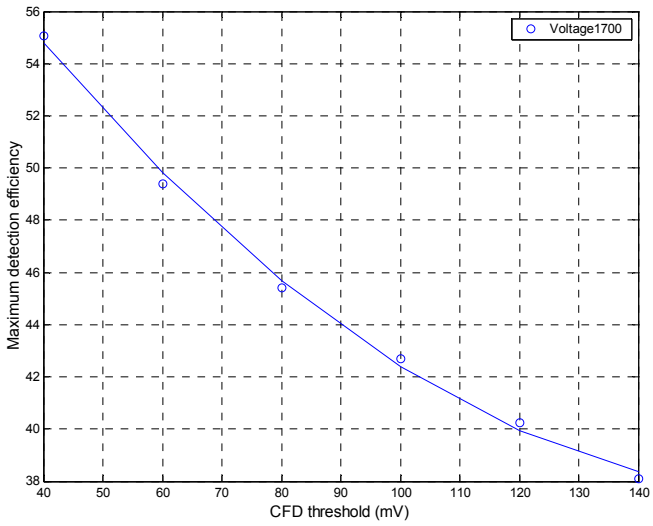




(a) (b)

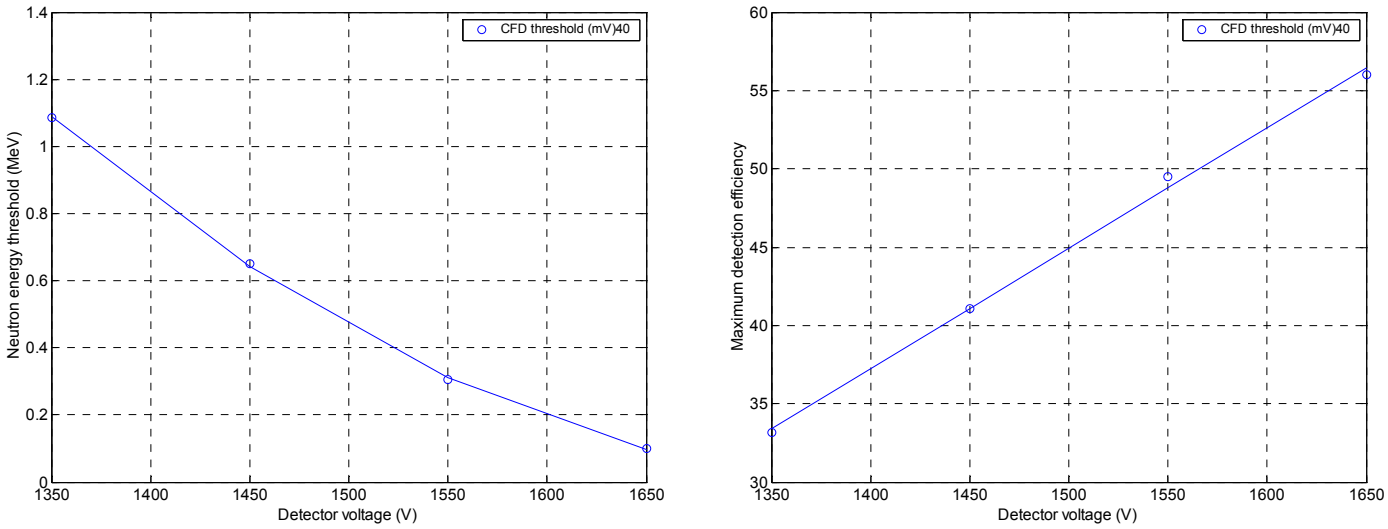
Fig. 20. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of detector voltage for fixed CFD threshold for detector 511.





