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# William David Coolidge (1873–1975) Biography with special reference to X-ray tubes

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William Coolidge (1873–1975) is famous for the invention and development of the hot cathode X-ray tube, sometimes called the Coolidge X-ray tube, which immediately made the previous designs of gas X-ray tube obsolete. He was born in Hudson, Massachusetts, studied at Massachusetts Institute of Technology, and graduated with a PhD in Physics from the University of Leipzig. In 1905 he joined the General Electric Company (GEC) Research Laboratory at Schenectady and in 1913 invented the Coolidge X-ray tube which is the prototype of modern apparatus. He was consultant in X-rays to GEC for some quarter of a century, 1945–1961. As well as his work with X-rays, he developed the first successful submarine detection system, with Irving Langmuir (1881–1957), and during World War II undertook research relating to radar, the atomic bomb, rockets and anti-submarine devices. He was also, during WWII appointed to President Roosevelt's Advisory Committee on Uranium. He obtained 83 patents during his lifetime (all assigned to GEC). Coolidge spent his entire career with GEC, from 1905 when he joined the company at Schenectady to work in lamp research, until his death when he was an Emeritus Director of Research & Development. One of the most complete lists to be published of papers by Coolidge is found in the References.

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**Key words:** tungsten, incandescent lamps, gas tubes, hot cathode X-ray tubes, William David Coolidge, Wilhelm Conrad Röntgen, Irving Langmuir, Thomas Edison, Gustav Heinrich Wiedemann, Paul Drude, Arthur Amos Noyes, Willis Rodney Whitney, Edwin Wilbur Rice, General Electric Company, Massachusetts Institute of Technology, Wimshurst electrostatic machine

## Introduction

Today's designs of X-ray tubes can be said to be direct descendants of the original Coolidge X-ray tube which was developed in the 1910s and which immediately made obsolete the designs of other X-ray tubes, based on the design principle of the pear-shaped gas tube used by Wilhelm Conrad Röntgen (1845–1923) when he discovered X-rays in November 1895. William Coolidge (1873–1975) will forever be famous for his invention, for example for radiotherapy, even in the era of high energy linear accelerators which generate X-ray beams of a few MV, hot cathode tubes are still used for deep X-ray therapy (typical energies 200–300 kVp) and for superficial X-ray therapy (typical energies 60–120 kVp). Neither have they become obsolete in diagnostic radiology in the era of CT scanning and MR scanning. As well as his work with X-rays, he also developed the first successful submarine detection system, with Irving Langmuir (1881–1957), and during World War II undertook research relating to radar, the atomic bomb, rockets and anti-submarine devices. He obtained 83 patents during his lifetime. Among his many awards and honours were the Rumford Medal of the American Academy of Arts and Sciences (1914), the Hughes Medal of the Royal Society (1927), the Gold Medal of the American College of Radiology (1927) and the Faraday Medal of the Institute of Electrical Engineers, England (1939). Biographies have been written by former employees of GEC, about William Coolidge [1, 2] of which that by Chauncey Guy Suits (1905–1991) [1] gives much family and personal data on Coolidge: as does the biography by Miller [3].

## Parents, home & grade school

William David Coolidge belonged to the 8$^{th}$ generation of American-born Coolidge family, descended from John and Mary Coolidge who arrived in America in 1630 with Governor John Winthrop and settled in New England. Another

**Figure 1.** William David Coolidge at age 96 years [2]

Coolidge descendent from John & Mary was the 30th President of the USA, Calvin Coolidge (1872–1933). John owned 30 acres in Watertown, Massachusetts and was Deputy to the Great & General Court of the Massachusetts Bay Colony. He had several sons who founded separate branches of the family in New England, mainly near Boston.

**Figure 2.** William Coolidge age 5 years [3]

William Coolidge, an only child (Fig. 2) was born in Hudson, Massachusetts, a town of some 3,500 inhabitants about 25 miles west of Boston. His father was a shoemaker and farmer of 7 acres. His mother was a dressmaker. The farm was mostly covered with apple and peach trees with also a vegetable garden. Livestock included a horse, a cow and a flock of chickens. It is recorded [3] that William 'rose at six in the morning in a room which was, in winter, both cold and dark. He dressed by the light of an oil lantern and washed in cold water in the kitchen. After breakfast he walked a mile to the nearest school.' School was primitive: a one-room building catering for six grades and run by only one lady teacher. After school ended each day he had a regular routine of farm chores.

