

The Detection of Explosives Using an Inertial Electrostatic Confinement D-D Fusion Device

Alex L. Wehmeyer

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Master's thesis.

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

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by

Alex L. Wehmeyer

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Abstract

Typical explosive compositions contain low Z material (C, H, N, O) which are not easily detected using conventional x-rays or metal detectors. However, 2.45 MeV neutrons produced in a D-D fusion reaction can be used for detection of explosives or other clandestine materials in suitcases, packages, or shipping containers. Steady-state D-D operation is possible using an Inertial Electrostatic Confinement (IEC) fusion device. The University of Wisconsin IEC device has produced D-D neutrons at 1.8 x 10⁸ neutrons/second at a cathode voltage of 166 kV and a meter current of 68 mA.

This thesis describes a proof-of-principle experiment using an IEC fusion device for the detection of composition 4 (C-4), a military plastic explosive. Several experiments were conducted in order to optimize the experimental setup for the detection of the 10.83 MeV gamma rays resulting from the thermal neutron capture in nitrogen within the explosives. The nitrogen in the C-4 was detected using an IEC fusion device with a confidence greater than 95%.

Additional experiments were performed altering the cathode's size (diameter), geometry, and material composition in an attempt to optimize the neutron production rate. Results indicate that significant differences in neutron production rates are not achieved by altering the geometry or material composition of the cathode. However, the neutron production rate was found to increase approximately 21% by doubling the cathode's diameter from 10 cm to 20 cm. In addition, increasing the cathode voltage from 34 kV to 94 kV at a meter current of 30 mA increased the neutron production rate from 1.2×10^6 n/s to 2.8×10^7 n/s.

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Table of Contents

Abstract	i
Acknowledgements	ii
Table of Contents	<i>iii</i>
Table of Figures	vii
Table of Tables	x
Chapter 1 Introduction	1
1.1 Introduction	1
1.2 Experimental Objective	2
1.3 References	3
Chapter 2 Previous Work	4
2.1 Introduction	4
2.2 Thermal Neutron Analysis	5
2.3 Fast Neutron Analysis	6
2.4 Pulsed Fast Neutron Analysis	6
2.5 Pulsed Fast/Thermal Neutron Analysis	7
2.6 Neutron Backscatter	7
2.7 References	8
Chapter 3 Theory of Activation and Detection of Explosives	9
3.1 Composition of Explosive Materials	9
3.2 Thermal Neutron Capture by CHNO	12
3.2.1 Thermal Neutron Capture by Carbon	12
3.2.2 Thermal Neutron Capture by Hydrogen	13

	iv
3.2.3 Thermal Neutron Capture by Nitrogen	13
3.2.4 Thermal Neutron Capture by Oxygen	14
3.2.5 Summary of Thermal Neutron Capture by CHNO	15
3.3 Moderation of Neutrons to Thermal Energy	17
3.4 Characteristic Gamma Rays from Thermal Neutron Capture in Hy	ydrogen and
Nitrogen	
3.5 Detection of Characteristic Gamma Rays	19
3.6 References	20
Chapter 4 Theory of IEC Fusion and IEC Fusion Research at the U	niversity of
Wisconsin	23
4.1 Theory of IEC Fusion	23
4.2 IEC Fusion Research at the University of Wisconsin	26
4.3 References	
Chapter 5 Experimental Technique and Equipment	
5.1 Introduction	
5.2 Preliminary Considerations Outside the Experimental Setup	
5.2.1 Neutron Reactions with ¹⁴ N	
5.2.2 Chemical Formula of Composition 4, C-4	32
5.2.3 Procurement of Composition 4, C-4	
5.2.4 Initial NaI Calibration	
5.3 Design of an Explosive Detection System	40
5.3.1 Design of UW(C-4)DET-01	40
5.3.2 Design of UW(C-4)DET-02	42

	v
5.3.3 Design of UW(C-4)DET-03	45
5.3.4 Design of UW(C-4)DET-04	51
5.3.5 Design of UW(C-4)DET-05	55
5.3.6 Design of UW(C-4)DET-06	58
5.4 Optimizing Neutron Production Rate Experimentation	58
5.4.1 Introduction to Optimizing Neutron Production Rate	58
5.4.2 IEC Device Operation for Optimizing Neutron Production Rate	60
5.5 References	63
Chapter 6 Experimental Results	65
6.1 Explosives Detection Results from 23 & 24 March 2005	65
6.2 Explosives Detection Results from 24 & 25 March 2005	66
6.3 Optimizing Neutron Production Rate Results	67
6.3.1 Cathode Geometry	67
6.3.2 Cathode Material	68
6.3.3 Cathode Size	69
6.3.4 Cathode Voltage	70
Chapter 7 Discussion of Results	72
7.1 Discussion of Explosives Detection Results	72
7.1.1 Observations	72
7.1.1.1 Explosive Detection Results from 23 & 24 March 2005 (Run 1317	
and Run 1318)	72
7.1.1.2 Explosive Detection Results from 24 & 25 March 2005 (Run 1319	
and Run 1320)	73

	vi
7.1.2 Discussion of Results	74
7.1.2.1 Discussion of Results from 23 & 24 March 2005 (Run	1317 and Run
1319)	74
7.1.2.2 Discussion of Results from 24 & 25 March 2005 (Run	1319 and Run
1320)	76
7.2 Discussion of Neutron Production Rate Optimization Results	77
7.2.1 Observations	77
7.2.1.1 Cathode Geometry	77
7.2.1.2 Cathode Material	77
7.2.1.3 Cathode Size	78
7.2.1.4 Cathode Voltage	79
7.2.2 Discussion of Results	80
7.3 References	81
Chapter 8 Conclusions	82
8.1 Explosives Detection	82
8.2 Optimizing Neutron Production Rates	83
Chapter 9 Suggestions for Future Work	84
Appendices	86
Appendix A MCNP5 Textfile for UW(C-4)DET-03	87
Appendix B MCNP5 Textfile for UW(C-4)DET-04	94

Table of Figures

Chapter 2 Previous Work

Figure 2-1	Technologies for Bulk and Trace Detection of Explosives
Chapter 3	Theory of Activation and Detection of Explosives
Figure 3-1	Atomic Fraction of CHNO in Explosives and Other Materials11
Figure 3-2	Carbon (n,γ) Cross Section vs. Neutron Incident Energy12
Figure 3-3	Hydrogen (n,γ) Cross Section vs. Neutron Incident Energy13
Figure 3-4	Nitrogen (n, γ) Cross Section vs. Neutron Incident Energy
Figure 3-5	Oxygen (n,γ) Cross Section vs. Neutron Incident Energy15
Figure 3-6	Inelastic Scattering Cross Section to the First Excited State of ¹² C16
Figure 3-7	Inelastic Scattering Cross Section to the 2 nd Excited State of ¹⁶ O16
Figure 3-8	Typical Energy Spectrum from Thermal Neutron Activation (TNA)
	Analysis with and without Explosives Simulant
Chapter 4	Theory of IEC Fusion and IEC Fusion Research at the University of
	Wisconsin
Figure 4-1	Schematic of Inertial Electrostatic Confinement Fusion
Figure 4-2	Fusion Cross Sections for Selected Fusion Fuels
Figure 4-3	Fusion Reactivities as a Function of Energy in a Spherical IEC Device25
Figure 4-4	Typical IEC Fusion Reactions and their Product Energies25
Figure 4-5	Schematic of the University of Wisconsin IEC Device

Chapter 5 Experimental Technique and Equipment

Figure 5-1	$^{14}N(n,p)^{14}$	⁴ C Reaction	Cross Section		31
------------	--------------------	-------------------------	----------------------	--	----

N N N N N N N N N N N N N N N N N N N	viii
Figure 5-2 ${}^{14}N(n,\alpha){}^{11}B$ Reaction Cross Section	.32
Figure 5-3 C-4, 1.4 Package	.34
Figure 5-4 20 g Vial of C-4	.35
Figure 5-5 3" x 3" NaI(Tl) Detector from Ortec, Model Number 905-4	.37
Figure 5-6 microBASE from Ortec	.37
Figure 5-7 NaI(Tl) Calibration using a 1 μ Ci ⁶⁰ Co Source	.38
Figure 5-8 NaI(Tl) Calibration using a PuBe Source	.39
Figure 5-9 UW(C-4)DET-01 Experimental Setup	.40
Figure 5-10 Difference in Energy Spectrum Based on Placement of Thin Lead Sheet	.42
Figure 5-11 Typical Energy Spectrum after IEC Device Shutdown	.43
Figure 5-12 ¹²⁸ I Decay, $t_{1/2} = 24.99$ minutes (Theoretical Data vs. Experimental Data)	.44
Figure 5-13 127 I (n, γ) Reaction Cross Section	.45
Figure 5-14 8" x 4" NaI(Tl) Detector	.46
Figure 5-15 Calibration of Individual PMTs on 8" x 4" NaI(Tl) Detector	.48
Figure 5-16 Final Calibration of 8" x 4" NaI(Tl) Detector using all 3 PMTs	.49
Figure 5-17UW(C-4)DET-03 Experimental Setup with Top Lead Layer Removed	.50
Figure 5-18 UW(C-4)DET-03 Detailed Experimental Setup	.50
Figure 5-19 MCNP5 Model of UW(C-4)DET-03	.51
Figure 5-20 CAD Representation of UW(C-4)DET-04	.52
Figure 5-21 Explosives Planar Configuration within a Paraffin Sheet	.53
Figure 5-22 Explosives Vertical Array Configuration	.53
Figure 5-23 Construction Process for UW(C-4)DET-04	.54
Figure 5-24 MCNP5 Modeling and Calculations for UW(C-4)DET-04	.55

	ix
Figure 5-25 PuBe Spectrum using the 8" x 4" NaI(Tl) Detector	56
Figure 5-26 Experimental Results from UW(C-4)DET-05	57
Figure 5-27 10 cm and 20 cm, Latitude/Longitude, WRe Inner Grids	59
Figure 5-28 Symmetric and Latitude/Longitude Configurations, 10 cm, WRe Inne	r
Grids	59
Figure 5-29 Cathode Materials for 10 cm Diameter, Symmetric Grids	60
Figure 5-30 Fabrication of Standardized IEC Grid	61
Figure 5-31 Voltage Scan Methodology Used for All Sets of Experiments	62
Figure 5-32 Current Scan Methodology Used for All Sets of Experiments	62
Chapter 6 Experimental Results	
Figure 6-1 Experimental Results with and without C-4 from 23 & 24 March 2005	566
Figure 6-2 Experimental Results with and without C-4 from 24 & 25 March 2005	567
Figure 6-3 Cathode Geometry Neutron Rate vs. Current	68
Figure 6-4 Cathode Material Neutron Rate vs. Current	69
Figure 6-5 Cathode Size Neutron Rate vs. Current	70
Figure 6-6 Representative Voltage Scan for 10 cm Diameter Inner Cathode Grids	71
Chapter 7 Discussion of Results	
Figure 7-1 Experimental Results with and without C-4 from 23 & 24 March 2005	73
Figure 7-2 Experimental Results with and without C-4 from 24 & 25 March 2005	74
Figure 6-3 Cathode Geometry Neutron Rate vs. Current	77
Figure 6-4 Cathode Material Neutron Rate vs. Current	78
Figure 6-5 Cathode Size Neutron Rate vs. Current	79
Figure 6-6 Representative Voltage Scan for 10 cm Diameter Inner Cathode Grids	80

Table of Tables

Chapter J Incorver of Activation and Detection of Explosives
--

Table 3-1	Common High Explosives and Their Compositions	10
Table 3-2	The Average Number, n, of Elastic Scatters Required to Slow a Neutron	
	from 2.45 MeV to 0.025 eV is Lowest in Hydrogen	18

Chapter 1 Introduction and Experimental Objective

1.1 Introduction

In 1983, the U.S. Embassy and U.S. Marine Barracks in Beirut, Lebanon were attacked by suicide bombings resulting in 305 deaths. In 1988, 270 people were killed over Lockerbie, Scotland from the terrorist bombing of Pan Am Flight 103. In 1993, six people were killed from a car bomb at the World Trade Center in New York City, New York. When a truck bomb exploded at the Murrah Federal Office Building in Oklahoma City, Oklahoma in 1995, 168 people were killed. In 1996, 19 people were killed by a truck bomb at U.S. Military Housing in Dhahran, Saudi Arabia. Additional truck bombs killed 223 people at the U.S. Embassies in Kenya and Tanzania in 1998. In 2000, 19 people were killed from the suicide bombing of the USS Cole. These are only a few of the well known terrorist activities that have occurred over the past twenty years [1].

