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Reactive not Proactive: Explosive Identification Taggant History and Introduction of the Nuclear Barcode Taggant Model

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Abstract: Regulations governing explosives have often included requirements to provide information about the manufacturer, type, and batch of a commercially produced explosive. The first method of encoding information about an explosive was simply writing desired information on the explosive's packaging. Marking explosives in this way can be considered the first identification taggant. Identification taggants that encode information have evolved over the course of over 100 years in the United States. Identification taggants are particularly useful as they allow explosives to be tracked back to the manufacturer and purchaser. Correlations can be seen in the evolutional advances in identification taggants and events (wars and terrorist activities) that lead to regulations governing explosives. The information presented in this paper walks through the evolution of identification taggants, since 1917, and identifies the corresponding event that led to increased regulations governing explosives. The paper illustrates that the efforts in identification taggants have been primarily reactionary and highlights the need for a more proactive approach in taggant research and implementation. Understanding the previously developed identification taggants has led to successive generations of taggant candidates, including a modern candidate known as the Nuclear Barcode. The nuclear barcode focuses on allowing identification taggant to survive the detonation process intact, prevent counterfeiting or obscuration, enhance forensic detection of explosives, as well as providing a sufficiently large number of potential codes to enable labeling individual batches of product. The nuclear barcode is designed to accomplish these goals inexpensively while also not affecting the properties or sensitivity of the tagged explosive.

Keywords: Identification Taggant · Detection · Neutron Activation Analysis

1 Introduction

Commercial explosives are a valuable resource used in industries such as mining and construction. Throughout history, terrorist attacks and accidents have demonstrated the potential for misuse of commercial explosive materials to cause harm to both people and property [1]. Balancing the economic value of explosives while minimizing the destructive risks has been a topic of both scientific interest and government policy for over one hundred years in the United States [1,2]. This paper discusses specific developments in both of these topics that occurred within the United States. However, these are not exclusive to the United States, and parallel developments have occurred in other countries as well; the United States is used as a representative example.

Regulations exist to reduce the misuse of explosives by addressing aspects such as the use, transport, and storage of these materials. These regulations have been historically enacted in response to emergent circumstances such as war, increased concerns over terrorism, new technology, and new uses for explosives. This reactive approach means that there are inevitable loopholes that can be found by a motivated party that will only be closed after an unfortunate event. Regulations governing explosives have often included requirements to provide information about the manufacturer, type, and batch of a commercially produced explosive. Taggants are one technology that has been developed to identify explosives.

There are two categories of taggants used with explosives: detection taggants and identification taggants. Detection taggants are designed to make explosives easier to detect and enable a sensor to produce a signal when explosives are present. One implementation of detection taggants is adding volatile chemicals to certain types of plasticized explosives. Unlike untagged explosives, bomb-sniffing dogs (for example) can detect these volatile chemicals by smell [1]. Additional technologies designed to detect either these volatile chemicals or other components of the explosive itself are used in the equipment present at airports or government buildings. Detection taggants and their attendant technologies will not be further discussed in this

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paper. A review of the subject is available in other works [3]. Identification taggants provide information about the explosive when they are recovered. The key distinction between detection taggants and identification taggants is that identification taggants cannot be used until the explosive has been located. Once the explosive has been found, detonated or undetonated, the identification taggant can be read, and the information about the explosive can be retrieved such as the manufacturer of the explosive, the type of the explosive, a batch or lot number.

Identification taggants are used in fields such as pharmaceuticals and automotive manufacturing to provide information about materials [4,5]. One example use is to prove the source or manufacturer of a product to safeguard against counterfeits [5], or for tracing materials that are then used to produce unlicensed copies or illegal goods [5].

The technology used to create and encode identification taggants has changed over time, and many different approaches have been developed such as: small particles, biological sensors, radionuclides, and combinations of chemical compounds. Additionally, simply writing identifying information on a casing around an explosive can be considered an identification taggant. Tagging explosives in some way that provides information about the explosive has been pursued for more than 100 years [6]. This paper will show the progression of taggant technology and how it relates to specific events. Taggant technologies have progressed over the course of the 100 years of development and have identified key characteristics of a successful taggant. These key characteristics have encouraged us, the authors, to propose the creation of a new identification taggant, the Nuclear Barcode that is proposed to satisfy the key characteristics of a successful identification taggant better than previously developed taggants.

2 Historic Events and their Relation to Taggant Development

To have a clear understanding and a proactive look at the development of new identification taggants, it is important to know the history that has shaped explosives regulations and requirements for manufacturers over time. A timeline of events and laws passed within the United States that surround identification taggants for explosives is shown in Figure 1.

From the events and laws shown in Figure 1, there have been four eras of identification taggant development: the early explosives regulations era, the initial taggants era, the updated taggants era, and the modern taggants era. To this final era, we add the recently developed Nuclear Barcode.

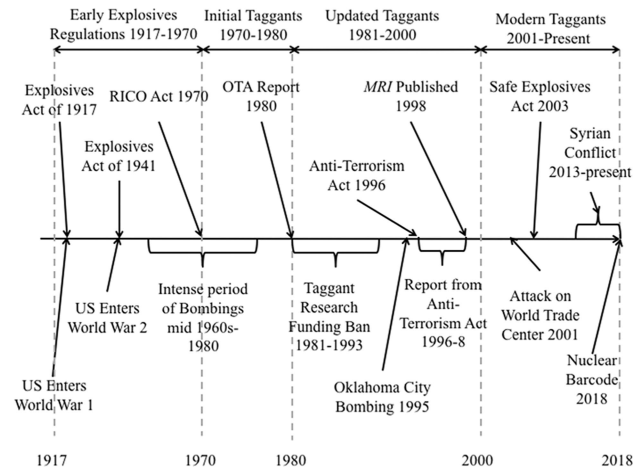

Figure 1. History of Identification Taggants Timeline in the US.