A typical hobby for the boys of the area, including William, was fishing all year, with holes chopped in the ice when it was winter. In addition, for William, photography became a lifelong hobby and during this period he built a basement darkroom in the farmhouse and constructed his own camera, including the shutter. This still left room for baseball, hiking, skating and primitive skiing.

## Electric contraptions

Whilst at grade school he built a contraption that would at a pre-set time, ring an alarm bell, close the open window of his bedroom, and open the door into the hall to admit heat from the warmer part of the house. He also built an electric motor to drive his mother's sewing machine: but unfortunately this never worked [3].

## Hudson High School

After grade school he attended Hudson High School, where he hated elocution so much that his father paid for private tuition. During this time, in order to help with the family finances, he left school for a while and took a job in a local factory, the Apsley Rubber Company. His work initially consisted of folding rubber raincoats for shipment from the factor to retailers and later working as an assistant to the company bookmaker. Perhaps not surprisingly, after a few months he decided to return to High School. He was to graduate Valedictorian in his class of 13 pupils. The subject of his Valedictory discourse was *Life is Opportunity*.

## Massachusetts Institute of Technology, Boston

Coolidge assumed that because of the limited financial resources of his family he would not be going to college at the end of his final school year. However, this changed when a friend who had been impressed by his scholastic achievements and his mechanical and electrical aptitudes suggested he might be able to obtain a state scholarship to MIT (known at the time as Boston Tech). He successfully applied for a scholarship and in the fall of 1891 started his studies at MIT (Fig. 3).

**Figure 3.** Coolidge in 1891 when he entered MIT [3]

MIT in 1891 consisted of only three buildings accommodating 1,200 students, and offering an engineering degree. At this time only the Military Academy at West Point was the only other institution where an engineering degree could be obtained.

The electrical engineering syllabus taken by Coolidge included some chemistry, mathematics, literature, modern languages and philosophy as well as professional engineering courses. In the chemistry course he was instructed by Willis Rodney Whitney (1868–1958) who was to have a major effect on his future professional life. He spent the summer between his junior and senior years at the East Pittsburgh plant of Westinghouse Electric and gained valuable knowledge of electrical manufacturing processes. Illness kept him out of MIT for a year so he graduated in 1896. In the year following graduation his interests went towards science studies and he took a position at MIT as an Assistant in Physics.

Probably the earliest publication on X-rays from MIT was by Charles Ladd Norton (1870–1939) [4] who in 1893 was a member of the Department of Electrical Engineering & Physics, becoming an instructor in 1895 and therefore must have been well-known to Coolidge.

## X-ray experiments in 1896

At the time of Röntgen's discovery of X-rays in November 1896, knowledge of which did not reach the U.S.A. till early January 1897. Coolidge was then at MIT where it is known that he experimented with X-rays, although his name did not appear as a co-author on any 1897 X-ray publications. The most important physicists and American universities and colleges involved with X-ray experimentation who published their results in 1896 included Thomas Alva Edison (1847–1931), Arthur Willis Goodspeed (1860–1943) of the University of Pennsylvania, Michael Idvorsky Pupin (1858–1935) of Columbia University, John Trowbridge (1843–1923) of Harvard University and Arthur Williams Wright (136–1915) of Yale University [5].

During the summer of 1896 Coolidge built at home an electrostatic machine with which he made a number of X-ray experiments. Most of the work was done in a small machine shop operated by one of his father's friends in Hudson. He later sold this machine to a local doctor for medical X-ray work [3].

There are now no published records of the equipment design but it was almost certainly what was sometimes termed an *influence machine*. An 1896 example of such a machine is the Wimshurst (Fig. 4) [6], but there were several other commercial designs made by American companies such as Waite & Bartlett of New York and Wagner & Company of Chicago. From the early 1880s and they were to be found in college, university and school laboratories, well before the discovery of X-rays. The number and sizes of the glass or mica circular plates varied. For example, an 1887 version of the Wimshurst machine had 12 plates each of 30″ (76 cm) diameter.