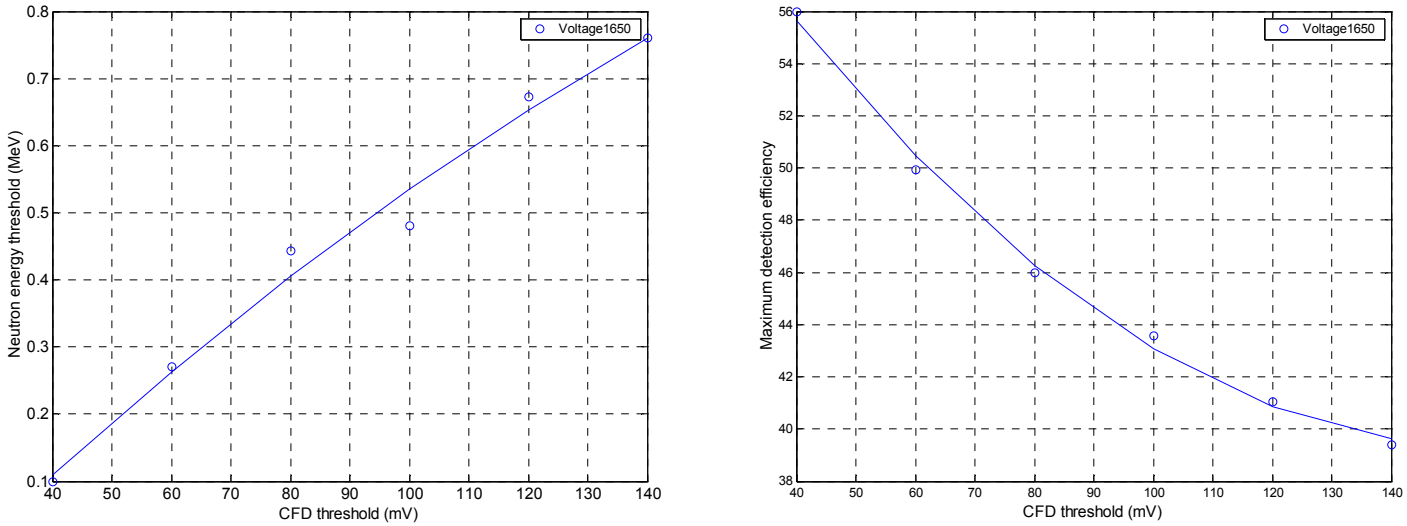
(a) (b)

Fig. 21. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of CFD threshold for fixed detector voltage for detector 511.



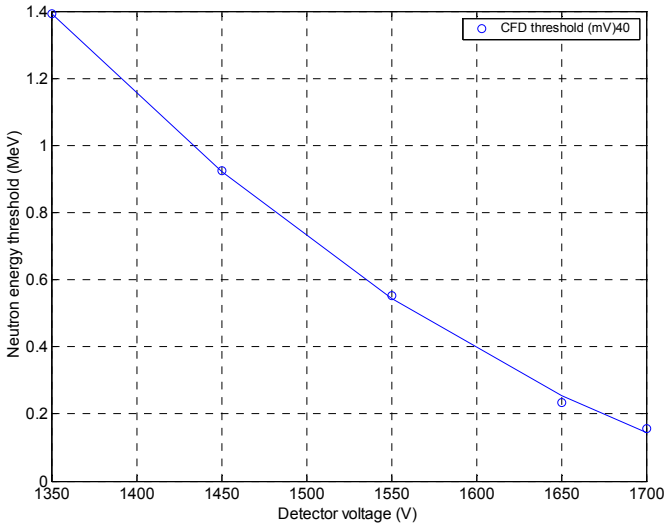
(a) (b)

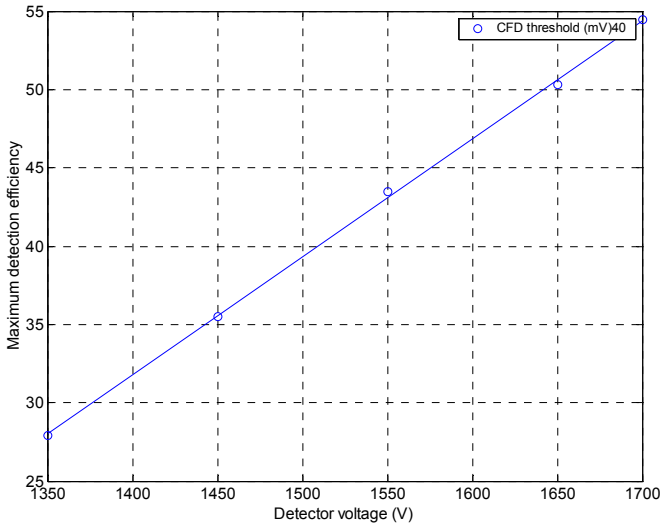
Fig. 22. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of detector voltage for fixed CFD threshold for detector 512.



