NPS-IJWA-01-003

EXPLOSIVE DETECTION TECHNOLOGIES
FOR
AIRLINE SECURITY

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This report was prepared for and funded by:
Federal Aviation Administration,
Joint Experimentation command and
Office of Naval Research
through the CDTEMS program

This report was prepared by:

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sou gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect o this collection of information suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.			
1. AGENCY USE ONLY	2. REPORT DATE Jun 2000	3. REPORT TYPE AND DATES COVERED Technical 1 Oct 98 - 1 May 00	
4. TITLE AND SUBTITLE Explosive Detection Technologies for Airline Security		5. FUNDING NUMBERS ONR# N0001400WR20307	
6. AUTHOR(S) Xavier K. Maruyama			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Institute for Joint Warfare Analysis Naval Postgraduate School Monterey, CA 93943-5000		8. PERFORMING ORGANIZATION REPORT NUMBER NPS-IJWA-01-003	
9. SPONSORING/MONITORING AGENCY(s) Federal Aviation Administration Institute for Joint Warfare Analysis		10. SPONSORING/MONITORING AGENCY REPORT NUMBER None	
The views expressed in this report are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government			
12A. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited		12b. DISTRIBUTION CODE	
13. ABSTRACT (maximum 200 words) Aviation safety and security has become a topic of paramount national concern. Informed decision making requires an appreciation of trends in technology in response to projected future terrorist activities. In the area of security, explosive detection is made possible by a bewildering array of newly offered equipment. This document describes the science and engineering of the various technologies. The information presented here was written for airline security but it applies also to a wide range of military problems.			
14. SUBJECT TERMS Terrorist	Ariline Security	Explosive Devices	15. NUMBER OF PAGES 124 16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

EXPLOSIVE DETECTION TECHNOLOGIES FOR AIRLINE SECURITY

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ABSTRACT

Aviation Safety and Security has become a topic of paramount national concern. Informed decision making requires an appreciation of trends in technology in response to projected future terrorist activities. In the area of security, explosive detection is made possible by a bewildering array of newly offered equipment from industrial vendors and government and academic laboratories. Techniques such as ion mass spectrometry, gas chromatography, electromagnetic induction, thermal neutron analysis, fast pulsed neutron analysis, infrared cameras, x-ray computer assisted tomography, transmission and back scattered tomography and microwave radar techniques, as well as the use of dogs, for the detection of explosives, drugs and other contraband are offered in a bewildering variety to the airline industry. It is hoped that this document will serve as a primer describing the science and engineering of what is involved in the various technologies. Here, the goal is not so much a scientific engineering text, but a translation of scientific and engineering descriptions into a language which the educated general public can understand. This primer has been written with two levels in mind. There would be one level which could be appreciated by a non-technical person, and a second level which could be appreciated by a technical person who is being introduced into a field not his own.

FORWARD

The "battlefield" of the twenty-first century is no longer confined to locations where massed armies or navies confront each other. One of the most unpleasant facts of the world today is the prevalence of unconventional warfare where civilians and civil infrastructure are targeted. In many instances, these are manifest as terrorist acts. Because of media coverage and the associated publicity, the most spectacular criminal terrorist acts are often committed against civil aviation.

Protection of the general public from these criminal acts no longer are confined to enforced police functions. Technology increasingly plays a role and many professionals are required to make decisions which affect aviation security. Sometimes these decisions are made inadvertently because the person making the decision understands only a particular aspect, such as budgeting, but is not an expert on other dimensions such as technical utility. Aviation security demands that the total system be effective. Local optimization many times does not lead to the best implementation of resources. It is a difficult task for any individual to understand all the ramification of any a particular decision, but awareness of other parts which are affected by their decisions can lead to more sensible systems.

Hopefully, this manuscript will provide an understandable description which can be appreciated by the non-specialist who needs to interface with those who work in aviation security. Detailed referencing and documentation is not provided, because those tasks are better left for more specialized sources. The bibliography contains sources for this purpose.

Technology for explosive detection changes constantly, and the best products at any particular time may not be the best at a later date. The science and technology associated with various devices are described in this work, but a conscious attempt has been made to avoid naming particular products or companies, so that the reader is not unduly influenced by this writing when making decisions which require more informed product selection decisions. It is the intent of the author that, after reading this work, the reader will feel sufficiently informed and knowledgeable in the subject of explosive detection for aviation security to engage in more meaningful discussions and studies as required in his present position.

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ACKNOWLEDGMENTS

I attended the *Second Explosive Detection Technology Symposium & Aviation Technology Conference* sponsored by the Federal Aviation Administration in November 1996. At that conference many important and interesting topics were presented but the sheer variety of topics and technologies introduced was bewildering and intimidating. Subsequently, in January 1997, *the International Conference on Aviation Safety and Security in the 21st Century* was sponsored by the White House Commission on Aviation Safety and Scurity and the George Washington University. Attendance at those two conferences made me realize that if I were having difficulty following many of the discussions, there must be others, especially those without science and engineering backgrounds, who must be facing similar challenges.

Subsequently, the writing of this work was begun with the encouragement and advice from Dr. Wagih Makky of the FAA who was the overall chairman for *the Second Explosive Detection Technology Symposium*. Many people contributed their knowledge, time and encouragement for which the author is extremely grateful. Rough drafts of the manuscript were tried out on many personal friends, who had little to do with aviation security or engineering and science to see if this work was intelligible. To them, I hope that I have not overstepped the bounds of friendship and thank you for your patience and understanding. Others have given me more direct technical input for which I am most appreciative, in particular, Professor Robert Harney of the Naval Postgraduate School and Dr. Jim Fobes of the Federal Aviation Administration.

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CHAPTER 1

INTRODUCTION

INTRODUCTION

The loss of airplanes due to terrorist use of explosives in the later half of the 1980's decade caused the U.S. Federal Government to direct attention to the problem of aviation security. The Congressional Office of Technology Assessment (now defunct) produced two in-depth assessment studies concerning aviation, airline security, technology and the terrorism, *Technology Against Terrorism, The Federal Effort*, 1991, and *Technology Against Terrorism, Structuring Security*, 1992. The FAA Technical Center conducted the first and second International Symposium on Explosive Detection Technology in 1991 and in 1996. The White House Commission on Aviation Safety and Security was chartered on July 25, 1996, and issued a final report on February 12, 1997. These efforts focussed on aspects pertaining to policy, technical details and integration of security systems.

These and other efforts lead one to conclude that a combination of systems incorporating passenger profiling, bag matching and bomb detection technologies could be developed to significantly increase airline security. The throughput rate of individual explosives or bomb detection devices is not an appropriate parameter to regulate, but what is important is the throughput of the entire security system. These findings tell us that there is no single "silver bullet" technological fix for the airline security problem.

Instruments have been and are being developed for airline security. These can be considerably complicated from an engineering standpoint, but need not be incomprehensible "black boxes" for the educated decision maker who must make choices in the use of technology to enhance airline security. The purpose of this work is to explain the science of the technology incorporated into airline security systems so that the physics, chemistry and engineering tradeoffs can be understood and appreciated by most readers.

History [1]

Public awareness incidence of terrorist acts against civil aviation has intensified since the tragic incident on December 21, 1988, over Lockerbie, Scotland in the destruction of Pan Am Flight 103 in which 11 villagers and all 259 passengers enroute from Frankfurt to New York were killed. It was the worst civil aviation disaster ever in Britain and one of the worst in the history of civil aviation. Subsequent investigation established that the explosion was caused by a small amount of Semtex carried in the airliner's forward cargo hold. The crash of TWA 800 on July 17, 1996, raised the specter of an on board explosive being the cause. Although the latter was determined not to have been caused by a terrorist act, the public sense for the need for explosive detection technologies at airports was heightened.

Public awareness has increased when the carriers are American, but less so with other carriers, even though American lives have been lost. On September 19, 1989, UTA Flight 772 was destroyed over the Sahara Desert over Niger and Avianca Flight 203 was destroyed just after take off from Bogota, Columbia on a flight to Cali on November 27, 1989. The greatest loss of life was due to the destruction of a Boeing 747 operated by Air India on June 23, 1985. Flight FL310 was destroyed over the Atlantic Ocean killing all 329 occupants by an explosion caused by a bomb placed on board by a Sikh terrorist.

[1] A comprehensive listing of bombings on aircraft may be found at the website: http://home.eunet.no/~steinesa/Andre/Bomb/bomb.htm#1989 (accessed 4/21/00)

Explosions aboard aircraft resulting from acts of aviation sabotage have been systematically tracked since May 7, 1947, when a time bomb delivered to a Philippines Airlines aircraft by two ex-convicts who were hired by a woman and a man attempting to kill the husband, a passenger on the aircraft. In that event 13 passengers were killed. The first recorded hijacking was in May 1930 by Peruvian revolutionaries who seized a mail plane belonging to Pan American. The pilot, 22-year-old, Byron D. Richards, tricked the rebels into allowing him to deliver the mail and refused to fly on for the purpose of dropping propaganda leaflets over Lima. Thirty years later, the same pilot was instrumental in preventing the hijack by the Bearden father and son of a Continental Airlines jumbo jet from El Paso, Texas to Cuba. The long history of hijacking and aviation sabotage made the need to prevent the introduction of explosives onboard airplanes apparent to the industry, government and the flying public, but the best means to accomplish this goal is still a matter for discussion.

Although skyjacking were alarmingly common with 147 reported between 1967 and 1972, there were no security checkpoints to examine contents of passengers. On November 24, 1971, a man bought a $20 ticket for a flight from Portland to Tacoma using the name, Dan Cooper. A law enforcement officer erroneously referred to him as "D.B." and the initials stuck. D.B. Cooper passed a note to a flight attendant, as the jet became airborne. She thought he was hitting on her so she slipped it, unopened, into her pocket. Cooper told her to look at the note and informed her that he had a bomb. D.B. Cooper opened his brief case and revealed several red cylinders and a nest of wires. The note demanded $200,000 and four parachutes and that the plane be emptied except for him and four crewmembers.

D.B. Cooper received 10,000 in $20 bills when the plane landed at Seattle-Tacoma International Airport. Once the plane was refueled, Cooper instructed the pilot to fly towards Mexico at an altitude no higher than 10,000 feet with wing flaps down so that the plane flew at a speed slower than 200 miles per hour. The Boeing 727 was the only jet in which the stairwell could be opened in mid-flight. He jumped into the strong freezing winds somewhere above the small community of Ariel, Washington. D.B. Cooper has not been heard from since, although $5880 of his loot was found by a boy playing on the banks of the Columbia River in 1980.

Skyjacking was hardly an original crime. There were 40 in 1969 and more than 25 in the year Cooper did it. Up to this time, skyjacking had been a political crime, but D.B. Cooper helped to introduce greed and used the threat of a bomb rather than a gun. His parachute getaway elevated him to cult hero status, with a song, movie and celebrations in restaurants and bars in Salt Lake City, San Jose and in Ariel. D.B. Cooper's escapade was a major event that brought to public awareness the need for airline security and the need for passenger screening.

On 29 November 1987, Korean Air Lines Flight 858 exploded in mid-air over the Andaman Sea killing all 115 on board. A woman passenger, who had disembarked with her elderly companion at Abu Dhabi, later confessed that they had planted the bomb when they boarded at Baghdad. She stated that the operation had been planned by North Korean Intelligence Operations. The importance of scrutiny at each point on the itinerary of an airplane was made evident in this case.

The El Al Flight 016 incident of April 17, 1986, is often cited as an example for the case that proper scrutiny can be effective in preventing acts of airline terrorism. In that incident, a pregnant 19-year-old Anne-Marie Murphy was driven to the airport by her fiancé, Nezar Hindawi, to Heathrow International Airport for a flight to Israel. She accepted from him an overnight bag full of gifts for Hindawi's family in Israel. As she said good-bye, she was totally unaware of the bag's false bottom containing 1.5 kilograms of Grade-A explosives rigged to a timer concealed in a calculator set to detonate in flight above the Swiss Alps. An alert guard found Murphy - a non-Jewish pregnant woman traveling alone - to be quite suspicious and initiated the questioning and searches which revealed the explosive device. Evidence at the subsequent trial of Hindawi implicated Syrian intelligence, which had provided the bomb. Now, even innocents could be used as dupes for a determined terrorist with no concern for even those close to him.

The pre-flight procedure, while successful in this instance, however takes time and intrudes upon each innocent passenger. The airline soon developed an uncomplimentary reputation: "El Al" standing for "Every Landing Always Late." The balance between security, privacy and passenger throughput is difficult to maintain. Technology coupled with effective policy must be called upon to help to insure passenger security against explosives and at the same time insure that airline commerce is not unduly hampered.

FAA guidelines require a system throughput of ten bags per minute, or six seconds per bag. As daunting as this requirement is, if a plane is assumed to carry 200 passengers each checking in 2 bags, then 400 bags must be sent through the system in 40 minutes. From the perspective of the airline passenger, this translates into a realistic minimal arrival time one hour prior to departure at the airport, not counting additional time necessary to do other tasks such as finding parking and checking in. This simple arithmetic illustrates why system efficiency must be emphasized in any passenger security system.

Detection Need

As the brief history outlined above indicates, airline security clearly needs the capability to detect weapons. For the decade previous to the 1980's, this need was fulfilled mainly by the ability to detect metallic objects, which revealed the presence of guns and knives.

However, the awareness of and the use of plastic explosives create a much greater challenge today. Among the best known of these plastic explosives, and the one most frequently used by terrorists is Semtex, a series of commercial putty explosives produced at the huge explosive works in the city of Semptin, Czechoslovakia. These are various combinations of pentaerythritoltetranitrate PETN ($C_5H_8N_4O_{12}$) and RDX ($C_3H_6N_6O_6$) with different binders. These plastic explosives can be molded and disguised as innocent-looking objects, from the lining of a handbag to a toy or souvenir. Investigators believe that the bomb that destroyed Pan Am Flight 103 over Lockerbie was made of Semtex explosive small enough to be easily concealed within a radio-cassette player. The use of mineral oil as a plasticiser, for example, reduces the vapor pressure at normal temperatures and pressure, making reliable detection very challenging.

The availability of these more sophisticated explosives requires greater technological sophistication in their detection.

The requirement to detect contraband explosives has an oft-neglected advantage. Many of the means for detecting hidden explosives are instrumental in detecting other items that pose dangers for the traveling public. For example, incendiaries and flammables, while not technically explosives, can be used to create similar consequences on board an airplane. The inspection for explosives can oftentimes reveal the presence of these other dangerous items.

In today's world, the ability to introduce weapons of mass destruction, WMD, is not beyond the capability of terrorist and others with criminal intent. Chemical, biological and radiological devices can also be used to cause destruction of aircraft and their passengers. Beyond the destructive intent of the criminal mind, the profit generated by the illegal drug trade also plays a role in today's air commerce. Measures intended to protect against explosives transport can also be used to detect other illegal and harmful contraband. Emphasis on a single aspect of aviation security should not neglect aspects, which affect the integrated aviation security problem.

Trade-offs

A large array of current state-of-the-art detection systems is being developed. Each exploit different strengths but are also vulnerable to their own specific weakness usually arising from human factors and engineering limitations. Competing with the need for a reliable and assured security, combinations of different technologies and policy considerations provide promise for an economically and operationally feasible system. A secure system, which cannot accommodate a reasonable throughput of passengers, can effectively paralyze the air transport system. Currently, a throughput of 600 bags an hour is often stated as a requirement. If each person carries two bags which are required to be inspected on a 300 passenger plane, a throughput of 600 bags using a single detection system would mean that only one plane per hour could be processed. For any airport, this type of approach would make air transportation a non-viable mode of transport. Sequential screening reduces the number of items requiring time consuming critical inspection.

A combination of passenger profiling, interviews, and matching of passengers with baggage could considerably reduce intrusive inspections. "Human factors" oriented security is highly labor intensive and may be perceived to intrude upon personal privacy and may be perceived to be arbitrarily discriminatory against certain groups. The average passenger encounters delays at the airport, not only due to security inspection, but to more mundane processes such as traffic congestion, finding adequate and convenient parking, check in processing independent of security concerns, weather, cleaning of late arriving planes, lack of crews, mechanical breakdowns, and air traffic congestion on the tarmac and in the air. Delays required by explosive testing are only one of the myriad of irritants encountered by the air traveler, but can be perceived as the most unacceptable bottleneck by the traveler if his perceived comfort and tolerance is violated.

This work will not address these issues directly, but they are mentioned here in 00order to bring to the awareness of the reader that the security system cannot be imposed as an isolated problem.

The technology of explosive detection and security systems is complicated in engineering detail, but viewed from a science aspect, the understanding of the underlying principles can be comprehended by the educated layman. This treatise will attempt to give provide a general understanding of explosive and weapons detection technology to the level that possibilities and limitations can be appreciated.

CHAPTER 2

EXPLOSIVES

EXPLOSIVES

Explosions in common parlance usually refers to the release of energy within a very short time period. The explosion can come from mechanical, chemical or nuclear sources. In this context, even the bursting of a pressurized hull is an explosion. In the context of airline security, the distinction between explosions and explosives must be clearly made. Whereas explosions may be caused by sources other than explosives, explosives cause a violent and sudden release of mechanical energy, in the form of pressure and heat, due to chemical reactions.

CHEMISTRY OF EXPLOSIVES

Explosives can be categorized as high explosives, but also as propellants and pyrotechnics. The chemical reactions is primary the oxidation of a reactant, but depending on the specifics of how the reactants are mixed and the environment in which they react, the mechanical effects can be considerably different. The understanding of explosives is primarily an understanding of the chemical reactions that occur.

Chemical reactions may be considered as the conversion of reactants to products, symbolically written as *reactants* → *products*. The internal energy of the reactants is different from the internal energy of the product and this difference in internal energies is macroscopically manifest as pressure and heat. If the reactants contain more energy than the products, then that energy may be released as heat during the reaction. This is called an *exothermic reaction*. Reactions involved in burning and detonation are exothermic. The heat released can be transferred to the molecules in the surrounding medium as mechanical energy, which manifests itself as pressure. In contrast, when the products contain more internal energy than the reactants, then energy from another source must be added in order from the reaction to occur. Such a reaction is called an *endothermic reaction*.

Burning and detonation are reactions of two types. In the first type, there are two separate reactants, a fuel and an oxidizer, which react to form the products. A simple example of this is in the burning of methane, a common gas used for cooking, with oxygen, which is present in the air. To completely burn one molecule of methane, two oxygen molecules (four oxygen atoms) must participate in the reaction. The chemical reaction may be written:

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O$$

Here a single methane molecule containing one carbon and four hydrogen atoms react with two oxygen molecules, each containing two oxygen atoms to form a molecule of carbon dioxide and two molecules of water[2].

Note that no atoms appear or disappear in the reaction. The left or original reactants contain one carbon, four hydrogen and four oxygen atoms and the same number of each of the participating atoms appear on the right or final products. A chemical reaction is the rearranging of the atoms of the original reactant molecules into different product molecules.

The second type of reaction, which is by far the more common in explosives, the oxidizer and the fuel are contained together within the same molecule. Almost all explosives, with which we are concerned in airline security, may be characterized as a

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[2] A molecule of carbon dioxide is a combination of one carbon atom with two oxygen atoms and the water molecule contains two hydrogen atoms attached to a single oxygen atom.

substance which contains its own oxidizer within the initial molecule and is capable of an exothermic reaction resulting in a large release of heat. The starting molecule decomposes during the reaction and re-forms into products. For example, in the decomposition of nitroglycerine, $C_3H_5N_3O_9$, the reaction may be viewed as resulting in the decomposition into three carbon, five hydrogen, three nitrogen and nine oxygen atoms which recombine into nitrogen gas, N_2, water, H_20, carbon dioxide, CO_2, and oxygen, O_2, molecules. The explosion of nitroglycerine may be described with the following reaction formula:

$$C_3H_5N_3O_9 \rightarrow 3C + 5H + 3N + 9O \rightarrow 1.5N_2 + 2.5H_2O + 3CO_2 + 0.25\ O_2$$

More conventionally, the intermediate step is eliminated and only integer numbers of molecules appear in the reaction formula and we write the same reaction as:

$$4C_3H_5N_3O_9 \rightarrow 6N_2 + 10H_2O + 12CO_2 + O_2$$

Note here again that conservation of atoms applies and there are 12 carbon, 20 hydrogen, 12 nitrogen, and 36 oxygen atoms on each of the left and right hand sides of the equation. However, the number of molecules can increase (or in general, increase or decrease depending on the specific reaction.)

Almost all explosive materials with which we deal are molecules which contain carbon, C, hydrogen, H, nitrogen, N, and oxygen, O, or the combination CHNO. They are called organic compounds, meaning that the molecule is built on a skeleton of carbon atoms. The detection of explosives generally involves probing the chemistry of a suspected substance and determining the presence of these four species. Although these four species are in general quite common, explosives have specific characteristic ratios of abundances of these atoms so that identification need not be an insurmountable task.

Detonation

In order for a detonation to occur, the explosive must not only react fast, but must also produce gas and heat. Three criteria are necessary:

- The reaction propagates at speed greater than the speed of sound in the medium in which the detonation occurs.
- There is a production gas or gases.
- Heat is produced.

If any one of these three criteria is not met, a detonation does not occur, even though a chemical reaction may take place.

The reaction propagation velocity for most explosives is between 1 to 9 kilometers per second, which translates to a non-trivial 0.6 to 5.6 miles per second, which is between 2100 to 20,000 miles per hour. As a comparison, the speed or sound in air is a third of a kilometer per second or 760 miles per hour.