## General Electric Company

That G.E. (which was in 1905 to employ Coolidge) experimented with X-rays from the earliest days can be seen from an 1896 publication by the then Technical Director of General Electric, Edwin Wilbur Rice Jr (1862–1935) who was later to become President of G.E. His experimental set-up is shown in Figure 5 [7, 8]. He showed a *skiagraphy* of a purse containing coins and a key. The Wimshurst is shown schematically on the far right of Figure 5 with a spark gap

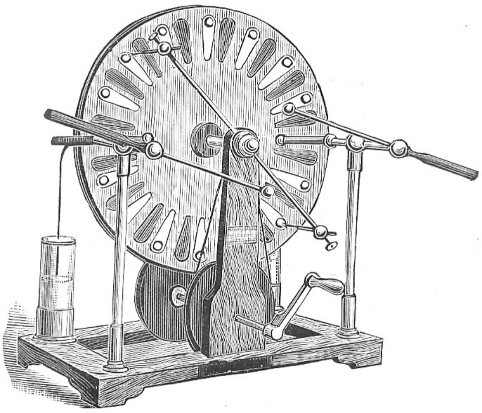

**Figure 4.** The Wimshurst electrostatic machine [6]

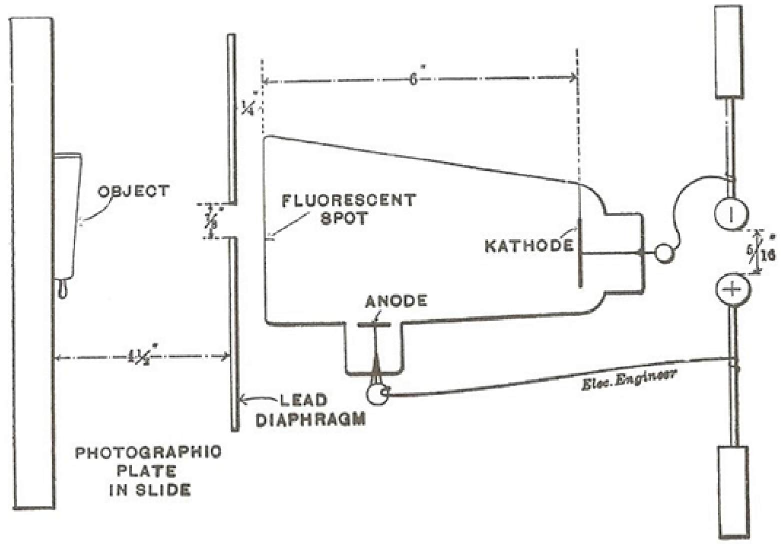


**Figure 5.** Schematic diagram of Rice's 1896 X-ray experiment [7, 8]

of 5/16 inches. His reason for publishing this work was his introduction of a lead diaphragm containing a small central opening of 0.875″ diameter, opposite the fluorescent spot. The X-ray image took 60 minutes with this set-up, but only 30 minutes if the diaphragm was removed. However, the diaphragm made the 'shadows' sharper. The X-ray tube was the early pear-shaped design rather than the spherical glass bulb design which was generally adopted by mid-1896.

In addition, Edwin James Houston (1847–1914) and Arthur Edwin Kennelly (1861–1939) who were electrical engineers who formed a consulting company were employed by G.E. in 1896 to provide a review of Edison's experiments, [5, 9].

## Leipzig University

In 1897 Coolidge applied for a grant, for the following year, to undertake graduate work at the University of Leipzig. This was encouraged by Whitney who had also studied in Leipzig. The grant was topped-up by a loan from a friend as it was not sufficient to cover all expenses for this European graduate study. His teachers included the physicist Gustav Heinrich Wiedemann (1826–1899) who is famous for being the editor 1877–1899 of *Annalen der Physik* {*Wiedemann's Annalen*}, *Leipzig*; and Paul Drude (1863–1906) a famous optical physicist. Coolidge's first two published papers are to be found in *Annalen der Physik und Chemie* 1899 [10, 11].

During vacations Coolidge took short trips to Italy and Bavaria, taking photographs which he developed in an improvised darkroom in Leipzig. He also made great efforts to improve his German by talking to Germany students at all opportunities (avoiding English and American students!), attending German church services and living with a Germany family.

In his second year in Leipzig he became Lecture Assistant to Drude. In July 1899 he received high marks in all examinations and was awarded his doctorate summa cum laude. His dissertation was published in *Annalen der Physik*. During this time, in 1899, Wilhelm Conrad Röntgen (1845–1923) visited the Leipzig Physikalisches Institute, and as Drude's assistant Coolidge was able to meet and talk with the discoverer of X-rays. Apparently Coolidge was greatly impressed by this experience [1].