In 2001, 864 terrorist attacks were conducted in the international community. September 11, 2001 marked the worst terrorist attack in modern history claiming the lives of 3315 people and injuring countless others after four civilian airplanes were hijacked and flown into the World Trade Center Twin Towers in New York City, the Pentagon in Washington, D.C., and a Pennsylvania field [2].

As a result of this attack, several security measures have been initiated within the United States since September 11, 2001. On November 19, 2001, the Aviation and Transportation Security Act was signed into law by President George W. Bush. The Aviation and Transportation Security Act required all United States airports to procure and utilize explosive detection systems. It states that all United States airports must "have sufficient explosive detection systems to screen all checked baggage no later than December 31, 2002, and that as soon as such systems are in place at an airport, all checked baggage at the airport is screened by those systems [3]." Additionally, the Department of Homeland Security was established with the Homeland Security Act of 2002. The Container Security Initiative was announced in January 2002 by the United States Customs and Border Protection, a division of the Department of Homeland Security. One of the four core elements of the Container Security Initiative is "using detection technology to quickly pre-screen containers that pose a risk [4]."

An explosive detection system which quickly, efficiently, reliably, and economically detects explosives is needed. This system must detect explosives prior to the explosives damaging infrastructure, aircraft, and/or personnel.

1.2 Experimental Objective

Security from further terrorist attacks at home or abroad is a priority and part of this priority includes continuous improvement of airport and port security. This research seeks to develop a new method of detecting explosives for use in airport and port security. Specifically, the objective of this proof-of-principle experiment is to detect composition 4, C-4, a military high explosive, utilizing the neutron flux created from fusion reactions within an Inertial Electrostatic Confinement (IEC) Device. This thesis investigates the use of an IEC Device for explosives detection. In addition, the objective is accomplished by modeling the University of Wisconsin IEC Device in a general Monte Carlo N-Particle (MCNP5) transport code, version 5, developed by Los Alamos National Laboratory, determining the effect of neutron production rates from the D-D fusion reaction by altering the cathode's size, geometry, and material composition, and detecting C-4 utilizing prompt gamma neutron activation analysis techniques.

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Chapter 2 Previous Work

2.1 Introduction

Numerous technologies exist for the detection of explosives. These technologies focus on bulk detection or trace detection of explosives as shown in Figure 2-1.



Figure 2-1. Technologies for Bulk and Trace Detection of Explosives. See Reference 1 for more discussion [1].

Only detection technologies from neutron induced reactions will be considered in terms of previous work and their relevance to this proof-of-principle experiment. As shown in Figure 2-1, several different neutron detection technologies exist. A brief discussion of thermal neutron analysis, fast neutron analysis, pulsed fast neutron analysis, pulsed fast/thermal neutron analysis, and neutron backscatter techniques follows below.

2.2 Thermal Neutron Analysis

Thermal neutron analysis is a method based on the interaction of thermal neutrons with the nuclei of the explosives material. This interaction results in the capture of the thermal neutron and the emission of a characteristic gamma ray. The thermal neutrons are produced by slowing down fast neutrons from radioisotopes, neutron generators, or accelerators. The characteristic gamma rays are detected by scintillation detectors. Based on the energy of the characteristic gamma ray, specific nuclei of the explosives material can be determined [2].

An example of one such thermal neutron analysis explosives detection system is that developed by Science Applications International Corporation through a contractual relationship with the Federal Aviation Administration in 1985 [3]. This thermal neutron analysis system was specifically designed for the inspection of checked airline baggage at airports within the United States. It utilized a radioisotope, ²⁵²Cf, as its source for neutrons [4]. The source strength for the ²⁵²Cf was 3.5 x 10⁸ neutrons/second [3].

2.3 Fast Neutron Analysis

Fast neutron analysis is similar to thermal neutron analysis. The major difference between the two explosive detection techniques is the energy of the neutrons. Fast neutron analysis is a method based on the interaction of fast neutrons with the nuclei of the explosives material. This interaction results in inelastic neutron scattering and the emission of characteristic gamma rays [2]. Additionally, unlike thermal neutron analysis, this method allows for the measurement of the characteristic gamma rays from carbon and oxygen. This is attributed to the fact that carbon and oxygen detection requires neutrons with energies greater than 5 MeV and 7 MeV respectively [5].

A fast neutron analysis explosives detection system was also being studied by Science Applications International Corporation through a contractual relationship with the Federal Aviation Administration. This fast neutron analysis system would require an accelerator to produce 14 MeV neutrons from the D-T fusion reaction [3].

2.4 Pulsed Fast Neutron Analysis

Pulsed fast neutron analysis differs from fast neutron analysis because a pulsed beam of neutrons is utilized instead of a steady state beam of neutrons [3]. Additionally, the pulsed operation allows for time-of-flight measurements in order to obtain spatial information regarding the explosives material. The location of the explosives within the interrogated material can be created on a three dimensional map to guide individuals to the specific location of the explosives [5].

2.5 Pulsed Fast/Thermal Neutron Analysis

The pulsed fast/thermal neutron analysis technique incorporates the technologies previously described in thermal neutron analysis, fast neutron analysis, and pulsed fast neutron analysis. Pulsed fast/thermal neutron analysis utilizes a high energy neutron source for the measurements of the characteristic gamma rays from carbon and oxygen. It then uses the low energy neutrons produced after numerous collisions for the measurement of hydrogen and nitrogen [6].

A pulsed fast/thermal neutron analysis explosives detection system was developed at the Applied Physics Institute, Western Kentucky University. This project was partially supported by Department of Defense contracts DAAD07-98-C-0116 and DAAD05-98-C-022. This explosives detection system is called PELAN (Pulsed Elemental Analysis with Neutrons) and utilizes 14 MeV neutrons from a pulsed deuterium-tritium reaction as its neutron source [6].

2.6 Neutron Backscatter

Neutron backscatter is a technique which detects the low energy backscattered neutrons produced from collisions with hydrogen in the explosive material. An increase in the number of low energy backscattered neutrons detected would indicate the presence of hydrogen. Additionally, for the purpose of detecting the explosives in landmines, a measurement of the time behavior of the backscattered neutrons could indicate the depth of the landmine buried within the soil [7].

2.7 References

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Chapter 3 Theory of Activation and Detection of Explosives

3.1 Composition of Explosive Materials

Typical explosives are composed of carbon, hydrogen, nitrogen, and oxygen (CHNO) [1]. This composition is a direct result of explosives needing both oxidizing and reducing agents. Strong oxidizing agents are nitrogen, oxygen, fluorine, and chlorine. However, nitrogen and oxygen are primarily used in explosives because the chemistry is simpler and the cost is cheaper than using fluorine and chlorine. Carbon and hydrogen are used in explosives as the reducing agents [2].

Explosives cause an exothermic reaction. An exothermic reaction exists when the reactants contain more energy than the products and the excess energy is released as heat during the reaction [3]. When the explosive material detonates, the heat from the reaction is called the heat of explosion. The heat of explosion is the greatest when the amount of oxidizing agents causes all of the fuel to burn to its highest oxidized products or lowest internal energy states. The highest oxidation states of carbon and hydrogen, when burned with oxygen, are carbon dioxide (CO₂) and water (H₂O) respectively. Additionally, any nitrogen in the reactants tends to form nitrogen molecules (N₂) instead of nitrogen oxides since N₂ has a lower state of internal energy [1].

To determine the products in an explosive reaction, the "simple product hierarchy for CHNO explosives" is used. This "simple product hierarchy for CHNO explosives" is:

- 1. All the nitrogen forms N₂.
- 2. All the hydrogen is burned to H_2O .
- 3. Any oxygen left after the H₂O formation burns carbon to CO.
- 4. Any oxygen left after CO formation burns CO to CO₂.
- 5. Any oxygen remaining forms O₂.
- 6. Traces of NO_x are always formed.

Therefore, the amount of nitrogen and oxygen present in an explosive material is very important if an individual desires to have all of the C burned to CO_2 and all of the H burned to H_2O in order to produce the maximum heat of explosion per unit weight of the explosive material [1].

The basic composition of explosives is the same as many foods, fabrics, and polymers. However, the high concentration of nitrogen and oxygen make explosives unique [4]. Table 3-1 lists numerous high explosives and their compositions.

Explosives Based on Nitrogen	Formula	wt% C	wt% H	wt% N	wt% O	sum N+O
Ammonium Nitrate (AN)	$H_4N_2O_3$	0	5.04	35.01	59.97	94.98
Ammonium Picrate (Expl D)	$C_6H_6N_4O_7$	29.28	2.46	22.76	45.5	68.26
Cyclonite (RDX)	$C_3H_6N_6O_6$	16.22	2.72	37.84	43.22	81.06
Ethylenediamine Dinitrate	$C_2H_{10}N_4O_6$	12.91	5.42	30.1	51.58	81.68
Guanidine Nitrate	CH ₆ N ₄ O ₃	9.84	4.95	45.89	39.32	85.21
Hexamethylenetriperoxide Diamine	$C_6H_{12}N_2O_6$	34.62	5.81	13.46	46.11	59.57
Hexanitrohexaazaisowurtzitane	$C_6H_6N_{12}O_{12}$	16.45	1.38	38.36	43.82	82.18
Hydrazine nitrate	$H_5N_3O_3$		5.3	44.2	50.09	94.29
Mannitol hexanitrate	$C_6H_8N_6O_{18}$	15.94	1.78	18.59	63.69	82.28
Monomethylamine Nitrate	CH ₄ N ₂ O ₃	13.05	4.38	30.43	52.14	82.57
Nitrocellulose	$C_6H_7N_3O_{11}$	24.24	2.37	14.14	59.23	73.37
Nitroglycerine (NG)	$C_3H_5N_3O_9$	15.87	2.22	18.5	63.41	81.91
Nitrotriazolone (NTO)	$C_2H_2N_4O_3$	18.47	1.55	43.08	36.9	79.98
Octogen (HMX)	$C_4H_8N_8O_8$	16.22	2.72	37.84	43.22	81.06
Pentaerythritol Tetranitrate (PETN)	$C_5H_8N_4O_{12}$	19	2.55	17.72	60.73	78.45
Picric Acid	$C_6H_3N_3O_7$	31.46	1.32	18.34	48.88	67.22
Tetrazene	$C_2H_8N_{10}O$	12.77	4.29	74.44	8.5	82.94
Tetryl	C7H5N5O8	29.28	1.76	24.39	44.58	68.97
Trinitrobenzene (TNB)	$C_6H_3N_3O_6$	33.82	1.42	19.72	45.05	64.77
Trinitrotolouene (TNT)	$C_7H_5N_3O_6$	37.02	2.22	18.5	42.26	60.76
Triaminoguanidine Nitrate (TAGN)	CH ₉ N ₇ O ₃	7.19	5.43	58.67	28.72	87.39
Triaminotrinitrobenzene (TATB)	$C_6H_6N_6O_6$	27.92	2.34	32.55	37.19	69.74
1,3,3-Trinitroazetidine (TNAZ)	$C_3H_4N_4O_6$	18.76	2.1	29.17	49.98	79.15
Trinitrochlorobenzene	C ₆ H ₂ ClN ₃ O ₆	29.11	0.81	16.97	38.78	55.75
Trinitropyridine	$C_5H_2N_4O_6$	28.05	0.94	26.17	44.84	71.01
Urea Nitrate	CH ₅ N ₃ O ₄	9.76	4.09	34.14	52	86.14
Average (%)		20.29	2.98	30.81	46.14	76.95
Standard Deviation		<u>+</u> 8.15	<u>+</u> 1.38	<u>+</u> 11.01	<u>+</u> 8.01	<u>+</u> 8.47

Table 3-1. Common High Explosives and Their Compositions [2].