2.1 Early Explosives Regulations (1917–1970)

The Explosives Act of 1917 standardized requirements for licensing, manufacturing, storing, and distributing explosives and explosive ingredients in the United States upon the nation's entry into World War 1. One of the main concerns was over the availability of explosives for acts of sabotage or "bomb outrages"; acts that would be called terrorism today. This measure was intended to be a temporary one, applying only during the war, and its provisions expired in 1919 [6]. An almost identical law, the Federal Explosives Act, was passed upon the United States' entry into World War 2 in 1941, with updated language and an updated list of explosive ingredients. This law, like the 1917 version, also was explicitly a wartime measure and expired at the end of World War 2. The passage of the Organized Crime Control Act of 1970 introduced permanent federal regulations for explosives, in Title IX, for the first time.

2.1.1 Explosives Act of 1917

Due to exceptional circumstances, a uniform set of rules and regulations surrounding explosives was deemed necessary upon the entry of the United States into World War 1 [6,7]. The Explosives Act of 1917 was the first federal law passed regulating explosives. Prior to the passage of this act, explosives regulations were left to the states and municipalities. Some states and cities had significant regulations on explosives that were used as a template for the regulations coming from this act. Other states had no regulations on explosives, and these new regulations were the first to apply in these localities [6].

To reduce the possibility of misuse, the Explosives Act of 1917 required users and manufacturers of explosives to obtain a license. This license could only be issued by a designated authority and would include information about the licensee and required certification that the licensee was a loyal citizen of the United States [6]. Strictly following the wording of the Explosives Act of 1917 would require purchasers of approximately 1,500 materials, including goods such as cotton or starch, to hold an explosives license [6]. As this would be impractical, the list of materials that would require licensure was reduced to oxidizers commonly used in explosives such as ammonium nitrate, as well as commercially produced explosives like nitroglycerin [6]. Additionally, sellers of explosives were required to verify that purchasers had the proper license and issue receipts that contained a description of the intended use for the explosives [6].

The increased burden on law-abiding citizens placed by the Explosives Act of 1917 was justified due to the extraordinary circumstances of World War 1 [6,7]. With the war's end, the law expired, and its provisions were no longer enforced. The Explosives Act of 1917 was credited with significant reductions in the availability of explosives for crimes or terrorism, as well as, injuries and damage from unintentional detonations caused by improper storage [6]. Due to the efficacy of this program, permanently implementing this act was discussed to resolve issues stemming from anarchists and other movements that were engaging in domestic terrorism [6]. Ultimately, no provision was made to adopt the Explosives Act of 1917 as a permanent law.

2.1.2 Federal Explosives Act (1941)

With the entry of the United States in World War 2, the same concerns arose surrounding the use of explosives that were present before the passage of the Explosives Act of 1917. Despite the lack of an official declaration of war, the provisions of the Explosives Act of 1917 were revived sometime between the beginning of World War Two and the end of 1940 [8]. After declaring war, the Federal Explosives Act was passed on December 26, 1941 [9]. This act amended and renamed the Explosives Act of 1917 [9]. The amendments were small details such as changing the list of explosives ingredients, not significantly altering the original 1917 act [9]. Notably, at the end of the war and thus the expiration of the act, the regulations stayed in place with the Federal Explosives Act. Additionally, the new Federal Explosives Act also implemented similar regulations to the ones drafted for the 1917 act, with expanded sections on storage and transport [9]. Overall, the changes to the Explosives Act of 1917 by the Federal Explosives Act were not substantial. The primary purpose was the same with both acts: prevent the use of explosives during wartime by those intending on using them against the United States' government.

2.1.3 Organized Crime Control Act (1970)

By 1970, there had been sufficient change in society to require a more extensive set of federal explosives regulations outside of a formally declared state of war. The requirement of marking explosives with a manufacturer, type of explosive, and a date or batch code shows the change in societal opinion of the necessity of explosives regulations. Domestic bombings by groups such as the bombing of the State Department Building in Washington, DC by Weather Underground in 1975, as well as other bombings throughout the 1960s and 1970s presented new challenges for investigators [10]. In the period between 1917 and 1970, federal explosives regulations evolved from an emergency proposal implemented due to the World Wars to a fully-fledged regulatory regime recognizable today in the modern Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF). This new regulatory regime stands in contrast to the ones created under the original Explosives Act passed in 1917, and the refreshed 1941 version. These two acts created regulations specifically applicable only during wartime that: "The operation of this law will doubtless cause inconvenience to persons engaged in legitimate business; it may embarrass worthy citizens in the pursuit of their livelihood…" [7].

With the passage of the Organized Crime Control Act in 1970, federal explosives law continued to evolve. Title IX of the act permanently enacted updated requirements in the same style as the earlier Explosives Act of 1917 and the Federal Explosives Act of 1941. The Organized Crime Control Act affected regulations of every aspect of explosives, though with less effect on transportation. It also implemented, for the first time, federal explosives regulations while the country was not at war [11]. Many of these regulations have been updated in the years since the passage of the Organized Crime Control Act, but they originate from this law [11]. Additionally, the act also gave the ATF regulatory responsibility for all explosives, where it remains today [11].