In general, gases are 500 to 1000 times less dense than solid or liquid materials, so the volume occupied by the detonation product gas is three orders of magnitude greater than that volume originally occupied by the explosive. This volume expansion does not consider the additional expansion due to the rise in temperature of the reactant products.

Heat generated is normally within the range of 400 to 1200 calories per gram. It takes roughly 620 calories to take one gram of water from room temperature to steam. To raise the temperature to the boiling point and still keep the water in its liquid form, only 80 calories are necessary[3]. To put this in perspective, a pint of water weighs about a pound, which is 454 grams. There is enough energy in the explosive to bring five to fifteen times its weight in water to the boiling point, which may not seem impressive except when one realizes that this is done in a time scale of about a tenth of a millisecond. In a millisecond, an object dropped has traveled fifty microns, or about the width of a human hair.

Oxygen Balance

Explosion products are complex with materials being formed both in the direct explosion reaction and by subsequent reaction with the surrounding atmosphere. Direct products from a chemical explosive usually include the combustion products: carbon dioxide (CO_2), carbon monoxide (CO), water vapor (H_2O), and molecular nitrogen (N_2). The products may also include molecular hydrogen (H_2) and molecular oxygen (O_2), along with nitric oxide (NO). In addition to these relatively stable products, reactive species may also be formed including hydroxyl (OH), monatomic hydrogen (H), monatomic oxygen (O), and monatomic nitrogen (N), in addition to small amounts of ionized gases and associated electrons. These latter are electrically charged and, although present in small amounts, they make the initial combustion products electrically conductive.

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[3] In raising the temperature of water, one must consider the specific heat, which is the heat necessary to raise a specific amount of water a specific temperature. For example, it takes one calorie of heat to raise one gram of water one degree Centigrade. [The unit, centigrade, is identical to the metric unit, Celsius. The centigrade is one hundredth the temperature difference between the freezing point and the boiling point of water. The temperature unit Celsius is named after the inventor of the temperature scale, *Anders Celsius* (1701-1744).]

The general formula for a CHNO explosive is $C_cH_hN_nO_o$, where the subscripts c,h,n and o are the number atoms in a molecule of the explosive. If all the carbon could be burned to form carbon dioxide, CO_2, the number of oxygen required would be twice the number of carbon atoms. Similarly, to burn[4] all the hydrogen to form water, H_2O, one oxygen would be required for every two hydrogen atoms. The consumption of all the carbon and hydrogen would require that the $2c + h/2 = o$. When this condition is met, there is a balance between the oxygen and the fuel. Whatever nitrogen is in the explosive can then combine with itself to form diatomic nitrogen molecule. If there is an excess of oxygen compared to the fuels, carbon and hydrogen, we describe the explosive as being over-oxidized. If there is not enough oxygen to completely burn hydrogen and carbon, we call the explosive under-oxidized. This concept can be quantified as a percentage oxygen balance, OB, by applying the formula:

$$OB\ (\%) = 100\ (16/MW)\ [o-(2c+h/2)]$$

Where MW refers to the molecular weight, which is the sum of the atomic weights of all the atoms. Since we know the generic formula, $C_cH_hN_nO_o$, the molecular weight of the explosive can be easily computed as:

$$MW = 12\bullet c + 1\bullet h + 14\bullet n + 16\bullet o$$

For example, applying these formulas to nitroglycerine, $C_3H_5N_3O_9$, molecule, the numbers atoms of carbon, $c = 3$; of hydrogen, $h = 5$; of nitrogen, $n = 14$; and of oxygen, $o = 9$. Consequently, the molecular weight[5],

[4] Burning is equivalent to oxidation as a chemical process.

$$MW = 12\bullet(3) + 1\bullet(5) + 14\bullet(3) + 16\bullet(9) = 227.$$

The oxygen balance is then,

$$OB\ (\%) = 100\ (16/MW)\ [o-(2c+h/2)] = 100\ (16/227)\ [9-(2\bullet3+5/2)] = 3.5\ \%,$$

telling us that there is a three and a half- percent more oxygen than would be required for a completely efficient combustion of the carbon and hydrogen fuel.

Similarly, for trinitrotoluene, TNT: $C_7H_5N_3O_6$, c = 7, h = 5, n = 3, and o = 6 and the molecular weight is:

$$MW = 12(7) + 1(5) + 15\ (3) + 16(6) = 227$$

with an oxygen balance,

$$OB\ (\%) = 100\ (16/MW)\ [o-(2c+h/2)] = 100\ (16/227)\ [6-(2\bullet7+5/2)] = -74\ \%,$$

indicating that TNT is very under-oxidized and if the temperature is high enough, the left over combustion products can consume the oxygen from the air and produce greater explosive effects. Note also that the molecular weights of TNT and nitroglycerine are

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4 In most chemistry books, the atomic and molecular weights are not exact integers as presented here. There are two reasons for this discrepancy. First, due to the Einstein relationship, $E = mc^2$, equating energy and mass, when the constituent protons and neutrons and electrons are joined together into nuclei and atoms, the mass, which is equivalent to weight for our purposes, is slightly modified from the sum of the constituent masses. Second, atoms can be found as isotopes, each having the same number of protons and electrons with identical chemical properties, but having a different number of neutrons in the nucleus. The atomic weight is weighted average of the isotopic abundance's as found on the surface of the earth. These two effects cause calculational numerical differences, but do not change the concepts conveyed in our discussion. Of the two effects, the isotopic effect is larger.

identical, but the ratio of the constituent atoms is considerably different. The presence of the three nitrogen atoms attached to a benzene type structure (toluene) is the basis for the name tri-nitro toluene.

As the two examples of nitroglycerine and TNT illustrate, nitrogen is found in all common explosives. Nitrogen as a gas constitutes approximately 78 % of air, but is relatively rare in the solid form. Solids, which have a relatively high nitrogen density such as melamine, $C_3H_6N_6$, have low oxygen density, if at all. Almost all explosive detection devices explore the chemistry constituency of the object under search to determine if it falls into the CHNO atomic composition with a nitrogen and oxygen relative ratio consistent with known explosives.

Before continuing our discussion of detection characteristics, we digress to consideration of the effects of explosive detonations.

CHAPTER 3

EXPLOSIVE EFFECTS

EXPLOSIVE EFFECTS

An explosion is a phenomenon that results from a sudden release of energy. The exact source of the energy is relatively immaterial in the manifest effects. It may come from an explosive such as TNT, wheat flour dust in a grain elevator, over-pressure of steam in a boiler, or the ignition of fumes in an aviation fuel tank. Consequently, the determination of the cause of a catastrophic failure of an airplane in flight may require considerable detective work before an exact cause can be determined.

The importance of the suddenness of the release of energy can be appreciated by considering from our everyday experience the puncture of a pneumatic tire. If the energy release is sudden, as in a blowout, the effect is that of a small explosion and the tire walls may be shattered. Any person or object unlucky enough to be in the vicinity may suffer injury or damage. If, however, there is a slow release, as by leakage, there is no explosion.

EXPLOSIVE STRENGTH

In considering explosives, the distinction is made between detonation and deflagration. In a detonation, the transfer of energy from the explosive reaction to the surrounding medium is primarily mechanical through shock pressure forces. Explosives such as TNT, which explode by this mechanism, are termed "detonating explosives" or "high explosives." Decomposition of an explosive by the detonation process proceeds rapidly and the mechanical effects are relatively independent of the ambient conditions, but are quite dependent on the density of the explosive. Detonation velocities are greater than the speed of sound and the pressure rise far exceeds the infinitesimal pressure rise associated with a sound wave. Because the detonation velocity is supersonic, there effectively is no forewarning to those persons or objects to be damaged by the shock wave.

A second mechanism for the propagation of an explosive reaction throughout an explosive is thermal. In this case, material surrounding an initial exploding site is warmed above its decomposition temperature so that it explodes. Propellants exhibit this explosion mechanism, and are known as "deflagrating explosives" or "low explosives." Transfer of energy by this thermal mechanism is a relatively slow process and is dependent on external conditions such as the ambient temperature. Deflagration speeds are always subsonic.

Detonating explosives can break a target into small fragments long before the target can be pushed or moved away. Such an explosive like TNT can be characterized by the ability to shatter and can be said to have high brisance. An unconfined explosive detonated in an open area with plenty of space to expand can still shatter an object placed along side it because of brisance. In contrast, a deflagrating material exhibits only minor brisance effect since there is enough time for the heat to be dissipated into the open surroundings. For military uses, a relatively dense high explosive with high brisance is desired for localized attack on hard targets such as armor plate. For soft targets, such as flimsy structures or area effects, brisance is not pertinent and explosive yield is the parameter of importance. An airplane is designed to be as light as possible and consequently relatively weak, so even a deflagrating explosion may cause catastrophic results.

The single most important property of an explosive affecting the ability to cause damage is the amount of energy released. The energy can be expressed directly in conventional energy units such as Joules or foot-pounds, but a relative measure may be more practical. The practical relative values are known as explosive yields. A generally accepted standard for energy release is that in the explosion of TNT, (symmetrical 2,4,6-trinitrotoluene)[6], an explosive chosen because chemically pure material is relatively available for calibration purposes. TNT is relatively safe to handle and for specimens of known density and crystalline nature, it gives quite reproducible explosion effects. Measurements of the energy in the blast wave has determined that TNT generates about 4680 joules per gram. However, these measurements, especially under field conditions are subject to uncertainties due to variability in measurement techniques and exact composition of the explosive sample. Therefore, a "standard" gram of TNT is defined as the blast energy of 4610 Joules. In thermochemical units, this is 1100 calories[7].

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[6] Symmetrical 2,4,6 trinitrotoluene means that the molecule consists of a benzene ring with methyl radical, CH3, attached to one of the 6 inner ring carbons making it toluene. Attaching a hydrogen to each of the ring carbons is the configuration for benzene. The hydrogen attached to three of the ring carbons are replaced with nitro-radicals, NO_2, in positions 2,4 and 6 creating a symmetric arrangement of nitro-radicals. Positions 1 has methyl and position 3 and 5 have hydrogen attachments.

[7] By definition 4.184 joules equals 1 calorie, which is the energy necessary to raise the temperature of one gram of water one degree centigrade (Celsius). This thermochemical calorie with lower case "c" is one one-thousandth of the Calorie associated with nutritional energy. The Calorie used in diets is usually designated with a capital case "C".

These definitions date to the earlier days of nuclear weapons when a standard ton of TNT was defined as the energy release of one million kilocalories or one billion calories. Today the convention is to associate such large energies with 4.61 million kilojoules per tonne of TNT. The tonne is the metric ton or one thousand kilograms or about 2204 pounds avoirdupois, the common English pound. It is very close to 2200 pounds which is called a long ton. When we look into details, an answer to a simple question such as

Explosive strength of a chemical explosive is the magnitude of its explosion relative to that from the same quantity of reference TNT. For example, pentaerthritol tetranitrate, PETN, gives blast waves with about 150 % of the energy from the same mass of TNT. Hence, PETN is said to have 150 % the explosive strength of TNT.

EXPLOSIVE DAMAGE

An explosion does not give its target any advance warning since the blast wave travels faster than the speed of sound. The first manifestation is a forceful blow from the instantaneous pressure jump in its shock front. Almost immediately thereafter, there is the crushing effect of blast overpressure (pressure above atmospheric pressure, 14.7 lb/in^2), and a wind with velocity exceeding that found in the strongest hurricane. The blast wave effects decrease quasi-exponentially with time until atmospheric pressure is achieved (zero overpressure). The pressure decrease overshoots and there is a slight negative phase with a reversed blast wind. Finally, the blast wave subsides and atmospheric pressure returns. By this time, the damage has been done.

Distance offers assured protection against damage from explosives. As a general guide, the protection afforded by distance is more desirable in practice than that provided by protective barriers since they are more predictable. With barriers such as walls, unanticipated effects can occur, such as the case where reflected shock waves from two barriers might at some points reinforce each other or be channeled to a particular point

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"what's a ton?" requires some explaining. No wonder scientists and engineers always seem to be arguing.

and cause greater damage than might be anticipated. Guidelines as to how far away parking is allowed are the outcome of the quantity-distance standards, which have evolved from past experiences. The quantity-distance standards are somewhat arbitrary rules which have been set by the Department of Defense [*DoD Ammunition and Explosive Safety Standards*, published by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., Stock Number 008-007-02900-2 and newer revisions. A useful table may be found in Table II of *Explosive Shocks in Air*, Gilbert F. Kinney and Kenneth J. Graham].

The standards prescribed for safety distances are not simply the result of theoretical calculations, but have included empirical evidence from experiments and actual explosive accidents. On July 10, 1926, at Picatinny Arsenal, about three and a half miles from Dover, N.J., there occurred a series of explosions on the Lake Denmark Ammunition Depot of the United States Navy. This depot contained 160 buildings on 461 acres partly overgrown with trees and brush. 44 of the buildings were for storage of high explosives, smokeless powder, projectiles, and black powder. At about 5:15 p.m., lightning struck and black smoke was observed issuing forth from one of the magazines. There were immediate efforts to quell the fire with streams of water when, five minutes later, a tremendous detonation occurred. Five minutes later another explosions followed in another store house about 150 feet from the first detonation. A third series of explosions followed. The total amount of explosives in the three explosions was more than 670,000 + 1,600,000 + 180,000 pounds and estimated to be the equivalent of more than one thousand tons TNT.

On April 16, 1947, the ammonium nitrate cargo on the SS Grandcamp, a 7,176 gross ton Liberty ship owned by the French government detonated at a pier in Texas City, Galveston County, Texas. In this accident, approximately 600 persons died and 3000 were injured. Sixteen hours later, the ammonium nitrate cargo on the SS High Flyer, a 6214 gross ton Liberty ship owned by Lykes Bros. Steamship Company detonated at another pier. The second explosion materially increased the property damage caused by the first explosion and injured another 50 to 100 persons, but only one person is believed to have been killed.

The explosion disintegrated the SS Grandcamp and threw its cargo of bagged shelled peanuts, bagged ammonium nitrate, tobacco, sisal binding twine, bunker oil, and other substance about 2000 to 3000 feet into the air. It floated the Longhorn II, a steel barge with eleven foot draft, over the top of a freight car stop at the end of the spur and up on the shore without damaging the barge.

The second explosion hurled a two thousand-pound turbine from the deck of the SS High Flyer about 4000 feet into the cooling tower of the refinery of the Republic Oil Refining Company.

A stack of several tons of unburned ammonium nitrate was found in the debris about 150 feet from the berth of the SS Grandcamp four days after its explosion. The ammonium nitrate was found undamaged still in paper bags, but on the next day, burning timbers in the rubble ignited the ammonium nitrate recreating some additional excitement.

These and other events illustrate very clearly that large standoff distances are required to protect against explosive effects. Unanticipated secondary events can cause additional damage. Although we speak colloquially of "safe" distances, the concept of "safe" is a definition, which may be a statutory limit with some degree of arbitrariness.

For a mass of explosives between 0 and 20 kg (0 to 44 lb.), a safety distance of 21 meters (70 feet) from inhabited buildings and 13 meters (43 feet) for public traffic ways is specified for chemical explosives storage. For storage of fragmentation munitions, the distances are increased to 380 and 230 meters (1250 and 760 ft) respectively. The distances do not scale directly with amount of explosives. Increasing the amount of explosives by a factor of five to between 100 and 120 kg (220 to 265 lb.) the distances are 56 and 33 meters (185 and 110 ft.) respectively for inhabited buildings and public traffic ways for the storage of chemical explosives. However, for the storage of fragmentation munitions, the safe distances remain 380 and 230 meters.

The large standoff distances sometimes specified by various law enforcement agencies have their origin from these Department of Defense standards concerning the storage of munitions.

SCALING

The characteristics of a blast wave generated by an explosive depend on the explosive energy release and the nature of the medium through which the blast propagates. For consideration in airline and airport security, the medium for most cases can be assumed to be air and the characterization can be fairly simple. Scaling laws allow us to take known results from one explosive yield and apply them to calculate the results to an explosive yield, which is pertinent to a particular situation.

The scaling law for explosion is bas ed on fundamentals of geometrical similarity and is identical, in principle, with scaling laws used in other engineering applications, such as naval and aircraft engineering. By translating data obtained for models in water or wind tunnels, performance can be predicted for full-scale ships, airplanes, or missiles. Similarly, effects for explosives can be predicted. Basically, the energy released is a given amount and that energy must be extended into a particular volume. The blast wave must conserve momentum, but that momentum must be applied over the area covering the volume under consideration.

Two explosions can be expected to give identical blast waves at distances, which are proportional to the cube root of the respective explosive energy release. This applies because the explosive energy is contained in a volume, which is proportional to third power of the distance from the source. This simply means that the volume is equal to $4\pi/3 \cdot r^3$, as we learned in solid geometry. For example, an eight kilogram TNT yield would have the same blast wave effect at 20 feet as an one kilogram TNT yield would have at 20 feet. The cube root of eight is two, so the distance is in the ratio of two to one.

If the yields are known for cases 1 and 2 and the same effect as D_1 from explosive 1 would be found for explosive 2 at a distance D_2 if

$$D_2 = D_1(Y_2/Y_1)^{1/3}.$$

Similarly, to get the same effect, the yield must be increased as the cube of the ratio of the respective distances.

$$Y_2 = Y_1 \bullet (D_2/D_1)^3$$

where the subscripts 1 and 2 refer to the two explosives yields, Y. and their respective distances, D. The exponent 3 tells us to take the cube of the ratio of distances. An example in the use of this formula is to consider 1 kilogram of TNT (Y_1) at a distance of 20 feet (D_1). To observe the same effect at a distance of 80 feet (D_2), then the first charge must be replaced with 64 kilograms of TNT (Y_2) at the original charge's location.

Other scaling laws for blasts effects have been well characterized and formulas for scaling of overpressure (the pressure jump associated with the shock wave), time of arrival of shock waves, impulse (the integrated product of the force over the duration of the pressure pulse), and blast wind velocity can be calculated. Almost all effects scale as the one-third power of the explosive yield, although temperature change due to the explosive effect must be taken into account. When dealing with explosions in the air, the effects must also take into account the changes in density, temperature and pressure due to the altitude. The obvious limit in taking into account altitude effect is to recognize that when the atmosphere is rarefied, there are almost no shock effects because there is no medium through which the shock wave can propagate. These effects require more sophistication than a simple geometric scaling law because the altitude effects consider more than distances. For example, at 30,000 to 35,000 feet altitude, the atmosphere is roughly one third as dense as at ground level. Between 55,000 and 60,000 feet, there is only one tenth as much atmospheric density as on the ground. Atmospheric density does not decrease linearly with altitude.

However, the situation becomes more complicated in reconstructing the damage effects due to an explosion within an airplane at a high altitude because the pressure within the passenger cabin may be different from the pressure within the cargo hold, which may be considerably different from outside atmospheric pressure.

DYNAMIC LOADS

The blast wave generated in an explosion imposes a dynamic load on any object in its path. This dynamic load is characterized by a rapidly reaching peak load, which then decreases as the blast wave decays. The net effect of the load depends both on the nature of the blast wave and the geometry and construction of the object.

That geometry plays an important role can be appreciated by considering a blast wave impinging upon a pointed object head on and from the side. In the first case, there may be less damage because the shock can easily go around the object, whereas in the second case, the full force of the wave is borne broadside by the object.

Blast waves from an explosion damage a structure by causing it to deform. Where the structure is unable to yield, the structure can be broken. If the structure yields, it may be deformed, or sometimes be sufficiently elastic that it can return to its original shape. Ductile materials may not necessarily fracture even when the deformation is plastic and result in permanent damage. This property can be characterized by the ductility ratio, which is defined as the ratio of the total elastic plus plastic deformation that an item can withstand without complete failure to its limiting or maximum elastic deformation.

Among the more complex, and in many respects, the more puzzling characteristic of an explosive shock front is its behavior when the shock front is reflected. Reflections can be normal reflection, which occurs when the shock impinges head-on onto its unyielding surface with the plane of the shock front parallel to that of the surface; oblique reflection where a shock impinges with a small angle between the plane of the shock and plane of the reflecting surface; and Mach stem formation where the shock front impinges on a surface near grazing incidence. Unexpected results can occur because the primary shock front can be reinforced by the reflected front. The effects on pressure, temperature and speed under these conditions need not necessarily be the algebraic sum of the individual primary and reflected shock fronts, but could exceed that resulting from the simple addition of the two.

CRATER FORMATION

When an explosion occurs above, at or below the ground surface, a crater can be formed. The mechanism of crater formation depends on the height or depth of the explosive blast. From the dimension and characteristics of the crater, the amount of yield can be reconstructed, but this requires knowledge of the ground material. There are different effects in hard granite and sandy soil, so immediate estimates of the yield of the explosion may have to be modified after careful consideration of target material characterization. In general, a crater is formed, but ejecta from the crater may ball back and also create a raised lip around the original crater. Consequently, the apparent crater boundary need not be the same as the true crater boundary. Depending on the temperatures achieved, the affected material may be ruptured and may even be partly melted to form a plastic zone.

GENERAL CONSIDERATIONS

The effects of an explosion are complicated, but the physics has been solved to present an engineering problem. There are many parameters to consider, so an accurate characterization may not always necessarily be possible. However, as a general consideration, the best defense against an explosion is to be far away from it. In most cases, if the amount of explosives is relatively small, the greatest physical danger to personnel comes from fragments and from loss of structural support. If the yield is large, than shock wave effects become important even very far from the source of the explosion. In areas in which flammables or explosives are stored, the danger of sympathetic explosions dictates safe standoff distances. Judgment needs to be exercised between an ideal explosive safety consideration solution and reasonable trade-off including traffic flow and personnel safety. Assumptions as to how large a standoff distance is required for a given explosive yield to protect an airport terminal require assumptions, which may not be immediately obvious. Those who create statutory limitations need to be cognizant of the competing requirements for an integrated operational system.