(a) (b)

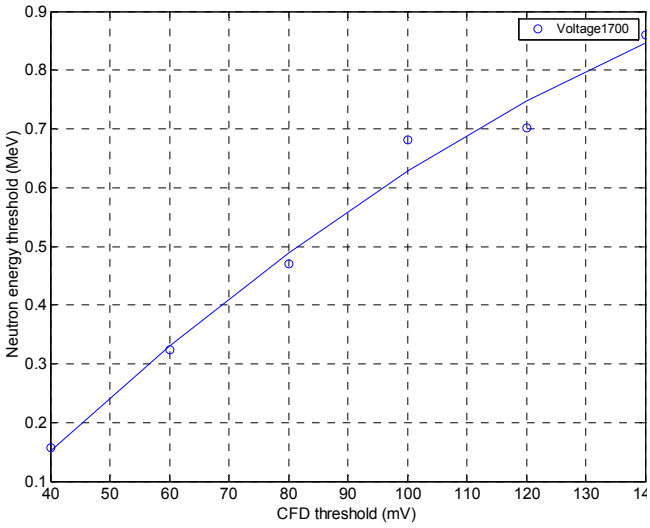
Fig. 23. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of CFD threshold for fixed detector voltage for detector 512.

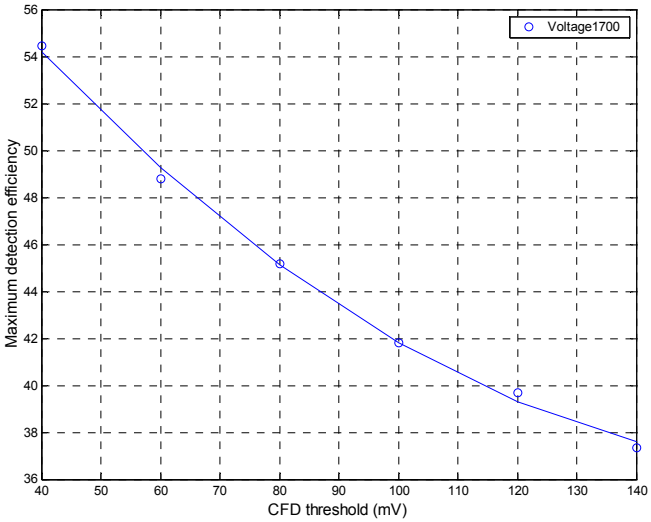




(a) (b)

Fig. 24. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of detector voltage for fixed CFD threshold for detector 513.





(a) (b)

Fig. 25. Plots showing (a) neutron energy threshold and (b) maximum detection efficiency as a function of CFD threshold for fixed detector voltage for detector 513.

Table 1. Coefficients of fit given by Eq. (2)

Detector number	a_1	a_2	a_3
503	4.507e-6	-0.0179	17.76
504	3.962e-6	-0.0157	15.49
505	4.845e-6	-0.0179	16.54
506	6.757e-006	-0.0233	20.16
507	4.359e-006	-0.0169	16.36
508	1.016e-006	-0.00625	7.550
509	3.414e-006	-0.0135	13.10
510	4.601e-006	-0.0172	15.92
511	6.514e-006	-0.0233	21.03
512	5.767e-006	-0.0206	18.39
513	4.553e-006	-0.0175	16.66

Table 2. Coefficients of fit given by Eq. (3)