The Organized Crime Control Act required that all explosives manufactured after February 12, 1971, were to bear a label with the manufacturer, type of explosive, and a date or batch code [11]. These markings were required to be on the wrappings immediately around the explosives such as a cartridge or bag and serve as an identification taggant [11]. Requiring a manufacturer label on the packaging of the explosive enables undetonated explosives to be identified and tracked with every sale. Table 1 summarizes the different events and reactions prompted between 1917 and 1970.

2.2 Initial Taggants (1971–1980)

Manufacturer information included on the wrappings, labels or receipts can be lost by simply removing this labeling, or

Table 1. Summary of Events and Reactions between 1917 and 1970.

Event	Reaction
US involvement in World War 1	Passage of Explosives Act of 1917 – First federal regulation governing explosives
US involvement in World War 2	Passage of Federal Explosives Act of 1941
Increased Domestic Bombings	Passage of Organized Crime Control Act in 1970 Initial taggant research efforts begin

by detonation, which will destroy any wrappings around the explosive. This deficiency was recognized almost immediately by the ATF and others in government who began investigating better methods in 1972 [12]. In 1974, the Advisory Committee on Explosives Tagging, consisting of eleven government agencies and three external groups, was formed to investigate methods of implementing identification taggants. A study began in 1976 on the most promising candidates run by Aerospace Corporation [12].

In 1978, the Senate Judiciary Committee began hearings on a bill, 'Senate bill #2013', that would require the use of identification taggants and detection taggants in explosives manufactured for use in the United States [12]. Approximately a year later in 1979, the Senate Committee on Government Affairs was considering a separate bill, 'Senate bill #333' that would impose the same tagging requirements as part of a larger anti-terrorism bill [2]. The first bill, under consideration by the Judiciary Committee, held hearings for approximately a year and a half that included testimony from many sources, including the ATF and the company running the taggant study that had began in 1976 [12]. The Congressional Office of Technology Assessment (OTA) was enlisted to provide a report, entitled *Taggants in Explosives* to the Committee on Government Affairs, and also used the information gleaned from the same taggant study [2].

The research conducted for the ATF by Aerospace Corporation and reported on in *Taggants in Explosives* was the first large-scale test program developed for identification taggants in the United States [2,12]. As such, an important objective was first to define the evaluation criteria for a successful identification taggant. Five taggant evaluation areas were decided upon as the most important areas to determine if a particular taggant method would be effective:

1 *Taggant recoverability* – the ability of the taggant to be collected in the field despite the debris and other material present in a post-blast environment.
2 *Survivability of the taggant* – the ability to read the information encoded from the recovered taggant even after being in the explosion.
3 *Utility* – the amount of information the taggant could provide for investigators once the taggant was recovered and the information read.
4 *Compatibility of the taggant with explosives* – any change to the properties of the explosive such as its sensitivity, the amount of energy released, stability in storage, or other properties because of the introduction of an identification taggant.
5 *Cost of a taggant program* – the cost of the taggant itself, and additional costs to manufacturers, sellers, and regulators for tracking the new taggants, and any other costs a taggant program might impose [2].

Three categories of explosives taggants had been developed by the writing of *Taggants in Explosives* in 1980 and could be evaluated using these criteria: radiological, chemical, and physical taggants [2].

Radiological taggants were the first category of identification taggant under consideration. One or more radioactive isotopes are added to the explosive to serve as an identifier. Detection of radioactive materials has been well developed, thus allowing radiological taggants to be recovered rapidly [2]. Since radiological taggants depend on the presence of particular isotopes, they are unchanged during the process of detonation. Recovering and reading taggants based on them does, however, require specialized lab equipment and procedures unlikely to be available for police work [2]. Radiological taggants provide two advantages. First, there are a large number of available radioactive isotopes that can potentially be used, which provides the potential for many unique identifiers or including more information [2]. Additionally, radiological taggants emit radiation, which enables them to serve as detection taggants as well as identification taggants. While this behavior makes detecting radiological taggants easy, it also poses a potential health hazard by exposing people who work with explosives, such as blasters and manufacturers, to radiation. This might also cause additional regulatory costs to manufacturers since workers exposed to radiation as part of their job fall under additional regulations [2]. There are also potential issues of public backlash with anything that potentially could expose the public to radiation [2].

Chemical taggants were the second category. One chemical taggant was discussed, but not tested, in *Taggants in Explosives* that was based on combinations of different concentrations of ethanol solutions of rare earth salts [2]. This taggant could then be recovered from the post-blast residue. This proposed chemical taggant system relied on identifying the rare earth elements and their concentrations, which would survive detonation. Other proposed chemical taggants might not survive detonation due to the high-temperature environment created during the detonation process. This chemical taggant provided a sufficient number of unique combinations of rare earth elements and concentrations that would provide many potential codes [2]. The reason this taggant was not tested was that the ethanol solutions could cause sensitization of the explosives, which would make handling unsafe. Unlike radiological taggants, there was no handheld, portable technology developed to detect the presence of a chemical taggant rapidly; so complex laboratory analysis would be needed [2]. The identification procedure and equipment for reading the identification taggant are complicated and require specialized equipment, which increases the cost of reading the taggant, and would not be available for forensics work in 1980 [2].