As shown in Table 3-1, explosives contain a very high concentration of nitrogen and oxygen averaging 77% by weight. Comparing the CHNO atomic densities of explosives to other common materials also illustrates the high concentration of nitrogen and oxygen in explosives relative to these other materials as shown in Figure 3-1.



Figure 3-1. Atomic Fraction of CHNO in Explosives and Other Materials [5].

3.2 Thermal Neutron Capture by CHNO

As briefly discussed in Chapter 2, the interaction of thermal neutrons with the nuclei of the explosives material can result in the capture of the thermal neutron and the emission of a characteristic gamma ray. Since explosives contain significantly greater quantities of oxygen and nitrogen than other materials, it would be useful to be able to identify explosives based on these higher concentrations. Therefore, the probability of capturing a thermal neutron by CHNO will be discussed.

3.2.1 Thermal Neutron Capture by Carbon

The (n,γ) reaction cross section for carbon is shown in Figure 3-2. The cross section for the (n,γ) reaction at a thermal neutron energy of 0.0253 eV is 3.51 mb [6].



Figure 3-2. Carbon (n,γ) Cross Section vs. Neutron Incident Energy [7].

3.2.2 Thermal Neutron Capture by Hydrogen

The (n,γ) reaction cross section for hydrogen is shown in Figure 3-3. The cross section for the (n,γ) reaction at a thermal neutron energy of 0.0253 eV is 332.6 mb [6].



Figure 3-3. Hydrogen (n,γ) Cross Section vs. Neutron Incident Energy [7].

3.2.3 Thermal Neutron Capture by Nitrogen

The (n,γ) reaction cross section for nitrogen is shown in Figure 3-4. The cross section for the (n,γ) reaction at a thermal neutron energy of 0.0253 eV is 79.5 mb [6].



Figure 3-4. Nitrogen (n,γ) Cross Section vs. Neutron Incident Energy [7].

3.2.4 Thermal Neutron Capture by Oxygen

The (n,γ) reaction cross section for oxygen is shown in Figure 3-5. The cross section for the (n,γ) reaction at a thermal neutron energy of 0.0253 eV is 0.19 mb [6].



Figure 3-5. Oxygen (n,γ) Cross Section vs. Neutron Incident Energy [7].

3.2.5 Summary of Thermal Neutron Capture by CHNO

The probabilities of a thermal neutron capture reaction occurring within carbon and oxygen are too small for detection of carbon and oxygen directly by means of thermal neutron activation analysis. In order to detect carbon and oxygen in an explosives material, neutrons with energies greater than 5 MeV and 7 MeV respectively are required for the emission of characteristic gamma rays resulting from inelastic collisions [8]. The inelastic scattering cross sections of carbon and oxygen are shown in Figures 3-6 and 3-7.



Figure 3-6. Inelastic Scattering Cross Section to the First Excited State of ¹²C [9]. (See reference 9 for information regarding the listed evaluated nuclear data libraries: ENDF, JEF, JENDL, and BROND.)



Figure 3-7. Inelastic Scattering Cross Section to the 2nd Excited State of ¹⁶O [9]. (See reference 9 for information regarding the listed evaluated nuclear data libraries: ENDF, JENDL, and BROND.)

However, the probabilities of a thermal neutron capture reaction occurring within hydrogen and nitrogen are large enough for detection by means of thermal neutron activation analysis. Since high nitrogen concentrations are characteristic of explosives material, detection of nitrogen is the key and detection of hydrogen may be used in order to determine what type of explosive material is present from the ratio of the nitrogen concentration to the hydrogen concentration.

3.3 Moderation of Neutrons to Thermal Energy

The (n,γ) reactions for hydrogen and nitrogen described in Section 3.2 are based on neutrons at thermal energies of 0.0253 eV. Most neutrons are not initially at thermal energies. Therefore, in order to slow down a neutron to thermal energy, the neutron must have numerous elastic scattering collisions in order to decrease its energy. The number, n, of elastic scattering collisions needed to slow a neutron from its initial energy, E_i , to a lower energy, E_f , in a material of atomic weight A can be found by [10]:

$$n = \frac{1}{\xi} \ln(\frac{E_i}{E_f})$$
 (Eqn 3-1)

where

$$\xi = 1 + \frac{\alpha}{1 - \alpha} \ln(\alpha)$$
 (Eqn 3-2)

and

$$\alpha = \frac{(A-1)^2}{(A+1)^2}.$$
 (Eqn 3-3)

Material	A	α	ξ	n
Н	1	0	1	18.4
D	2	0.111	0.725	25.4
С	12	0.716	0.158	116.6
0	16	0.779	0.120	153.4

This means that materials with smaller A numbers are more effective at slowing down neutrons than materials with large A numbers as shown in Table 3-2.

Table 3-2: The Average Number, n, of Elastic Scatters Required to Slow a Neutron from2.45 MeV to 0.025 eV is Lowest in Hydrogen.

Therefore, water, heavy water, and paraffin wax are typically used as moderating materials for neutrons. However, all of these materials, with the exception of heavy water which is often cost prohibitive, contain large quantities of hydrogen which might affect the detection system's ability to distinguish between hydrogen from the explosives material and hydrogen from the moderator.

3.4 Characteristic Gamma Rays from Thermal Neutron Capture in

Hydrogen and Nitrogen

The thermal neutron capture cross section for hydrogen is 332.6 mb with the emission of a 2.223 MeV characteristic gamma ray [6]. The thermal neutron capture cross section for nitrogen is 79.5 mb with the emission of several characteristic gamma rays. The characteristic gamma ray of interest for nitrogen detection has a thermal neutron capture cross section of 11.3 mb, approximately 14% of the total nitrogen

thermal neutron capture cross section, and energy of 10.829 MeV. The 10.829 MeV characteristic gamma ray from nitrogen allows for the detection of explosives because it is the highest energy gamma ray resulting from thermal neutron capture of all nuclei by almost 1 MeV [6].

3.5 Detection of Characteristic Gamma Rays

A detector must be used that is capable of identifying nitrogen's 10.829 MeV characteristic gamma ray, as well as its single and double escape peaks, and hydrogen's 2.223 MeV characteristic gamma ray. A scintillation detector is ideally suited for this purpose. A typical spectrum from thermal neutron activation analysis of C-4 simulant is shown in Figure 3-8.

The energy spectrum shown in Figure 3-8 illustrates the difference in the high energy region between thermal neutron activation analysis with and without C-4 simulant. The energy spectrum from thermal neutron activation analysis with C-4 simulant shows the 10.83 MeV signature from the explosives simulant. The energy spectrum also shows some of the challenges involved in the detection of explosives since the nitrogen signature from the C-4 simulant is several orders of magnitude lower than the rest of the energy spectrum. Although the nitrogen signature is relatively weak, it is easily identifiable relative to the energy spectrum from thermal neutron activation analysis without C-4 simulant. Additionally, there are only a few sources of background in the nitrogen region which include: cosmic rays, neutron interaction in the detector crystal, and electronic pile up which pushes lower energy pulses into the high energy region [11]. The relatively low number of hydrogen counts and the dip in the energy

spectrum after the hydrogen signature is due to the implementation of a pulse width sensitive pile-up rejector which was developed in order to minimize pile up since the gamma ray energy of interest is several orders of magnitude smaller than the background of other gamma rays in the spectrum [12].



Figure 3-8. Typical Energy Spectrum from Thermal Neutron Activation (TNA) Analysis with and without Explosives Simulant [11].

3.6 References

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Chapter 4 Theory of IEC Fusion and IEC Fusion Research at the University of Wisconsin

4.1 Theory of IEC Fusion

Inertial electrostatic confinement (IEC) fusion concepts within the United States began in the mid 1960's with the work of Philo T. Farnsworth [1] and Robert L. Hirsch [2]. These concepts establish a negative potential well, within a spherical geometry, which causes ions to oscillate until they fuse. Figure 4-1 illustrates the basic principles behind this concept:



Figure 4-1. Schematic of Inertial Electrostatic Confinement Fusion [3].

As shown in Figure 4-1, IEC fusion is achieved by:

- 1. Creating a deep negative electric potential well.
- 2. The potential well traps positive ion fuels.
- The positive ion fuels radially oscillate within the potential well.
4. Radial oscillations continue until the ions fuse or are lost due to charge exchange scattering [3].

Several fuel cycles can be used for IEC fusion with the deuterium-tritium (D-T) fuel cycle having the highest cross section (Figure 4-2). Advanced fuel cycles have also been investigated including D-³He, D-D, and ³He-³He [4, 5]. However, as shown in Figure 4-2, the advanced fuels have a significantly lower cross section at the typical operating voltages of an IEC fusion device. Additionally, as shown in Figure 4-3, the advanced fuels have lower fusion reactivities at the typical operating voltages of an IEC fusion device.



Figure 4-2. Fusion Cross Sections for Selected Fusion Fuels [6]



Figure 4-3. Fusion Reactivities as a Function of Energy in a Spherical IEC Device [6].

The primary three fuel cycles studied around the world and their fusion reactions are shown in Figure 4-4.



Figure 4-4. Typical IEC Fusion Reactions and their Product Energies [7].

4.2 IEC Fusion Research at the University of Wisconsin

The UW IEC device used in this work is an aluminum cylinder with an inner diameter of 91 cm and an inner height of 65 cm as shown in Figure 4-5.



Figure 4-5. Schematic of the University of Wisconsin IEC Device [8].

This device is a vacuum chamber with a pumping system that allows for base pressures around 10⁻⁷ torr. A 50 cm diameter, stainless steel, outer grid (anode) is kept at ground potential while a concentric, inner cathode grid of various dimensions and material is kept at a negative potential. A boron-nitride or alumina insulator is used around the high voltage molybdenum feedthrough in order to allow for operation down to

-200 kV_{metered} on the inner cathode grid. The high voltage power supply runs through three sets of resistors, placed within a silicon oil bath, totaling 200 k Ω prior to reaching the inner cathode grid (ie. if the IEC device is operating at 60 kV_{metered} and 30 mA, the true cathode voltage is 54 kV). During operation, the inner and outer grids form a negative electric potential well within the center of the IEC device. High energy deuterium ions can recirculate through this negative electric potential well leading to the D-D fusion reaction shown in Figure 4-4.

The UW IEC device was normally operated at a background gas pressure of 2 mtorr for this experiment. Some of the background deuterium gas is ionized outside of the 50 cm diameter stainless steel anode by three 200 W light bulb filaments placed equidistant around the vacuum chamber. The deuterium ions, subject to the large negative electric potential well, are then accelerated towards the negatively charged inner cathode grid and subsequently create the D-D fusion reaction or are lost due to scattering. A ³He neutron detector, calibrated with a PuBe source, is used to measure the neutron production rate while a residual gas analyzer measures the gas and impurity levels within the vacuum chamber [7].

Research at the University of Wisconsin has also used the D-³He reaction to produce medical isotopes for Positron Emission Tomography [7, 8]. The IEC fusion device has also been used to investigate the implantation of D⁺ and He⁺ in candidate fusion first wall materials [9]. Current additional research includes designing an ion source for ³He-³He fusion [5], using the IEC device for Highly Enriched Uranium (HEU) detection [10], designing a direct conversion system [11], investigating the atomic physics effects on IEC ion radial flow [12], and using the 2.45 MeV neutrons from the D-D fusion reaction for explosives detection.

4.3 References

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Chapter 5 Experimental Technique and Equipment

5.1 Introduction

The D-D fusion reaction can be used for explosives detection using the University of Wisconsin (UW) IEC Device [1]. The 2.45 MeV neutrons generated from the D-D fusion reaction can activate, for detection purposes, the low Z materials found in explosives. Specifically, the neutrons, once thermalized, will be captured by the ¹⁴N nuclei, with a thermal capture cross section of 11.3 mb, resulting in a characteristic gamma ray of 10.829 MeV [2].

A common technique for explosives detection utilizing thermal neutron activation analysis uses neutrons produced from the radioactive decay of ²⁵²Cf. However, this method of explosives detection poses a significant health hazard and there is no way to stop the radioactive decay of ²⁵²Cf and radiation protection is always a concern [3]. Furthermore, if an explosive device were detonated during inspection using a ²⁵²Cf source, a significant health hazard would arise from the fragmentation of the ²⁵²Cf source.