Detector number	a_1	a_2
503	0.0693	-69.54
504	0.0718	-72.27
505	0.0739	-68.46
506	0.0769	-69.46
507	0.0755	-74.57
508	0.0754	-66.85
509	0.0697	-60.36
510	0.0743	-67.14
511	0.0741	-70.54
512	0.0768	-70.31
513	0.0753	-73.69

Table 3. Coefficients of fit given by Eq. (4)

Detector number	a_1	a_2	a_3
503	-3.24e-005	0.0135	-0.419
504	-2.18e-005	0.0107	-0.196
505	-2.72e-005	0.0122	-0.269
506	-5.81e-005	0.0163	-0.387
507	-2.95e-005	0.0124	-0.273
508	-3.15e-005	0.0132	-0.336
509	-5.46e-005	0.0166	-0.342
510	-3.56e-005	0.0138	-0.415
511	-3.95e-005	0.0139	-0.342
512	-1.49e-005	0.0092	-0.233
513	-2.46e-005	0.0114	-0.264

Table 4. Coefficients of fit given by Eq. (5)

Detector number	a_1	a_2	a_3
503	0.000699	-0.283	63.77
504	0.00117	-0.368	65.41
505	0.000819	-0.296	62.78
506	0.000981	-0.331	64.56
507	0.000745	-0.294	63.76
508	0.00112	-0.354	65.66
509	0.00107	-0.334	62.47
510	0.000841	-0.308	65.73
511	0.00107	-0.356	67.33
512	0.00123	-0.382	68.95
513	0.00101	-0.347	66.46

The voltages for the 11 detectors that correspond to varying maximum neutron detection efficiencies for a fixed CFD threshold of 40 mV are given in Table 5.

Table 5. Voltages and neutron energy thresholds for detectors 503 through 513 corresponding to varying efficiencies (CFD threshold fixed at 40 mV)

Detector number	Voltages (V) and, in parenthesis, neutron energy thresholds (MeV) for efficiency 30%	35%	40%	45%	50%
503	1437 (1.34)	1510 (1.00)	1582 (0.72)	1654 (0.48)	1726 (0.29)
504	1425 (1.16)	1494 (0.87)	1564 (0.62)	1633 (0.41)	1703 (0.24)
505	1333 (1.28)	1401 (0.97)	1468 (0.70)	1536 (0.47)	1603 (0.29)
506	1300 (1.28)	1359 (0.97)	1424 (0.68)	1489 (0.44)	1554 (0.26)
507	1386 (1.31)	1452 (1.01)	1518 (0.75)	1585 (0.52)	1651 (0.33)
508	1300 (1.14)	1352 (0.95)	1418 (0.73)	1485 (0.50)	1551 (0.30)
509	1300 (1.32)	1368 (1.02)	1440 (0.73)	1511 (0.49)	1583 (0.28)
510	1308 (1.29)	1375 (0.96)	1443 (0.68)	1510 (0.43)	1577 (0.23)
511	1357 (1.40)	1424 (1.05)	1492 (0.76)	1559 (0.53)	1627 (0.36)
512	1306 (1.32)	1371 (0.98)	1436 (0.70)	1501 (0.46)	1566 (0.27)
513	1377 (1.19)	1443 (0.88)	1509 (0.62)	1576 (0.38)	1642 (0.20)

5. CONCLUSIONS

This report presents the results of the characterization of 11 large liquid scintillators. The neutron energy threshold and maximum detection efficiency were determined as a function of voltage and CFD threshold. Fits to the response of each detector are provided. The results can be used to select the experimental settings in the operation of the detectors to ensure consistent response and repeatability.

REFERENCES

1. J. T. Mihalczo, J. A. Mullens, J. K. Mattingly, and T. E. Valentine, "Physical Description of Nuclear Materials Identification System (NMIS) Signatures," *Nuclear Instruments and Methods in Physics Research Section A,* **450**, 531 (August 2000).