## Return to MIT 1899–1905 & starting work at the General Electric Research Laboratory in Schenectady

His application to MIT for a teaching position coincided with an opening in the Physics Department for the fall term of 1899 and in 1900 Coolidge became a research assistant to the chemist Arthur Amos Noyes (1866–1936), where he remained for five years [12, 13]. During this period at MIT he also published work on an apparatus for calibrating voltmeters [14]. Willis Whitney worked in an adjacent laboratory to Noyes at MIT, and he was also commuting to Schenectady during these formative years of the General Electric Research Laboratory which was founded in 1900. Whitney offered Coolidge a job and William started at the GE Research Laboratory in 1905.

## Incandescent lamp research

Whitney had already made improvements in lamp filaments for what was called the GEM lamp, which was about three times more efficient than Thomas Edison's lamp. Research and experimentation on lamps was taking place in both Europe and the USA. For example, the Austrian chemist Carl Auer von

Welsbach (1858–1929) produced a gas mantle with a filament of osmium. The powdered metal was extruded, then sintered and mounted in the bulb. The resulting lamp worked but was extremely fragile. (The Welsbach Street Lighting Company of America in 1896 installed the first gas lamps with mantles in the USA, in Freehold, New Jersey.) A similar process had been undertaken with tantalum powder, but with the same fragile effect.

Alexander Just (1874–1937) and Franz Hanaman (1878–1941) in Vienna also used a similar process to produce a tungsten filament. These were made by extruding a paste of tungsten powder and a carbonaceous binder to produce a fine thread, then removing the carbon by heating in an atmosphere of hydrogen and water vapour. In 1905 Just & Hanaman then patented a process for producing tungsten filaments by plating carbon filaments with tungsten, then removing the carbon by heating. However, the problem of brittleness still remained.

These early tungsten lamps were more efficient than those with a carbon filament, because they could operate at a higher temperature, due to the high melting point of tungsten. However, their brittleness meant that they were of limited practical use.

General Electric purchased rights under the Just & Hanaman patent and Coolidge started working with tungsten (abandoning his previous work with tantalum filaments) and found that sintered filaments of tungsten will lose their brittleness if passed through a rolling mill with heated rollers: a discovery that greatly improved the efficiency of light bulbs. It then took Coolidge some three years of research to develop a process whereby tungsten was made sufficiently ductile at room temperatures to permit drawing through diamond dies. Close control of temperatures, of tungsten powder grain size, and of trace metal additions (particularly thorium) contributed to the final successful result. GE lamps with ductile tungsten filaments appeared on the market in 1911 and have dominated the lighting industry ever since. The technique for producing ductile tungsten filaments passed from the General Electric Research Laboratory into commercial production first at Harrison and then totally at the Cleveland Wire Works (GE as formed in 1892 contained the Edison Lamp Works at Harrison, New Jersey).

The history of incandescent lamps with ductile tungsten filaments can be found in references by Miller [3]. Hirst [15] and Jeffries [16, 17]. A selection of papers written by Coolidge on ductile tungsten are listed in the References section [18–20] for 1910–1912.

## Roentgen ray research: X-ray tubes

Coolidge first published on Roentgen ray research in March 1912 [21] but it was not until 1913 that the so-called *hot cathode X-ray tube*, also called the *Coolidge X-ray tube*, was to become available commercially. Until this time the standard X-ray tube worldwide was the gas tube, and more than 100 designs were made. The pear-shaped glass bulb version was used by Wilhelm Conrad Röntgen (1845–1923) when he discovered X-rays in 1895. This was sometimes termed a *Crookes' tube* after Sir William Crookes (1832–1919). However, the bulb shape was rapidly changed to become spherical and two major improvements were made by incorporating a metal target and a concave-shaped cathode, the *focus X-ray tube*. Figure 6 is a schematic diagram of the original pear-shaped X-ray tube.