CHAPTER 4

EXPLOSIVE AND DETECTION CHARACTERISTICS

EXPLOSIVE AND DETECTION CHARACTERISTICS

The detection of explosives for airline security requires non-invasive examination of containers, which may range from handbags to hold luggage to cargo containers. The expectation of finding explosives is quite small, perhaps no greater than one in a billion pieces of luggage. The economics of air transport, measured in terms of costs and in terms of passenger inconvenience requires a throughput rate that does not spend much time interrogating containers with no suspected contraband. The inspection system will have fulfilled its purpose with its deterrence effect in addition to its capability to find explosives. There is no single universal solution to the problem of finding hidden explosives, so at this time, we seek a system comprised of a gauntlet of barriers whose sum will deter those determined to introduce explosives into the air transport system. Although the probability of a piece of baggage containing explosives is extremely small, should that small probability event occur, the consequence is considerable. The task is not simple.

A general set of criteria for a system integrating explosive detection devices (EDDs) must fulfill several qualitative criteria. The explosive detection system (EDS) must have a probability of detection of close to 100 % for bulk explosives. The probability of false positive alarms[8] should be commensurate with the ease of verifying the cause of the alarm, i.e. if the passenger is present with their luggage, a much larger false positive alarm rate can be tolerated than if the passenger is absent. The testing must be as close to automated as practical and should have as little reliance on human

[8] A false positive is a miss-identification of an object as an explosive when it is not. A false negative arises when an explosive is not identified and is permitted to pass through the inspection barrier. False positives can be tolerated with the expense of consuming time for further inspection and verification. False negatives cannot be tolerated, since that would introduce the explosive beyond the inspection barrier.

judgment as possible. Finally, the system must not be susceptible to thwarting and should be difficult to circumvent. This last criterion requires recognition that the system must be able to find the explosive when hidden, camouflaged, or even when the intruder understands the detection system. An assumption that the threat is only from external passengers and that we are not susceptible to threats from inside operatives is extremely dangerous.

As previously noted, each explosive has a distinct chemical composition, so that detection becomes a challenge in chemical identification. The first recognition is that the principal components of most common explosives are CHNO, carbon, hydrogen, nitrogen and oxygen. These are also the components of many common organic and inorganic materials[9].

As a class, explosives are rich in nitrogen and oxygen, but relatively poor in carbon and hydrogen. Individual atomic concentrations[10] are not a particularly good discriminant for explosives since many high atomic concentrations of oxygen are found in many materials, for example as water, sand, dacron, silk and cotton. Very few items have high densities of nitrogen, the most common exceptions being certain plastics such as melamine[11], polyurethene and solid nitrogen. If a single element is to be used as an indicator of explosives, it would be nitrogen. Once the presence of nitrogen is

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[9] In chemistry, organic refers to the presence of carbon which is associated as constituents of living organisms. Inorganic chemistry refers to chemistry not associated with carbon compounnds.

[10] Here, by atomic concentration, we mean that a material is composed with a significant percentage of the atoms of oxygen or of nitrogen.

[11] Melamine is most commonly associated with dishes used for everyday use in homes. Melamine dishes are rarely used as "good china" among middle class Americans, but are the dishes used by the "kids" when there is no company.

discovered, then more careful discrimination would be made to eliminate the exceptions. Recall that an explosive contains its own oxidizer, consequently, in addition to the use of nitrogen as a discriminant, a high concentration of oxygen would also be an important indicator.

Although explosives can have a wide range of densities, robust explosives such as TNT, Semtex, PETN and C-4 tend to have similar densities between 1.5 and 1.9 grams. Roughly, this is one and a half to twice the density of water, a quarter to a third the density of steel, and approximately the density of aluminum. If a non-metallic object "feels" in weight similar to aluminum, it may be worth further inspection.

Most explosives are not amorphous, but have specific crystalline structure. In principle, the unique crystalline structure can be used to distinguish explosives from other light materials, which tend not to be crystalline and from metals, which are crystalline, but have different signatures. The technique used to observe crystalline structure is called x-ray Bragg scattering.

In principle, the ideal way to determine if a piece of luggage contains explosives or not is to do a chemical analysis. Thermal neutron analysis, ion mass spectrometry, and gas chromatography are all methods to do chemistry. Sometimes the chemistry is done using nuclear techniques, such as in thermal neutron analysis, but basically, the technique is to identify the chemical constituents of the object being inspected.

The ubiquitous airport x-ray machine does not try to determine luggage content by chemistry, but rather they try image hidden objects by looking at differences in density between one object and another. X-ray machines are useful in finding dense objects such as metals, and from the inferred shape, determining whether firearms are being carried. However, they do not give unique signals for most light materials such as paper, clothing and most explosives. In fact, sugar can be used to simulate the military explosive C-4 since their x-ray interaction properties are almost identical.

An exception to the general statement that x-rays are not useful in detecting light materials is the case where the x-rays being observed are not seen transmitted through the object, but are seen reflected by the object under interrogation. Backscattered x-rays can be useful for detecting lighter elements.

No single macroscopic attribute of explosive is a unique signature of explosives, but correlation between these properties can prove to be quite useful indicators of explosives. Explosives not only have high nitrogen concentrations, but a measurement of nitrogen and oxygen concentration in moles per cubic centimeter[12] show that their ratio falls within a relatively tight range. No non-explosives and innocuous materials are contained in this range, with low concentrations of either the oxygen or of the nitrogen. Non-explosives tend to not have both high oxygen and nitrogen concentrations simultaneously.

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[12] Moles per cubic centimeter is a measure of the number of molecules (or atoms) of in a given volume. No matter what the element, a gram atomic weight of an element, i.e. a number of grams equal to its atomic number, for example 16 grams of oxygen and 14 grams of nitrogen, contains the same number of atoms which is equal to $N_o = 6.02 \times 10^{23}$, the Avaogadro's number. (Amadeo Avogadro, 1776 – 1856, Italian physicist who hypothesized that equal volumes of gases, whether elements, compounds or mixtures, ehen they are at the same pressure and temperature, contain the same number of molecules. He did no prove this assertion, but his hypothesis proved to be correct. This concept has been extended to include solids as well, with the definition of a mole.)

Technically speaking, a mole has two equivalent definitions. It is the amount of a compound equal in grams to its molecular weight, or it is Avogadro;s number of molecules of the compound. We have for our purposes extended this to apply to atoms in our discussion. Our discussion is a bit sloppy from a purist's perspective, but is operationally useful.

Carbon and hydrogen concentration ratios are relatively unique for explosives with a few common items, such as cellulose and saran wrap, having similar ratios. The measurement of this ratio requires accuracy's which are not easily attainable outside of an analytical chemistry laboratory. Even in the laboratory, the techniques, especially for the measurement of hydrogen, are difficult and generally destructive. (This points out another requirement for airport security inspections which is often not explicitly stated: Whatever detection techniques are used, they must be non-destructive, otherwise we'd have a lot of unhappy passengers.)

Oxygen and carbon concentrations tend to be fairly unique to explosives. In our previous discussion of explosive efficiency, we wanted all carbon to be fully oxidized and ideally an oxygen balance of 0 %. The oxygen to carbon ratio is effectively a measure of the oxygen balance.

The ability of the material to attenuate x-rays (meaning that it blocks transmission of x-rays) versus the material density when correlated at different x-ray energies can be exploited to determine explosives as a group is fairly useful. This correlation is exploited in so-called dual energy x-ray machines.

All in all, explosive detection tries to identify material constituents with one form of chemical identification or other, even though the techniques may be classified as nuclear, or else with interaction involving electro-magnetic radiation. Most commonly x-rays are the electro-magnetic radiation exploited, but microwaves and radio-frequency waves have also been applied. An obvious, but commonly not thought of as being technical, method of interrogation is simple observation. This is interaction with the optical spectrum of electromagnetic radiation since the human eye is sensitive to the visual part of the electromagnetic spectrum.[13]

TAGGANTS

After the bomb explosion on board Pan Am Flight 103, some authorities suggested adding a variety of identification taggants, additives that can provide information before and after a blast, about the nature and source of an explosive. A 1998 National Research Council (NRC) study concluded that economic and social constraints make their implementation at this time nearly impossible. Without making judgments on the desirability or feasibility of the use of taggants in explosives, a description of what they constitute will now be given.

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[13] Prior to the mid 19th century, electricity and magnetism were thought to be unrelated to each other. The Scottish physicist, James Clerk Maxwell, 1831 –1879, based on the observations of the many past and contemporary scientists, was able to integrate them into a set of equation's known today as Maxwell's Equations. Visible, infrared and ultraviolet radiation were found to be the same basic phenomena. Today we know that this set of equations explained a range of phenomena known as the electromagnetic spectrum. The electromagnetic spectrum are described with characteristic frequency and wavelengths whose product is the speed of light. In our ordinary experiences, we encounter long wavelength radio waves with wavelengths of kilometers to x-rays whose wavelengths are a billionth of a millimeter. The same laws of physics apply to all electromagnetic waves. The visible portion of the spectrum centered between the infrared and ultraviolet electromagnetic waves, occupies a very an extremely small portion of the electromagnetic spectrum. In the visible portion of the spectrum, different colors are manifestations of different wavelengths ranging from red, orange, yellow, green, blue and violet in descending order of wavelengths.

Pre-detonation Taggants

Plastic and sheet explosives are usually manufactured with very low vapor pressure, RDX[14] or PETN[15], as the primary energetic ingredient. They are difficult to detect with vapor detectors, including with the use of explosive sniffing dogs. Accordingly, the Ad Hoc Group of Specialists on the Detection of Explosives, who report to the United Nations Council of the International Civil Aviation Organization (ICAO), proposed that volatile marker chemicals be added to plastic and sheet explosives during manufacture. Four detection markers have been identified, with one of these, DMNB[16] identified as a viable detection marker to be added in low concentration to plastic and sheet explosives. The addition of detection markers at this time has been recommended only to the extent required by the International Civil Aviation Organization Convention primarily because of economic considerations. Annually, more than five billion pounds of commercial explosives costing between $0.10 to $ 0.15 per pound are used annually just within the United States alone. An estimated lower limit cost for marking with DMNB is projected to be of the order of $0.02 and $0.20 per pound for a marking at the 0.1 to 1 percent level. This relatively high cost limits its implementation except for the highest value commercial explosives.

Other pre-detonation markers proposed include the substitution of carbon, hydrogen, oxygen or nitrogen components at some minute level with a radioactive

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[14] RDX is the high explosive 1,3,5-trinitro-1,3,5-triazacyclohexane.

[15] PETN is the high explosive pentaerythritol tetranitrate.

[16] DMNB is 2,3-Dimethyl-2,3-dinitrobutane. Its use is in full accord with the ICAO Convention, ratified by the United States in April 1997, which requires detection marking of plastic sheet explosives.

isotope.[17] Beyond the marking of the explosives directly, other low-vapor-pressure components of the explosive device such as commercial booster, detonating cords, and detonating caps have the potential for marking. ANFO[18], which was used in the destruction of the Alfred P. Murrah Federal Building in Oklahoma in 1995, requires a detonating device. Perhaps the tagging of the auxiliary detonator could make the identification of hard-to-detect explosives and explosive mixtures feasible.

As the 1998 NRC report notes the desirability of the use of taggants must be weighed against the improvements in capabilities for detecting unmarked explosives.

Post-blast Identification Taggants

Identification of the source and date of manufacture of the explosive may be a useful post-blast tool for forensic purposes. Various concepts have been proposed, broadly classed as particulate, isotopic or biological. Currently, only one taggant, currently manufactured by Microtrace Inc. has been subject to extensive testing in the Unites States and was the subject of a 1980 Congressional Office of Technology

[17] Isotopes are the same chemical elements except with the number of neutrons different. If the nucleus is inherently unstable it will suffer radioactive decay. Any substitution of the main elements of CHON in an explosive must be with a relatively long half half-life isotope. Of the explosive component elements, only tritium, a 12.3 year half-live isotope of hydrogen and carbon-14, a 5730 year half-life radioactive isotope of the stable carbon nucleus are candidates. There is the theoretical possibility that elements other than carbon, hydrogen, oxygen or nitrogen might be introduced as radioactive markers, but operational feasibility studies have not been conducted. The advantage of measuring radioactivity is that extremely small amounts can lead to detectable signatures. However, dealing with radioactivity introduces other complications such as additional storage and manufacturing requirements, which may not be easily addressed.

[18] ANFO is ammonium nitrate fuel oil mixture. Ammonium nitrate which is commonly used as a fertilizer is by itself not an explosive. However, as a slurry mixed with fuel oil (diesel oil), the combination is a powerful explosive.

Assessment report. The Microtrace taggant is essentially a very small chip composed of multi-colored layers. The combination of possible colored layer orderings effectively act as bar codes in which information about manufacturer, batch number, manufacture date and other pertinent descriptive attributes can be embedded. With a relatively small number of colors a large amount of information can be stored. For example, with five different colors, 60 combinations are possible; with six colors, 360, and with seven colors, 2520. Following this ordering, allowing for multiple layers, one can easily see that that the possible number of combinations is considerable[19].

Needless to say, these taggants must be sufficiently robust to survive a blast. Taggants are used in Switzerland with microscopic color coded plastic chips. However, the application situation in Switzerland is considerably different from that in the United States. The Swiss explosives market is some seven-hundred-fold smaller than in the United States. In the United States, explosives are used in virtually all mining operations, whereas no comparable mining is done in Switzerland.

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[19] The number of combinations possible is the number of colors factorial divided by 2, written as N!/2, where N is the number of colors, and the symbol "!" is the factorial which is a mathematical operation in which one multiplies the number N by each of the numbers N-1, N-2, down to N-(N-1) = 1. For example $3! = 3 \cdot 2 \cdot 1 = 6$; and $7! = 7 \cdot 6 \cdot 5 \cdot 4 \cdot 3 \cdot 2 \cdot 1 = 5040$. The division by 2 accounts for the possibility that one cannot distinguish between the ordering of the colors being right side up and up side down.

Using the example of red, blue and yellow; the orderings which are possible are red-blue-yellow; red-yellow-blue, blue-red-yellow; blue-yellow-red; yellow-blue-red; and yellow-red-blue. Noting that if we cannot distinguish between red-blue-yellow and yellow-blue-red, we have $3!/2 = 6/2 = 3$ combinations possible.

Many more combinations are possible if we are allowed to use the colors more than once, for example red-red-yellow-blue; yellow-red-blue-red; etc. Consequently, a relatively small number of colors sequentially embedded in a chip can store a tremendous amount of information.

ADDITIVES TO MAKE EXPLOSIVES INERT

Many common chemicals could potentially be used as explosives for bombs, but in practice, commercial and military explosives constitute the greatest threat for airline security. Sophisticated explosives used in nuclear weapons are intentionally made as inert as possible in order to prevent accidental detonation. Consequently, it may make sense to view the identification of detonators as a worthwhile activity.

For terrorist activity on the ground, the most commonly accessible explosive material is ammonium nitrate. Ammonium nitrate is produced in enormous quantities for use both as fertilizer and as a legitimate blasting agent. Although considerable effort has been expended to find a way to reduce the effectiveness of ammonium nitrate as an explosive, currently no known technique or technology is known which would not affect its effects as a fertilizer. In principle, chemical suppressants or diluents could be introduced to render explosives inert, but they generally would only make them more difficult to detonate, much in the same way that fire retardants are added to textiles and polymers to make them less flammable. In Northern Ireland, limestone is added to ammonium nitrate in order to lessen their use for explosives. However, techniques for defeating attempts to inert explosives have always been found.

EXOTIC EXPLOSIVES

The emphasis in explosive detection has been the detection of traditional military explosives, which are organic chemicals, usually, containing only four types of atoms: carbon, (C), hydrogen (H), oxygen (O), and nitrogen (N). To achieve maximum volume change, gas formation and heat release, explosives are designed to be dense, to have high oxygen content, and to be maximally exothermic. Usually, explosives contain NO_2 which upon detonation transforms the nitrogen atoms into nitrogen gas (N_2) while the oxygen combines with hydrogen and carbon to form gaseous water vapor (H_2O), carbon monoxide (CO) and carbon dioxide (CO_2). Explosions are different from combustion in that detonation reactions require that the source of oxygen be near at hand, in the same molecule, or in a neighboring molecule, as in the intimate mixture of ammonium nitrate and fuel oil (ANFO).

Explosives are often classified by their stimuli and response. Propellants or deflagrating or low explosives are combustible materials containing the oxygen necessary for their combustion. Black and smokeless powder (colloided nitrocellulose) are low explosives. High explosives have a higher rate of reaction and produce high pressures rapidly. For example TNT creates a shock wave that travels at about 6000 meters per second, whereas gun powder detonation waves travel some 60 times slower.

High explosives are characterized as primary and secondary explosives, differentiated by the way they are initiated. Primary explosives are detonated by simple ignition-spark, flame or impact. Secondary explosives require a detonator or primary explosive. They can be initiated by large shocks, which may be the result of the shock wave caused by a primary explosive. Lead axide, lead picrate, teracene, nitrogen sulphide (N_4S_4), copper acetylide, and nitrosoguanidine are examples of primary explosives. Nitrocellulose, nitroglycerine, dynamite, TNT, picric acid, liquid oxygen mixed with wood pulp, fuming nitric acid mixed with nitrobenzene, and compressed acetylene and cyanogen are examples of secondary explosives.

Present explosive detection technology has concentrated on the detection of military explosives, which fall under three general categories, all of which contain nitro,

NO_2, groups. Nitrate esters, which contain O-NO_2 groups, include nitroglycerine, PETN (active component in DETA sheet), and nitrocellulose. These are generally the least stable military explosives and lose NO_2 readily making them relatively susceptible to vapor detection. Nitroarenes contain C-NO_2 and are typified by TNT (a component of Composition B) or picric acid. The third category contain nitroamines with N-NO_2 groups include RDX and HMX which are often the active component of plastic-bonded explosives such as Composition B, C-4, and Semtex.

However, there are many energetic compounds and common explosives, which may not meet military demands, but could be used effectively as terrorist tools. Possible non-nitro-explosives can be found described in propellant, pyrotechnic and fuel/air explosive literature. Many are classified as composite explosives which are intimate mixtures of fuel and oxidizers. Peroxides can function both as oxidizers and as stand-alone explosives. Self-igniting systems such as boranes, phosphorus and alkali metals do not require blasting caps. Ammonium nitrate fuel oil (ANFO) is the most available class of explosive which does not contain the conventional NO_2 nitro-group.

Civilian nitrogen containing explosives include nitromethane, CH_3NO_2, which is commonly used as an industrial solvent and as a fuel additive in hobby rockets and race cars. Although it might be classified as a conventional explosive, its melting point is $-17°$ Centigrade and its boiling point is $101°$ C with a density only 15 %greater than water. Although it has a unique odor, bottled up, nitromethane could easily pass for water or wine and defeat present detection schemes. Picatinny Liquid Explosive (PLX), a slightly yellow liquid composed of 95 % nitromethane and 5 per cent ethylenediamene in a whisky bottle and 350 grams[20] of Composition C4 in a radio were reportedly left by

[20] There are 454 grams in a pound. 350 grams is only 12 ounces, about a can of beer in volume.

two passengers who got off in-route in the November 1987 downing of Korean Air Flight 858 in which 115 remaining passengers lost their lives.

Ammonium nitrate, (AN, NH_4NO_3), is perhaps the most important raw material used as an industrial explosive. In 1986 over 11 billion pounds were produced in the United States with 80 % used as fertilizer and 20 % used in the explosive industry. It was patented as an explosive in 1867 by two Swedish chemists, who later sold the invention to Alfred Nobel who used AN in dynamite. During World War I, Amatol was developed as a mixture of AN and TNT. Ammonium nitrate by itself was not considered an explosive until 1921 in which a disaster occurred in Oppau, Germany, killing 600 people. In 1947, two shiploads of AN detonated at Texas City, Texas. When combustible non-explosives are added to ammonium nitrate, they react with the excess oxygen to produce greater gas and heat creating higher pressures and temperatures. Rosin, sulfur, charcoal, sugar, oil and paraffin are suitable additions, although fuel oil is most often used. ANFO is a mixture containing 5-6 per cent fuel oil with the ammonium nitrate fertilizer. Since the middle of the twentieth century, ANFO has almost completely replaced dynamite in the mining industry.

Mercury Fulminate, $Hg(ONC)_2$, is a primary explosive, sensitive to heat, friction and light and easily decomposed. Until the development of lead azide, mercury fulminate was practically the only explosive used in detonators. Mercury is dissolved in concentrated nitric acid, ethanol is added and white crystals of mercury fulminate is formed and separated by washing. Several do-it-yourself explosive books provide detailed synthesis information.

Heavy metal azides[21], ($Pb(N_3)_2$, AgN_3), explode with shock. These are described in terrorist handbooks as explosives, which can be readily created in the kitchen. We should be aware that sodium azide may soon become readily available as it is used in most automobile air bags with about half a pound found in many passenger-side air bags.

In addition to non-conventional, nitrogen bearing explosives, there are a variety of nitrogen-free explosives among which include oxides of chlorine such as perchlorate which can react violently and produce toxic fumes; calcium hypochlorites, which can be obtained from swimming pool chlorine (HTH); and alkali[22] metals which can spontaneously ignite on exposure to air or water. Some finely powdered non-alkali metals including lead, iron, nickel, cobalt and aluminum will also burst into flame in the presence of air. A syrupy mixture of powdered aluminum and carbon tetrachloride has been suggested as a sensitive explosive with the reaction:

$$Al + CCl_4 \rightarrow AlCl_3$$

Thermite is used for welding in shipyards and for railroads and can be applied to react explosively. The most common thermite reaction is:

$$8\ Al + 3\ Fe_3O4 \rightarrow 4\ Al_2O_3 + 9\ Fe$$

This reaction generates a tremendous amount of heat and can create molten iron whose melting point is above 1530°C. This reaction welds by melting iron and allowing the molten metal to flow between metallic surfaces and create a bond.