APPENDIX A

Table A1. Experimental results for detector 503 (a)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1800	80	0.429	45.76	1.97
1400	40	1.475	27.25	4.17
1450	40	1.167	30.78	3.38
1500	40	1.001	34.43	2.69
1550	40	0.774	38.31	2.44
1600	40	0.627	41.71	2.11
1650	40	0.487	45.31	1.81
1700	40	0.312	48.58	1.57
1750	40	0.218	51.81	1.32
1750	60	0.431	46.21	1.84
1800	40	0.037	53.98	1.10
1800	100	0.605	42.83	2.17
1800	120	0.695	39.95	2.45
1800	140	0.850	37.71	2.68
1800	60	0.331	48.49	1.60
1350	40	1.819	23.47	4.46

Table A2. Experimental results for detector 503 (b)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1350	40	1.819	23.47	4.46
1400	40	1.475	27.25	4.17
1450	40	1.167	30.78	3.38
1500	40	1.001	34.43	2.69
1550	40	0.774	38.31	2.44
1600	40	0.627	41.71	2.11
1650	40	0.487	45.31	1.81
1700	40	0.312	48.58	1.57
1750	40	0.218	51.81	1.32
1800	40	0.037	53.98	1.10
1800	60	0.331	48.49	1.60
1800	80	0.429	45.76	1.97
1800	100	0.605	42.83	2.17
1800	120	0.695	39.95	2.45
1800	140	0.850	37.71	2.68
1750	60	0.431	46.21	1.84

Table A3. Experimental results for detector 504 (a)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1800	40	0.1	55.82	0.93
1400	40	1.352	27.31	3.67
1450	40	1.102	31.54	2.96
1500	40	0.854	35.47	2.58
1550	40	0.702	39.87	2.17
1600	40	0.527	43.74	1.84
1650	40	0.393	46.81	1.62
1700	40	0.280	50.30	1.39
1750	100	0.646	40.34	2.30
1750	120	0.764	38.39	2.49
1750	140	0.876	36.46	2.81
1750	40	0.182	52.92	1.2
1750	60	0.392	46.80	1.65
1750	80	0.510	43.54	1.95
1350	40	1.49	24.54	4.4

Table A4. Experimental results for detector 504 (b)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1350	40	1.499	24.54	4.4
1400	40	1.352	27.31	3.67
1450	40	1.102	31.54	2.96
1500	40	0.8543	35.47	2.58
1550	40	0.702	39.87	2.17
1600	40	0.527	43.74	1.84
1650	40	0.393	46.81	1.62
1700	40	0.280	50.30	1.39
1750	40	0.182	52.92	1.2
1800	40	0.1	55.82	0.93
1750	60	0.392	46.80	1.65
1750	80	0.510	43.54	1.95
1750	100	0.646	40.34	2.30
1750	120	0.764	38.39	2.49
1750	140	0.876	36.46	2.81

Table A5. Experimental results for detector 505 (a)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1700	40	0.1	57.14	1.24
1400	40	0.930	34.76	2.77
1450	40	0.752	39.26	2.27
1500	40	0.595	43.27	1.91
1550	40	0.425	46.13	1.66
1600	40	0.313	50.27	1.41
1650	100	0.699	41.83	2.20
1650	120	0.781	39.21	2.44
1650	140	0.922	37.15	2.62
1650	40	0.168	52.46	1.6
1650	60	0.383	47.72	1.63
1650	80	0.525	43.86	2.08
1350	40	1.22	30.57	3.3

Table A6. Experimental results for detector 505 (b)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1350	40	1.22	30.57	3.3
1400	40	0.930	34.76	2.77
1450	40	0.752	39.26	2.27
1500	40	0.595	43.27	1.91
1550	40	0.425	46.13	1.66
1600	40	0.313	50.27	1.41
1650	40	0.168	52.46	1.6
1700	40	0.1	57.14	1.24
1650	60	0.383	47.72	1.63
1650	80	0.525	43.86	2.08
1650	100	0.699	41.83	2.20
1650	120	0.781	39.21	2.44
1650	140	0.922	37.15	2.62

