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GEORGE CLYDE HALE, HOOSIER CHEMIST AND PIONEER IN ORDNANCE RESEARCH AND THE CHEMISTRY OF THE EXPLOSIVE, RDX

Marvin Carmack
Department of Chemistry
Indiana University
Bloomington, Indiana 47405

ABSTRACT: During the 1920's, Dr. George C. Hale, a native of Indiana, developed and published a procedure for the preparation of a powerful new explosive which he named cyclonite, subsequently known as RDX. Although his research was carried out and published just after World War I, practical industrial processes for the manufacture of this explosive, as well as necessary experience with its use, did not follow until many years later. During World War II, intensive collaborative research efforts in several countries made possible large-scale and efficient production in the United States in time to have an important influence on the outcome of World War II.

An important achievement in World War II was the development of processes for the manufacture of large quantities of the explosive, RDX (also known as cyclonite or hexogen; Fig. 1A), from hexamethylenetetramine (also known as hexamine; Fig. 1B) by nitrolysis with 98% nitric acid. The story of this achievement revolves about the scientific activity of a Hoosier chemist, George Clyde Hale (Urbanski, 1967; Edward, 1990).

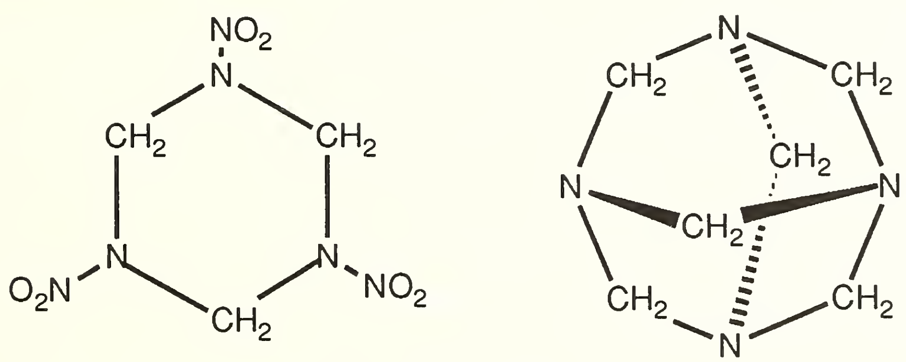

Figure 1. **A.** RDX or cyclonite. **B.** Hexamine.

George Clyde Hale was born September 29, 1891, in Cass, Sullivan County, Indiana, to Charles and Rosettie Bledsoe Hale. Charles Hale was a coal miner who ran a grocery store. At the age of 18 or 19, George taught school before entering Indiana University in 1911. As a chemistry major, George was active in the chemistry fraternity, Alpha Chi Sigma, and the Boosters' Club, and served as an Assistant Instructor. His grades rose from average to nearly straight A's, and he earned both the A.B. and M.S. degrees in 1915. George continued as a graduate student until 1917, when he took a job at the U.S. Army Ordinance Picatinny Arsenal in Dover, New Jersey. Since before the Revolutionary War, Picatinny has been a center for ordnance production and research.

George Hale moved up the ranks of civilian scientists at Picatinny, serving finally as Chief of the Chemical Department or Branch of the Technical Division. He spent the year 1920-21 in Germany with the Army of Occupation studying German ordnance methods.

During his early years at Picatinny Arsenal, Hale developed a process for the nitrolysis of hexamine to produce a compound, which he named cyclonite (Fig. 1A; Hale, 1925). Cyclonite is now generally known by its World War II name, RDX, given by British workers at the Woolwich Research Department to their compound, X. The Germans' name for cyclonite was hexogen.

Cyclonite was recognized as a much more powerful explosive than the long favored 2,4,6-trinitrotoluene, TNT. Cyclonite was said to be in "perfect oxygen balance," meaning that its chemical composition is such that during an explosion it is completely converted into gaseous carbon monoxide, nitrogen, and water, with no left-over residue of carbon. Moreover, cyclonite has a very fast rate of detonation and is therefore extremely "brisant." In demonstrations of the capability of cyclonite in comparison with that of TNT, a small cone of cyclonite will punch a clean segment completely through quarter-inch-thick steel armor plate, while a similar cone of TNT will produce a gently rounded concavity.

In spite of its favorable characteristics, ordnance experts of the World War I era and the 1920's judged cyclonite to be too sensitive and dangerous for military use. It was also considered too costly to manufacture. It must be remembered that the chemical industry in the United States up to and immediately after World War I was not large and sophisticated.

The first procedures for making cyclonite involved use of an enormous excess of 96% to 98% nitric acid for the nitrolysis of hexamine. Less than half of the carbon from the starting hexamine could be recovered as useful, pure explosive. Vast quantities of nitrogen oxides had to be recycled to resynthesize the nearly anhydrous nitric acid for reuse. Accordingly, Hale's process was not put into use in the United States for nearly two decades of the post-World War I period.