Physical taggants were the third category discussed, and the only category to undergo significant testing as part of the research conducted by Aerospace Corporation. Initially, two physical taggants were to be tested, one developed by 3M Corporation that was composed of small particles made from stacked colored layers of plastic, and one developed by Westinghouse composed of small ceramic particles doped with fluorescent rare earth compounds. These particles were small and designed to be introduced in relatively large numbers such that removing each of the individual particles would not be humanly possible. Due to concerns over liability, the Westinghouse taggant was not tested during this research program [2]. The physical taggant developed by 3M can be both recovered and read with simple equipment in the field on a theoretical basis, but it was determined that performing both of these tasks in a labroatory environment would be necessary in practice. In order to read the code, the taggant particles must be separated from the debris present at the blast site; these separation procedures were, however, determined to be simple, and can be performed with a small amount of training [2]. Testing of the 3M taggant showed that a number of particles would survive and be readable using a microscope [2]. The sequence of colors in the taggant particle encodes information, and a ten-layer particle with ten different colors produces a large number of codes. Theoretically, only one particle would need to be recovered, but increased accuracy could be obtained when additional particles were found [2]. The 3M taggant was tested with a range of different commercial explosive products and found to be compatible with all but one booster material, and one variety of smokeless powder [2]. The cost of tagging an explosive with 0.05 % by weight using the 3M taggant was calculated as being a 2.3 % to 23.5 % increase depending on the type of explosive being considered, with the largest percentage increase coming from detonating cord which had the lowest cost basis [2].

The testing performed by Aerospace Corporation and the cost analysis performed in *Taggants in Explosives* show that the 3M physical taggant was a viable identification taggant, assuming the few material incompatibilities could be resolved [2]. This made the 3M taggant a very promising candidate. In 1978, two bills were under consideration in the United States Senate, though ultimately, neither Senate bill #2013 nor Senate bill #333 became law. Senate bill #2013, under consideration by the Senate Judiciary Committee, raised concerns by the committee members about whether the proposal included black and smokeless powders used in ammunition [12]. If these two materials were covered, additional concerns over the compatibility and cost were raised [12]. This uncertainty appears to have caused discussion on this bill to stop. Senate bill #333, which prompted the writing of *Taggants in Explosives,* required additional study [2]. As written, the bill would involve tagging any explosive material, including blasting agents such as ammonium nitrate, as well as black and smokeless powders [2]. The costs of implementing a taggant program while covering these materials increased the total program cost to an estimated 268 million dollars a year in the most comprehensive program [2]. The cost estimate was likely the reason for the failure of this second bill. Table 2 summarizes the events that occurred between 1971 and 1980, and reactions into investigating identification taggants.

Table 2. Summary of Events and Reactions between 1971 and 1980.

Event	Reaction
Passage of Organized Crime Control Act (1970)	Initial taggants created
Senate Bill 2013 (1978)	Considered taggant requirements for all explosives Raises concerns over compatibility with taggant in black powder and smokeless powder used for sport shooting
Senate Bill 333 (1978)	Considered taggant requirements for all explosives Commissioned *Taggants in Explosives*
Taggants In Explosives (1980)	Identified evaluation criteria for successful identification taggant Identified cost, survivability, and compatibility with explosives as major areas Provided three recommended courses of action

2.3 Updated Taggants (1981–1998)

After the publication of *Taggants in Explosives*, identification taggant research continued in both government and industry [1,13]. *Taggants in Explosives* recommended one of three courses of action:

1. Enact legislation requiring the addition of identification taggants contingent on the technical feasibility
2. Do not pass legislation but recommend research into identification taggants
3. Take no legislative action and encourage the executive branch to enhance alternative methods of investigating taggants [2].

Congress opted to specifically ban appropriations for taggant programs by the ATF from 1981 to 1993 [1].

Almost simultaneously with the publication of *Taggants in Explosives*, the country of Switzerland enacted a federal statute that required taggants to be added to explosives

[1]. This legislation was enacted as a result of an increase in bombings that occurred during the late 1970s [1]. This statute requires that all explosives (dynamites, slurries, water gels, ammonium nitrate/fuel oil (ANFO), black powder) manufactured for consumption in the Swiss market must have a unique taggant per manufacturer that is changed twice a year [1], and a sample of the taggant is maintained by the Swiss federal government. Three taggants are approved: the Microtaggant® (a commercially produced version of the 3M taggant tested in *Taggants for Explosives*; HF6, which is a Swiss developed version of the Microtaggant®; and one called "…Explotracer that consists of orange polyethylene chunks permeated with fluorescent markers, embedded iron particles, and rare-earth oxides" [1].

According to Swiss authorities, the addition of identification taggants into explosives has helped law enforcement track explosives that were used, or attempted to be used, in terrorist or criminal acts [1]. In Switzerland, 254 incidents where explosives, were used in either improvised explosive devices or safecracking, occurred between 1984 and 1994. Of these, 44.4% were successfully solved when taggants were recovered in 63 cases. Of the remaining 191 cases where taggants were not recovered, only 16.2% were solved [1]. Therefore, the Swiss experience shows that when identification taggants are used and recovered, the case is twice as likely to be solved under their taggant program [1].