These health hazards are significantly reduced using an IEC device as the neutron source. Radiation protection is only a concern while the IEC device is operating. Once the IEC device is turned off, the health hazard essentially disappears. Additionally, if an explosive device were detonated during inspection of a container using the IEC device, the fusion of D-D immediately ceases and no health hazard would arise since deuterium alone is stable and there is very little induced radioactivity in the IEC device.

The following sections describe the design process and evolution of the University of Wisconsin's explosives detection system. This system was designed for detecting C-4. Therefore, each design is designated UW(C-4)DET-#, where the # indicates the design number in order of progression. The first experimental setup was designated UW(C-4)DET-01.

5.2 Preliminary Considerations Outside the Experimental Setup

5.2.1 Neutron Reactions with ¹⁴N

The emission of 10.83 MeV gamma rays due to the (n,γ) reaction was identified as the key reaction for the detection of explosives. Additional neutron reactions, $^{14}N(n,p)^{14}C$ and $^{14}N(n,\alpha)^{11}B$, were also identified for nitrogen. However, these reactions did not assist in the detection process. The cross sections for these reactions are shown in Figures 5-1 and 5-2.



Figure 5-1. ¹⁴N(n,p)¹⁴C Reaction Cross Section [4].



Figure 5-2. ${}^{14}N(n,\alpha){}^{11}B$ Reaction Cross Section [4].

These reactions did not assist in the detection of explosives because the products of the reactions are 14 C which has a half-life of 5730 years and 11 B which is stable.

5.2.2 Chemical Formula of Composition 4, C-4

In order to accurately predict the energy spectrum that could be expected while activating C-4, the CHNO content is needed. Numerous publications indicated that C-4 is approximately 90% RDX by weight and RDX is $C_3H_6N_6O_6$. If the assumption is made that no nitrogen exists within the other 10% of C-4, then an approximation of the nitrogen content can be made. The nitrogen content of RDX is

$$\% N_{RDX} = \frac{6(14.007)}{3(12.011) + 6(1.0079) + 6(14.007) + 6(15.999)} \times 100 = 37.8\%$$

Therefore, a 480 g sample of C-4 which is 90% RDX by weight would have 163.3 g of nitrogen as shown below.

480
$$g_{c-4}(0.90)(.378) = 163.3 g_{nitrogen}$$
.

However, one source indicated that the chemical formula for C-4 could be approximated as $C_{1.82}H_{3.54}N_{2.46}O_{2.51}$ [5]. Using this chemical formula, a 480 g sample of C-4 would contain 165.4 g of nitrogen.

5.2.3 Procurement of Composition 4, C-4

Composition 4, C-4, is a military plastic explosive. Explosives are controlled by federal regulations and possession of explosives is normally limited to individuals that have a permit or license. However, students who are employed by public schools may receive or possess explosives on behalf of the school if the possession is within the scope of their employment [6, 7]. Therefore, possession of explosives was not an issue. However, finding a dealer for the procurement of explosives was difficult and coordination had to be made with the University of Wisconsin's Police Department in order to meet the storage requirements outlined in the federal regulations.

A distributor of explosives was found which sells a small package of C-4 which contains 24 - 20 g vials, 480 g total, of C-4 explosives which they designate: C-4, 1.4 package. The explosives are packaged so that the package meets the requirements of the Department of Transportation's explosive classification of Division 1.4. Division 1.4 consists of explosives that present a minor explosion hazard where the explosive effects are largely confined to the package and no projection of fragments of appreciable size or range is to be expected. Additionally, an external fire must not cause instantaneous explosion of the contents of the package. In order to get approval for the C-4, 1.4 package, a representative from the explosives distributor stated that his company had to demonstrate that detonation of a central 20 g unit, by means of an internally placed No. 8 blasting cap, would not cause a mass detonation. Therefore, the explosives distributor could ship this package to the University of Wisconsin. The package containing the explosives is shown in Figure 5-3 and Figure 5-4 shows a single vial containing 20 g of the military plastic explosive, C-4.



Figure 5-3. C-4, 1.4 Package.



Figure 5-4. 20 g Vial of C-4.

However, prior to ordering the explosives, approval from both the University of Wisconsin's purchasing department and safety office was required. A meeting with the University of Wisconsin's safety office was conducted and a chemical hygiene plan was developed for the use of explosives within the University of Wisconsin's IEC Laboratory. Additionally, storage and handling procedures for the C-4 was discussed and coordinated with the University of Wisconsin Police Department.

Once final approval from the University of Wisconsin was received, the C-4 package was ordered. Additionally, information was requested through the Holston Army Ammunition Plant which manufactured the explosives. A material safety data sheet (MSDS) and a certificate of analysis for the lot number of the purchased C-4 was

provided. According to the certificate of analysis, the C-4 that would be used in this work was 90.4 % RDX and 9.6 % binder.

Based on this data, an approximation for the chemical formula of this lot of C-4 was made assuming that all of the nitrogen and oxygen are provided by the RDX and the binder consists of only carbon and hydrogen. This calculation was performed using the computer program Engineering Equation Solver (EES) and the approximate chemical formula for this lot of C-4 was $C_{0.8075}H_{1.614}N_{1.035}O_{1.035}$.

5.2.4 Initial NaI Calibration

Prior to setting up the experiment, initial tests were performed with a 3" diameter x 3" thick NaI(Tl) detector in order to ensure that it was not only functioning properly but that it was calibrated in order to allow for an energy spectrum which included the 2.22 MeV signature from hydrogen and the 10.83 MeV signature from nitrogen. The detector is an Ortec 3" x 3" NaI(Tl) detector (Figure 5-5) and microBASE. The microBASE is an all in one 14-pin photomultiplier tube base, preamplifier, amplifier, high voltage power supply, and multichannel analyzer with a USB interface specifically designed for NaI spectrometry and counting as shown in Figure 5-6.



Figure 5-5. 3" x 3" NaI(Tl) Detector from Ortec, Model Number 905-4 [8].



Figure 5-6. microBASE from Ortec. An all in one 14-pin photomultiplier tube base, preamplifier, amplifer, high voltage power supply, and multichannel analyzer with a USB interface [8].

Initial calibration of the detector and microBASE was performed with a 1 μ Ci sample of ⁶⁰Co. This source was chosen because it would allow for two peaks for calibration instead of one with it's emission of 1.17 MeV and 1.33 MeV gamma rays. The voltage setting and amplifier settings were adjusted until the location of these two peaks allowed for an energy spectrum greater than 11 MeV. The final calibration settings included a voltage of 800 V, an amplifier coarse gain of 1.0 and fine gain of 1.003, a lower level discriminator set at channel 12, and an upper level discriminator set at channel 12, and an upper level discriminator set at channel 1012. After a total of 500 s, 490 s of actual counting due to some dead time, the energy spectrum shown in Figure 5-7 was obtained.



Figure 5-7. NaI(Tl) Calibration using a 1 μ Ci ⁶⁰Co Source.

In order to further refine the energy calibration, a PuBe source was obtained from the University of Wisconsin Nuclear Reactor staff in order to utilize its emission of a 4.4 MeV gamma ray. Additionally, this PuBe source emits 2.2×10^6 n/s and resulted in the emission of 2.22 MeV gamma rays from hydrogen which surrounded the NaI(Tl) detector so the energy spectrum in Figure 5-8 not only allowed for further calibration with the 4.4 MeV peak from the PuBe source but also from the 2.22 MeV gamma ray resulting from thermal neutron capture in hydrogen.



Figure 5-8. NaI(Tl) Calibration using a PuBe Source.

Additionally, during the calibration with the PuBe source, a large dead time was encountered. The energy spectrum shown in Figure 5-8 was for a real time of 62 s and a live time of 261 s. The significant amount of dead time was a concern since the IEC device would be operating at even higher neutron production rates and would produce a significant amount of x-rays during operation. An experimental setup that would minimize the amount of dead time in the detector was clearly needed.

5.3 Design of an Explosive Detection System

5.3.1 Design of UW(C-4)DET-01

In order to minimize the noise in the detector from background and x-rays produced by the IEC device during operation, lead bricks were obtained from the University of Wisconsin Nuclear Reactor staff. These lead bricks were used around the entire housing of the detector except for the front face adjacent to the IEC device's cylindrical wall as shown in Figure 5-9. Lead bricks were not used against the IEC chamber wall because a 2" lead brick would attenuate the neutron flux by a factor of 4 or greater at 2.45 MeV and the neutron flux needed to be maximized for the neutron activation analysis of the explosives [9].



Figure 5-9. UW(C-4)DET-01 Experimental Setup.

Initial experiments were performed in order to check the signal from the detector while operating the IEC device. Initial energy spectrums at IEC operating voltages of 60 kV and less revealed the hydrogen peak at 2.22 MeV. However, as the operating voltage of the IEC device increased above 60 kV, the noise in the detector would increase with increasing cathode voltage until the detector was paralyzed. The IEC device would have to operate at significantly higher cathode voltages than 60 kV in order for the neutron production rate to be high enough for the identification of a nitrogen signature. In order to minimize the noise that resulted from increased cathode voltage and increased x-rays during IEC operation, a thin lead sheet, 1/8" thick, was obtained from McMaster-Carr that would be thin enough to allow for the penetration of the 2.22 MeV and 10.83 MeV gamma rays of hydrogen and nitrogen but thick enough to shield the detector from the lower energy x-rays (~100 keV) produced during operation.

Placement of the lead sheet was then tested in order to minimize its affects on the activation of the explosives. Experiments were performed with the lead sheet in front of the activation cell and behind the activation cell. As shown in Figure 5-10, the ideal placement for the thin lead sheet was behind the activation cell. This placement allowed for the shielding of the detector but did not influence the initial neutron flux in the activation cell.



Figure 5-10. Difference in Energy Spectrum Based on Placement of Thin Lead Sheet.

5.3.2 Design of UW(C-4)DET-02

During subsequent experiments with increased cathode voltage and current, the hydrogen peak would tend to get lost in what was originally thought to be noise. However, further investigation revealed that the reason for the loss of the hydrogen peak with increased cathode voltage and current was due to activation and subsequent decay of the iodine within the NaI(Tl) detector. Increased cathode voltage and current corresponded to increased neutron production rates. Increased neutron production rates corresponded to increased activation of the iodine. In order to confirm the iodine activation, background counts were taken prior to IEC device operation. Immediately after shutdown of the IEC device, additional counts were taken. These counts were taken for 60 s at two minute intervals. ¹²⁸I has a half life of 24.99 minutes with a maximum energy of 2.119 MeV. Figure 5-11 shows a typical 60 s count after IEC device shutdown which illustrates a typical β decay spectrum. Additionally, the maximum energy of the β decay spectrum corresponded to the maximum energy of the β decay for ¹²⁸I, 2.119 MeV. Finally, the half life of the measured counts matched the half life of ¹²⁸I as shown in Figure 5-12.



Figure 5-11. Typical Energy Spectrum after IEC Device Shutdown.



Figure 5-12. ¹²⁸I Decay, $t_{1/2} = 24.99$ minutes (Theoretical Data vs. Experimental Data).

In order to minimize the activation of the iodine within the detector, cadmium was wrapped around the detector in order to absorb the thermal neutrons. However, iodine has several resonances for neutron capture at higher energies as shown in Figure 5-13. Therefore, although the cadmium would decrease the iodine activation due to thermal neutrons, iodine activation would still occur within the detector. Additionally, the absorption of thermal neutrons in cadmium resulted in the emission of characteristic gamma rays for cadmium. However, these characteristic gamma rays are significantly lower in energy than the 10.83 MeV gamma rays produced by the thermal neutron absorption in nitrogen and would not interfere with the detection of explosives.



Figure 5-13. ¹²⁷I (n,γ) Reaction Cross Section [4].