Research on new ordnance materials was not strongly supported by the U.S. Congress during the 1920's and 1930's. The U.S. Military had tested cyclonite and decided against its use in 1923. Hale published his procedure for cyclonite in 1925 in the *Journal of the American Chemical Society* (Hale, 1925) and submitted an extended version to Indiana University as his Dissertation for the Ph.D. degree (Hale, 1926). The University granted George Clyde Hale his doctorate in chemistry in 1926 — the sixth such degree in chemistry awarded by that institution.

The potential advantages of cyclonite over TNT were recognized by scientists/industrialists in a number of the European countries. Several groups attempted, with varying degrees of success, to manufacture the explosive by variants of Hale's 1925 published procedure. In Hale's direct nitrolysis, there was no apparent way to utilize the small one-carbon by-products representing more than half of the starting hexamine. The unstable fragments were destroyed by the induction of a controlled "fume-off." The diluted nitric acid oxidized the organic by-products, thereby producing a vigorous evolution of gases including copious quantities of carbon dioxide and nitrogen oxides. Making this procedure economically feasible required recovery of the nitrogen oxides and spent acid and their reconversion to nearly anhydrous nitric acid. Hale showed that, for unknown reasons, very large excesses of 97% to 98% nitric acid were essential for forming cyclonite. Post-war research on mechanisms of nitration reactions have shown that nitronium ion, the essential nitrating intermediate, has its maximum concentration in nitric acid containing only 2% to 3% water. Because water is a by-product of the nitration, the large excess of the concentrated acid is necessary to minimize dilution of the nitric acid which results in a rapid decline of the equilibrium concentration of nitronium ion.

As the war clouds gathered over Europe and Hitler's military strength grew during the 1930's, the British saw the advantages of RDX (their name for cyclonite) as outweighing the engineering problems associated with its manufacture. At their Woolwich research center, they developed a process that embodied the essentials of the Hale procedure, with the controlled fume-off and recovery of acid. Some production on a relatively small scale was begun.

Meanwhile, in the United States, in June 1940, the National Defense Research Committee (NDRC) was organized by the Government to undertake urgent research of military problems. The NDRC was later merged with the Committee on Medical Research into the Office of Scientific Research and Development (OSRD; Baxter, 1946).

In September 1940, a scientific mission of high-level British scientists headed by Sir Henry Tizard arrived in Washington from London, bringing with them a "black box" containing highly classified information on British defense preparations. Contained in the information of the black box were details of the Woolwich RDX project.

The Tizard mission was the forerunner of many missions and exchanges of high-level scientific personnel and information. The new agencies created in Washington mobilized scientists and engineers in government, academia, and industry. Missions were established by Canada, Britain, and the United States to facilitate the exchanges of scientific results. This rapid mobilization proved highly successful, and unprecedented progress was made in the solution of extremely complex problems for the military operations.

On the urgent request of the British for help in making RDX available, Franklin D. Roosevelt agreed, as part of the Lend-Lease Act, signed into law on March 11, 1941, to build a plant in the United States to manufacture RDX by the Woolwich Process. From May until December of 1941, the U.S. Government negotiated an agreement with the DuPont Company to build the plant. Because RDX had never been produced in quantity in the United States, a mission from DuPont spent several months in England during the summer and fall of 1941 studying the Woolwich Process and concluded that an investment of 41.57 million dollars would be necessary for construction of a plant designed to produce RDX compositions at the rate of 100,000 pounds/day (Baxter, 1946).

The U.S. Government took title to a large tract of rich farmland in Vermillion County in western Indiana between the towns of Dana and Newport. Plant construction began on January 12, 1942. By mid-1942, a peak construction force of nearly 7,500 workers had completed 50% of the plant. Including a number of modifications and extensions, the plant was essentially completed by early December 1943 (Hagley Museum Archives).

The problem of the oxidation of by-products necessitating the recycling of enormous quantities of nitrogen oxides back into nearly anhydrous nitric acid was solved by elegant engineering. A long line of huge stainless steel towers was necessary to achieve this recovery. The resulting complex centered about the largest nitric acid plant in the world at that time. Production began in late October 1942. Between November 1942 and August 1945, the Wabash River Ordnance Plant produce a total of approximately 200,000,000 pounds of four different compositions containing RDX. The cost of the plant was well under original estimates and its capacity to produce RDX considerably exceeded original designs (Hagley Museum Archives).

Canadian scientists had been aware of the Woolwich work on RDX earlier than U.S. chemists and had made great progress on new processes that would more completely utilize the carbon units in the starting hexamine, and correspondingly greatly reduce the costly recycling of nitrogen oxides and dilute nitric acid. They had developed the Ross-Schiessler process that started with paraformaldehyde, ammonium nitrate, and acetic anhydride. This process had reached pilot stages of development, and several academic as well as government laboratories were deeply involved in further research on RDX and other explosives.