As a direct result of the bombing of the Alfred P. Murrah Building in Oklahoma City in 1995, and also influenced by the World Trade Center bombing in 1993, another reactive investigation into the state of identification taggants began [1]. The 1996 Antiterrorism and Effective Death Penalty Act required the compilation of a report of the effectiveness of taggants for explosives [1]. This report was published by the National Research Council in 1998 under the name *Containing the Threat from Illegal Bombings: An Integrated National Strategy for Marking, Tagging, Rendering Inert, and Licensing Explosives and Their Precursors*. This report, henceforth referred to as *Marking and Rendering Inert*, provided a second comprehensive look at the state of taggant technologies, their utility, and the potential for future legislation requiring identification taggants and other technologies to guard against explosives [1].

This report defined three types of identification taggants that were developed or under development in between the publication of *Taggants in Explosives* and 1998. The first type of identification taggant that *Marking and Rendering Inert* identified was a particulate taggant. This is another name for a physical taggant and was so named because the physical taggants developed at the time were mostly small particles [1]. The second type of identification taggant that was identified was an isotopic taggant. This is similar to a chemical taggant where various chemical compounds are added to the material to be tagged. However isotopic taggants also introduce specific isotopes of atoms at some of the sites in the chemical compound to encode information [1]. The third type of identification taggant that was identified was a biological taggant. This taggant used some biologically produced chemicals as a chemical taggant, such as DNA, or used conventional chemical taggants that were detected using biologically derived detection methods such as immunoassays [1].

Particulate or physical taggants continued to be the most fully studied identification taggant due to the 18 years of required use in Switzerland [1]. Different types of physical taggants have the potential to sensitize some or all explosives, due to the "gritty" nature of small particles. The added particles may create areas with higher than usual friction, which could sensitize or cause detonation of the explosive [1]. Additionally, physical identification taggants that can be used in explosives must be durable and unreactive in order to survive the detonation process. This means, however, that they are likely to survive in the environment indefinitely and thus present a contamination risk both in the environment and any raw materials produced via the use of explosives such as mining or quarrying [1].

Isotopic taggants were also evaluated, although limited experience and testing meant that such evaluations were mostly preliminary. The compatibility of isotopic taggants was judged to likely be acceptable since the proposed methods used parts per million of the additive. Explosives manufacturing processes of the time did not require this level of control, so it was deemed unlikely that the addition of such a low concentration of another material would materially affect the properties [1]. Incomplete testing prevented a full assessment of the survivability and recoverability of isotopic taggants in post-blast residue, as only small-scale tests had been performed [1]. Due to their low concentrations and the necessity of identifying the different isotopes present, analysis requires more specialized equipment and techniques such as mass spectroscopy, which reduces the number of facilities capable of performing the analysis [1,4,5]. The low concentrations of the isotopic taggants were thought to significantly reduce the chances of environmental risks or cause many issues with contamination of mined raw materials by the taggants, although not enough data was available at the time to fully assess their impact [1]. The cost of isotopic taggants is relatively high, but the low concentrations required make them useful on an overall cost basis [1,4].

Biological taggants were also limited by the same lack of experience and testing that had hampered isotopic taggants. The compatibility of a biological taggant was hard to assess given the preliminary nature of the research, though it is generally expected that low concentrations would lower the risk of incompatibility [1]. The survivability and recoverability of biologically based chemicals are uncertain due to the heat generated by detonation and the harsh environment present during the manufacturing of some types of explosives. An example of a harsh environment for biologically derived materials or chemicals is the manufacture of ammonium nitrate prills, which takes place at high temperatures (145 to 155 °C) and is strongly oxidizing as well [1]. A full evaluation of environmental acceptability and contamination of mined raw materials was not available at the time, but it was thought that the relatively low concentrations required would minimize the risk of biological taggants having a negative effect on these criteria. The cost of biological taggants depends on the production cost of the biological components. While not fully developed, it is expected that the low concentrations required would result in an acceptable cost for the benefits provided [1].

At the time of publication in 1998, *Marking and Rendering Inert* evaluated a comprehensive identification taggant program as too expensive for the current bombing risk environment. It proposed that further investigation into identification taggants so that in the event that the risk of bombings increased, at least one type of identification taggant would be evaluated and the costs and benefits of such a program could be evaluated again [1]. An additional conclusion of the report was that based on the Swiss experience with identification taggants, a taggant program has been shown to aid in solving crimes such as bombings [1]. The 1998 report mostly reiterated the results of the 1980 OTA report: using identification taggants was technically feasible, but the cost of the taggant program and concerns for safety still needed to be addressed [1,2]. An additional consideration from this new report was that many of the proposed taggant methods were underdeveloped and required live testing before they could be fully evaluated [1]. Table 3 summarizes the developments that occurred between 1981 and 1999.

2.4 Modern Taggants (2000–Present)

The most deadly terrorist attack ever in the United States occurred on September 11, 2001 with the attack on the World Trade Center and the Pentagon buildings. This prompted the passage of the Safe Explosive Act of 2002, part of Public Law 107–296 [14]. The major component of this law was to restrict the unlicensed handling of explosives further than the Organized Crime Control Act with the introduction of additional sitipulations for authorized users of explosives. As concerns over terrorism continued, research into identification taggants has continued as well. Most new technologies such as nanotechnology or DNA sequencing have been proposed as potential identification taggant methods. Older methods have also been adapted.

Table 3. Summary of Events and Reactions between 1981 and 1999.