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21 Azides are molecules containing a linear chain of three nitrogen atoms which contain considerable energy. They can be relatively stable against reaction with other molecules, but physical disturbances, such as a shock, can cause them to explode.

22 Alkali metals including lithium, sodium and postassium are among the most reactive elements because they have a single unpaired electron in the valence shell. These are classified as members of group 1A in the periodic chart.

Peroxides including hydrogen peroxide, (H_2O_2), in concentrated form can be a violent oxidizer in the presence of a fuel. In World War II, the United States Navy successfully used it as a propellant for submarine torpedoes. Phosphorous, P_4, self ignites in air above 34° C and must usually be stored in mineral oil or water. Finely divided phosphorous is combustible. Phosphorus can react exothermically with the oxygen in the air:

$$P_4 + 5\ O_2 \rightarrow P_4O_{10}$$

and can induce further reactions, which act explosively.

There are many other materials and reactions which can be used to obtain explosive effects including acetylides, hydrides, potassium permanganate, etc. Present efforts in explosive detection have focussed on detection of conventional explosives. The possibility of introducing non-conventional explosives by terrorists is to alert the reader that vigilance is multidimensional and that complacency can lead to disastrous consequences. More advanced explosive detection technology may not currently be available, but other avenues such as profiling, intelligence gathering and analysis, sound physical security practices and common sense play an important role for passenger security.

CHAPTER 5

DETECTORS AND TECHNOLOGY

DETECTORS AND TECHNOLOGY

Technologies relevant to airline security incorporate a variety of fields. Direct detection of explosives and other weapons are the subject of research and development involving advanced hardware. Physical protection includes alarms, barriers and access control. Procedural means for interrogation require knowledge of human factors. Other approaches such as passenger profiling must be sensitive to human rights issues and stereotyping. Incident response may differ for each situation. Data dissemination relies not only on current networked information technology, but also includes interagency coordination as well as simple human communication among security personnel. Sometimes the threat device may be undetected, but other associated components such as detonator wiring may reveal the presence of a weapon. A single approach or concern may not detect anomalies, but a layering of security approaches can provide an integrated system which is capable of instilling confidence that airline security works. The emphasis is on an integrated system.

Although the engineering details of how devices work may be quite complicated, the essential physics of detection technologies is fairly easy to understand. This basic understanding is facilitated because the technologies are those we encounter in our everyday experiences. In this chapter, we will attempt to describe operational and developmental systems in a context, which hopefully is consistent with our daily experience.

METAL DETECTORS

Although, in general, metals are not an inherent component of explosives, metal detection is an important component of any airline security system. In the early days of the airline industry, the greatest threat from terrorism or other criminal activity was the threat of hijacking. Metal containing firearms and knives were the weapons used to threaten crews and passengers. Metal detection could eliminate a considerable threat hazard by not allowing the introduction of weapons on board airplanes. Even when bombs were introduced as hijacking weapons as in the case of D.B. Cooper, the triggering and initiation mechanism required wiring. Detonators and timers usually contain detectable amounts of metal. Consequently, metal detection is a first defense against explosive devices.

Most metal detectors used at airports function either by detecting changes in induction caused by additional presence in the portal or by detecting eddy currents produced in metal within the portal by a radio frequency pulse. A drawback of inductive metal detectors is that they cannot detect nonmetallic objects such as plastic weapons or explosives.

In the simplest electrical circuit, there is a voltage source, resistance, capacitance and inductance. The voltage source is a power source, which drives the metal detection device. The amount of current that flows through the detector is depends upon the resistance. For a given voltage, the more resistance there is, the less current flows[23].

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[23] The relationship between voltage and resistance is given by Ohm's law, $V = IR$ where V is the voltage expressed in Volts, R is the resistance expressed in Ohms and I is the current expressed in Amperes. Since equivalently $I = V/R$, the lower the resistance, the greater the current for a given voltage. Short circuiting means that the resistance is lowered to nearly zero and the current approaches infinity. Since real circuits are not isolated, there will be some other part of the total circuit which will not be able to tolerate the large current. Hopefully, the weakest part of the total circuit is a fuse or a circuit

Capacitance is effectively caused by a gap in the circuit, in which a charge must build up on one side of the gap and an equal, but oppositely signed charge builds up on the other side. The simplest capacitor[24] can be constructed with two separated flat metal plates with a voltage applied across them. Energy is stored in the capacitor in the form of electric fields. Inductance[25] can be created by a wire looped into a coil. A current going through the coil creates a magnetic field, which stores energy within the coil. The presence of a foreign object within a coil is detected because the resistance, capacitance and/or inductance changes for the circuit. Mutual-inductance metal detectors are most susceptible to magnetic materials inserted within the interrogating coil[26].

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breaker and these can be replaced or reset. Unfortunately, in many instances, there are other components which cannot withstand the large currents driven by a short circuit and the damage is not easily repaired.

[24] The relationship between capacitance and voltage is expressed as $Q = CV$ where Q is the charge (of one sign) expressed in Coulombs stored on the plate, V is the voltage in Volts and C is the capacitance expressed in Farads. The capacitance depends on geometric factors such as the area of the metal plates and the gap distance between the two plates. It also depends upon the material filling the gap between the plates. The larger the plate and the smaller the gap distance, for a given voltage, the more charge that can be stored. Also more charge can be stored if the material between the plates is a good insulator. The capacitance is a measure of a physical object to store charge (capacity for charge storage).

[25] The relationship between the current and voltage in an inductor is given by $V = LI$ where V is the voltage across the inductor and I is the current flowing through the inductor. L is the Inductance expressed in units of Henry. For a simple coil of wire, L depends on the physical dimensions of the loop, the number of loop turns in the coil of wire and magnetic properties of the material within the coil. Transformers have soft ironm which is magnetic, wrapped with wire loops in order to increase the inductance.

[26] Strictly speaking, the description of L, the inductance is that for self-inductance. If there are two loops, the presence of one loop is noticed by the other loop. The effect is caused by the mutual inductance, which can be written in the simplest form as $V(2) = M \bullet I(1)$, where V(2) is the voltage across the second loop induced by a current I(1) in the other loop. M is the mutual inductance which is related to the geometry and material composition of the loops. The effect works reciprocally and $V(1) = M \bullet I(2)$ with the

If the current in one loop is time varying, such as a pulsed current, a voltage can be induced with a conductive material, which now effectively acts like the second current loop (eddy currents). Electromagnetic induction metal currents detect the presence of a conductive material by observing the effects of current induced in that material.

All types of metal detectors are "electromagnetic" and share common features. A search head contains one or more coils carrying a time-varying electric current, which may be a pulse. The time varying current generates a time-varying magnetic field, which propagates outward. Depending on the design, the field may be made somewhat directional to interrogate a particular region in space. If there is a metal (meaning conductive) target, the primary field causes (induces) a current to be set up in the target. The current induced in the target generates a secondary magnetic field, which can be detected by receiver coils in the primary metal detector unit.

A wide range of variations is possible for the metal detector. For example, the number of coils; the shape of the primary magnetic field; the time varying shape of the transmitted pulse including the frequency; and the configuration of the receiving coil can all be engineered differently to vary capabilities and cost of the metal detector. In some units, the same coil is used for transmitting and receiving. Pulses may be used so that the primary electromagnetic pulse does not interfere with the electromagnetic signature from the target. The head coils can be magnetic or air-cored. In situations where extremely weak return signals are expected, such as the case in the detection of buried landmines, the effects of the earth's intrinsic magnetic field must be taken into account and compensated.

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same mutual inductance. The relative orientation and spacing of the two loops with respect to each other can change the value of the mutual inductance M.

For interrogation of personnel, such as at the airport passenger terminal, throughput is important, so the coils may be configured as portals through which the passenger passes. The amount of metal, which can be detected, can be varied by changing circuit parameters such as resistance, capacitance and inductance. The setting of sensitivity may be determined by regulatory agencies that in turn must make judgement as to what are likely threats to be encountered. Detection of electromagnetic signatures is very sensitive to the distance between the target and the probe, so hand held metal detectors can be used to isolate and determine the precise location of the metal object being interrogated.

The induced current is not created instantaneously. If the primary (or transmitted) magnetic field is a pulse, the response current (eddy current) will mimic the time behavior of the primary. When the primary pulse ends, the response current does not immediately disappear, but will decay away gently since the energy source driving the eddy current has disappeared. Nevertheless, the decay persists for a little time, about a hundred microseconds or so. The persistence will depend predominately on the target's electrical conductivity and size. Low conductivity alloys or thin foils have very short decay time. Ionic conductivity in sea- or brackish water is low, so in that environment the signal may decay away very rapidly and metal detection becomes impractical.

These eddy currents generate a secondary magnetic field, which propagates in all directions, including back towards the search head, where it induces a small voltage in the coil. The received voltage from a target at the limit of the detection range may be only a few millionths of a volt (microvolts), perhaps one ten-millionth the voltage initially induced by the primary pulse (back-emf). The receiver ignores the signal during the transmit pulse and the immediate response (back-emf) time and only "looks at" the signal after a short delay. This insures that the transmitted and received signals are separated from each other and the received signal is not swamped by the transmitted signal.

If the target is both conductive and magnetic (ferrous) the return signature can be enhanced by the target's magnetic properties. However, even with a non-magnetic conductor, eddy currents will be set up in the target and a return signal can be detected.

If there is no target at all, nothing should happen. Actually, there will always be electrical "noise" associated with the receiver coil and circuitry and these must be made as close to zero as possible. In addition effects due to temperature and circuit warm-up and cool-down can make the receiver "drift" and these must be compensated. Looking inside a metal detector, the circuitry is complicated since human intervention would be too imprecise and slow.

In order to reduce false alarms to an acceptable level, inspectors may require subjects to empty their pocket of metal objects. This slows inspection and precludes covert inspection, but their visibility acts as a deterrent for the introduction of metallic weapons.

In the use of inductive metal detectors, it is important that its location be such that they avoid electromagnetic interference (EMI). EMI acts as a source of noise and may reduce the sensitivity of the detector. It is possible to increase the interrogating field, but because of concerns for the operation of cardiac pacemakers, the current standard for general public exposure[27] is 1 Gauss[28].

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[27] This standard is set by NILECJ-Std-0601.00 issued by the National Institute of Law Enforcement and Criminal Justice (now the National Institute of Justice) in June 1974 and by exposure guidelines set by the Bureau of Radiological Health (BRH) of the Food and Drug Administration (FDA). Some designers speculate that modern pacemakers are

Other methods for detecting metals include the measurement of reflection of radiofrequency[29] electromagnetic waves. In this approach smaller metal objects including knives, firearms and other weapons could be detected at short distances by low-powered radar[30] systems that can be used to "frisk" suspects electronically. Simple short-range radar systems can detect the presence of a metal object but generally would not distinguish weapons from innocuous objects such as watches and coins.

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less susceptible to such EMI from metal detectors and a committee of the American Society of Testing and Materials (ASTM) has debated on proposals to increase the limit to 3 Gauss. However, this effort was abandoned because there was no disinterested third party such as the National Institute of Health willing to do the human experimentation required to prove safety at this level.

[28] A Gauss is a unit for the measurement of magnetic fields. The earth's magnetic field within the United States is of the order of one-half Gauss and a refrigerator magnet provides about 100 Gauss on contact. The standard metric unit (SI = Systeme Internationale or MKS = meter-kilogram-second) of magnetic fields is the Tesla, T = 10,000 Gauss. The Gauss was in common use with the cgs = centimeter-gram-second system of units which is still commonly used in some technical fields.

[29] Radiofrequency electromagnetic waves (RF) are electromagnetic waves with wavelengths in the range of centimeters and meters. For all electromagnetic waves, the product of the wavelength and the frequency is exactly equal to the speed of light.

[30] Originally the acronym RADAR stood for Radio Detection and Ranging. By sending a electromagnetic wave pulse out towards a target, the pulse reflected from a metal target could be detected revealing the presence of a metal target. Because all electromagnetic waves travel at the speed of light, careful measurement of the time interval between when the pulse was sent out and when its reflected pulse was detected could reveal the range to target. The total distance traveled is half the distance traveled by the pulse since the pulse must make a round trip. $R = (c \bullet T)/2$, where R = range to target, and T = roundtrip time for the pulse. c is the speed of light equal to 300 million meters per second (3×10^8 m/s).

More expensive millimeter-wave radar systems have the resolution[31] to create TV-like images of objects. Nonmetallic objects also reflect radio waves and can be detected and imaged by radioreflectometry. This is called dielectrometry and could, in principle, be used to "frisk" suspects electronically for object shaped like nonmetallic weapons or explosives. A near perfect conductor such as a metal will reflect back almost all the radiofrequency electromagnetic radiation impinging upon it. A perfect insulator will not reflect any of the RF wave. Most non-metals are somewhere in between a conductor and insulator and are characterized by a property called the dielectric constant. Some of the impinging RF wave will be transmitted and some will be reflected. By measuring the amplitude of the reflected wave, an estimate of the dielectric constant[32] may be made and the target material may be guessed. There are some efforts to develop dielectrometers not only for detection of concealed explosives and weapons, but also for detecting other contraband such as drugs.

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31 In general, the resolution, or the ability to distinguish to two separated points, is limited by the wavelength of the probe radiation. Millimeter wave electromagnetic radiation would have wavelengths and resolution to "see" objects with features with millimeter characteristic differences. 90 gigaHertz (90 billion cycles/second) waves would have a resolution of about 3 mm whereas 30 GHz waves would have a resolution of 1 centimeter.

32 The dielectric constant (also called its relative permittivity) is determined by the response of the molecules to the presence of an electric field. The magnetic permeability is determined by the response of the material to the presence of a magnetic field. The square root of the product of the permittivity and the permeability is the index of refraction and determines how much an electromagnetic wave will bend going into the object. In addition, the speed of the electromagnetic wave a material is slower than in a vacuum. The speed of light in a material is the speed of light in a vacuum divided by the index of refraction.

For most purposes, air may be treated as having an index of refraction of 1.0 and water has an index of refraction of 1.33. This means that the speed of light (electromagnetic waves) in water is one third slower in water than in air. The permeability and permittivity depend upon the frequency of the electromagnetic wave traversing through it and accounts for different properties for different types of electromagnetic waves.

There are trade-offs in the application of these technologies. In most prototypes, the expense of the detection system lies in the source, detector and the signal processing equipment. The detectors are usually a horizontal array of solid state chips[33], which are mechanically scanned vertically. The collection of the imaging information takes time. Human exposure concerns must be addressed for differing wavelengths. As extreme cases, if 3 GHz were chosen, that frequency is that used in common kitchen microwave units and is specifically designed to excite water molecules[34]. 180 GHz with its shorter wavelength would provide better resolution. Detectors[35] specific to these frequencies are being developed and show promise. A limitation of higher frequencies is the atmosphere, which absorbs RF radiation in a very short distance. 30 – 90 GHz RF is a compromise of resolution, availability of sources, availability of detectors and human safety considerations and the time necessary to detect and process the image information. In many of these systems, the engineering feat of assuring fast passenger throughput and preserving a sufficiently short and small exposure level is a non-trivial challenge.

Metal detection is the first line of defense against the introduction of weapons. There are pistols, which are primarily plastic, and explosives themselves do not contain metals. However, the firing pin, the detonation cap and wiring are usually metal and most of the time an alert inspector can get sufficient information to interrogate and inspect a suspect person or object for closer scrutiny. The introduction of metal detectors at airports has detected numerous weapons, knives, guns and even hand grenades.

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33 One detector for detection microwave radiation is composed of Gallium Arsenide tiles. Different detectors are capable of detecting different wavelengths (or frequencies), so a system designed for one frequency may not compatible detectors for another frequency.

34 Should this frequency be applied, besides the lack of resolution, human safety would be a critical concern since the body is composed mostly of water. We do not want to "cook" the suspect even if he were trying to sneak a weapon on board.

35 Shottky-barrier diodes.

Airplane hijackings have been reduced substantially from the 1960's and 1970's prior to D.B. Cooper's infamous hijacking exploit, which played an instrumental role in the public awareness of the need for passenger inspection. If one recognizes its limitations, metal detection is a critical component of the inspection system to insure airline security.

DETECTION WITH X-RAYS

The non-invasive examination of containers presents challenges whether we are examining handbags, hold luggage or cargo containers. Ideally, the inspector would have x-ray vision powers capable of visualizing the contents of the container. (X-rays penetrate into the object and substitute for "Superman" powers.)

Sometime around December 1895, the German physicist, William Conrad Roentgen (1845 – 1923), discovered a mysterious and invisible form of radiation that streamed from the positively charged electrode of a vacuum tube. The vacuum tube was created by a talented glassblower and mechanic, Johann Geissler, in the middle part of the 19th century. These tubes were made possible by Geissler's invention of the mercury pump, which allowed the manufacture of evacuated glass tubes with two electrodes sealed within them. Geissler's tubes are the precursor of today's TV sets and the cathode ray tube necessary for computer displays. Various metals, if included in the tube, would glow[36] in brilliant colors and the Geissler tube was a popular novelty. Roentgen played

[36] Fluorescence is the property of a substance to produce visible light while it is being acted upon by radiant energy, such as ultraviolet rays or x-rays. In many substances, the energy from the radioactivity excites atomic electrons and when they return to lower energy states, visible light is emitted. Consequently, although glowing and radioactivity do not necessarily go hand-in-hand, many radioactive substances can be seen to "glow."

with these tubes and discovered that certain minerals could be caused to glow and the radiation could penetrate materials, which were opaque to light.

The difference between Roentgen and rest of us grown up kids is that he was observant and curious. Roentgen was a scientist not known for neatness and just happened to have some fluorescent mineral lying around. Being a good scientist, he was able to recognize that a new phenomenon was being observed and systematically study it. The newly discovered radiation could expose photographic plates, which were wrapped in black paper. He called the new radiation "X rays" for "x", the generally used symbol for unknown quantities in mathematics. William Conrad Roentgen was able to show that the radiation was different from the cathode rays within the tube[37]. The X-rays could penetrate wood and flesh but could be blocked by metal and bone. He was able to produce pictures of a set of weights in a small box and of the bones of his wife's hand[38]. They were the first X-ray photographs. For his work, Roentgen received the Nobel Prize in 1901.

The medical community almost immediately recognized the utility of X-rays to visualize parts of the human body inaccessible to observation without intrusion. Material

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[37] The positively charged terminal is called the anode and the negatively charged terminal is called the cathode. Now we know that cathode rays are negatively charged electrons and X-rays are electromagnetic radiation. Electromagnetic radiation can be described as particles and waves called photons with the product of the wavelength and frequency equal to the speed of light. X-rays have wavelengths which are about the diameter of atoms. Roentgen was able to show that cathode rays (electrons) would be deflected by a nearby magnet, whereas, X-rays would not be deflected by the magnetic field just as a beam of visible light would not be affected by the presence of a magnet.

[38] Physicists can tend to be resourceful. Using his wife's hand with her wedding band, Roentgen did not have to rely upon hired help or graduate students for this historical recording. Being married to physicists in those days may not have been the safest thing because sometimes the spouse became part of the experiment.

science progressed because the X-ray provided a probe with wavelength and, consequently, resolution sufficiently small to see details of atomic and crystalline structure. The structure of the double helix of a strand of DNA, the molecule that carries genetic information could be seen with X-rays. The structural integrity of welds in ship hulls could be inspected with X-rays. And today, X-rays contribute towards insuring passenger safety from the introduction of firearms, explosives, drugs, flammable materials and other objects, which could endanger passenger safety.

The basic X-ray interaction with materials is fairly straightforward, but complicated engineering refinements tremendously enhance their visualization capability. Basic X-rays whether found at the airport or the dentist's office, dual or multi-energy X-ray scanners, back scatter X-ray scanners, computer tomography (CT) X-ray scanners all require the understanding of the physics of the interactions of X-rays with matter.

The ability of matter to block X-ray transmission through it is characterized by its attenuation coefficient. If an incident X-ray of intensity I_o (photons/second) strikes a slab of material of thickness, t, the intensity on the other side of the slab is I, where the original intensity has been diminished by an exponential factor:

$$I = I_o \exp(-\mu t),$$

where μ is a characteristic of the material called the attenuation coefficient. If the thickness is expressed in centimeters, the attenuation coefficient[39] is expressed in inverse

[39] There are other ways to express the attenuation coefficient. As we have presented it here, μ is the linear attenuation coefficient expressed in units of inverse centimeters. If we express the thickness of the slab in terms of the linear thickness times the material density, we call the attenuation the mass attenuation coefficient expressed in units of 1 / ($gm/cm^2 - cm^2/gm$). The reason to use the mass attenuation coefficient rather than the linear attenuation coefficient is that thickness, T, is essentially a measure of the number of atoms in the path of the X-ray. The mass attenuation coefficient allows for easy

centimeters, (1 / cm). The minus sign tells us that as the thickness increases, the intensity diminishes. The exponential function rapidly becomes smaller. For example, exp(-0) =1; exp(-0.5) = 0.61; exp(-1) = 0.37. The inverse of μ, $\mu^{-1} = 1/\mu$, is called the attenuation length and tells us what amount of material would diminish the initial incident flux by a factor[40] of "e" = 2.718.