Table A7. Experimental results for detector 509 (a)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1650	40	0.120	54.61	1.24
1500	40	0.522	44.17	1.84
1550	40	0.389	48.35	1.49
1550	40	0.391	47.90	1.54
1600	100	0.770	39.74	2.30
1600	120	0.860	37.71	2.60
1600	40	0.230	50.94	1.31
1600	60	0.463	45.91	1.81
1600	80	0.626	42.84	2.04
1450	40	0.704	40.56	2.15

Table A8. Experimental results for detector 509 (b)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1450	40	0.704	40.56	2.15
1500	40	0.522	44.17	1.84
1550	40	0.389	48.35	1.49
1550	40	0.391	47.90	1.54
1600	40	0.230	50.94	1.31
1650	40	0.120	54.61	1.24
1600	60	0.463	45.91	1.81
1600	80	0.626	42.84	2.04
1600	100	0.770	39.74	2.30
1600	120	0.860	37.71	2.60

Table A9. Experimental results for detector 508 (a)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1600	80	0.501	44.42	1.95
1400	40	0.773	39.13	2.34
1450	40	0.614	42.11	2.00
1500	40	0.451	46.55	1.63
1550	40	0.315	50.06	1.48
1600	100	0.671	41.82	2.20
1600	120	0.800	39.09	2.4
1600	40	0.133	53.44	1.14
1600	60	0.369	48.16	1.63
1350	40	0.965	34.51	2.85

Table A10. Experimental results for detector 508 (b)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1350	40	0.965	34.51	2.85
1400	40	0.773	39.13	2.34
1450	40	0.614	42.11	2.00
1500	40	0.451	46.55	1.63
1550	40	0.315	50.06	1.48
1600	40	0.133	53.44	1.14
1600	60	0.369	48.16	1.63
1600	80	0.501	44.42	1.95
1600	100	0.671	41.82	2.20
1600	120	0.800	39.09	2.4

Table A11. Experimental results for detector 506 (a)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1600	80	0.551	44.33	1.95
1350	40	1.003	33.72	2.78
1400	40	0.798	38.58	2.31
1450	40	0.574	42.36	2.03
1500	40	0.411	46.05	1.72
1550	40	0.253	50.32	1.45
1600	100	0.683	41.21	2.12
1600	120	0.724	38.93	2.39
1600	40	0.184	52.86	1.13
1600	60	0.357	48.22	1.62
1350	120	1.002	34.78	2.76

Table A12. Experimental results for detector 506 (a)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1350	40	1.00	33.72	2.78
1400	40	0.798	38.58	2.31
1450	40	0.574	42.36	2.03
1500	40	0.411	46.05	1.72
1550	40	0.253	50.32	1.45
1600	40	0.184	52.86	1.13
1600	60	0.357	48.22	1.62
1600	80	0.551	44.33	1.95
1600	100	0.683	41.21	2.12
1600	120	0.724	38.93	2.39
1350	120	1.002	34.78	2.76

Table A13. Experimental results for detector 507 (a)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency
1350	40	1.444	26.49
1400	40	1.232	31.14
1450	40	0.920	35.37
1500	40	0.774	38.81
1550	40	0.588	43.24
1600	40	0.445	46.53
1650	40	0.300	49.32
1700	100	0.664	41.60
1700	120	0.757	39.42
1700	140	0.900	37.69
1700	160	0.952	35.42
1700	40	0.157	53.37
1700	60	0.390	48.72
1700	80	0.537	44.76

Table A14. Experimental results for detector 507 (b)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency
1350	40	1.444	26.49
1400	40	1.232	31.14
1450	40	0.920	35.37
1500	40	0.774	38.81
1550	40	0.588	43.24
1600	40	0.445	46.53
1650	40	0.300	49.32
1700	40	0.157	53.37
1700	60	0.390	48.72
1700	80	0.537	44.76
1700	100	0.664	41.60
1700	120	0.757	39.42
1700	140	0.900	37.69
1700	160	0.952	35.42