5.3.3 Design of UW(C-4)DET-03

After conducting numerous experiments which utilized a high nitrogen content fertilizer, 45 % nitrogen by weight, and a 3" x 3" detector, the nitrogen signature could not be identified. The decision was made to replace the 3" x 3" detector with a much larger detector in order to improve the efficiency of the detector and the solid angle. The efficiency would increase in a larger detector since the volume of the crystal would increase resulting in a higher probability of interaction with the 10.83 MeV gamma rays from the nitrogen. However, the largest detector that could be found commercially without placing a special order was an 3" x 3" NaI(Tl) detector. Therefore, attempts were made to identify if any other groups at the University of Wisconsin had a larger scintillation detector.

An 8" diameter x 4" thick NaI(Tl) detector was volunteered by Dr. Nickles of the Medical Physics Department at the University of Wisconsin. This detector is shown in Figure 5-14.



Figure 5-14. 8" x 4" NaI(Tl) Detector.

In order to begin experiments with this new detector, it had to be calibrated. Initial tests were performed in order to ensure that all three photomultiplier tubes (PMTs) were functioning properly. One of the PMTs did not work and it was determined that one of its wires had been broken. After resoldering this wire, the PMT was functioning like the other two PMTs.

Individually, each PMT was connected to a preamplifier and then to an oscilloscope in order to view the signal that resulted from the PMT after applying voltage to it. A ¹³⁷Cs source was placed on the face of the detector, directly in line with the PMT that was being tested. The raw signal from the PMT was amplified resulting in all of the pulses to be greater than 10 V after the signal went through the preamplifier. This was a problem and needed to be fixed in order to have any chance at detecting the 10.83 MeV gamma rays from nitrogen. Therefore, the preamplifier was disassembled and a 50 M Ω resistor was replaced with a 200 k Ω resistor. This dropped the pulse from the ¹³⁷Cs source to less than 0.5 V which was acceptable.

After modifying the preamplifier, each PMT was individually calibrated using a ¹³⁷Cs source and a ⁶⁰Co source in order to ensure that the gain from each PMT was matched. This was accomplished by adjusting the applied voltage to the PMT until the same signal was achieved for each PMT as shown in Figure 5-15. The amplifier coarse gain and fine gain were held constant for each PMT at 128x and 1.19x respectively. PMT 1 and PMT 2 required the same voltage setting, 850 V, in order to produce the same location for the signal. PMT 3 required a voltage setting of 885 V in order to produce the same location for the signal.



Figure 5-15. Calibration of Individual PMTs on 8" x 4" NaI(Tl) Detector. Counting Time = 150 seconds.

After the correct voltages for each PMT were found, all three PMTs were connected to high voltage power supplies and the outputs of the three PMTs were daisy chained through a single preamplifier which was connected to an integrated amplifier/multichannel analyzer. Connecting all three PMTs resulted in the location of the peaks to be triple its original location for a single PMT. Therefore, the amplifier gain had to be decreased in order to allow for an energy spectrum that would include the 10.83 MeV nitrogen signature (Figure 5-16).



Figure 5-16. Final Calibration of 8" x 4" NaI(Tl) Detector using all 3 PMTs.

The UW(C-4)DET-03 setup is shown in Figures 5-17 and 5-18. In addition to changing the size of the detector, another modification to this setup from previous designs was the addition of borated polyethylene. Borated polyethylene was purchased from Thermo Electron Corporation which consisted of 5 % boron by weight. The borated polyethylene allowed for further moderation of the neutrons after the activation cell to enhance the probability of neutron absorption by the cadmium surrounding the detector. Additionally, since the material contains 5 % boron by weight, it also absorbs thermal neutrons since boron has a thermal neutron absorption cross section of 755 barns [10].



Figure 5-17. UW(C-4)DET-03 Experimental Setup with Top Lead Layer Removed.



Figure 5-18. UW(C-4)DET-03 Detailed Experimental Setup.

The experimental setup for UW(C-4)DET-03 shown in Figure 5-16 was modeled using MCNP5 as shown in Figure 5-19.



Figure 5-19. MCNP5 Model of UW(C-4)DET-03.

As seen in Figure 5-19, the explosives, located in position C, were not subject to the peak thermal neutron flux. Therefore, the design needed to be altered in order to position the explosives at the peak thermal neutron flux in order to maximize the possibility of identifying the nitrogen signature during the conduct of experimental runs.

5.3.4 Design of UW(C-4)DET-04

Based on the initial MCNP5 calculations, the experimental setup was altered in order to position the explosives closer to the IEC chamber walls. This was accomplished by creating a planar cavity within one sheet of paraffin wax in order to house the explosives during thermal neutron activation analysis experiments. Figure 5-20 shows a CAD representation of this design created by Greg Sviatoslavsky from the University of Wisconsin, Figure 5-21 shows the explosives placed within the cavity, Figure 5-22 illustrates the position of the explosives relative to the rest of the experimental setup, and Figure 5-23 illustrates the construction process for UW(C-4)DET-04.



Figure 5-20. CAD Representation of UW(C-4)DET-04



Figure 5-21. Explosives Planar Configuration within a Paraffin Sheet.



Figure 5-22. Explosives Vertical Array Configuration.



1. Bottom Layer of Lead



2. Borated Polyethylene and Cadmium Housing for Nal(TI) Detector.



 Nal(TI) Detector Placed within Borated Polyethylene and Cadmium Housing.



4. Additional Sheets of Borated Polyethylene Placed Behind the Detector.



5. Wood Structure Place around the Housing for Structural Support.



7. Thin Lead Sheet Placed in Front of Borated Polyethylene.



8. Wax and Explosives Cavity Placed in Front of Thin Lead Sheet.



6. Additional Sheets of Borated Polyethylene Placed in Front of Detector.



9. Additional Lead Bricks Placed Around Wood Structure for X-ray Shielding.

Figure 5-23. Construction Process for UW(C-4)DET-04.

MCNP5 calculations for this new design indicated that the position of the explosives was now at the peak of the thermal neutron flux and that the average thermal neutron flux within the explosives increased from 856 n/cm²-s in UW(C-4)DET-03 to 1220 n/cm^2 -s in UW(C-4)DET-04 for a uniform volume source of 1 x 10^8 n/s. The MCNP5 modeling and calculations are shown in Figure 5-24.



Figure 5-24. MCNP5 Modeling and Calculations for UW(C-4)DET-04.

5.3.5 Design of UW(C-4)DET-05

Additional MCNP5 calculations were made based on the design of UW(C-4)DET-04 including the total number of (n,γ) reactions that would occur within the explosives due to thermal neutron capture in nitrogen. Based on these calculations, an approximation of the number of 10.83 MeV gamma rays that would be detected by the detector could be made. Using a neutron production rate of 5 x 10⁷ n/s and assuming a 5% detector efficiency and a solid angle of 4 %, based on the surface area of the face of the detector and the distance of the detector from the explosives, approximately 195 gamma rays at 10.83 MeV would interact with the detector crystal during a 600 s experimental run. Due to the poor resolution of the 8" x 4" NaI(Tl) detector, and the background noise during an experimental run of 600 s without explosives being in the 150-200 counts per channel region, the nitrogen signature was not detectable. Therefore, the design was modified in order to move the detector closer to the explosives in order to increase the solid angle.

Positioning the detector closer to the explosives would increase the solid angle by a factor of 10. However, the activation of the iodine in the crystal would also increase since the neutron flux within the crystal would increase by moving the detector closer to the neutron source. Therefore, the hydrogen peak would not be identifiable during these experimental runs but the nitrogen peak should still be identifiable.

Additional calculations were performed with the increased solid angle and using the same assumptions as previously stated, the number of 10.83 MeV gamma rays interacting with the detector crystal was found to increase to approximately 1880. However, the resolution of the detector in the high energy region was extremely poor. Figure 5-25 shows the calibration of the detector using the 4.4 MeV gamma rays emitted from a PuBe source.



Figure 5-25. PuBe Spectrum using the 8" x 4" NaI(Tl) Detector.

The FWHM of the 4.4 MeV peak from the PuBe source was approximately 100 channels covering an energy range of 1.3 MeV. The entire peak covered over 200 channels. The detector's resolution also decreases with increased energy since it is proportional to $\sqrt[1]{\sqrt{E}}$. Therefore, the resolution would be even worse at 10.83 MeV than at 4.4 MeV. However, if an assumption is made that the 1880 - 10.83 MeV gamma rays are evenly distributed over 100 channels in the nitrogen region, this would correspond to approximately 18 counts per 600 seconds per channel. Each channel in the nitrogen region already had approximately 200 counts without the explosives so the additional counts from the nitrogen in the explosives was almost within one standard deviation of the counts without explosives. Therefore, the nitrogen counts were lost in the spectrum and were not identifiable as shown in Figure 5-26.



Figure 5-26. Experimental Results from UW(C-4)DET-05.

5.3.6 Design of UW(C-4)DET-06

Based on the poor resolution of the 8" x 4" NaI(Tl) detector, a final design change was made in which the same design as UW(C-4)DET-05 was used but the detector was replaced with the 3" x 3" NaI(Tl) detector. Although the smaller detector decreased the efficiency of the detection system and the solid angle, the increased resolution would hopefully be able to identify a signature from the nitrogen in the explosives. MCNP5 calculations predicted that approximately fifty nine (59) 10.83 MeV gamma rays would interact with the detector based on 0.5 % efficiency, 6 x 10^7 n/s neutron production rate, 10 % solid angle, and a 600 s experimental run. Although the number of 10.83 MeV gamma rays was relatively small, since the resolution was increased with the 3" x 3" detector, the nitrogen signature should be identifiable when comparing the energy spectrum from experiments conducted with C-4 versus experiments conducted without C-4.

5.4 Optimizing Neutron Production Rate Experimentation

5.4.1 Introduction to Optimizing Neutron Production Rate

In order to achieve better statistics, increase the probability of detecting explosives, and decrease the amount of time required for the detection of explosives, the neutron production rates needed to increase. In an attempt to optimize the neutron production rates in the UW IEC device, three variables of the inner cathode grid were changed in order to determine the effect of each variable independently. These variables were cathode diameter, cathode geometry, and cathode material composition. In the first set of experiments, the inner cathode diameter was varied from 10 cm to 20 cm while maintaining a latitude/longitude geometry and WRe material composition as shown in Figure 5-27.



Figure 5-27. 10 cm and 20 cm, Latitude/Longitude, WRe Inner Grids.

In the second set of experiments, the cathode geometry was varied from latitude/longitude to symmetric while maintaining a 10 cm diameter and WRe material composition as shown in Figure 5-28.



Figure 5-28. Symmetric and Latitude/Longitude Configurations, 10 cm, WRe Inner Grids.
Finally, the cathode material was varied from WRe to Re while maintaining a 10 cm diameter and a symmetric grid geometry.



Figure 5-29. Cathode Materials for 10 cm Diameter, Symmetric Grids.

5.4.2 IEC Device Operation for Optimizing Neutron Production Rate

Typically, the UW IEC device had been operated utilizing a 10 cm, WRe, inner cathode grid in a latitude/longitude geometry. Recently, a method was developed to manufacture the inner cathode grids utilized within the IEC device in a uniform manner [11]. Previously, the inner cathode grids had been made by hand and small variations existed between each of them. Currently, a wax mold is created in order to make each of the grids identical. This established consistency and uniformity in each of the grid designs as shown in Figure 5-30.



1. Mold produced from rapid prototype model



4. Wires spot welded at junctions



2. Wax poured into mold



5. Wax form melted away at ~80 °C



3. Wires wound around wax form



6. Finished grid cathode

Figure 5-30. Fabrication of Standardized IEC Grid [12].

In order to determine if the new symmetric grid geometry and mold for the inner cathode grids would significantly change the neutron production rate, experiments compared the previous 10 cm, WRe, latitude/longitude inner cathode grid to the new 10 cm, WRe, symmetric inner cathode grid.

For this set of experiments and each of the following experiments, the same methodology was used. After the IEC device was pumped down to a background pressure around 10⁻⁷ torr, two conditioning runs were performed and monitored utilizing a residual gas analyzer in order to ensure that each experiment began with similar gas and impurity levels within the vacuum chamber. Following the conditioning runs, two voltage scans were performed and then two current scans were performed as shown in Figures 5-31 and 5-32. Furthermore, each experiment was performed utilizing a constant background D-D gas pressure of 2 mtorr.