Event	Reaction
Appropriations Ban (1981–1993)	ATF not permitted to research taggants
Bombing of Alfred P. Murrah Building (1995)	Passage of Antiterrorism and Effective Death Penalty Act
Antiterrorism and Effective Death Penalty Act (1996)	Commissioned Marking and Rendering Inert
Marking and Rendering Inert (1998)	Provided updated evaluation criteria for identification taggants Summarized status of research performed between 1980 and publication (approximately 1998) Emphasized importance of cost, compatibility, and survivability as the major evaluation areas

The Safe Explosives Act included the most significant changes to explosive licenses and eligibility since the passage of the 1941 Federal Explosives Act. Under this law, all purchasers and users of explosives must hold a license or permit. Previously, only purchasers or users of explosives across state lines were required to hold a license or permit [15]. Additional changes were made to categories of people prohibited from handling explosives [15].

Research into taggants has continued to the modern day [16,4,5,17], though available testing information and data remain scarce [5]. No new categories of identification taggants have been identified; however, improvements and refinements to the categories of physical, chemical, and biological taggants have occurred. Physical taggants remain an active area of research [4,16,18,19,5]. One type of physical taggants that have been proposed are particles containing quantum dots that emit light at specific frequencies, and the combination of frequencies can be used to encode information [4,5]. Physical taggants where rare earths or other fluorescent materials such as dyes are introduced to a carrier particle have been developed as well [4,16,5,17]. These particles encode information in the colors and intensities of the light they emit [4,16,5]. These approaches are similar to the first taggants, which use different concentrations of various elements contained within a particle [20,21] but exploit the fluorescence of the dyes or rare earths to increase recoverability of the particles [16,5].

Small ceramic or metal oxide particles that contain fluorescent rare earth materials have been proposed as a taggant that can be used to identify if a particular type of material has been used [19,18,17]. The combination of rare earths used and the intensity of the fluorescence can create a way of encoding information [4,5,18]. These particles can be recovered in the field using a UV lamp [19]. Analysis of the particle requires the use of sophisticated laboratory equipment and is correspondingly expensive [18,19].

Similar glass particles have also been proposed as an identification taggant, where the concentration of the different fluorescent rare earth elements is used to encode information, unfortunately large charges that might be used in mining or other legal uses (>500 lbs) do not allow the glass microspheres to survive detonation [16,17]. The taggant elements can be added to the liquid glass, thus allowing for an even distribution of the elements that make up the identification taggant in the final particle [16,17]. Small spherical glass particles, called microspheres, are already used in commercially produced explosives [16]. This identification taggant changes the composition of the microspheres that are added [16,17]. As with other physical taggants such as the Microtaggant®, recovery of the taggant is the major concern [1,17]. Tests were performed to judge the recoverability of these microsphere taggants, and showed mixed results the taggant could be recovered for small charges, but not for larger charges [16,17].

Due to the rapid development in the area of biology, DNA based identification taggants continue to be proposed and developed [1,4,5]. Unique codes based on a sequence of nucleotides can encode the information that would be needed for in identification taggant. Only low concentrations of taggant are needed due to the amplification that can be obtained using polymerase chain reaction (PCR) techniques [4,5]. DNA sequences have been used commercially to tag pharmaceutical products like cancer drugs [4] as well as other anti-counterfeiting uses [5]. DNA sequences can theoretically be of any length, which allows for a practically unlimited number of codes [4,5]. Reading these sequences using a technique such as PCR is well understood, but the reagents, equipment, and expertise needed are a significant cost [4,5]. Additionally, the stability of a DNA sequence when subjected to the heat created by detonation is unknown and might preclude the use of DNA based identification taggants with explosives [1].

There has been a notable change from previous cycles in the United States where government efforts lead to research in identification taggants. Taggant research has shifted from crime to terrorism and the use of explosives in asymmetric warfare has caused the development of identification taggants to shift its priorities as well. Current technologies are suited for commercially manufactured explosives but are of limited use for homemade explosive materials. The increased use of improvised explosive devices in Afghanistan in the recent decade and the need to identify ammonium nitrate crossing the border into Afghanistan illustrates the challenges that identification taggants can overcome [22]. The modern experience shows that a universal identification taggant that can be used effectively in identifying both commercially manufactured explosives and also homemade ones will be necessary for an effective identification taggant program.

An older technique, neutron activation analysis, has become more capable with modern computing power, software, and semiconductor manufacturing technology. This technique can be used on samples regardless of their physical state and is thus well suited to analyzing post-blast residue to find chemical taggants. The authors have proposed a new identification taggant for explosives called the nuclear barcode, which utilizes this technique to detect a rare earth based identification taggant in the post-blast residue. Table 4 summarizes the events between 2000 and their reactions.

Table 4. Summary of Events and Reactions between 2000 and the current day.

Event	Reaction
September 11th Terrorist Attacks (2001)	Passage of Safe Explosives Act of 2002 Creation of Department of Homeland Security
US involvement in conflicts in the Middle East (2003–current)	Renewed interest in identification taggants for antiterrorism

3 Nuclear Barcode

The nuclear barcode is a proposed identification taggant. It falls between a physical taggant and a chemical taggant that uses the combination of concentrations of rare earth and other elements to encode information. This provides a large number of possible codes. The present design of the nuclear barcode would use 20 different concentrations of eight elements, giving a total of 20^8 or 25.6 billion unique combinations. This number can be increased further by using a larger number of elements used or by using a larger number of concentration levels. The number of codes allows for a relatively large amount of information to be included in the codes such as the type of explosive, manufacturer, and enable identifying individual batches of the explosive products. This capability would represent a notable improvement compared to the system mandated in Switzerland which changes codes every six months [1]. The nuclear barcode is designed to be read from a sample of the post-blast residue. The nuclear barcode uses neutron activation analysis (NAA) to identify the concentration levels, which identifies the elements present in a sample by their nuclei and not their chemistry, so any chemical form of the taggant elements can be used, as long as the elements are added in the correct concentrations.