If there is one centimeter of water in the path of the X-ray, there are as many molecules as in 10 meters of steam. If the path length is expressed as the physical path length times the density of either water or steam, the thickness of water or steam can be expressed as a gram/cm^2 of H_2O, for both states of matter. It is more convenient to express thickness in units which measures the amount of material and the convention of mass attenuation coefficient is used. The mass attenuation coefficient is the product of the density and the linear attenuation coefficient. Unfortunately, the same symbol, μ, is conventionally used for both the mass and the linear attenuation coefficient. In both cases, μ is a measure of the ability of the intervening material to remove X-rays from the original intensity.

The mass attenuation coefficient depends on the material and the energy of the X-ray traversing through it. Bones and metals have a mass attenuation coefficient greater than through skin and flesh. Consequently, for medical X-rays, most of the X-rays pass through the soft tissue and the bone appears dark because the X-rays have been removed from the primary path.

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comparisons of gases and solids where the physical densities differ by a factor of a thousand or so.

[40] e is the base of the natural system of logarithms and has a numerical value of approximately 2.71828... .

The ubiquitous airport X-ray machines can quite readily produce an image of dense materials, but cannot easily image lighter materials or lighter materials masked by the denser image. Unfortunately, the mass attenuation coefficient cannot give unique signals for explosives since most light materials (plastics, paper, clothing) have essentially the same absorption effects[41] as explosives. Some discrimination between materials is possible because different materials absorb differently and shades of gray may be observed. In a sophisticated system, as many as 80 shades of gray are possible depending on the degree of absorption. These shades of gray may be displayed as different colors (pseudo-colors) to produce an artificially enhanced visual presentation. The simple x-ray machine cannot distinguish between a thin slab of metal and a thick slab of a less dense weaker absorber. Simple X-ray systems rely upon humans to interpret the observed pattern. Pattern recognition depends on many factors including training, experience and attention quality of the observer. Pseudo-color presentation can remove some of the subjective elements and less experienced operators may be able to discern patterns that might be hidden in a gray shade presentation.

Dual and Multi-Energy Systems

Dual-energy scanners are really two X-ray systems whose beams are generated from sources that have maximum intensities at different energies[42]. The attenuation

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[41] The two most important effects for attenuating X-rays is absorption and scattering. With absorption, the X-ray energy is absorbed by the intervening material, whereas scattering redirects the X-ray into another direction. This scattered X-ray may appear in other directions and can have the effect of creating background or "fogging" of images taken elsewhere.

[42] X-rays peaked at specific energies can be obtained by judicious choice of anode materials. In an x-ray tube, the cathode is a source of electrons and the electrons are accelerated by a potential difference between the cathode and the anode. When the

coefficients are functions of the X-ray energy and can produce different gray scale presentations of same target. Generally, higher energy x-rays suffer less absorption than lower energy x-rays impinging on the same target. While areas of heavy elements are dark in both views, areas of light elements differ. The lower-energy x-ray image will be darker. Comparison of both images, light elements such as carbon, nitrogen and oxygen may be emphasized. The use of the dual energy system allows some discrimination among organic substances which are usually composed of lighter elements, inorganic substances usually containing heavy elements and opaque materials which contain a lot of heavy element matter. By false color imaging, the organic material might be presented as a bright colored object, indicating the need for closer scrutiny. Here operator skill is crucial for good discrimination and avoidance of false positive identification.

If more than two x-ray energies are used, the system is classified as a multi-energy system. Usually the multi-energy x-rays are produced by a single x-ray tube that transmits a broad spectrum of energies. These systems cannot distinguish among light elements, but can be useful in overcoming the countermeasure of hiding explosives behind an object made of a heavy element. As a practical matter, if the entire beam is absorbed, then all that is seen is a dark blob. Almost a full centimeter of steel would be required to fully absorb the x-ray beam.

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electron slams into the anode, interaction with the atomic nucleus slows down the electrons and a spectrum of X-rays are generated with energies up to that determined by the voltage difference between the cathode and anode. The process of slowing down the electrons produce x-rays. These x-rays are called bremsstrahlung from the German words *bremsen* meaning braking and *strahlung* meaning rays. X-rays produced in this manner are thus "braking radiation" coming from the braking of the cathode ray electrons.

In addition, atomic electrons may be knocked out of their normal position in the target anode atom. When electrons "fall" back into these "stripped" atoms, energy is released in the form of x-rays. These x-rays have very specific energies. These x-rays are energy specific to the target atom and are called characteristic x-rays.

Backscatter X-Rays

The x-ray attenuation coefficient contains two terms, one for absorption and another for scattering. The absorption phenomenon is primarily caused by the photoelectric effect[43] which is the absorption of the x-ray energy by an atomic electron. The electron gains kinetic energy sufficient to free it from the atom. The probability for the photoelectric interaction increases with the atomic number, Z, which is the number of electrons in an atom. The scattering effect depends primarily on Compton scattering, which may be viewed as the scattering of a x-ray by an individual electron. The Compton scattering phenomenon is relatively independent of the atomic number. Therefore, the resulting backscatter signal favors low Z elements, especially low Z elements of high density such as plastic explosives.

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[43] In the 1880's it was observed that electromagnetic radiation (light) striking metal caused electrons to be freed from the surface. The electromagnetic radiation, which for our purposes is x-rays, is absorbed by the atomic electron and sufficient energy is given to the electrons near the surface to free them from the metal. It took Albert Einstein (1879 – 1955) to properly explain the phenomenon in 1905 using Max Planck's new quantum theory of radiation to explain the photoelectric effect. The phoelectric effect is the basis for the photographer's light meter and for other light-sensing devices.

Max Planck (1858-1947) introduced the radical idea that light came in packets called photons. Later this concept could be extended to include the whole electromagnetic spectrum from radio waves to gamma rays. This was a radical departure from the concepts predominant at that time in which light was considered to be waves. Quantum Theory, or Quantum Wave Theory reconciled the seemingly incompatible concepts. Mathematics is a language which incorporates particle-wave duality, whereas the English language (and for that matter all other spoken languages) has difficulty expressing the vagaries of the atomic world.

A closely related effect is the photovoltaic effect which converts electromagnetic radiation into a flow of electrons parallel to the surface of certain materials such as thin silicon crystals. Here the photons impart enough energy to free the electrons from the individual atoms, but the electrons do not leave the crystalline structure. The photovoltaic effect is the basis for solar cells.

By observing x-rays, which have been backscattered, rather than those which have been transmitted through a target, a direct measurement of elements with low atomic number can be imaged. A system with a large area detector on the same side as the x-ray source can also be combined with a detector on the other side. By combining the information from both sides it is possible to determine the locations of heavy element objects as well as of light element objects. In these systems, the source x-ray beam must be relatively narrowly focused into a pencil beam so as not to directly interfere with the detector. Rather than a single large area detector, a line detector can be scanned across the target body or alternatively, the detector can be fixed and the pencil x-ray beam may be swept across the target body. Operator experience is a definite asset to identifying weapons, explosives and contraband, but there are efforts to make the system more amenable for automatic detection. Advances in computation and computation algorithms give hope for using backscattered electron systems for an automatic detection system.

In addition to their use for detection of contraband, firearms and explosives at airports, the backscattered x-ray systems have application for inspecting visitors to prison facilities and embassies where security is also of paramount concern.

Computerized Tomography X-Ray Scanners

If a series of detectors can see the transmitted x-ray from a variety of directions, the density of materials from several path directions can be reconstructed. As in conventional x-ray systems, the density of each location along the path of a beam can be determined an array of detectors placed on a rotating circumferential element around an object. The x-ray beam is a fan beam that traverses the object under study. As in medical computer axial tomography (CAT), densities of a cross sectional two-dimensional slice can be determined. The inspected object is moved through the detector/ beam station by means of a conveyer belt, providing a series of multiple slices. Because all three dimensions are interrogated, by application of computer projection techniques a three dimensional view of the densities of the parts of an inspected body can be created. The spatial resolution of the order of millimeters can be obtained. In principle, the spatial resolution is as good as molecular dimensions since the x-rays have very short wavelengths, but practical realities such as the diameter of the x-ray pencil beam and detector size limit the resolution.

The CT system operates and looks very much like the medical CAT (computerized axial tomography) scanner. The origin of airport security CT is medical CAT where fast scanners were developed to freeze the image of the human heart even as it was beating. In principle, dual- and multi-energy CT is possible, as is incorporation of backscatter techniques. The reconstruction of the data from detecting x-rays is computer intensive.

Computerized Tomography X-ray Scanners are extremely sophisticated and implementation costs are of concern. The intensive data gathering and computation required is time consuming and the present estimates of several hundred bags per hour is too slow for use on all checked baggage. The CT system has promise for a final inspection system after most of non-suspect baggages have been cleared using other systems such as ordinary x-ray machines.

RADIATION SAFETY ISSUES

X-rays are electromagnetic radiation, which are classified as ionizing radiation. Ionizing radiation[44], which includes, alpha rays, beta rays, protons, neutrons, and gamma rays, as well as x-rays, transfer enough energy to an atomic electron so that it is stripped from the atom, thereby ionizing the atom. Ionized atoms are extremely chemically active and can create reactions in biological cells. As nature has spent several billion years perfecting the cell, whatever chemical random reaction occurs within the cell have a far better chance of being harmful than helpful for the living organism. These disruptions can kill the cell, or, worse yet, can alter it in such a way so that the alteration is passed on when the cell divides into two cells. This propagation of altered cells is called a mutation, which may become responsible for causing cancer.

Although X-rays were discovered in 1895, it was not until the 1920s that it was universally recognized that excessive radiation exposure could be harmful. Prior to that

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[44] Alpha rays are composed of alpha particles which is the nucleus of the helium atom constituted of two protons (positively charged) and two neutrons.

Beta rays are electrons which are negatively charged.

Gamma rays are very energetic photons usually associated with nuclear processes. X-rays are also photons of lesser energy, usually associated with atomic electron processes.

Protons are the positively charged particles which are the building blocks of the atomic nucleus. Neutrons are similar building blocks of the atomic nucleus; however, they are not charged.

Ordinary natural radioactivity produces only alpha, beta, gamma and x-radiation. Protons and neutrons are usually associated non-normal or non-natural processes such as nuclear weapons detonation, reactors, high energy particle accelerators, exploding stars (supernova). Protons and neutrons can arise from cosmic ray interactions, but the atmosphere protects us, at least near the earth's surface. Inside a high flying airplane, the radiation level is higher due to cosmic rays.

time, scientists, physicians and industrial workers often received a massive radiation dose[45] and many developed malignancies and some died due to their cancerous effects even years after the exposure had ceased. In the early days, physicians used to test the x-ray tube by sticking their hands in front of it and observing their own bones. The initial unit of absorbed dose was the skin erythema dose, which was the amount of radiation necessary to cause reddening of the skin.

The dose is a physical measure of the energy absorbed. For human beings, we are more concerned with the biological effects of the ionizing radiation. Alpha rays create more ionization than do beta, x- or gamma rays of the same energy, so they have a greater biological damaging effect. Alpha particles are more massive and travel relatively slowly compared to the speeds of the other radiation particles. The slower speed allows for greater interaction with atomic electrons in the biological medium. To account for the biological effectiveness of the radiation, the unit rem, Roentgen Equivalent Man, is used. REM is a cgs unit. The MKS unit is the Gray equal to 100 rem. Although there are technical differences, for practical purposes, a rem and a rad are equivalent for x-rays.

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[45] Dose is a measure of energy deposited per mass of material. The common unit of dose is the rad, radiation absorbed dose, which is equal to 100 ergs per gram of material. An erg is a unit of energy in the cgs (centimeter-gram-second) system which was common in many scientific fields until about the 1970's. Today, the SI (systeme internationale) or MKS (meter-kilogram-second) system of units is more commonly used. In that system, the unit for dose is Sievert equal to 1 Joule of energy absorbed per kilogram of material. 100 rads = 1 Sievert. A Sievert provides enough energy to raise the temperature of a kilogram of water (2.2 pounds equal to about 2.2 pints) about one quarter of a degree centigrade or 2 degrees Fahrenheit (That's akin to raising the temperature of two pints of beer by leaving it on the table for less time than it takes to consume the beer.) In terms of heat, a rad is pretty small, raising the temperature of a gram of water 0.0023 degree Centigrade. This comparison illustrates that the damage caused by ionizing radiation is not caused by direct energy input, but by atomic and chemical processes induced by ionization.

The environment exposes us to about 180 millirem per year, about half of which comes from natural sources such as cosmic rays[46] and radioactivity from heavy elements such as uranium and thorium in rocks and the other from man-caused sources. Medical diagnostic x-rays expose the average person living in the United States to almost as much as radiation as from natural sources. Other sources such as eating trace radioactive isotopes in foods such as No-Salt, bananas and dates add about 20 millirem. Smaller amounts are attributed to fallout from atmospheric nuclear weapons detonation prior to the Atmospheric Test Ban Treaty signed in the 1960's and to television screens. For the average person, the nuclear power industry's contribution to radiation exposure is miniscule (maybe about 0.003 millirem per year) compared to the radiation exposure due to natural causes.

Under current practice, a person who is not classified as a radiation worker[47] should be exposed to no more than 100 millirem per year of radiation from non-environmental sources, an amount equivalent to that from natural radiation at sea level[48].

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[46] The atmosphere protects us from cosmic rays, most of which come from solar flares. At sea level, cosmic rays exposes us to about 41 millirem, whereas in the mile-high city of Denver, Colorado, cosmic ray exposure is 70 millirem and at 10,000 feet altitude in Leadville, Colorado, the exposure is 160 millerem per year. In a flight across from Washington D.C. to San Francisco, the author measured about 1.5 millirem inside a large commercial jet. This exposure was primarily due to cosmic rays at a flying altitude of 30,000 feet which had penetrated the airplane fuselage.

[47] A radiation worker is classified as a person who is in a radiation protection program and is carefully monitored medically and for exposure to radiation. These persons have an occupational reason, such as reactor operators, physicists working with accelerators, scientist working with radioactive sources, to work in a radiation environment. Radiation workers are limited to 5 rads per year of exposure. (There are provisions where greater exposure is allowed in order to save lives).

[48] The allowable exposure is a strictly regulatory limit. Airplanes flying at 30,000 feet may expose the passenger and crew to radiation levels 30 times that found on the ground since there is not as much atmosphere protecting the flyer as on the ground. This

An additional requirement is that exposure does not exceed 2.5 millirem per hour. These two requirements put limits on both the source strength and the amount of time a person can stay in a non-natural radiation environment. For practical purposes, in the aviation safety community, if the radiation exposure requirements are met for the operator of a x-ray interrogation device, the general passenger population will be well within the exposure limits. Beyond staying within the statutory limits, a general rule of ALARA, As Low As Reasonably Achievable, is observed. ALARA[49] is a practice in prudence with the general philosophy that, the less exposure to radiation, the better.

The radiation level from x-ray machines used for checking hand baggage is less than that from dental x-rays. The radiation exposure is almost non-existent on the outside of the scanner. Part of the reason for the bulkiness of x-ray equipment is to provide enough shielding and distance between the x-ray source and the operator and passengers. Computerized Tomography X-Ray scanners provide perhaps a hundred times more exposure, if the bare x-ray unit were not shielded. The CT machines require many x-ray images to be taken in order to construct a three dimensional image. The exposure due to a CT scanner can be likened to that used for cancer therapy. Looking at a CT x-ray scanner, one notices that it is much bulkier than a hand baggage machine. Much of that bulk can be attributed to the need for shielding to confine the radiation exposure to the baggage being interrogated.

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additional radiation does not fall within the exposure limited by the Nuclear Regulatory Commission since it is from "natural" sources.

[49] You might notice that the next time you get a dental x-ray, the operator places a lead filled apron over your body and then leaves the room. The apron reduces your exposure, but since the dental technician has to give many x-rays, he minimizes his annual exposure by leaving the room each time he performs an x-ray.

Because the x-ray exposure to the target is minimal, manufacturer advisories usually dictate that the very fastest films (ASA 800 and above) may be affected by going through the hand baggage checking x-ray machine. Fast film should be declared separately and not sent through the CT machine.

Because the emphasis is ALARA, developmental work in x-ray machines is to create techniques and detectors which minimize the amount of x-ray needed to obtain a contrast image.

The backscatter x-ray machines are considerably more efficient for detection. This is partly because the primary x-ray beam does not have to penetrate a thick body. Any x-ray that does not go completely through a body into the detector contributes to the dose in a conventional machine. For the backscatter machine, the x-rays are bounced back to the detector and the absorption within the target body need not be as great. An image requires about the same amount of exposure[50] as would be obtained from cosmic rays flying for a few minutes in an airplane at 30,000 to 40,000 feet. Consequently, the backscatter x-ray machine can be used to search people who may try to access restricted areas. Should the backscatter x-ray scanner be required to check baggage, the x-rays would need to get though the baggage walls and the backscattered x-rays would also have to return through the same wall. Backscattered x-rays are best used to interrogate items close to the surface on the side of the x-ray machine. Consequently, when this technique is used for baggage inspection, the machines may have x-ray sources on two sides, or else the bags may have to be turned 180° so both sides may be interrogated.

[50] The exposure is of the order of 10 microrem or less.

VAPOR ANALYSIS

Explosives may sometimes be detected in trace amounts because they may be volatile. Man-made vapor detectors must first collect a sufficiently large sample of molecules; second, remove interfering materials and impurities and then the sample must be concentrated. Finally, the technique must test the remaining material so that a unique signature of the presence of explosive compounds may be detected.

The problem with many explosives is that they have very low vapor pressure[51] so that the first step, the collection of an adequately large sample of molecules presents a formidable challenge.

The volatility of explosive ranges from EGDN, which will be present in a saturated volume of room temperature air at a relatively high concentration of one part in ten thousand[52], to HMX which has a vapor pressure which will present concentrations of the order of two parts in one hundred trillion. A saturated vapor of nitroglycerine will

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[51] Molecules are in constant motion. In a solid or a liquid, molecules can escape and go into the surrounding air. The molecules which are above the solid or liquid exert a pressure. At equilibrium vapor pressure, just as many molecules re-enter the solid or liquid as escape. Vapor pressure refers to the pressure exerted by a vapor when it is in equilibrium with the solid or liquid. The magnitude of the vapor pressure depends on the nature of the solid or liquid and on the temperature. Molecules which have a large mutual attraction have a small tendency to escape into the vapor phase. Such a material has a low vapor pressure. As the temperature of a material is raised, the average kinetic energy (energy of motion) of its molecules increases. The number of higher energy molecules capable of escaping the solid or liquid increases so that the vapor pressure increases.

[52] EGDN is very similar in molecular construction to automobile anti-freeze and like its antifreeze cousin, even a relatively insensitive detection device such as the human nose is able to smell its presence.

contain about one molecule per million molecules of air; ammonium nitrate and TNT[53] will be present in concentrations of about one part in 100 million; and plastic explosives will have even smaller concentrations; PETN and RDX having concentrations of about one part in a trillion. To put this in perspective, one part in a trillion is comparable to a single shot glass of single malt scotch poured into Loch Ness, Scotland.

Whatever vapor detection scheme is used, the concentration of the sample is a critical step towards improving the chances of explosive detection. However, the concentration step may also concentrate other benign molecules and the incidence of false alarms may increase considerably.

Samples to be checked for the presence of explosives may be collected from the air around the target person or luggage or else a "swipe" may be taken over a container to collect any loose contaminants. In manufacturing or packaging explosives, it is very difficult to place the explosive into a case without some trace amount of the explosive being deposited on the container. In most scenarios, the most suspect contamination region would be the area around the luggage lock.

The sample is collected by running the air or the luggage over a surface onto which the sticky explosive molecules attach themselves. The explosive molecules are now concentrated onto a solid surface, which is then heated within a contained volume. In the case of sniffing, the molecules are driven off of the surface and carried away in a stream of smaller volume of gas than the originally sampled air.

[53] Vapor detection may rely upon vapors other than the explosives, but rather upon other molecules which are almost always found in the explosive. For example, it is suspected that dogs trained to sniff explosives may be detecting dinitrotoluene, DNT, a common contaminant in trinotrotoluene, TNT. DNT may be found in concentrations of ne part in a million, whereas TNT may be in concentrations which may be 100 times less.

The process of heating drives off the explosive from the sampling surface and may even break-up the explosive compound and a large fraction of the molecules may be lost in the heating process. This step may increase the concentration of explosive molecules, but the absolute number of molecules will most likely be diminished. The thermal instability of the explosive compounds may cause a degradation of the explosive molecule into smaller fragments that may go unrecognized by some detection equipment.

On the other hand, other detection equipment may rely upon the fragmentation of the explosive molecules. For example, energetic electrons or atoms of inert gas may break up the explosive molecules and the fragments themselves may be analyzed to expose the presence of the explosive. This process is used in two stage vapor detectors such GS/MS, gas chromatography and mass spectrometry.

Although it is quite possible to detect trace amounts of known explosives in a laboratory setting, the real world does not always present a controlled environment. The chemistry and the physics are known, but the engineering to make the equipment operationally useful is a continuing challenge.

Vapor detection schemes have the advantage of being amenable to automation. A portal through which passengers may pass could be the air collection device. The sampled air can be collected, concentrated, sent through a detection device and a fairly distinct electronic signal could alarm the operator as to the presence of explosives. In such a system, human error and lack of training may be minimized since the interpretation of the collected information is automated. Vapor detection does not suffer the public relations issues presented by ionizing radiation devices such as those using x-rays and can be used to interrogate living subjects.