Figure 5-31. Voltage Scan Methodology Used for All Sets of Experiments.



Figure 5-32. Current Scan Methodology Used for All Sets of Experiments.

5.5 References

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Chapter 6 Experimental Results

6.1 Explosives Detection Results from 23 & 24 March 2005

Several experimental runs were made using the University of Wisconsin's cylindrical IEC device and UW(C-4)DET-06. Some experimental runs were performed with 480 g of C-4 inserted into the vertical explosives array configuration. Other experimental runs were performed without the C-4.

For both of these experimental configurations, the settings for the 3" x 3" NaI(Tl) detector were a voltage of 800 V, an amplifier coarse gain and fine gain of 0.80 and 0.8011 respectively, a lower level discriminator set at channel 250, and an upper level discriminator set at channel 1012. These experimental runs were performed at a cathode voltage of 130 kV and a current of 60 mA for approximately ten minutes using deuterium gas and a background gas pressure of approximately 2 mtorr. The actual experimental runs lasted longer than ten minutes since a dead time of approximately 10 % was encountered in the detector. Longer experimental runs were not possible due to heating of the aluminum IEC chamber walls. In order to maximize the amount of time for these experiments, multiple fans were used in order to air cool the chamber walls. However, once the temperature of the chamber walls approached 70 °C, the experimental runs were terminated to protect the vacuum seals and glass ports in the chamber.

The experimental conditions described above resulted in a neutron production rate of approximately $6 \ge 10^7$ n/s. The results from these experimental runs (Run 1317 and Run 1318) with and without C-4 are shown in Figure 6-1.



Figure 6-1. Experimental Results with and without C-4 from 23 & 24 March 2005.

6.2 Explosives Detection Results from 24 & 25 March 2005

Two additional experimental runs were made using the University of Wisconsin's cylindrical IEC device and UW(C-4)DET-06. The first experimental run (Run 1319) was performed with 480 g of C-4 inserted into the vertical explosives array configuration. The second experimental run (Run 1320) was performed without the C-4.

The same procedures were followed as described for the experimental runs performed on 23 & 24 March 2005 (Run 1317 and Run 1318). The only difference was that these experiments were performed at a cathode voltage of 135 kV and a current of 60

66

mA which resulted in a neutron production rate of approximately 6.3×10^7 n/s. The results from these experimental runs with and without C-4 are shown in Figure 6-2.



Figure 6-2. Experimental Results with and without C-4 from 24 & 25 March 2005.

6.3 Optimizing Neutron Production Rate Results

6.3.1 Cathode Geometry

Additional experiments were performed in an effort to optimize the neutron production rates. The early experiments compared two different inner cathode grids. The first grid consisted of a 10 cm, WRe, latitude/longitude design. The second grid consisted of a 10 cm, WRe, symmetric grid design. A comparison of the neutron





Figure 6-3. Cathode Geometry Neutron Rate vs Current.

6.3.2 Cathode Material

Once a comparison of the cathode geometry was completed, experiments to determine the variation in neutron production rate as a function of the grid material were performed. For these experiments, the first grid consisted of a 10 cm, WRe, symmetric grid design and the second grid consisted of a 10 cm, Re, symmetric grid design. A comparison of the neutron production rates of the two inner grids as a function of current is shown in Figure 6-4.



Figure 6-4. Cathode Material Neutron Rate vs Current.

6.3.3 Cathode Size

Finally, once the comparison of the cathode geometry and material composition were complete, the question of a variation in neutron production rate as a function of the size of the inner cathode grid was investigated. For this experiment, the first grid consisted of a 10 cm, WRe, latitude/longitude design. The second grid consisted of a 20 cm, WRe, latitude/longitude design. A comparison of the neutron production rates from these two inner grids as a function of current is shown in Figure 6-5.



Figure 6-5. Cathode Size Neutron Rate vs. Current.

6.3.4 Cathode Voltage

Voltage scans were performed for each grid in addition to the current scans shown in Figures 6-3, 6-4, and 6-5. In Figures 6-3, 6-4, and 6-5, the neutron production rate appears to "rollover" or reach an asymptote as the current is increased instead of being proportional to the current. This "rollover" in the neutron production rate is due to the experiments being performed at a constant metered voltage (the true cathode voltage decreases with increasing current). Figure 6-6 shows the dependence of neutron production rate on true voltage at various currents. Although this voltage scan is for one run of a 10 cm diameter, WRe, latitude/longitude grid, it is representative of all of the runs that were performed with 10 cm grids regardless of geometry or material composition.



Figure 6-6. Representative Voltage Scan for 10 cm Diameter Inner Cathode Grids.

Chapter 7 Discussion of Results

7.1 Discussion of Explosives Detection Results

7.1.1 Observations

7.1.1.1 Explosive Detection Results from 23 & 24 March 2005 (Run 1317 and Run 1318)

The 2.22 MeV characteristic gamma rays from hydrogen are not distinguishable from the background due to neutron capture within the NaI crystal and the subsequent β decay of ¹²⁸I. In addition, the lower level discriminator was positioned above the hydrogen region to minimize the dead time. Therefore, counts were not recorded in the 2.22 MeV region. Based on the NaI calibration performed on 23 March 2005, the 10.83 MeV gamma rays should appear around channel 824 on the MCA. Additionally, the single escape peak and double escape peak should appear around channels 791 and 747 respectively as shown in Figure 7-1. A separation between the energy spectrum with C-4 and the energy spectrum without C-4 was observed in the nitrogen region of 10.83 MeV which corresponded to channels 815-830 on the MCA.



Figure 7-1. Experimental Results with and without C-4 from 23 & 24 March 2005.

7.1.1.2 Explosive Detection Results from 24 & 25 March 2005 (Run 1319 and Run 1320)

Similar results were obtained from the experiments conducted with and without C-4 on 24 & 25 March 2005 as shown in Figure 7-2. Again, a slight separation between the energy spectrum with C-4 and the energy spectrum without C-4 was observed in the nitrogen region of 10.83 MeV which corresponded to channels 815-830 on the MCA.



Figure 7-2. Experimental Results with and without C-4 from 24 & 25 March 2005.

7.1.2 Discussion of Results

7.1.2.1 Discussion of Results from 23 & 24 March 2005 (Run 1317 and Run 1318)

Using the UW(C-4)DET-06 setup at neutron production rates of 6×10^7 n/s, a separation is identifiable in the nitrogen region between the energy spectrums with and without C-4. This separation is the result of the emission and detection of 10.83 MeV gamma rays resulting from thermal neutron capture within the nitrogen of the C-4.

A determination of the minimum detectable amount (MDA) is needed in order to estimate the smallest signal that can be detected in this explosives detection setup and still give valid results. Detailed analysis indicates that this experiment detected C-4 with reasonable statistical certainty and is based on a 5% false-negative probability. Using the "Currie Equation" [1], the minimum number of counts needed to ensure a false-negative rate no larger than 5 % is given by $MDA = 4.653\sigma_{N_B} + 2.706$. In this equation, σ_{N_B} is the standard deviation of the background counts without a source present. For these experiments, N_B is the number of counts without the C-4 present.

The nitrogen region of interest in this experimental setup is from channel 815-830 on the MCA. For the experimental run without C-4, $N_B = 33$ counts. Based on this value of N_B , the minimum number of counts needed above background (to determine the MDA) for positive detection of C-4 in the nitrogen region is 29 counts. Therefore, the total number of counts in the nitrogen region needed for positive identification of explosives is 62 counts ($N_B + MDA$). During the experimental run with C-4, the number of counts in the nitrogen region, N_{C-4} , was 89 counts which exceeded the 62 counts needed for positive identification. Therefore, it was concluded that C-4 was detected with a statistical certainty greater than 95%. Furthermore, the total number of counts attributed to the C-4 in the nitrogen region was 56 counts ($N_{C-4} - N_B$) which agreed remarkably well with the 59 counts that were determined based on MCNP5 calculations and approximations for the detector efficiency and solid angle as discussed in Section 5.3.6.

7.1.2.2 Discussion of Results from 24 & 25 March 2005 (Run 1319 and Run 1320)

Similar to the results discussed above, using the UW(C-4)DET-06 setup at neutron production rates of 6.3×10^7 n/s, a separation is identifiable in the nitrogen region between the energy spectrums with and without C-4. This separation is the result of the emission and detection of 10.83 MeV gamma rays resulting from thermal neutron capture within the nitrogen of the C-4.

Again, the nitrogen region of interest in this experimental setup is from channels 815-830 on the MCA. For the experimental run without C-4, $N_B = 57$ counts. The increase in N_B in this set of experiments is due to the increased operating conditions required to achieve higher neutron production rates which resulted in increased background radiation and noise within the system. Based on this value of N_B , the minimum number of counts needed, MDA, for positive detection of C-4 in the nitrogen region is 38 counts. The number of counts in the nitrogen region needed for positive identification of explosives is 95 counts, $N_B + MDA$. During the experimental run with C-4, the number of counts in the nitrogen region, N_{C-4} , was 112 counts which exceeded the 95 counts needed for positive identification. Therefore, C-4 was again detected with a statistical certainty greater than 95%. Furthermore, the total number of counts attributed to the C-4 in the nitrogen region is 55 counts ($N_{C-4} - N_B$) which agreed reasonably well with the 61 counts that were determined based on MCNP5 calculations and approximations for the detector efficiency and solid angle.

7.2 Discussion of Neutron Production Rate Optimization Results

7.2.1 Observations

7.2.1.1 Cathode Geometry

No significant difference (< 5% at all cathode voltages) in neutron production rate was achieved by altering the geometry of the cathode for a constant voltage, background D-D gas pressure, size, and material. (See Figure 6-3 reproduced below)



Figure 6-3. Cathode Geometry Neutron Rate vs Current.

7.2.1.2 Cathode Material

No significant difference (< 8% at 90 kV and < 5% at 120 kV) in neutron production rate was achieved by altering the material of the cathode from WRe to Re for

a constant voltage, background D-D gas pressure, size, and geometry. (See Figure 6-4

reproduced below)



Figure 6-4. Cathode Material Neutron Rate vs Current.

7.2.1.3 Cathode Size

The neutron production rate was found to increase approximately 21% by doubling the cathode's diameter from 10 cm to 20 cm for a constant voltage, background D-D gas pressure, geometry, material, and 50 cm anode diameter. (See Figure 6-5 reproduced below)



Figure 6-5. Cathode Size Neutron Rate vs. Current.

7.2.1.4 Cathode Voltage

Increasing the true cathode voltage from 34 kV to 94 kV at a meter current of 30 mA increased the neutron production rate from 1.2×10^6 neutrons/second to 2.8×10^7 neutrons/second for a constant background D-D gas pressure and a constant cathode size. (See Figure 6-6 reproduced below)



Figure 6-6. Representative Voltage Scan for 10 cm Diameter Inner Cathode Grids.

7.2.2 Discussion of Results

Increasing the cathode size does not significantly alter the number of beam-target and charge exchange reactions occurring within the IEC device. However, the higher neutron production rate can be attributed to an increase in the number of beambackground reactions occurring within the cathode due to the increased path length traveled by the energetic ions. The neutron production rate increase of approximately 21% can be explained by the dependence of the total D-D reaction rate on beambackground reactions. Previous experiments [2] indicate that 22% of the D-D reactions occur from beam-beam and beam-background reactions while 78% of the D-D reactions occur from beam-target and charge exchange reactions. Preliminary modeling also indicates that beam-background reactions, not beam-beam reactions, are responsible for the majority of this 22% contribution. Doubling the cathode size effectively doubles the path length traveled by the energetic ions. Therefore, doubling the path length would result in doubling the number of beam-background reactions that occur within the cathode. This would result in a neutron production rate increase of approximately 22% as observed experimentally.

7.3 References

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Chapter 8 Conclusions

8.1 Explosives Detection

Five major conclusions can be made from the results of this proof-of-principle experiment:

1) Explosives detection using the D-D fusion reaction in an IEC device is possible. This experiment successfully and repeatedly used the neutron flux created from the D-D fusion reaction in an IEC device to detect the nitrogen in the C-4 with a confidence greater than 95%.