Preliminary testing of the nuclear barcode has occurred. Five explosive charges were prepared using a commercial binary explosive [23]: two of these explosives were each tagged with a quantity of holmium or samarium sulfates, and the fifth was not tagged as a control. These charges were then detonated either within a steel cylinder to collect the post-blast residue for tests 1, 3, and 5, or suspended over a steel plate for tests 2 and 4. Samples of the post-blast residue were collected using a cotton ball to sample around the center of the cylinder or on the center of the plate. The samples were irradiated at the Missouri S&T Reactor (MSTR) at 200 kW for 10 minutes, and the samples counted for 1 hour using Canberra's ProSpect software. The net number of counts for these samples of the two taggant elements is shown in Table 5. A successful test was indicated by the number of counts being greater than the error. All tests were successful and indicated that the nuclear barcode can be identified within the tagged explosives. A complete analysis of these results was previously published

Table 5. Preliminary testing of the nuclear barcode showing detectability of samarium and holmium in post-blast residue produced by commercial binary explosive.

Test	Taggant Element	Taggant Undetonated Concentration (ppb)	Holmium Net Counts	Samarium Net Counts	Mass of Post-Blast Residue (g)
1	Holmium	19600	2,236 ± 668	290 ± 1,306	0.550
2	Holmium	19600	98,026 ± 1,744	–	0.139
3	Samarium	19700	63 ± 1,490	10,872 ± 1,299	0.169
4	Samarium	20100	3,372 ± 1,762	66,381 ± 2,589	0.382
5	Control	0	766 ± 1,802	849 ± 988	0.362

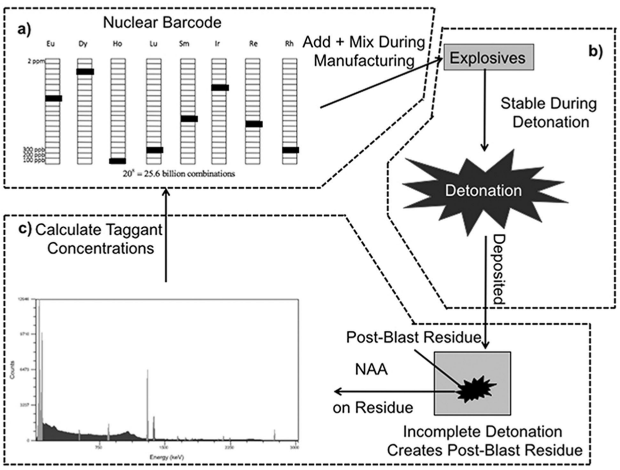

Figure 2. Nuclear barcode schematic showing: creating (upper section), using (right section), reading (lower section) in an explosive, and results of the nuclear barcode (bottom left).

by the authors [24]. The taggant elements were found in each test where a rare earth taggant was added and were not present in the control test. This is summarized in Table 5 [24].

The elements used to create the nuclear barcode taggant are relatively expensive, being rare earth elements or precious metals, but they only need to be added in small concentrations. The use of NAA enables the higher cost taggant elements to be used in concentrations down to 100 parts per billion (ppb), thus decreasing the cost of the taggant materials. This represents a tradeoff that reduces the cost of the taggant materials but increases the cost of the analysis, however, this tradeoff is economically favorable overall. Preliminary studies have been performed using the rare earth elements holmium (Ho), samarium (Sm), and europium (Eu) [23]. The most expensive of these materials cost approximately $ 15 per gram. At the average concentration of 1 ppm, this is a sufficient quantity to tag one metric ton of explosives, and add about 1.5 ¢ per kilogram of explosives in material costs. This low material cost enables the tagging of any explosive material and may be suitable for use with some explosive precursors used in improvised explosive devices (IEDs) as well. A schematic illustrating the use of the nuclear barcode is shown in Figure 2.

As a taggant that is introduced at low concentrations, the effect of the nuclear barcode on the reactivity of explosive materials is likely minimal. Concentrations of components in manufacturing of explosives are not controlled with ppm tolerances, and the addition of these materials is not expected to pose a problem for the long-term stability of the explosives either. Preliminary testing to evaluate these has shown no notable reactivity of two types of explosives with the rare earth elements holmium, samarium, and europium. Charges of a commercial binary explosive as well as composition B have been tagged with one or three rare earth elements at concentrations from 1 ppm to 14 ppm, with no apparent change in explosive properties.