Soon after formation of the NDRC, U.S. academic scientists were recruited to take up research aimed at improving the efficiency of munitions manufacture under contract with the NDRC. Even before much information concerning previous research on explosives had become available, a network of collaborating academic research teams had been organized. These included Professors Werner E. Bachmann at Michigan, John R. Johnson at Cornell, and Frank C. Whitmore at Penn State. Between November 1940 and April 1941, the team of Bachmann and associated workers at Michigan had found an optimal combination of the best features of the older processes for manufacturing RDX. Starting with hexamine, ammonium nitrate, nearly anhydrous nitric acid, and acetic anhydride, they achieved greater than 80% yields of RDX utilizing *all* of the carbon content of the starting hexamine, and were able to obviate the complex and costly recycling of nitrogen oxides (Jenner, 1990; Sheehan, 1990).

Three companies carried out pilot studies of the Bachmann Process under contract with the U.S. Government. One of these moved so rapidly and successfully that plans for a full-scale plant were drawn up before the pilot studies were completed. The Tennessee Eastman Corporation on the Holston River in eastern Tennessee enjoyed an advantage with respect to the Bachmann Process, because for years the plant had been the site of acetic anhydride production. In an amazingly short time for such a totally new and complex engineering development, Tennessee Eastman had in operation a large plant with production lines at the Holston Ordnance Plant. Originally designed to produce 170 tons/day, the plant's operating efficiency and ingenious modifications enabled production to be increased by June 1943 to 340 tons/day. The combined capacities of Wabash River and Holston Plants had the potential of producing approximately 500 tons of RDX compositions daily, which was more than enough to satisfy the military demands for the duration of the war. The cost of the research programs at the three universities — Michigan, Cornell, and Penn State — came to only $45,000, yet saved an estimated $200,000,000 in construction costs had the same production at the Holston Plant been based on the inefficient Woolwich Process.

The rapid achievement of the means to produce large quantities of RDX was a significant factor in the Allies' winning of the Battle of the Atlantic. Early in World War II, defenses against German submarines depended upon the use of depth charges loaded with the classic TNT compositions, but the new German submarines had been designed to withstand them without rupturing. Allied ships were being destroyed at an intolerable rate. When new depth charges loaded with RDX compositions became available, however, the German submarines became vulnerable, and the tide of the Battle of the Atlantic turned about in favor of the Allies.

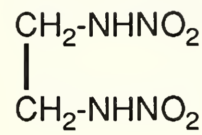

Figure 2. EDNA or haleite.

In his approximately thirty years service at Picatinny Arsenal, George Hale developed many new materials and devices and held many patents. In addition to the cyclonite process, he received a patent in 1935 for a new explosive, ethylene-dinitramine (EDNA or haleite; Fig. 2). Named in honor of Dr. Hale, haleite received considerable research attention during World War II in the NDRC, and the DuPont Company engineered and built a plant to make it. Haleite is somewhat less sensitive than RDX and can, for example, be press-loaded into small shells.

Dr. Hale was able to visit the Wabash River Ordnance Plant in late 1943 and see the realization of his research of nearly two decades earlier and know that it had, at long last, become an important contribution to the war effort.

Dr. Hale (Fig. 3) was honored by the U.S. Army Ordnance in 1946. He died on November 3, 1948, and was buried in the Dugger (Sullivan County, Indiana) Cemetery. In May 1962, a modern new laboratory for explosives research was dedicated at Picatinny Arsenal and named the George C. Hale Building. In the presence of Mrs. Hale and numerous high officials, a bronze plaque was unveiled with this inscription:

GEORGE C. HALE
1891 - 1948
THE EFFORTS WHICH ARE
UNDERTAKEN HERE PERPETUATE
THE IDEALS AND ASPIRATIONS
TO WHICH DR. GEORGE C. HALE
DEVOTED HIS LIFE. THIS
BUILDING IS A MEMORIAL
TO HIS LEADERSHIP AND HIS
CONTRIBUTION TO THE FIELD
OF EXPLOSIVE RESEARCH

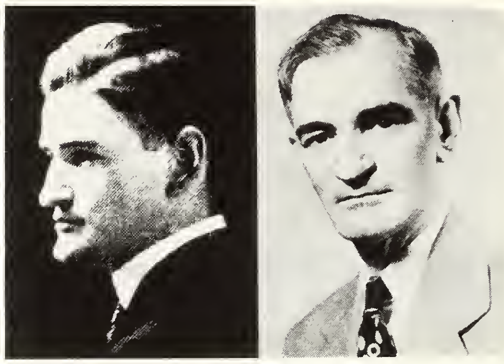

Figure 3. Dr. George Clyde Hale: Left: As a senior at Indiana University in 1915 (from the *Arbutus* Senior Yearbook at Indiana University). Right: Dr. Hale as a senior scientist at Picatinny Arsenal in the 1940's.

ACKNOWLEDGMENTS

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