Table A15. Experimental results for detector 510 (a)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1650	80	0.467	46.28	1.76
1400	40	0.826	36.93	2.58
1450	40	0.693	40.76	2.16
1500	40	0.486	44.76	1.72
1550	40	0.321	47.93	1.57
1600	40	0.216	51.88	1.25
1650	100	0.586	43.62	2.08
1650	120	0.724	41.01	2.24
1650	140	0.816	38.84	2.47
1650	40	0.070	55.01	1.17
1650	60	0.293	49.81	1.48
1350	40	1.120	32.70	3.07

Table A16. Experimental results for detector 510 (b)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1350	40	1.120	32.70	3.07
1400	40	0.826	36.93	2.58
1450	40	0.693	40.76	2.16
1500	40	0.486	44.76	1.72
1550	40	0.321	47.93	1.57
1600	40	0.216	51.88	1.25
1650	40	0.070	55.01	1.17
1650	60	0.293	49.81	1.48
1650	80	0.467	46.28	1.76
1650	100	0.586	43.62	2.08
1650	120	0.724	41.01	2.24
1650	140	0.816	38.84	2.47

Table A17. Experimental results for detector 511 (a)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1700	80	0.525	45.40	1.82
1450	40	0.855	37.03	2.46
1550	40	0.488	45.15	1.84
1650	40	0.261	51.68	1.36
1700	100	0.648	42.69	2.09
1700	120	0.735	40.25	2.34
1700	140	0.834	38.09	2.52
1700	40	0.145	55.07	1.23
1700	60	0.348	49.39	1.58
1350	40	1.387	29.14	3.51

Table A18. Experimental results for detector 511 (b)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1350	40	1.387	29.14	3.51
1450	40	0.855	37.03	2.46
1550	40	0.488	45.15	1.84
1650	40	0.261	51.68	1.36
1700	40	0.145	55.07	1.23
1700	60	0.348	49.39	1.58
1700	80	0.525	45.40	1.82
1700	100	0.648	42.69	2.09
1700	120	0.735	40.25	2.34
1700	140	0.834	38.09	2.52

Table A19. Experimental results for detector 512 (a)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1650	80	0.443	45.97	1.73
1450	40	0.650	41.06	2.1
1550	40	0.303	49.50	1.53
1650	100	0.480	43.56	2.05
1650	120	0.672	41.05	2.24
1650	140	0.761	39.38	2.44
1650	40	0.1	55.98	1.43
1650	60	0.270	49.94	1.48
1350	40	1.084	33.18	2.86

Table A20. Experimental results for detector 512 (b)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1350	40	1.084	33.18	2.86
1450	40	0.650	41.06	2.1
1550	40	0.303	49.50	1.53
1650	40	0.1	55.98	1.43
1650	60	0.270	49.94	1.48
1650	80	0.443	45.97	1.73
1650	100	0.480	43.56	2.05
1650	120	0.672	41.05	2.24
1650	140	0.761	39.38	2.44

Table A21. Experimental results for detector 513 (a)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1700	80	0.470	45.18	1.95
1450	40	0.924	35.52	2.68
1550	40	0.552	43.49	1.87
1650	40	0.234	50.29	1.43
1700	100	0.681	41.80	2.15
1700	120	0.702	39.68	2.43
1700	140	0.859	37.33	2.55
1700	40	0.156	54.45	1.07
1700	60	0.323	48.79	1.59
1350	40	1.39	27.92	3.78

Table A22. Experimental results for detector 513 (a)

Voltage	CFD threshold	Neutron energy threshold (MeV)	Max efficiency	Energy of max efficiency
1350	40	1.391	27.92	3.78
1450	40	0.924	35.52	2.68
1550	40	0.552	43.49	1.87
1650	40	0.234	50.29	1.43
1700	40	0.156	54.45	1.07
1700	60	0.323	48.79	1.59
1700	80	0.470	45.18	1.95
1700	100	0.681	41.80	2.15
1700	120	0.702	39.68	2.43
1700	140	0.859	37.33	2.55