The nuclear barcode provides solutions to the two largest issues raised in both *Tagging of Explosives* and *Marking and Rendering Inert*: the cost of taggant, and the potential for an identification taggant to sensitize the explosive to which it was added. Since NAA is used to analyze the low concentrations of taggant elements, the cost of analyzing a sample will be high, since research reactors and neutron sources that can be used for NAA are few in number. This higher cost can be minimized by analyzing fewer samples; under ideal circumstances, only one sample would be required. The nuclear barcode is non-radioactive until it is read. Once exposed to a strong neutron source like a research reactor, the sample of the post-blast residue will become radioactive, as has been seen in preliminary experiments. This means that additional safety precautions must be observed to make sure that there is no additional risk. It is often the case that gamma detectors are collocated with strong neutron sources, which are heavily controlled spaces, and minimizes the risks to the general population. Additionally, the implementation of a two day delay period between irradiating the sample and counting the sample was sufficient for any activity to decay to safe levels for handling. Sensitization of explosives is also controlled through the use of low concentrations of taggant elements. The nuclear barcode also retains the advantages of modern identification taggants: survivability of the taggant in the post-blast residue, and forensic utility of the taggant. These traits make the nuclear barcode a promising candidate as an identification taggant for explosives.

The utility of the nuclear barcode can be estimated by determining how long the nuclear barcode can produce unique batch codes until having to repeat a code. In the United States, 3.1 million metric tons of explosives were sold for use in 2014 [6]. Assuming that the United States represents approximately 20 to 25 % of the world explosive market based on the United State's contribution to global GDP, the global production and sale of explosives in one year is 15.5 million metric tons. Assuming that the average size of a batch of explosives is 5000 kg, or just over 10,000 pounds, then for an identification taggant scheme that uses a unique code per batch of explosives a total of 3.1 million unique codes will be used to tag one year of production [1]. Not all explosive products are produced in the same size batch, with specialist products such as boosters or dynamite produced in much smaller quantities than ANFO. To account for these variations, it will be assumed that 10 times more codes are required than estimated based on the batch size of 5000 kg, meaning that 31 million unique codes must be used each year. At this rate, the 25.6 billion codes produced by the nuclear barcode will last for 825 years before having to repeat codes. This calculation is based on the nuclear barcode hitting its design goals. A reduction in the number of elements used or the number of different concentrations used by the nuclear barcode will reduce this number significantly by reducing the number of unique codes.

4 Conclusions and Future Work

Throughout the one hundred years of taggant development, the same cycle has repeated several times. The cycle begins with a triggering event such as a terrorist attack involving explosives or a major war. This event prompts the government to consider changes to law or regulations that would provide more identifying information about the explosives. During the drafting of these laws or regulations, studies are performed into mechanisms that can provide the type of information desired, such as identification taggants. The proposed mechanisms are then evaluated, and laws and regulations are finalized or ultimately rejected. Additional mechanisms are proposed and investigated, and the cycle begins again when the next triggering event occurs.

The implementation of a modern identification taggant would quickly provide useful information for criminal forensic investigations to detect and identify explosives used and aid in investigations of terrorist attacks involving explosives. A modern example is the necessity of ways of tracing the components used in improvised explosive devices in the ongoing Afghanistan conflict [22]. Studies conducted in 1980 and 1998 have both shown that while technology existed that could be used as an identification taggant, the cost of a program and safety concerns were issues that would need to be resolved prior to implementation. Additionally, any identification taggant must be rigorously tested before being utilized. The 1998 report *Marking and Rendering Inert* identified other promising candidates, but concluded that the lack of full-scale testing meant that a more thorough evaluation would be needed.

Table 6. Comparison Method for Identification Taggant Technologies.

Taggant	R[a]	S[b]	U[c]	C[d]	Cost
Radiological	5	5	3	5	4
Chemical	3	3	5	4	3
Physical/ Particulate	5	5	4	4	4
Isotopic	5	5	5	5	1
Biological	3	3	5	5	2
Nuclear Barcode	5		5		

[a] R=Recoverability. [b] S=Survivability. [c] U=Utility. [d] C=Compatability

The 1980 and 1998 studies shared five evaluation criteria for identification taggants: recoverability, survivability, utility, compatability with explosives, and cost. Recoverability is the liklihood that the taggant will survive detonation and be collected. Survivability is the liklihood that the information encoded by the taggant will survive detonation. Utility is a measure of the number of unique codes that the taggant method can create. Compatability with explosives requires that the taggant material not effect the explosive performance nor negatively effect storage or handling of the tagged explosive. The cost of a taggant is based on the cost of the taggant material itself, the cost of reading the taggant, as well as any additional costs for administrating a large taggant program.

The effectiveness of the different taggant technologies in meeting the identified evaluation criteria must be evaluated based on prior rsearch. Table 6 presents a initial matrix for comparing the different taggant technologies based on scoring from one to five. With this method, a score of five represents extremely high performance, and one extremely low performance in that category for the first four categories. Cost can also be ranked on the same one to five scale, with higher scores corresponding to lower taggant cost and cheaper analysis costs. It must be noted that the completion of Table 6 is an ultimate goal, and represented here is an first step.

The nuclear barcode is actively under development. This is reflected in the blank spaces in Table 6 corresponding to survivability, compatibility, and cost of the nuclear barcode. The preliminary results suggest that the nuclear barcode is highly recoverable, as in all tests the nuclear barcode can be found in the post blast residue. As a result, it has been assigned a preliminary score of five in recoverability. The large number of unique taggants and the corresponding length of time that the nuclear barcode can produce unique batch codes also provides a preliminary score of five in the utility of the nuclear barcode. More testing than presented previously will be required to fully assess the nuclear barcode across these same five criteria [24]. Developing a future taggant that can successfully meet these criteria is the first step in creating a universally viable identification taggant. The development of such a taggant would be a great boon to law enforcement.

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