Gas Chromatography

Gas chromatography[54] was introduced to the scientific community by A.T. James and A.J.P Martin in 1952. This instrument separates out mixtures of trace amounts of molecules and by correlating the time it takes from input to output with times for known molecules, identification may be made. The basic operating principle of the gas chromatograph requires the volatilization of a sample in a heated inlet port (injector), separation of the components of the mixture in a specially prepared column and detection of each component by a detector. An important component of gas chromatography is the carrier gas, such as helium or hydrogen, to transfer the sample from the injector, through the column and into the detector. The column separates out the various parts of the sample and the time to pass through the sample to the detector is measured. For gas chromatography, only those substances, which will not break up into smaller molecular parts, are suitable. The temperature at the injector and in the column must be carefully controlled.

Helium is generally the carrier gas, but hydrogen and nitrogen are used in some chemistry applications. However, for explosive detection, hydrogen and nitrogen are not

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[54] A number of separation procedures are based on differences in the degree to which various substances are adsorbed onto the surface of an inert material. (An inert material is one that does not undergo a chemical change.) Separations that use adsorption differences are known as chromatographic procedures. The word chromatography means 'graphing of colors' and arose from its use in separating pigments. For example, a solution containing a mixture of colored pigments may be washed through a column packed with alumina (aluminum oxide, the white "rust" found on exposed aluminum surfaces). The various components will move through the column at different speeds due to differences in the degree to which they are adsorbed and will separate out into different color bands.

In this discussion, the distinction between adsorption and absorption must be made. Adsorption is adherence to a surface and absorption is passage through the interior. Water is absorbed by a sponge.

good carrier gases because these are major components of explosives and the carrier gas should not be mistaken for the constituents of the explosive sample. The pneumatics, meaning the pressure control, must be such that the velocity of the carrier gas is stable and reproducible.

Temperature control is important. Ideally, the programmed injector temperature is held near the boiling point of the suspected explosive, and the column temperature must be kept constant. In addition, temperature control may also be used to cool the sample vapor so that higher concentrations may be achieved.

The gas chromatographic column separates different types of molecules from each other. The hollow column contains a thin layer of a nonvolatile chemical which is either coated onto the walls of the column (capillary columns) or coated onto an inert solid that is then added to the column (packed column). The components of the injected sample are carried through the column by the carrier gas and selectively retarded. The temperature of the oven in which the gas chromatographic resides is gradually increased so that higher boiling and more strongly retained components are successively released. In this set-up, at the lower temperatures, the most volatile molecules, which interact least with the column chemical, pass through first. As the temperature is raised, those that adhere to the column are released and take more time to pass through the column.

The gas chromatograph can be used with a variety of detectors, some of which may themselves be used as discrimination devices. The gas chromatograph has the advantage of being the first stage discriminator in a vapor sampling system and other systems such as chemiluminescence, mass spectrometry, and electron capture detectors may be used in combination.

Flame ionization, thermal conductivity, flame photometric and electron capture detectors are found for general chemistry use. Their application for airline security and explosive detection depends on the ingenuity of the manufacturer. The sample, which has passed through the gas chromatograph, passes through a hydrogen/air flame. Ions[55] and electrons created in the flame cause a current to flow in the gap between two electrodes. This small current can be amplified and measured and is used to indicate the passage of the sample. A variant of this flame ionization detector is the thermionic specific detector in which a small alkali [56] salt bead is placed in the burner jet. Nitrogen and phosphorous compounds react with the salt bead and enhance the current.

The temperature of a hot filament is continuously monitored. The constant flow of the helium carrier gas maintains a constant temperature. However, when a compound of a different thermal conductivity passes over the hot filament, the temperature changes, thereby indicating the passage of the sample.

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[55] An ion is an atom or molecule which has one or more of its electrons removed. Because the electron is negatively charged, the ion is positively charged. Both electrons and ions can act as charge carriers and cause a current to flow between the electrodes.

Ions may also be formed by adding extra electrons to a neutral atom or molecule. In this case the ion is negative. In general, ions are atoms or molecules which are not electrically neutral due to the absence or presence of an electron or electrons from their normal state.

[56] Salts are formed atoms which are held together by the mutual attraction of positive and negative ions. In solution, the charges are retained by the ions. Generally, salts do not form molecules, but in their solid form are crystalline in structure. Alkali metals are highly reactive metallic elements including lithium, sodium, potassium, rubidium, cesium and francium. The most common salt is sodium chloride, common table salt which form crystals of positive sodium ions and negative chlorine ions. Sodium chloride is an example of a alkali salt bead.

In a flame photometric detector the sample is burned in a hydrogen/air flame as in the flame ionization detector, and optical filters are used to observe wavelengths[57] specific to sulfur and phosphorous. In principle, other specific wavelengths could also be detected to detect other elements. The photons of the specific wavelength may be changed into a measurable current with the use of photomultiplier tubes[58].

In the electron capture detector, a radioactive source[59] is used to ionize the carrier gas. Electrons from the ionization migrate to the anode and produce a steady current. If the gas chromatograph releases a compound that captures electrons, the current is reduced because the resulting negative ions move more slowly than electrons. The

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57 When an element is heated, certain specific wavelengths of light characteristic of the element are seen. These wavelengths correspond to the energy emitted as photons when electrons which have been excited from their normal states return. What we mean by color is the wavelength of the electromagnetic radiation (photons). The product of the frequency and wavelength of electromagnetic radiation equals the speed of light, so color is associated uniquely with wavelength and light.

58 When a photon of the right energy range hits the face of a photomultiplier tube (photocathode), an electron is released (photo-electric effect). This electron is accelerated to a plate (dynode) within the photomultiplier tube which is at a different electrical potential from the photocathode. When the electron strikes the dynode, several electrons are released. (usually 5 or more) These electrons are further accelerated to the next stage dynode which is at a higher electrical potential, where upon more electrons are released from the impact of each of the electrons. The photomultiplier tube consists of a series of dynodes and a final anode in which at each stage there is a multiplication of electrons. At the final stage anode, a measureable current is detected. If ten stages are used with a factor of five multiplication of electrons at each stage, the number of electrons are 1, 5,25,125, … ,10^7. The original single photon has resulted in ten million electrons at the anode, resulting in a current that can be measured.

59 The radioactive source is often ^{63}Ni (nickle), which is a beta emitter. Beta particles are electrons which come from within the nucleus. ^{63}Ni is chosen because it has a half-life of 100 years, so does not need changing during the lifetime of the instrument. In the beta decay of 63Ni, the nickel nucleus releases an electron and transforms itself into 63Cu (copper), which is stable.

electron capture detector is very sensitive to materials that capture electrons. Most explosive molecules have this behavior[60].

Gas Chromatography with Chemiluminescence

Hand held units and walk-through detectors are available which collect samples by effectively "vacuuming" the target. In the hand held units, the collection unit sucks air from near a surface which has been heated with infrared lamps. The heating is important since vapor pressure is increased by a factor of ten for every increase of ten degrees centigrade. The sample is then injected into a gas chromatograph, which separates out different molecules by their time of flight through the gas chromatograph columns. With proper calibration, molecules of different types can be identified by the gas chromatograph. At the detector end of the gas chromatograph, molecules, which might be suspected to be explosives, are heated until they are broken up into fragments. Among these fragments is nitric oxide, NO. Nitric oxide[61] reacts with ozone, O_3, and yields photons (ultraviolet light) of a particular wavelength, which can be detected. This

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[60] The ability of an atom to attract electrons to itself in a chemical bond is referred to as electronegativity. Electronegativity are approximate measures of the relative tendencies of elements to attract electrons, but this property varies with the type of chemical environment in which an element is situated. The constituents of most explosives, carbon, nitrogen and oxygen have relatively high electronegativity. A related but not fully identical concept, the electron affinity, refers to the energy change that occurs when an electron is added to a gaseous atom or ion. The electron capture detector exploits the concept of electronegativity and not necessarily of electron affinity.

[61] Nitric oxide (NO) from the automobile internal-combustion engine combines with oxygen in the air to form NO2. Ultraviolet radiation from the sun, which is also responsible for sunburn, breaks up the nitric oxide, NO_2, into NO and atomic oxygen, O. The oxygen atom combines with the normal oxygen molecule, O_2, to form ozone, O_3, which is a very reactive molecule consisting of three oxygen atoms. The ozone reacts with other molecules, including hydrocarbons to form smog.

reaction detects the presence of nitrogen. With the additional information that the original molecule behaved as one in a group that includes explosives, an alarm can be set to expose the presence of explosives. The detection and analysis is not a simple task and a combination of gas chromatograph column lengths and temperature cycles can be optimized so that response to trace amounts of plastic explosives can be given. The same chemical reaction responsible for smog is used in a gas chromatograph with chemiluminescence to detect explosives, albeit with very much smaller quantities.

Mass Spectrometry

One of the most powerful analytical instruments is the mass spectrometer, especially used in conjunction with the gas chromatograph. A complete mass spectrum of the individual atoms can be obtained from a few nanograms[62] of material.

In a mass spectrometer, a gaseous sample is introduced into the instrument and is then bombarded by a stream of high-energy electrons[63]. Collisions between the electrons and the atoms or molecules of the gas produce positive ions. These ions of a given mass

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62 A nanogram is a billionth of a gram. Even a such a small amount of TNT would contain almost three trillion molecules.

63 What may be considered high energy to one person is low energy to another. High and low energy are relative terms. In the mass spectrometer, the electrons have been accelerated over a 70 volt electrical potential difference. The electrons have a speed of about 5000 kilometers per second, which is very fast, but still relatively slow compared to the speed of light, 300,000 kilometers per second. Chemists would call this electron high energy, but a nuclear physicist would consider these low energy. In the context of the mass spectrometer, these electrons are high energy because they have sufficient energy to easily knock out one or more of the electrons in the atom or molecule and create ions.

and a single[64] positive charge are accelerated towards a negatively charged wire grid. The ions pass through the grid and enter between the poles of a magnet. The accelerating grid gives the same energy to all the singly positive ions, but because the masses of different ions are different, the ion speeds are different. The magnetic fields bend moving charged ions. The more massive ions have more momentum and are more difficult to bend. The ions are separated according to their masses because the radius of curvature of the bend depends on the masses of the ions. Lighter ions have smaller radii of curvature and more massive ions have larger radii of curvature. By continuously changing the strength of the magnet, the ions of different masses have the correct radius of curvature to pass into a small detector.

An important component of the mass spectrometer is the vacuum system. The path through which the ions must traverse must be free of other molecules or ions so that the sample ion does not suffer further collision in its path from ionization, through the magnetic field to the detector. Typically, vacuums between10^{-5} to 10^{-8} torr[65] are

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[64] The energies of the bombarding electrons are chosen that the most probable ionization is caused by knocking out one electron from the neutral atom or molecule.

[65] A torr is the pressure necessary to support a column of mercury one millimeter high. Atmospheric pressure will support a column of mercury 760 millimeter or approximately 30 inches high. The torr is a metric unit named after Evangelista Torricelli (608 – 1647) who became Galileo Galilei's assistant just three months before the great man's death. Prior to this time, water was used to measure pressure, but a water column of 10.3 meters or over 30 feet was needed to measure atmospheric pressure. Torricelli came up with the brainstorm to substitute water with the denses material known, mercury, which is 13.6 times that of water.

Galileo (1565 – 1642), who discovered the moon Jupiter had many interests. Besides being the first to understand the falling motion on earth, he formulated the thoughts which made us realize that a suction pump could only pump water up to a certain limit, about 10.3 meters.

required. Vacuums better than 10^{-8} torr are required in the manufacture of semiconductors.

Some mass spectrometers use electrical quadrupoles instead of magnets to separate ions of different masses. An electric quadrupole consists of four cylindrical rods, two positively and two negatively charged. The cylinders of like charge lie opposite of each other. In this configuration, cylinders of opposite charge are placed separated but adjacent to each other. There is a small space through which charged ions can travel between the quadrupole cylinders. The electric quadrupole has the feature that a charged particle traversing in the exact center axis between the two positive and two negative cylinders will not suffer a deflection. If the ion is not exactly on the center, the ion will suffer a defection because the electrical forces from the four charged cylinders do not exactly cancel. The sample ion stream is injected into the charged quadrupole rods. Both a direct current (DC) and an oscillating radiofrequency (RF) signal is applied across the rods, with adjacent rods having opposite charge.

The ion stream entering the quadrupole is forced into a corkscrew motion through the space between the four rods. The combination of the DC and RF field applied to the rods induces deflection of the ion stream from the central axis. At a particular combination of DC and RF fields, only ions of a particular mass follow a path through the axis. Ions of greater and lesser mass follow an unstable decaying path and end up colliding with the walls of the quadrupole pass. The DC/RF field is swept to pass through ions of different masses and a mass spectrum[66] is obtained.

[66] A mass spectrum is a graph of number of ions plotted against the mass. The resolution of mass spectrometers are better than half the mass of a proton or neutron, so separation of molecules according to their molecular weights is possible. In analyzing ions of a single element, there is sufficient resolution to see different masses due to difference in isotope mass.

At the output of the mass spectrometer, whether it is a magnetic or quadrupole analyzer, a detector is present to measure the presence of the ion. Usually the detector consists of a material coated with cathode material so that the ion striking the detector will cause electrons to be released. After that the same series of events as in the photomultiplier tube causes a cascade of electrons and results in a sufficient current to be detectable. The multiplication need not necessarily be that of electrons, but the material could be chosen to produce an ion cascade. The detector multiplication stages need not be physically in stages, but could be a bent tube in which each electron or ion impact directs more electrons or ions to another part of the detector where further multiplication of the signal can progress. Such a device is sometimes called a "channeltron" because the charged particle cascade is "channeled" down to the final stage.

Ion Mobility Spectrometer

Functionally, the ion mobility spectrometer[67], IMS, is similar to the gas chromatograph in that differing molecular species are separated in traversing through the instrument. The difference in time in a gas chromatograph depends upon the adhesion of the molecules to the column coating and the separation is due to molecular and atomic interactions. In the case of the ion mobility spectrometer, the time separation occurs because of speed differences between molecules of different mass.

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[67] Descriptions of ion mobility spectrometers are not commonly found in introductory chemistry texts. The IMS is not a precise analytical chemistry tool, but a rather straightforward simple device that measures the mass of molecules. IMS is akin to weighing the molecule. The molecular mass is determined, but there may be many different molecules with the same mass. IMS is more useful as tool for detecting the presence of molecules which are different from that normally expected in an environment. Discussion of IMS may be found more commonly in process engineering texts.

Air containing vapor or a stream of airborne particles from an area to be tested is drawn into a sampling probe. Air and explosive molecules diffuse through a membrane or a filter into a chamber where a sealed ^{63}Ni radioactive[68] source ionizes the sample. The ionization of the sample is due to the beta particle from the decay of nickle-63. Every twenty milliseconds or so, a small burst of ions is released into a separation region by an electronic gating grid. These ions move under the influence of an electric field down a drift tube against the flow of a separation gas. The speed of the ions is determined by their mass, charge, physical shape and the amount of diffusion[69] in the presence of the separation gas. Heavier, complicated ions, such as explosives, tend to travel more slowly than lighter, simpler ions, such as found in air. The ions reaching the collector can be detected as an electric current signal. The time and the magnitude of the peak caused by the number of ions into the detector are analyzed and a mass separation is achieved.

Much of the work in development of ion mobility spectrometer is related to the detection of environmental pollutants, but the results are easily applicable to the detection of explosives. In the airport security environment, the same IMS technology can also be

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68 ^{63}Ni is a radioactive beta (electron) emitter with a half-life of 100 years. In the transformation of its nucleus from ^{63}Ni to ^{63}Cu, an electron with an energy of 66 kiloelectron volts is emitted. These decay electrons have about 2.5 times the energy typically used to illuminate a television screen. The source is sealed with a very thin metal foil (usually aluminum) in order to prevent radioactive nickle from spilling out into the chamber. Nickle-63 has a long enough half-life so that the source does not have to be constantly replaced.

A half-life is the period of time for half the radioactive nuclei to have decayed into different nuclei, usually called the daughter nucleus. In the case of 63Ni, starting out with a million nuclei, after a hundred years, only half a million of the nuclei would be nickel-63. The remainder would have transformed into the daughter, copper-63.

69 By diffusion is meant the deviation from a straight line path.

used to detect narcotics. The IMS usually does not unequivocally identify the presence of a particular explosive, but usually provides a signature that some unexpected molecule, which may be an explosive, is present. There is little dispute that IMS is capable for explosive detection in the laboratory environment. The challenge in the development of ion mobility spectrometer is its operational sensitivity and utility.

Canines

Operationally, dogs have been used to detect explosives, not only in the airport environment, but also in other environments, such as for the detection of landmines. These dogs must be specifically trained to detect explosives. A canine trained for narcotics detection or for finding people buried in a collapsed building may not necessarily be useful for explosive detection. Dogs require extensive training and need to be bonded and trained by a handler who must respond to explosive detection alarms with the dog. Veterinary care, attention, high protein diet and grooming are all required to maintain the dog's value. In addition, periodic refresher training for both dogs and handlers is required. Like humans, dogs have a limited attention span, and must be given recreation breaks to maintain its efficiency and alertness. The cost of maintaining an explosive detection canine is high because of the need for these requirements in addition for the salary and maintenance of the handler.

Dogs have an extremely sensitive odor detection capability[70]. The olfactory mechanism are probably the least understood of the senses which include hearing, seeing,

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[70] There is suspicion that the trained dog may be detecting the more volatile dinitrotoluene, DNT, rather than trinotrotoluene, TNT. It is practically impossible to create the explosive TNT without having trace amounts of DNT which has a vapor pressure two orders of magnitude greater.

touching and smelling. It is only within the past decade that it was discovered that mammals recognize odors via roughly one thousand receptors in the nasal cavity. When they encounter a molecule, these receptors change shape, prompting the nerve to send a smell signal back to the brain, which produces the sensation of odor. Smell receptors are distributed more or less randomly within the nasal cavity and the information from these receptors is then focused onto elegantly structured "smell maps" within the all-important olfactory bulbs, which are a pair of blueberry-sized structures that serve as the relay center between the nose and the brain.

Each nerve cell in the olfactory epithelium holds only one type of receptor, but there are many thousands of every type of nerve fiber, and thus of every type of receptor, scattered across the epithelium. But when those nerve cells send their signals through connecting tissue, or axons, back to the olfactory bulbs, the axon projecting from the same class of fibers ends up hitting a single node in one of the bulbs. In that way, the relative chaos of the odor-collection mechanism is reduced to a military-like order of information within the bulb. The smell system considers an odor from multiple angles, with one receptor recognizing one chemical signature of the odor molecule – say, a fatty acid chain of a particular length – while another receptor tunes into a slightly different segment of the odor. The brain then synthesizes the disparate bits of information into a coherent label that experience has recorded as, for example, TNT. With a thousand receptors to mix and match, the number of possible combinations for detecting smells is stupendously large. However, the human brain lacks the processing capability to utilize all the possible olfactory signals. The dog, having evolved to make greater use of olfaction for survival, may be able to process smell signals in greater combinations, thus explaining their olfactory sensitivity.

The understanding of the olfactory detection mechanism is in its infancy, but should not be overlooked as possibly leading to a breakthrough technology for explosive detection.

Chemical detection methods exploited to date for use in airline security have emphasized the mechanical detection of explosive signatures. They are still extremely rudimentary in the combination of mechanical detection using several sensors and signal processing. In effect, the olfactory system of living creatures is as powerful as it is because the senses exploit a combination of sensors and data integration.

Electronic Noses

In the past few years, researchers have begun to develop electronic systems that tend to mimic the sensory system. The combination of advances in sensor materials and in powerful computer chips hold forth a promise of non-biological devices, which could potentially detect threats from bacteria in food to explosives in luggage or land mines. The design of a typical electronic nose has two major components: a sensor that detects odors and a set of electronic components that interprets the resulting signals. The sensor incorporates various materials, which could include metal oxides or advanced polymers. When exposed to certain volatile compounds, the sensor material changes some characteristic such as color, size or their resistance to electricity. The full understanding of the mechanism to detect the "smell" is not necessary since the computer analysis of the detected change can be correlated to "pre-learned" signals from known compounds.

The individual components can be very small, with perhaps dozens incorporated onto a single computer chip. They can respond to odors in concentration well below what the human olfactory system can detect. In addition, they can be made sensitive to hazardous mixtures that may even be odorless to people.

Interest in this technology comes from many industries. Laboratories of the U.S. Department of Agriculture are aware that electronic noses can recognize gases produced by bacteria in tainted poultry; the transportation industry sees potential for identifying spoilage of foods in refrigerated trucking; changes in corn, canola and soybean oils could be correlated by electronic noses rather than subjecting human taste testers to the rather unpleasant task of discrimination; and these techniques could, in principle, be able to differentiate between tomatoes picked green or vine-ripened.

Beyond the obvious applications for the food industry, environmental sampling may identify sources of pollution. The ability to "sniff" explosives is being addressed by projects sponsored by the Defense Advanced Projects Research Agency in an effort to detect land mines. Direct detection of explosives may find their way into systems developed for airport security.

Variants of the "electronic nose" include the "electronic tongue". When the sensor is submersed in a liquid, small polystyrene beads coated with one of several fluorescent materials display distinct pattern of colors. Electronic tongues could find operation in quality control of food processing and as quick, in-office, medical diagnostic tests such as blood and urine analysis.

In one particular effort [SN98], a sensor uses a single type of fluorescent-doped polymer that glows brightly after exposure to daylight but dims dramatically when even a single molecule of explosive vapor attaches anywhere along the polymer molecule. Detection of TNT concentration at levels as low as 100 parts per quadrillion are claimed.

This concentration level is equivalent to an eyedropper of chemical dissolved in a volume that could fill 25 Exxon Valdez-size supertankers.