2) The 2.45 MeV neutrons produced from the D-D fusion reaction could be used to detect explosives other than C-4 and other clandestine materials in suitcases, packages, or shipping containers.

3) MCNP5 calculational results matched the experimental results remarkably well. MCNP5 was also a great asset for modeling the experiment in order to optimize the design configuration for the detection of the 10.83 MeV gamma rays resulting from the thermal neutron capture in nitrogen within the C-4.

4) Multiple 3" x 3" NaI detectors are better suited for the detection of explosives instead of one 8" x 4" NaI detector due to the increase in detector resolution.

5) This experiment represents the first known detection of explosives using an IEC fusion device.

8.2 Optimizing Neutron Production Rates

During this study of D-D neutron production rates, the only variables studied which significantly altered the neutron production rate were the cathode size, voltage, and current. Five major conclusions can be made from the results of the optimizing neutron production rate experimentation:

1) No significant difference (< 5% at all cathode voltages) in neutron production rate was achieved by altering the spherical cathode's geometric arrangement of grid wires.

2) No significant difference (< 8% at 90 kV and < 5% at 120 kV) in neutron production rate was achieved by altering the material of the cathode wires.

3) The neutron production rate increased approximately 21% by doubling the spherical cathode's diameter.

4) The increased neutron production rate with increased voltage takes advantage of the increasing fusion cross section with increased ion energy. Increasing the true cathode voltage from 34 kV to 94 kV at a meter current of 30 mA increased the neutron production rate from 1.2×10^6 neutrons/second to 2.8×10^7 neutrons/second.

5) The increased neutron production rate with increased current is due to the increased number of energetic ions passing through the plasma. Increasing the cathode current from 30 mA to 60 mA at a meter voltage of 100 kV increased the neutron production rate from 2.8 x 10^7 neutrons/second to 4.3 x 10^7 neutrons/second.

Chapter 9 Suggestions for Future Work

In order to identify the hydrogen and nitrogen signature resulting from thermal neutron activation analysis, the NaI(Tl) detector should be shielded from the neutrons as much as possible. Placement of the NaI(Tl) detector in a direct line-of-sight of the neutrons turned out to be non-optimal. In order to minimize the amount of pile-up and increase the separation between the energy spectrums, with and without explosives, in the high energy region of the detector, pile-up rejection systems should be incorporated into the electronic setup. Additionally, more than one scintillation detector should be used for the detectors in order to increase the solid angle. Additonal detectors will also decrease the duration of time needed for the positive identification of explosives.

Increased neutron production rates are needed in order to increase the separation between energy spectrums with and without explosives. Additionally, although it was not critical for this proof-of-principle experiment, increased neutron production rates are needed in order to minimize the duration of interrogation in order for this application to be practical for commercial use in airport or port security. Experimental results indicated that increased neutron production rates can be achieved by varying the cathode size, voltage, and current. Additional experiments should be conducted to determine the affect of varying the anode to cathode distance on neutron production rates.

These experiments were limited to approximately ten minutes of IEC operation, once the chamber walls approached 70 °C, in order to protect the vacuum seals and glass ports in the chamber. In order to allow for increased operational time for experimental operation and in order for this application to be practical for commercial use, a permanent

water cooling system must be incorporated into the IEC device instead of relying on the current air cooling system.

Finally, switching the fuel cycle from D-D to D-T would not only increase the neutron production rate by approximately two orders of magnitude at the same operating conditions, it would also allow for the detection of oxygen within the explosives. This would further enhance the detection system because the specific type of explosives could be identified by using the N/O ratio.

Appendices

Appendix A MCNP5 Textfile for UW(C-4)DET-03

```
Model of UW-Madison IEC Fusion Device [UW(C-4)DET-03]
С
c box explosives configuration at 1e8 n/s
c box cavity of C-4 at 5.325 cm
C
c ell# Mat#
                Den
                        Surface combinations
C
c Inside of IEC Chamber
        0
                    -201 -203 205
   10
c Aluminum IEC Chamber
   20
         2
               -2.7
                     206 - 202 - 204 (203 : 201 : -205)
c Lead Surfaces
   30
         3 -11.34 301 -302 303 -304 305 -306
                                                     $ Bottom
          3 \quad -11.34 \quad 307 \ -308 \ 309 \ -310 \ 311 \ -312
   31
                                                     $ Top
   32
          3 -11.34 313 -314 315 -316 317 -318
                                                     $ Right
   33
          3 -11.34 319 -320 321 -322 323 -324
                                                     $ Left
          3 -11.34 325 -326 327 -328 329 -330
                                                     $ Lead Shielding
   34
c Wax Surfaces
         4 -0.93 401 -402 403 -404 405 -406
   40
                                                     $ Front
          4 -0.93 407 -408 409 -410 411 -412 #50 $ Middle
   41
              -0.93 413 -414 415 -416 417 -418
   42
          4
                                                     $ Back
c C4 Explosives
   50
          5 -1.7 -500
c Cadmium Sheet surrounding 8x4 NaI detector
   60
          6 -8.65 (601 :-604 )-602 603 -605
c Detector Housing Area
    Solid Borated Polyethylene Sheets
С
   70
          7 -0.93
                     701 -702 703 -704 705 -706
    Borated Polyethylened Holding NaI Detector
С
   71
          7 -0.93
                     707 -708 709 -710 711 -712 &
                     #60 #72 #73 #74 #75
    Air Behind PMTs for Cable Connections to HV and PreAmp
С
   91
         9 -0.00125 707 -708 710 -720 711 -712 &
                     #73 #74 #75
c 8x4 NaI Detector
   72
         72 -3.67
                    -713 714 -715
c 3 PMTs on back of NaI Detector
   73
         8 -0.00125 715 -719 -716
   74
          8 -0.00125 715 -719 -717
   75
          8 -0.00125 715 -719 -718
С
c Wood Structure
          8 -0.00125 801 -802 803 -804 805 -806
   80
                                                     $ Left
          8 -0.00125 807 -808 809 -810 811 -812
   81
                                                     $ Right
   82
          8 -0.00125 813 -814 815 -816 817 -818
                                                     $ Back
С
c Air inside of End of Universe
   90
          9 -0.00125 -900
                           #10 #20 #30 #31 #32 #33 &
                            #34 #40 #41 #42 #50 #60 &
                            \#70 \ \#71 \ \#72 \ \#73 \ \#74 \ \#75 \ \&
                            #80 #81 #82 #91
```

```
c End of Universe
  92 0
                 900
c Surface cards
С
c IEC Fusion Device Dimensions
С
c ID of IEC Chamber
 201 c/z 0 -47.01 45.5
С
c OD of IEC Chamber
 202 c/z 0 -47.01 47
С
c Top Lid of IEC Chamber
     pz 32.5
 203
          pz 36.5
 204
С
c Bottom Lid of IEC Chamber
 205
     pz -32.5
 206
          pz -36.5
С
c Activation Chamber Dimensions
С
c Bottom of Lead Surface
 301
       pz -23
 302
           pz -18
 303
          py 4
 304
          ру 76
 305
          px -25.5
 306
          px 25.5
С
c Top of Lead Surface
 307
          pz 18
           pz 23
 308
 309
          py 4
 310
          ру бб
 311
          px -22.5
 312
          px 22.5
С
c Right Side of Lead Surface
      pz -18
 313
 314
          pz 18
 315
          py 4
 316
          ру бб
 317
           px 17.5
           px 22.5
 318
С
c Left Side of Lead Surface
 319
      pz -18
          pz 18
 320
 321
          ру 4
 322
          ру бб
           px -22.5
 323
           px -17.5
 324
С
```

```
c Front Wax Moderation
        pz -18
 401
 402
           pz 18
 403
           ру О
           py 4
 404
            px -15.5
 405
 406
           px 15.5
С
c Middle Wax Moderation
 407
      pz -18
 408
           pz 18
 409
           py 4
           ру 14
 410
           px -15.5
 411
 412
           px 15.5
С
c C4 Explosives within Middle Wax
 500
          box -3.28 5.325 -3.28 6.56 0 0 0 6.56 0 0 0 6.56
С
c Back Wax Moderation
 413
           pz -18
 414
           pz 18
 415
           ру 14
 416
           ру 26
 417
           px -15.5
 418
           px 15.5
С
c Lead Shielding for Detector
 325
          pz -18
           pz 18
 326
 327
           ру 26
 328
           ру 26.4
 329
           px -15.5
           px 15.5
 330
С
c Borated Polyethylene Moderation and Absorption
          pz -18
 701
 702
           pz 18
 703
           py 26.4
 704
            py 34
 705
            px -15.5
 706
            px 15.5
С
c Cadmium Sheet
 601 cy 10.16
           cy 10.31
 602
           ру 34
 603
 604
           py 34.15
 605
           py 44.31
С
c Detector Housing Cell
c Borated Polyethylene
 707
           pz -18
            pz 18
 708
 709
            py 34
```

```
710
           py 51
            px -15.5
 711
 712
            px 15.5
 720
            ру 66
c NaI Detector within Cell
            cy 10.16
 713
 714
            py 34.15
 715
            py 44.31
c PMTs attached to NaI Detector
 716
           c/y 4 3 3
 717
            c/y -4 3 3
 718
           c/y 0 -4 3
            ру 54.47
 719
С
c Left Outer Wood Casing
 801
           pz -18
 802
            pz 18
 803
            py 4
 804
            ру бб
 805
            px -17.5
 806
            px -15.5
С
c Right Outer Wood Casing
 807
            pz -18
 808
            pz 18
 809
            py 4
 810
            ру 66
 811
            px 15.5
 812
            px 17.5
С
c Back Outer Wood Casing
            pz -18
 813
 814
            pz 18
 815
            ру 66
 816
            ру 68
 817
            px -17.5
 818
            px 17.5
С
c End of Universe
 900
            so 120
С
c Planes for tally segments within front paraffin wax block
 941 py 1
 942 py 2
 943 py 3
С
c Planes for tally segments within back paraffin wax block
  944 py 16
 945 py 18
 946 py 20
 947 py 22
 948 py 24
С
c Planes for tally segments within c4 block
  951 py 5.981
```

```
952 py 6.637
  953 py 7.293
  954 py 7.949
  955 py 8.605
  956 py 9.261
  957 py 9.917
  958 py 10.573
  959 py 11.229
С
c Planes for tally segments within borated polyethylene
  971 py 28
  972 py 30
  973 py 32
С
c Plane for tally segment within cadmium sheet
  961 py 34.15
С
c Planes for tally segments within NaI detector
  975 py 36
  976 py 38
  977 py 40
  978 py 42
C DATA CARDS
mode n
c mode p not used for this problem - neutrons only
c Aluminum
m2
    13027 1.0
С
c Lead
m3
     82207 1.0
С
c Paraffin Wax
m4 6012 -0.851395 1001 -0.148605
С
c Urea Fertilizer
c m5 7014 2.0 1001 4.0
                             6012 1.0 8016 1.0
C
c Cadmium
     48112 1.0
mб
С
c Borated Polyethylene
   5011 0.2124 6012 3.11 1001 6.22
m7
С
c NaI Detector
m72
     11023 1.0
                  53127
                          1.0
С
c Wood Structure and PMTs Modeled as Air Need to Input Material
     7014
            78
                 8016
m8
                          21
С
c Air Inside Universe
m9
    7014
           78 8016
                          21
С
c C4 explosive
m5 6012 0.8075 1001 1.614 7014 1.035
                                             8016 1.035
```

```
С
c Nitrogen
mll 7014 1.0
imp:n,p 1 22r 0
C
c cell flux tally within IEC chamber
f104:n 10
e104 2.5e-8 1e-6 1e-3 1.0 2.45 t
fm104 le8
С
c cell flux tally segmented within front wax moderation
f404:n 40
fs404 -941 -942 -943
                           t
sd404 1116 1116 1116 1116 4464
e404 2.5e-8 1e-6 1e-3 1.0 2.45 t
fm404 le8
С
c cell flux tally segmented within back wax moderation
f424:n 42
fs424 -944 -945 -946 -947 -948
sd424 2232 2232 2232 2232 2232 2232 13392
e424 2.5e-8 1e-6 1e-3 1.0 2.45 t
fm424 le8
С
c cell flux tally segmented within lead sheet
f344:n 34
c sd344 446.4
e344 2.5e-8 1e-6 1e-3 1.0 2.45 t
fm344 le8
С
c cell flux tally segmented within borated polyethylene
f704:n 70
       -971 -972 -973
fs704
                             t
sd704 1785.6 2232 2232 2232 8481.6
e704 2.5e-8 1e-6 1e-3 1.0 2.45 t
fm704 le8
С
c cell flux tally segmented within cadmium sheet
f604:n 60
         -961
fs604
                   t
sd604 50.091 98.006 148.097
e604 2.5e-8 1e-6 1e-3 1.0 2.45 t
fm604 le8
С
c cell flux tally segmented within NaI detector
f724:n 72
fs724 -975 -976 -977 -978 t
sd724 599.94 648.59 648.59 648.59 749.10 3294.81
e724 2.5e-8 1e-6 1e-3 1.0 2.45 t
fm724 le8
С
c cell flux tally segmented within c4 cell
f504:n 50
       -951 -952 -953 -954 -955 -956 -957 -958 -959 t
fs504
```

```
sd504 28.23 28.23 28.23 28.23 28.23 28.23 28.23 28.23 28.23 28.23 28.23
282.3
e504 2.5e-8 1e-6 1e-3 1.0 2.45 t
fm504 le8
С
c source is cylindrical monoenergetic volume source
sdef erg=2.45 rad=d1 axs=0 0 1 pos=0 -47.01 0 ext=d2 cel=10
     -47.01 -1.51
si1
si2
      32.5
С
f14:n 50
c 1e8*atom density N-14 barn-cm
fm14 2.50170208245e6 11 102
С
С
print 110
nps 5000000
```