Because the electronic nose relies upon a change in some physical characteristic such as fluorescence, size and electrical resistance, when a particular chemical is encountered, a detailed understanding of the chemistry in not necessary. What is required is pattern recognition, which can be correlated with known explosive samples. With an electronic nose, the more it is used, the more feedback can be given to the system so that it can experientially "learn" from experience.

These systems offer the advantage over canines and humans in that the effects of subjectivity and fatigue can be diminished. However, their application is still in the research stage and readily available off-the-shelf technology has not yet been fully developed.

NUCLEAR CHEMISTRY

Techniques relying on nuclear physics[71] can be used to detect the presence of contraband. However, although the signatures rely on nuclear interactions, what is

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[71] An atom is composed of a very dense positively charged nucleus and negatively charged electrons. In the simplest model, the electrons can be thought to be in planetary like orbits around the nucleus. The positive electrical charge of the nucleus is exactly matched by the negative electrical charge of the electrons, so the atom is electrically neutral. In this model, if the nucleus of the lightest atom, the hydrogen nucleus were to be represented by a basketball, the electron would be in an orbit about 20 miles away. The electron has a mass about one two thousandths that of the hydrogen nucleus.

The nucleus is composed of protons which are positively charged and neutrons which are electrically neutral. For lighter atoms, the number of protons is about the same as the actually being determined is the chemical composition of the object being interrogated. Nuclear-based, explosive detection systems can detect unique and generally unambiguous signatures of contraband via the unique nuclear structure of the isotope.

Nuclear techniques use highly penetrating radiation as probes and induce penetrating radiation signatures. The radiation is generally neutrons and/or gamma rays. Gamma rays are photons and are electromagnetic radiation with the same intrinsic characteristics as x-rays, except with very much greater energy[72]. The gamma ray is more penetrating than the x-ray because of its higher energy. The neutron is generally

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number of neutrons. For example, ordinary oxygen has 6 protons and 6 neutrons in its nucleus. (The lightest atom, hydrogen, is an exception to this general rule and the ordinary hydrogen nucleus has only a proton and no neutron.) For heavier atoms, the number of neutrons exceeds the number of protons. For example, the nucleus of the lead atom has 82 protons and 126 neutrons. The number of electrons in a neutral atoms equals the number of protons. When one or more electrons are stripped off of the atom, there is an excess of positive charge and the partially stripped atom is called a positive ion. When extra electrons attach themselves to a neutral atom, the system is called a negative ion.

When reactions or combinations are made in which the atomic electrons are affected, we generally call this a chemical reaction. Nuclear reactions are those events in which the protons and neutrons inside an atomic nucleus is disturbed.

Nuclei with the same number of protons have the same number of electrons and are the same element. Even though the same number of protons exist in a nucleus, a different number of neutrons may be in the nucleus. These are called isotopes. Isotopes of the same atom behave almost identically in chemical reactions. However, the nuclear physics of isotopes is very different.

[72] The distinction between x-rays and gamma rays is somewhat arbitrary. They are both photons, electromagnetic radiation. One simple convenient distinction could be that x-rays are created in atomic processes by the movement of electrons and gamma rays come from within the nucleus and are the result of movement or rearrangements of protons and neutrons. Another distinction could be that generally, x-rays have energies of the order of thousands of electron volts. Gamma rays have energies in the millions of electron volts. There is an ambiguous overlap in these distinctions.

more penetrating because it does not possess an electrical charge and its interaction with atoms is by direct collision with the atomic nucleus. Charged particles such as protons and electrons can interact with each other at a distance by their electromagnetic interactions. The neutron must rely upon the strong nuclear force, which has a much smaller range of interaction. Since the nucleus is contained in a very small volume of the atom, the chances for the neutron hitting the nucleus are generally very small.

The penetrability of nuclear radiation presents an advantage in making nuclear explosive detection systems amenable to fully automated operation and decision making. The level of interaction has the potential to make the interrogation effectively non-intrusive. With minimal need for human decision intervention, the throughput rate has potential to not adversely affect airport routine. Although these criteria are goals, in practice, the state of technology has not yet achieved their full promise for most systems.

Because nuclear techniques require ionizing radiation, radiation protection is a primary consideration, especially radiation protection of living beings, including the operator and passenger. In addition, there is a potential, in principle, for nuclear activation of the interrogated object. These safety considerations increase the engineering complexity and cost. The discussion of radiation safety issues, presented previously when x-ray systems were considered, applies to nuclear radiation as well. As a general consideration, the shielding requirements for neutrons and gamma rays are much greater than for x-rays.

The generic symbol to denote a nuclear reaction is (x,y), where x denotes the incoming projectile and y denotes the outgoing particle. In this context, particle may refer to a photon, an electromagnetic particle that includes, light, ultraviolet light, x-rays and gamma rays. Generically, gamma rays are designated with the Greek symbol gamma, γ. Other particles which are commonly used are neutrons, n, protons, p, the alpha particle[73], α, or electrons, β, standing for the beta particle. Sometimes y may be two or more symbols, e.g. np, indicating that more than one particle may be detected from the reaction. Examples of reactions used in explosive detection systems are (n,γ), (n,n), (n,x γ), (γ,γ) (γ,n), (γ,p) and (γ,xn). The x may designate other particles including other nuclei or fission fragments. In techniques using nuclear reactions, the construction and control of the probe and the detection of the signature constitute engineering challenges.

The design of an explosive detection system must include not only consideration of the reactions but many other technical issues. Among these are what sources of radiation to use. Radioisotopes and accelerators are two possible sources, and the application may depend on whether pulsed or steady state sources are to be used. The design of the detector is critical. Type, size, efficiency of detection, energy resolution, time resolution, sensitivity to probing radiation and stability all affect performance. Electronics and data acquisition hardware and software choices must be made, considering counting rate and data rate. Miniaturization may affect not only cost, but also feasibility of application. Structural and shielding materials may be affected by prosaic considerations such as the floor loading capacity of the part of the airport terminal in which the system is to be placed. In addition, the hardware and software required for decision analysis, image reconstruction, and the level of human operator intervention need to be considered.

[73] The alpha particle, α, is the nucleus of the helium atom composed of a tightly bound system of to neutrons and two protons.

Neutrons

Neutrons have the advantage of not having a charge, so it may penetrate a fair amount of material before encountering a capture or "collision". They do not interact with atomic electrons in any significant way because there is no charge to charge interaction. Because they are some 2000 times more massive than an electron, they almost do not "feel" the presence of electrons in their path. They suffer capture and "collisions" with atomic nuclei, but since neutrons and nuclei comprise only a very small fraction of the size of the atom, these interactions are relatively rare and the neutron stands a very good chance of probing deep into the inspected material.

The use of neutrons as a probe for explosive detection can be divided into two basic types, slow and fast, depending on the speed of the probing neutrons. Slow neutrons can be captured and fast neutrons can suffer resonant scattering[74].

Thermal Neutron Analysis (TNA)

Thermal neutron analysis (TNA) involves the use of neutrons, which are traveling through the inspected material at a slow enough speed[75] so that it can be captured. A

[74] Resonant scattering occurs at a specific neutron energy where the target nucleus looks apparently much larger than the geometrical size. The probability of an event occurring is expressed in terms of a "cross section". In the macroscopic world, the cross section is the geometrical size overlap of the target and the probe. If the cross section is large, there is a greater probability for the probe and the target interacting than if the cross section is small. In the microscopic world, the concept is extended to mean the probability of the occurrence of an interaction. If the cross section is large, the probability of the something happening is large, and if the cross section is small, the probability is small. The cross section is this context may have very little to do with the geometrical size of either the probe or the target.

[75] The neutrons are "thermal" in that their speed arises from the kinetic motion due to the temperature. At room temperature, the neutron has a speed of approximately 2.6 km/s which is " slow" compared to the speed of light, 300,000 km/s. Sometimes the term "thermal" may refer to the temperature as the neutron comes out of a reactor in which case the speed may be of the order of 5 km/s, which is still "slow".

slow neutron can suffer capture by nitrogen, which is an important constituent of explosives. Specifically, when a neutron is captured by the common nitrogen isotope, ^{14}N, the nitrogen-14 becomes nitrogen-15, ^{15}N. The nucleus of ^{14}N contains 7 protons and 7 neutrons. The nucleus of ^{15}N contains 7 protons and 8 neutrons. The ^{15}N which is formed by neutron capture is not formed in the lowest energy state, but as an excited nuclear state. The nucleus subsequently de-excites, almost immediately, and a very specific energy gamma ray of 10.8 MeV is released in the de-excitation process[76]. This gamma ray signature is very specific and there are no natural processes, which create gamma rays of this particular energy. In fact, only nuclear processes can create gamma rays of such high energy. The (n,γ) capture reaction in nitrogen constitutes a clear signature for the presence of nitrogen. In addition, to this particular reaction, other reactions involving the interaction of thermal neutrons with elements encountered in passenger bags are well known.

An item of luggage is moved through a "bath" of thermal neutrons generated by a radioactive source[77] or an neutron generator (particle accelerator[78]). The capture of a neutron in nitrogen results in a high-energy gamma ray produced by the reaction

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[76] 10.8 MeV is 10.8 million electron volts. A visible light photon has approximately 2 electron volts energy a medical x-ray has order 30 thousand electron volts (30 keV). Consequently, the gamma ray, γ, is many orders of magnitude more energetic.

[77] The radioactive source is usually californium-252, 252Cf, which spontaneously fissions releasing one to several neutrons. The neutrons have may have several million electron volt energy, but they are "thermalized" by passing through a shield containing many protons. [Notice that the symbol of californium is Cf rather than the postal symbol for the state of California, CA. Ca is the chemical symbol for calcium].

[78] The particle accelerator accelerates a proton (the nucleus of the hydrogen atom) to about 100 kiloelectron volts of kinetic energy on to a target containing heavy hydrogen (deuterium, an isotope of hydrogen with a nucleus containing one proton and one neutron). The proton strikes the deuteron and breaks it up into a proton and neutron. [Deuterium refers to the atom and deuteron refers to the nucleus]. The in the breakup,

$$^{14}N + \text{thermal neutron} \rightarrow {}^{15}N^* \rightarrow {}^{15}N + \gamma \text{ (10.8 MeV)}$$

Although in principle, similar reactions could be used to detect signature gamma rays from the capture of hydrogen, chlorine and other constituent elements,, currently thermal neutron analysis systems are designed to detect primarily nitrogen, not carbon nor oxygen. The system has limited spatial resolution. Because all nitrogen equivalently capture the thermal neutron, current TNA systems acting alone tend to have a high false alarm rate. The sensitivity of TNA to lower the quantity of explosives that can be found can be lowered, however, this increased sensitivity is achieved at the expense of increased false alarms.

Present systems contain moderate strength californium sources of approximately 80 millicurie[79], emitting 350 million neutrons per second (in addition to three billion alpha particles per second. The alpha particles do not constitute as significant a shielding problem as do the neutrons.) Neutron sources must be well shielded. The shielding consists of hydrogen rich materials surrounded by heavier elements. The neutron-hydrogen collisions slow down the neutrons, which must subsequently be captured in the shielding material. After capture gamma rays must be attenuated in a denser material such as lead. Consequently, the entire system must be very massive. Current systems weigh close to 14 tons and take up a large amount of real estate.

2.2 million electron volts of energy are released. The neutron from the reaction passes through a shield containing hydrogen and by many collisions, it slows down ("thermalizes"). These thermal (slow) neutrons sent into the inspection luggage.

[79] A Curie is a unit of radioactivity. A Curie (Ci) is 3.8 x 1010 disintegrations per second. The SI or metric system unit for radioactivity is a Becquerel (Bq) equal to one disintegration per second. Consequently, a Ci is 3.8 x 1010 Bq. Historically, a Curie is approximately the radioactivity found in one gram of radiuum.

Fast Neutron Analysis (FNA)

An improvement on thermal neutron analysis may be made by using more energetic neutrons. When neutrons of a significant fraction of the speed of light impinge upon carbon, oxygen and nitrogen nuclei, they are scattered into directions and with energies, which can be readily detected and distinguished. For instance, 14-MeV (million electron volt kinetic energy) neutrons[80] interacting with oxygen, carbon and nitrogen produce 6.1, 4.4 and 5.1 MeV gamma rays respectively. In these reactions, the nucleus scatters the neutron and the nucleus is placed into an excited state. The nucleus de-excites and releases a very specific energy gamma ray, characteristic of the target nucleus. The three specific neutron scattering reactions relevant to fast neutron analysis are:

$$n\ (14\ \mathrm{MeV}) + {}^{16}\mathrm{O} \rightarrow {}^{16}\mathrm{O}^{*} + n\ (7.9\ \mathrm{MeV})$$

$$\Downarrow$$

$${}^{16}\mathrm{O} + \gamma\ \ (6.1\ \mathrm{MeV})$$

$$n\ (14\ \mathrm{MeV}) + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{C}^{*} + n\ (9.6\ \mathrm{MeV})$$

$$\Downarrow$$

$${}^{12}\mathrm{C} + \gamma\ \ (4.4\ \mathrm{MeV})$$

[80] 14 MeV neutrons have speeds approximately 17 % that of the speed of light. The 14 MeV neutrons are produced by the d - t reaction in which deuteron is made to impinge on a target containing tritium. [Deuterium is heavy hydrogen with one proton and one neutron and tritium is radioactive heavy hydrogen with one proton and two neutrons. The nuclei of deuterium and tritium are called the deuteron and triton, respectively.] The reaction for the production of 14 MeV neutrons is d + t (_ + n + 17.6 MeV. The neutron carries away 14 MeV of kinetic energy and the remainder is carried away by the alpha particle. The alpha particle, being charged and more massive, does not travel very much further and captures a couple of electrons to become a helium gas molecule. The alpha particle is the nucleus of the helium atom containing two protons and two neutrons.

$$n\,(14\ \text{MeV}) + {}^{14}N \rightarrow {}^{14}N^{*} + n\,(8.9\ \text{MeV})$$
$$\Downarrow$$
$${}^{14}N + \gamma\ (5.1\ \text{MeV})$$

In the notation above, * indicates that the nucleus is in an excited state and the gamma ray of specific energy is emitted during the de-excitation process. The relatively high energy gamma rays are detected in these reactions.

The engineering differences for source, radiation shielding and the gamma ray detection array are significant between the fast neutron analysis, FNA, and the thermal neutron analysis, TNA. For fast neutron analysis, an accelerator, not a radioactive source must be used. Because the neutrons are significantly more energetic, almost certainly more shielding is required. The detectors could be the same, but in the scattering process, better differentiation of the gamma rays in energy and direction provides better discrimination among various reactions possibilities. Fast neutron analysis could also, in principle, detect hydrogen content as well if the scattered neutron were detected with information as to its energy. Consequently, a better detection system would be more beneficial for fast neutron analysis compared to that for thermal neutron analysis.

The obvious potential for FNA is that it makes an essentially unambiguous determination of the presence of common explosives. However, the FNA presents operational shortcomings because the fast neutrons create a significant background in the gamma-ray detector. The airport environment presents limitations because of the presence of passengers and airport personnel, so the additional needed weight and space for shielding and equipment has yet to be established. FNA however has been proved effective in laboratory use and for applications such as bore-hole-oil-well logging. The technique may also be applicable for the inspection of freight cargo, where personnel access and control can be significantly restricted.

Pulsed Fast Neutron Analysis (FNA)

A variant of the fast neutron analysis method of detection of explosives is the pulsed fast neutron analysis system. Here, the concept is the same as for PFNA, but lower energy neutrons may be used as a probe. The neutrons are sent out of the accelerator in short pulses as well collimated beams. At the lower energies, the overall gamma-ray production by nuclear reactions with explosive constituents such as oxygen, carbon, chlorine and nitrogen are about the same as for 14 MeV neutrons. However, the gamma-ray spectrum is much cleaner and shows a much better signal-to-noise ratio. By moving the neutron beam and / or the object being inspected, a two dimensional spatial map of the source of detected gamma rays from the atoms inside the baggage may be produced. A third dimension, the depth within the container that the reaction occurred, can be obtained from measuring the time between the pulse leaving the accelerator and the time of the arrival of the measured signal. This is possible because the neutrons have low enough speeds that time-of-flight is measurable[81].

The d-d reaction requires a larger accelerator than the d-t reaction because the reaction cross sections (probabilities) are a smaller at the same incident deuteron kinetic

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[81] For example, if the d-d reaction is used as the neutron source, the kinetic energy of the neutron is 2.48 MeV. The reaction for this process is d + d (3He + n + 3.3 MeV. The total energy released is 3.3 MeV with the neutron carrying 2.48 MeV and the 3He carrying 0.82 MeV. 3He is an isotope of helium with two protons and one neutron. The other stable isotope of helium is 4He or the _ particle. The neutron speed is about 20,000 kilometers per second, but with timing resolution of the order of a nanosecond (10-9 seconds), spatial resolution of the order of two centimeters can be achieved.

energy. Pulsed time-of-flight analysis could also be done using 14 MeV neutrons from the d-t reaction. However, they provide a poorer signal-to-noise ratio and require heavier shielding.

Pulsed fast neutron analysis, PFNA, is attractive because it provides unambiguous determination of the elemental composition characteristic of explosives.

OTHER NUCLEAR DETECTION METHODS

Although thermal neutron analysis, fast neutron analysis and pulsed neutron analysis are perhaps the most mature of the detection techniques using methods from nuclear physics, there are other exploratory concepts which have been proposed. The basic physics for these techniques are relatively well understood, however, the engineering to make them into effective operational systems has not been fully pursued.

Associated Nuclear Particle Production

The creation of the fast 14 MeV neutron using the deuterium-tritium reaction also creates a 3 MeV alpha particle. The direction of the neutron and the alpha particle are highly correlated[82]. Because the alpha particle is created within the accelerator system, its direction can be measured without interference from the baggage constituents. Likewise, when the neutron interacts with nuclei of the examined object, gamma rays

[82] The technique of measuring two events simultaneously is called coincidence measurements. The alpha-particle, the timing of the accelerator pulse, the gamma-ray and the neutrons can be detected in a correlated manner with the use of coincidence techniques.

may result. The direction and timing of the alpha particle can uniquely determine the timing and direction of the neutron. The direction and energy of the gamma ray and the time-of-flight information from the neutron can all be integrated to provide a three-dimensional mapping of the carbon, nitrogen and oxygen in the baggage. The correlation of the associated particles is adequate enough to see even small amounts of explosives.

Nuclear Resonance Absorption (NRA) of Gamma Rays

Nitrogen-14, ^{14}N, has a sharply defined excited state which almost immediately after formation decays into carbon-13, ^{13}C and a proton. The nitrogen excited state can be created with a gamma ray of a very specific energy, 9.17 million electron volts. In nuclear resonance absorption, a stream of gamma rays at the very specific energy, 9.17 MeV, is made to impinge upon the luggage to be inspected. On the opposing side, a gamma ray is placed. As long as the luggage does not contain nitrogen, the gamma-ray intensity detected is relatively constant. When nitrogen is introduced between the source of the gamma rays and the detector, the detected intensity falls significantly because the gamma rays can be absorbed preferentially. The absorption is very specific to ^{14}N and 9.17 MeV γ's. The specificity arises because of resonance[83] absorption. The reaction, which is exploited for NRA, is:

$$\gamma\,(9.172\,\text{MeV}) + {}^{14}\text{N} \rightarrow p + {}^{13}\text{C}$$

[83] Physical processes are resonant when a particular condition such as energy, frequency, or speed exactly matches conditions to enhance an effect. In nuclear resonant absorption, NRA, the gamma ray energy must exactly match the excitation energy of the 14N nucleus. By analogy, you may have experienced resonant effects when driving on a tire which is not balanced. At certain speeds, the tire (and consequently, the car) will shake because the rotation frequency and the cause of the imbalanced tire create just the right conditions to enhance the instability.

The gamma rays of this specific energy are created by the inverse reaction with accelerated protons on a target of ^{13}C nuclei. The inverse reaction to create the gamma ray is also created by a resonant condition.

$$p\ (1.748\ \text{MeV kinetic energy}) + {}^{13}C \rightarrow {}^{14}N^{*} \rightarrow {}^{14}N + \gamma\ (9.712\ \text{MeV})$$

The * indicates that the ^{14}N nucleus is first created in an excited state and the de-excitation of the ^{14}N emits a gamma ray of the specific energy.

The nuclear resonant absorption technique has the advantage of requiring a much smaller accelerator than for neutron production and requires much less shielding as gamma rays and protons are much easier to shield than are neutrons. However, at this time, the process is capable of observing the presence of only nitrogen, so false-alarm rates may be exceedingly high. The same objection can be made for thermal neutron analysis, however, TNA can use the ^{252}Cf isotope, which is considerably less expensive than an accelerator. Resonant absorption advantages can be lost if the gamma-ray detector is not energy sensitive. The driving cost for the NRA method may turn out to be efficient energy gamma-ray detectors with sufficient energy resolution.

Nitrogen-13 Production - Positron Emission Tomography

In this technique, a gamma ray beam activates the ^{14}N isotope[84] in explosives to an excited state of a radioactive isotope of nitrogen, ^{13}N. A neutron, which for this application does not play a significant role, is also emitted. The reaction is:

$$\gamma + {}^{14}N \rightarrow {}^{13}N^{*} + n$$

The nitrogen-13 decays with a ten minute half-life and emits a positron[85] (the positively charged antiparticle of an electron.) Each positron immediately annihilates with an electron in that region and two back-to-back 511-keV photons are emitted[86].

511-keV photons are unique signatures of positron annihilation. The simultaneous detection of both of the photons (coincidence measurement) allows for tracing back the path of the two photons and determine the source of the positron. This allows for excellent spatial resolution allowing for the location of the explosive to within better than a centimeter in all three dimensions.

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84 In nature, 99.6 % of the nitrogen is 14N. The remainder is 15N. The radioactive isotopes of nitrogen is 13N with a half-life of 9.9 minutes. They would not be in existence before the irradiation with the gamma-ray.

85 The laws of physics allow for the existence of matter and anti-matter. As we know it, our universe is composed primarily of matter. However, in certain reactions, we can allow for conditions where anti-matter appears. Anti-matter are identical to matter except that all the measurable properties except mass are opposite to that of matter. An electron which has a negative charge has a corresponding anti-electron which we call a positron. A positively charged protons have a corresponding negatively charged anti-proton. In effect the anti-particle is a mirror image of the particle. When you look at yourself in the mirror, the image appears to be you except certain properties have changed. The right-handed you appears left handed.

86 When a particle and anti-particle meet, they annihilate each other. The overall energy and momentum must be the same before and after they meet. In the case of the positron and electron, the most probable outcome are two photons whose energies are each equal to the rest mass energy of one of the positron and electron. They must go away from each other back-to-back since the momentum of each oppose other and the net momentum is zero, just as was the net momentum when the positron and electron came in contact with each other.

Because the radioactive nitrogen isotope has a ten-minute half-life, the irradiation and detection stations can be separated, reducing the background and simplifying considerably the detection system.

The gamma rays are created by a specifically designed radio-frequency linear accelerator (RF-LINAC)[87]. The accelerator first accelerates an electron beam to about 14 MeV energy. The electrons then strike a tantalum or tungsten target and produce gamma radiation with a maximum energy equal that of the electron beam. The gamma rays interact with the explosives and activate the nitrogen.

Pulsed Neutron Backscatter (PNB)

If fast neutrons interact with atomic nuclei in a manner such that the structure of the nucleus is not changed, then the neutrons will scatter in particular directions with its energy reduced by a unique amount depending on the species of the nucleus[88].

Scattering from carbon, oxygen and nitrogen all produce different back-scattering velocities (energies). The intensity of the back-scattered signals provide information on

[87] LINAC is short for linear accelerator. Although they are thought of as nuclear and high-energy physics research tools, they are also found in many medical hospital for cancer treatment. The x-rays used for cancer treatment is generated in a manner very similar to the application here.

[88] Scattering in which the participants of the scattering do not suffer a structural change is called elastic. In the macroscopic world, the collisions of billiard balls are elastic collisions. Should the billiard balls crack, then the collision is inelastic. In the case of billiard balls, when the cue ball is scattered forward it has the minimum energy loss. When the cue ball is scattered exactly backward, the cue ball stops and all its energy is transferred to the struck ball. There is a direct correlation of energy transfer to the scattering angle.

the amount of different elements present, while the ratios between the signals from various elemental nuclei scatterers indicate the chemical composition of the substance. Explosives have specific chemical compositions, which can be detected by detecting the neutrons at specific angles and with specific energies.

Nuclear Quadrupole Resonance Analysis

The atomic nucleus is not necessarily spherical which causes the electric field about it to be unique to that particular shape. The atomic electrons about the nucleus see the effects of the nuclear shape, electric quadrupole moment, and also the effect of the magnetic moment of the nucleus. The orbits of the electrons are perturbed from that which might arise from a simple spherically charged nucleus. These electron orbit perturbations differ from one kind of molecular site to another and can give us a method of chemical identification.

Quadrupole deformation of the nucleus is commonly found in many heavy atoms. Most light nuclei do not manifest this deformation, however, ^{14}N, which is found in most explosives, is an important example of a light atom behaving as if it possessed a non-spherical charge distribution.

These other nuclear detection methods are still in the exploratory stage. Optimization for explosive detection require integration of accelerator and detector technologies. High detection probabilities and low false-alarm rates are issues, which need continual improvement.

MILLIMETER WAVE DETECTION

All objects emit electromagnetic radiation[89] by the mere fact that they are at some finite temperature. The peak emission wavelength[90] depends specifically on the temperature, but the body emits radiation a spectrum[91] containing a continuous distribution of wavelengths. An object radiates[92] more when it is hot than when it is

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[89] Electromagnetic waves is the name given to waves which transfer energy from one place to another and include radar waves, radio and television waves, microwaves, infrared radiation, visible light, ultraviolet light to x-rays and gamma rays. Their behaviors are all governed by a single unified set of four equations called Maxwell's Equations. Prior to James Clerk Maxwell, 1831-1879, for whom the equations are named, electricity and magnetism were thought to be separate phenomena. That a relatively simple set of four equations can describe a variety of phenomena is truly one of the greatest discoveries of physics. ("Relatively simple" is a debatable adjective since the sophomore physics class which usually deals with electricity and magnetism has been the impediment to many budding engineers' and scientists' careers.

[90] The relationship between the temperature and the wavelength, λ_{max} , at which it radiates most strongly is given by Wien's law: , λ_{max} T = 2898 _m•K, where T is the absolute temperature expressed in Kelvin and the wavelength units are micrometers. This relationship tells us that the peak emission wavelength and the temperature are inversely related, so that the higher the temperature, the shorter the electromagnetic radiation's wavelength. The absolute temperature scale , Kelvin, has 0 degrees assigned to the theoretically lowest possible temperature and the same gradation as the centigrade or Celsius scale. Absolute zero in the Celsius scale is - 273 degrees.

[91] The spectrum of a radiator based solely on its temperature is described by the Planck distribution. The deduction of the formula for thermal radiation in 1900 is perhaps seminal works which led to the realization that quantum mechanics was the description necessary to describe objects at atomic scale. Max Planck (1857-1947) is truly one of the greatest "heroes" of modern physics. The relationship between the energy carried by single particle of light (quanta) and its frequency is given by $E = h\nu$, where E is the energy and ν is the frequency. The constant h is called Planck's constant and is now known with exquisite precision. In any equation of physics, the appearance of Planck's constant is a definite indicator that the equation is dealing with quantum mechanics.

[92] The amount of energy at all wavelengths radiated per unit time per surface area of a body at a particular temperature is given by the Stefan-Boltzmann law of radiation. This law tells us that the rate of radiation is proportional to the fourth power of the absolute temperature of the object.

cool. For example, the radiated heat you feel from an oven is mostly in the infrared wavelengths, whereas the hotter electrical element glows in the visible wavelengths of red to orange. At even greater temperatures of a nuclear bomb fireball, the temperatures may reach tens of millions of degrees and the peak radiation is at much, much shorter wavelengths in the x-ray portion of the electromagnetic spectrum.

All objects absorb radiation as well as radiate it. Some things absorb radiation faster than others. It is the color of the object that affects the rate of heat transfers by radiation. Black is most effective. For instance, most of us avoid wearing black clothing in the hot summer sun. Similarly, black asphalt in a parking lot will be hotter than the adjacent gray sidewalk on a sunny summer day, because black absorbs better than gray. The reverse is also true - that is, black radiates better gray. Thus on a clear summer night, the asphalt will be colder than the gray sidewalk, because black radiates the heat away more rapidly. An ideal radiator is the same color as an ideal absorber - jet black. An ideal absorber captures all the radiation that falls on it and radiates energy away depending on its temperature only. In contrast, white is a poor absorber and a poor radiator. A black object absorbs all the radiation falling upon it. In contrast, a white object reflects all radiation, like a perfect mirror. The ability to absorb or radiate electromagnetic radiation can be quantified with a parameter ε, called the emissivity.

For an object, emissivity depends upon the frequency of the radiation. At millimeter wave emissions, the human flesh has an extraordinarily high emissivity compared to the vast majority of other materials. Virtually all clothing is highly transparent to electromagnetic radiation at millimeter wavelengths. These characteristics are exploited in passive millimeter wave imaging.

Millimeter wave passive imaging technology offers the opportunity to detect metallic and non-metallic weapons, plastic explosives, drugs and other contraband concealed under clothing without the need for direct physical contact. Although the peak emission of the human body is at an infrared wavelength of approximately 10 micrometers, direct observation at infrared wavelengths is not practical because of the poor transparency of most clothing. The human body is not a perfect blackbody, but it emits a spectrum akin to the Planck distribution, albeit modified differently at different wavelengths. Looking at the emitted radiation at millimeter wavelengths, several advantages become apparent. The wavelength is sufficiently short as to provide adequate resolution[93] to distinguish features such as concealed weaponry. At these wavelengths, virtually all clothing[94] is transparent. In addition, human flesh has high emissivity at millimeter wavelengths. The combination[95] of these three properties allows for "seeing"

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[93] Resolution refers to the ability to discern details which are close together. When the wavelength of the interrogating radiation, whether it is acoustic or electromagnetic is much smaller than the object being interrogated, the features of the object can be discerned because diffraction effects (the wave self interference effects) are small. If the wavelength is of the same order of magnitude or larger than the object being interrogated, the details of the object may be blurred. In general, in order to see the presence of an object, the interrogating wavelength should be much smaller than the object. Millimeter wavelengths are smaller than the centimeter scale of firearms and explosives, so are useful for detection.

[94] If the clothing were coated with a conductive metal, it would be reflective to most electromagnetic radiation. However, most clothing is made of non-conductive insulating materials which are transparent to millimeter wavelength electromagnetic radiation.

[95] The wavelength chosen depends not only on the desired resolution, but also on the availability of detectors at that wavelength. Proprietary details include the exact nature of the focal plane detector array and the signal-processing algorithm required to present a visual display to the interrogator. Systems have been developed which operate at 94 gigahertz (GHz) frequency. The relationship between wavelength and frequency is that the product of the two is equal to the speed of the wave. Assuming that the electromagnetic wave travels at the speed of light in vacuum (or air), 94 GHz corresponds to 3.2 mm, about one eighth of an inch. This wavelength satisfies the criterion that wavelength be smaller than the object being interrogated.

through clothing to the "naked" body. Weaponry, explosives or other contraband would block the natural millimeter wave emission from the body and they would be seen outlined against the human body.

In practical implementation, passive millimeter wave detection systems can be packaged into a gateway scanner to scan passengers as they enter the waiting area. An advantage of the gateway scanner is that the portal walls surrounding the passenger can be covered with room temperature absorbers so that the imaging camera is provided with an uncluttered background for the image. Hand held scanners can be used in a manner similar to hand held metal detectors so that closer interrogation of a subject can be made for detailed localized searches of suspected areas. Video surveillance cameras can provide "real time" inspection of an area. A disadvantage of the area video surveillance system is that background clutter may be greater than from a confined and controlled area.

The millimeter detection method need not be passive. Active millimeter electromagnetic wave interrogation systems can be created in a manner similar to the use of radars. In this application, the different reflectivity properties of different objects are exploited and the determination of location, posture and activity of people in a room can be interrogated. These systems are sometimes called Through-the-Wall Imaging Systems (TWIS) and have potential for applications in hostage, terrorist, and drug bust situations. Here the wavelengths might be increased and the frequency decreased because detailed resolution is not as critical. In general longer wavelength electromagnetic radiation has greater transmission properties through most walls. An exception to this statement is pertains to ordinary kitchen microwave frequencies, which are designed to be absorbed by water vapors. Because concrete contains water, 2.3 GHz microwave frequencies are best avoided. 1.5 GHz microwaves with 10 cm wavelength have been exploited in prototype systems.

DETECTORS AND TECHNOLOGY, DISCUSSION

The detectors and technologies discussed in this chapter have ranged into a myriad of topics, which at times do not appear to have a coherent theme. This is because the detection of explosives is not a straightforward endeavor. We have attempted not only to simply catalogue the various methods, but to also provide supporting commentary, especially in the footnotes, so that the basic ideas can be understood.

Metal detectors, x-ray detectors and millimeter wave detection might have been grouped together in a single heading of sub-surface detection technologies. Vapor analysis including dogs and neutron techniques could have been grouped together under the heading of chemical detection. However, the differences and commonalties among the groupings could easily have been made in other ways. The critical goal in all of these techniques is the requirement to find an anomaly from objects, which are found in normal airport baggage, and to detect a method of identification.

Beyond the detection and identification requirements, the detection systems must also be aware of passenger concerns. Not only throughput and passenger inconvenience, but concerns such as radiation safety and privacy issues need to be considered. Again, we emphasize that all aspects of explosive detection systems need to be considered before implementation into the aviation industry.

The listing of detectors and technologies is by no means exhaustive. We have not discussed methods, which may use biological techniques such as immunoassay. There is credible work being done in using trained swarms of bees to detect explosives and contraband. Certain microbes fluoresce after encounter with certain explosive molecules such as TNT. Whether such a method is sufficiently "user friendly" in the airport scenario remains to be seen, but one needs to keep a receptive mind towards ideas which may at first glance appear nonsensical. The use of dogs and mechanical smelling techniques would have not too long ago appeared impractical in many circles. Today, they are approaching feasibility for routine use. Other methods and ideas will appear and the difficult task of the decision-maker is to determine the weighting of resources to apply towards their development and application.

Chapter 6.

Supporting Technologies

SUPPORTING TECHNOLOGIES

In addition to the direct investigation of luggage, there are other means which can enhance aviation safety and limit opportunities for introduction of firearms and explosives onto aircraft. This chapter briefly mentions these other topics in order to emphasize that the problem of aviation security requires a system solution, which considers all available means. Some of these topics are administrative and procedural; others can evoke quite sensitive public response[96] unless conducted with extreme awareness of privacy and civil liberty issues.

PASSENGER PROFILING

Some people believe that airlines should "profile" passengers and subject only those who "fit the profile" of terrorists to heightened security measures. In general, there are two types of profiling: by interviewing and by automated computer evaluation. Different profiles would be employed, depending on whether a flight was domestic or international. The specific criteria are kept secret, but among many it is thought that these criteria are not so closely held. Currently, passengers are asked a series of questions such as whether they packed their own bags and whether they have maintained

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[96] For example, a fairly comprehensive discussion of issues is contained in the 14 January 1997 statement of the Legislative Counsel of the American Civil Liberties Union, Washington D.C. on "Civil Liberties Implications of Aviation Security Passenger Profiling before the International Conference on Aviation Safety and Security in the 21st Century." At the heart of the matter is the prohibition against unreasonable search and seizure as provided by the Fourth Amendment of the United States Constitution. Amendment IV: "The right of the people to be secure in their persons, houses, papers, and effects, against unreasonable searches and seizures, shall not be violated, and no warrants shall issue, but upon probable cause, supported by oath or affirmation, and particularly describing the place to be searched, and the persons or things to be seized."

it within their view since it was packed. They are asked to identify themselves with official documentation such as a driver's license or passport. The responses elicited, the nervousness of the passenger, as well as secret criteria which might include ethnic origin, appearance, etc., can trigger varying degrees of heightened security interrogation.

Profiling has been presented as an attempt to eliminate from further scrutiny, passengers who do not present a risk. Opponents of profiling have claimed there are other effects such as stereotyping and discrimination of certain categories of persons with unacceptable consequences. Even being selected for further interrogation subjects the "selectee" to stigmatization by fellow passengers.

Arguments against passenger profiling claim that profiling can never be effective because the incidence of aviation terrorism is so rare that the statistics of small numbers dominate. Profiling looks for the last event and historical evidence is that consistent patterns do not emerge. "Profiles tend to turn up the same "usual suspects" time and time again. Their characteristics that triggered the heightened security measures often do not change. The usual suspects, though, aren't guilty. Rounding up the usual suspects may have been "O.K." in the movie Casablanca, but should not be "O.K." in America."

PRIVACY ISSUES

"X-ray vision" raises questions of privacy. In principle, both backscatter x-ray and millimeter wave detection systems have the ability to "see through" clothing, and with sufficient data processing, to reveal anatomical details of a person. Because of this possibility, operational system.s may have to be degraded from its ultimate capability. Male and female interrogation may need to be conducted separately. Their use may have to be curtailed to those instances where competent authority has a "reasonable suspicion" to justify more detailed interrogation. Concerns about the definition of illegal search and seizure and unreasonable intrusion of privacy are issues which need to considered before the introduction of such interrogation devices. If systems are employed which are passive and do not require the person being interrogated to know that they are the subject of interrogation, civil liberty concerns need to be addressed with care.

PASSENGER BAGGAGE MATCHING

It is assumed that terrorists, in general, are not on suicide missions. The likelihood of explosives carried in checked baggage is considerably diminished if the owner of the bags is onboard the same airplane. Positive passenger baggage matching programs have been instituted to achieve that goal. The first step in this process is the questioning at the check-in counter where a photo identification card is requested and the passenger is asked if the packing were done by them and if the bags have been in their possession continuously. The task is not easy even if only international travel is checked. Domestic positive passenger baggage matching is a non-trivial task since 100 per cent matching would involve billions of bags on more than 12 million domestic flights each year.

In order to have a manageable system the White House Commission on Aviation Safety and Security recommended a layered interrogation approach requiring increased scrutiny be adopted. Such a system would be initiated with passenger profiling. Safeguards need to exist so that profile should not contain or be based upon material of constitutionally suspect nature, e.g. race, religion, national origin of U.S. citizens.

Again, the challenges encountered include minimizing passenger delays and being sensitive to stereotyping.

Technology needs to be incorporated in order to make this a workable reality. Currently, bar codes are assigned to each baggage tag to match ticket stubs. The difficulty arises in insuring that the passenger who owns each bag being loaded boards the flight. Enhancements may include capabilities to incorporate positive photo identification directly with the bags. Other challenges occur during stopovers.

Currently, the matching of passengers to luggage is "administrative" (not actual) because some of the airline reservation systems are not compatible with the luggage sorting and loading system and information is not collected or verified at the aircraft on the flight ramp. These system compatibility problems become more complex when one considers interline transfer bags and compatibility between different airline systems.

Curbside and passenger counter check-in and luggage sorting areas can be viewed as fixed elements in the passenger baggage matching system. However, when baggage is being transferred from one airplane to another, a mobile positive passenger match system may be required. Among technologies, which might be applicable for this situation, are radio frequency (RF) linked readers and transmitters of barcode information. Sufficient information must be made available in order to allow identification of the bags with the passenger manifest, which must be checked against the boarding passes.

INTEGRATION OF BAGGAGE INSPECTION SYSTEMS

The assignment of an acceptable minimum level of security may not address the true capability of a system to detect explosives, because the assignment of the figure of merit must be conducted a somewhat artificial scenario. In effect, the normal state is that there are no explosives and, consequently, both ineffective and effective systems would both satisfy the requirement of preventing introduction of explosives onto a plane. In the event of a real attempt to introduce a hazard onto a plane, the success and failure of the explosive detection system depends on many factors. They include the type of hazard, the training of personnel, the mechanical capabilities of the device, the time allotted for interrogation, luck, etc., etc. The difficult task faced by decision makers is what requirements, procedures, and equipment should be allocated to insure a cost-effective safety capability. In this context, cost must also include passenger inconvenience. Procedures may include decisions as to what percentage of luggage require scrutiny at different levels.

The automatic explosive detection systems being introduced have different throughput capabilities. Because detectors have different capabilities, a protocol must be established to have a layering of systems so that time intensive interrogation is reserved for those which have already failed (or passed, depending on one's perspective) another detector's criterion. For example, computerized tomography x-ray scanners should not be taken for every bag that enters the system since they require a considerable amount of time. Operationally, decisions may be based upon airport structure, physical space, baggage flow, passenger flow, environment, capital cost and operational costs. Because the requirement is for the whole system to be optimized, technology decisions may be required for the choice of conveyers, carts, diverters, and adjustment capabilities to accommodate different peak load requirements. These decisions may also influence decisions as to whether centralized or decentralized systems should be incorporated.

BLAST RESISTANT LUGGAGE CONTAINERS

The inherent goal of any aircraft is to maximize the number of passengers and their baggage to be carried to a particular destination. In general, any weight carried to enhance aircraft functions is weight which diminishes the load capacity. Consequently, the general aircraft design philosophy has been to minimize aircraft weight. This has resulted in aircraft being very vulnerable to internal blasts, since internal explosions have not been a normal concern. Some studies indicate that it would not have taken an extraordinary amount of material to mitigate the explosion which brought down Pan Am 103 in 1988. Blast resistant luggage containers are being designed to harden aircraft against internal explosions. In order for blast resistant luggage containers to be acceptable to the aviation community, they must have reasonable tare weight and unit cost, have high durability, easy maintainability and minimum impact on airline operations.

New materials are being developed for such purposes as airframes and bullet proof vests, which may be of utility for luggage container manufacture. Material considerations are not the only concerns. Designed compartmentalization of luggage space may be a factor in mitigation of blast effects. Technical decisions are driven by the administrative decision as to how large an explosion that the container must withstand. The development of blast resistant luggage containers will require system optimization. A totally blast resistant container may weigh too much and container no space. The presently used containers weigh very little, but provide very little protection from internal blasts.

SUMMARY

SUMMARY

We no longer live in a world in which our only concern when boarding an airplane is whether the flight schedule is maintained. The traveling public should not suffer inordinately from anxiety concerning the possibility of terrorist acts. However, the air travel system must provide the environment so that the possibility of terrorism on board aircraft is minimized. But the accomplishment of this goal requires the recognition that security and transport of passengers to their destinations may sometimes be competing concerns.

This book hopefully has provided an introduction to the subject of explosive detection in aviation security, so that the educated non-specialist can appreciate the many topics which impinge upon a wise decision-making. A historical introduction gives us an appreciation for the need to implement explosive detection systems. In order to understand what the detector is supposed to detect, some appreciation for explosives in general and their effects has been provided. The bulk of the document deals with different detectors and their underlying science and technology. The final chapter emphasizes the need for recognition that it is the total system, not simply a component of the system which much work in order to insure the general public a safe and comfortable trip.

The author hopes that his document is of interest to many levels of aduiences. Hopefully, it can be used as a starting point to allow a few individuals to perform their jobs duties better.

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