Appendix B MCNP5 Textfile for UW(C-4)DET-04

```
Model of UW-Madison IEC Fusion Device [UW(C-4)DET-04]
С
c New vertical explosives array configuration at 1e8 n/s
c C-4 in planar cavity at 5 cm
C
c ell# Mat#
                Den
                        Surface combinations
C
c Inside of IEC Chamber
        0
                    -201 -203 205
   10
c Aluminum IEC Chamber
   20
         2
               -2.7
                     206 - 202 - 204 (203 : 201 : -205)
c Lead Surfaces
   30
         3 -11.34 301 -302 303 -304 305 -306
                                                     $ Bottom
          3 \quad -11.34 \quad 307 \ -308 \ 309 \ -310 \ 311 \ -312
   31
                                                     $ Top
   32
          3 -11.34 313 -314 315 -316 317 -318
                                                     $ Right
   33
          3 -11.34 319 -320 321 -322 323 -324
                                                     $ Left
          3 -11.34 325 -326 327 -328 329 -330
                                                     $ Lead Shielding
   34
c Wax Surfaces
         4 -0.93 401 -402 403 -404 405 -406
   40
                                                     $ Front
          4 -0.93 407 -408 409 -410 411 -412 #50 $ Middle
   41
              -0.93 413 -414 415 -416 417 -418
   42
          4
                                                     $ Back
c C4 Explosives
   50
          5 -1.7 -500
c Cadmium Sheet surrounding 8x4 NaI detector
   60
          6 -8.65 (601 :-604 )-602 603 -605
c Detector Housing Area
    Solid Borated Polyethylene Sheets
С
   70
          7 -0.93
                     701 -702 703 -704 705 -706
    Borated Polyethylened Holding NaI Detector
С
   71
          7 -0.93
                     707 -708 709 -710 711 -712 &
                     #60 #72 #73 #74 #75
    Air Behind PMTs for Cable Connections to HV and PreAmp
С
   91
         9 -0.00125 707 -708 710 -720 711 -712 &
                     #73 #74 #75
c 8x4 NaI Detector
   72
         72 -3.67
                    -713 714 -715
c 3 PMTs on back of NaI Detector
   73
         8 -0.00125 715 -719 -716
   74
          8 -0.00125 715 -719 -717
   75
          8 -0.00125 715 -719 -718
С
c Wood Structure
          8 -0.00125 801 -802 803 -804 805 -806
   80
                                                     $ Left
          8 -0.00125 807 -808 809 -810 811 -812
   81
                                                     $ Right
   82
          8 -0.00125 813 -814 815 -816 817 -818
                                                     $ Back
С
c Air inside of End of Universe
   90
          9 -0.00125 -900 #10 #20 #30 #31 #32 #33 &
                            #34 #40 #41 #42 #50 #60 &
                            \#70 \ \#71 \ \#72 \ \#73 \ \#74 \ \#75 \ \&
                            #80 #81 #82 #91
С
```

```
c End of Universe
  92 0
                 900
c Surface cards
С
c IEC Fusion Device Dimensions
С
c ID of IEC Chamber
 201 c/z 0 -44.685 45.5
С
c OD of IEC Chamber
 202 c/z 0 -44.685 47
С
c Top Lid of IEC Chamber
     pz 32.5
 203
          pz 36.5
 204
С
c Bottom Lid of IEC Chamber
 205
     pz -32.5
 206
          pz -36.5
С
c Activation Chamber Dimensions
С
c Bottom of Lead Surface
 301
       pz -23
 302
           pz -18
 303
          py 4
 304
          ру 76
 305
          px -25.5
 306
          px 25.5
С
c Top of Lead Surface
 307
          pz 18
           pz 23
 308
 309
          py 4
 310
          ру бб
 311
          px -22.5
 312
          px 22.5
С
c Right Side of Lead Surface
      pz -18
 313
 314
          pz 18
 315
          py 4
 316
          ру бб
 317
           px 17.5
           px 22.5
 318
С
c Left Side of Lead Surface
 319
       pz -18
 320
          pz 18
 321
          ру 4
 322
          ру бб
           px -22.5
 323
           px -17.5
 324
С
```
```
c Front Wax Moderation
        pz -18
 401
 402
           pz 18
           ру 2.325
 403
 404
           py 5.325
            px -15.5
 405
 406
           px 15.5
С
c Middle Wax Moderation
 407
      pz -18
 408
           pz 18
           ру 5.325
 409
           ру 14
 410
           px -15.5
 411
 412
           px 15.5
С
c C4 Explosives within Middle Wax
 500
           box -6.86 7.325 -6.86 13.72 0 0 0 1.5 0 0 0 13.72
С
c Back Wax Moderation
 413
           pz -18
 414
           pz 18
 415
           ру 14
 416
           ру 26
 417
           px -15.5
 418
           px 15.5
С
c Lead Shielding for Detector
 325
           pz -18
           pz 18
 326
 327
           ру 26
 328
           ру 26.4
 329
           px -15.5
            px 15.5
 330
С
c Borated Polyethylene Moderation and Absorption
          pz -18
 701
 702
           pz 18
 703
           py 26.4
 704
            py 34
 705
            px -15.5
 706
            px 15.5
С
c Cadmium Sheet
 601 cy 10.16
           cy 10.31
 602
           ру 34
 603
 604
           py 34.15
 605
           py 44.31
С
c Detector Housing Cell
c Borated Polyethylene
           pz -18
 707
            pz 18
 708
 709
            py 34
```

```
710
           py 51
            px -15.5
  711
 712
            px 15.5
 720
            ру 66
c NaI Detector within Cell
            cy 10.16
 713
 714
            py 34.15
 715
            py 44.31
c PMTs attached to NaI Detector
            c/y 4 3 3
 716
 717
            c/y -4 3 3
           c/y 0 -4 3
 718
            ру 54.47
 719
С
c Left Outer Wood Casing
           pz -18
 801
 802
            pz 18
 803
            py 4
 804
            ру бб
 805
            px -17.5
 806
            px -15.5
С
c Right Outer Wood Casing
 807
            pz -18
 808
            pz 18
 809
            py 4
 810
            ру бб
            px 15.5
 811
 812
            px 17.5
С
c Back Outer Wood Casing
            pz -18
 813
            pz 18
 814
 815
            ру бб
 816
            ру 68
 817
            px -17.5
 818
            px 17.5
С
c End of Universe
 900
        so 120
С
c Planes for tally segments within front paraffin wax block
 941 py 3.325
 942 py 4.325
С
c Planes for tally segments within middle parrafin wax block
  952 py 6.325
 953 py 7.325
 954 py 9.325
 955 py 10.325
 956 py 12
С
c Planes for tally segments within back paraffin wax block
  944 py 16
```

```
945 py 18
  946 py 20
  947 py 22
  948 py 24
С
c Planes for tally segments within c4 block
  951 py 8.075
С
c Planes for tally segments within borated polyethylene
  971 py 28
  972 py 30
  973 py 32
С
c Plane for tally segment within cadmium sheet
  961 py 34.15
С
c Planes for tally segments within NaI detector
  975 py 36
  976 py 38
  977 py 40
  978 py 42
c DATA CARDS
mode n
c mode p not used for this problem - neutrons only
c Aluminum
m2
     13027 1.0
С
c Lead
    82207 1.0
m3
С
c Paraffin Wax
     6012
           -0.851395 1001
                             -0.148605
m4
С
c Urea Fertilizer
c m5 7014 2.0 1001 4.0
                             6012 1.0 8016 1.0
С
c Cadmium
mб
    48112 1.0
С
c Borated Polyethylene
     5011
            0.2124 6012 3.11
                                1001 6.22
m7
С
c NaI Detector
m72
    11023 1.0
                  53127
                          1.0
С
c Wood Structure and PMTs Modeled as Air Need to Input Material
     7014
m8
           78
                 8016
                          21
С
c Air Inside Universe
   7014
           78
                 8016
m9
                          21
С
c C4 explosive
m5 6012 0.8075 1001 1.614 7014 1.035 8016 1.035
С
```

c Nitrogen m11 7014 1.0 imp:n,p 1 22r 0 c imp:p 0 6r 1 6r 0 1 0 7r C c cell flux tally within IEC chamber f104:n 10 e104 2.5e-8 1e-6 1e-3 1.0 2.45 t fm104 le8 С c cell flux tally segmented within front wax moderation f404:n 40 -941 -942 t fs404 sd404 1116 1116 1116 3348 e404 2.5e-8 1e-6 1e-3 1.0 2.45 t fm404 le8 С c cell flux tally segmented within middle wax moderation f414:n 41 fs414 -952 -953 -954 -955 -956 sd414 1116 1116 1949.6424 1116 1869.3 2232 9398.9424 e414 2.5e-8 1e-6 1e-3 1.0 2.45 t fm414 le8 С c cell flux tally segmented within back wax moderation f424:n 42 fs424 -944 -945 -946 -947 -948 t sd424 2232 2232 2232 2232 2232 2232 13392 e424 2.5e-8 1e-6 1e-3 1.0 2.45 t fm424 le8 С c cell flux tally segmented within lead sheet f344:n 34 e344 2.5e-8 1e-6 1e-3 1.0 2.45 t fm344 le8 С c cell flux tally segmented within borated polyethylene f704:n 70 fs704 -971 -972 -973 t sd704 1785.6 2232 2232 2232 8481.6 e704 2.5e-8 1e-6 1e-3 1.0 2.45 t fm704 le8 С c cell flux tally segmented within cadmium sheet f604:n 60 fs604 -961 t. sd604 50.091 98.006 148.097 e604 2.5e-8 1e-6 1e-3 1.0 2.45 t fm604 1e8 С c cell flux tally segmented within NaI detector f724:n 72 -975 -976 -977 fs724 -978 t. sd724 599.94 648.59 648.59 648.59 749.10 3294.81 e724 2.5e-8 1e-6 1e-3 1.0 2.45 t

```
fm724 le8
С
c cell flux tally segmented within c4 cell
f504:n 50
                 t
fs504
       -951
sd504 141.18 141.18 282.36
e504 2.5e-8 1e-6 1e-3 1.0 2.45 t
fm504 le8
С
c source is cylindrical monoenergetic volume source
sdef erg=2.45 rad=d1 axs=0 0 1 pos=0 -47.01 0 ext=d2 cel=10
sil -47.01 -1.51
      32.5
si2
С
f14:n 50
c atom density 14N barns-cm * 1e8
fm14 2.50170208245e6 11 102
С
С
print 110
nps 5000000
```