The glass envelope is airtight and has two electrodes sealed into it. The tube is evacuated to a low pressure with some gas molecules remaining (hence the name *gas tube*). The electric discharge when a high voltage is applied between the electrodes causes ionisation of the gas atoms, and the positive ions are driven towards the cathode by the electric potential across the tube. The bombardment of the cathode by these positive ions causes emission of electrons which on striking the target (which in Figure 6 is the large end of the glass wall of the tube) generate X-rays. There were many problems with these gas tubes, which

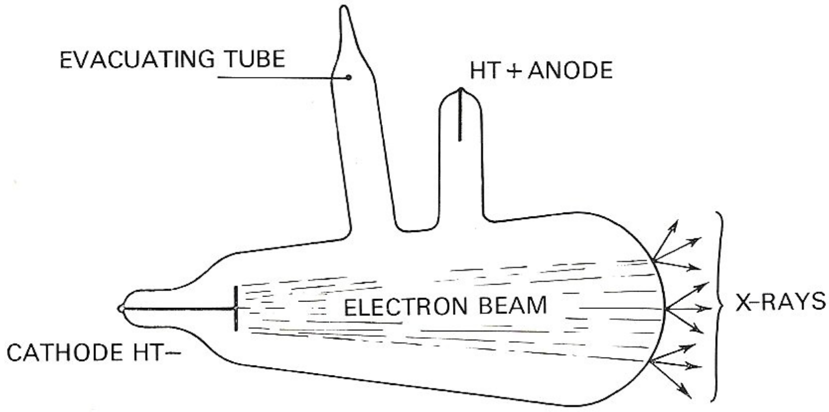


**Figure 6.** A gas X-ray tube [22]

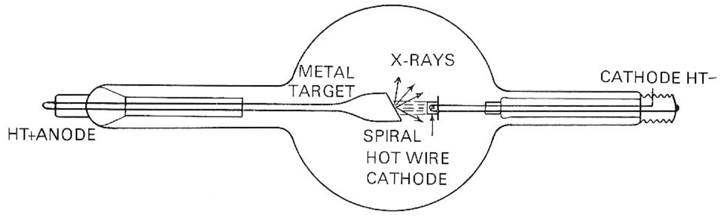


**Figure 7.** Coolidge X-ray tube [22]

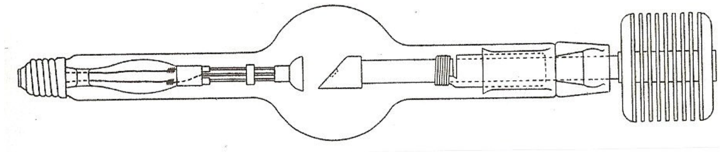

**Figure 8.** Radiator-type Coolidge X-ray tube [29]

were of very low power and could not produce high energy hard X-rays. Exposure times were lengthy, targets became overheated and tubes often did not last too long because they became punctured. Improvements in X-ray tubes for diagnosis and therapy were therefore badly needed and this need was filled by the hot cathode tube developed by William Coolidge. It became so successful that the gas tube soon became obsolete. Figure 7 is a schematic diagrams of a Coolidge tube such as was available in 1914 [23].

One of the disadvantages of the gas tube was the variation in the degree of the vacuum over a period of time. In the gas tube a reduction in gas pressure leads to a higher operating voltage and hence more penetrating (termed *harder*) X-rays. However, because there is less gas in the tube, the current falls and the intensity of the X-ray beam is reduced This is because the voltage across the tube and the current through it are inter-dependent.

In the X-ray tube produced by Coolidge the vacuum is as near perfect as possible and the electrons are produced by *thermionic emission*. The cathode is no longer a cold metal block (as in the later designs of gas tube), but a tungsten filament heated to incandescence by a current passing through it. The filament is usually mounted within, and electrically connected to, a shaped metal block which focusses the electrons on to the target. The intensity of the X-ray output depends only on the current in the electron beam, which is a function of the temperature of the filament. This can be controlled by adjusting the current in the filament. Thus with the Coolidge hot cathode X-ray tube the intensity and penetration of the X-ray output are independently controlled by adjustment of the filament current and tube voltage, respectively.

Coolidge continued to publish on hot cathode X-rays tubes after 1914, both original work and reviews, in 1915 [24–26], in 1917 [27, 28], in 1918 [29, 30]. A schematic diagram of a radiator type X-ray tube [29] is shown in Figure 7. It was built with a copper-backed tungsten target that operates over a wide range of energy ratings and which is capable of rectifying its own current. Many more published papers followed from 1919-onwards [31–84].

Albert Edward Coolidge = Martha Alice Shattuck
1849–1943 | 1849–1935

mar. 1908 | mar. 1916

Esther Westcott Woodward ??–1915 = William David Coolidge 1873–1975 = Dorothy Elizabeth MacHaffie 1888–1969

Elizabeth Coolidge ??–?? = ..... Smith

Lawrence David Coolidge 1913–2003 = Elizabeth Jane Ferguson

## Marriages

William had two children from his first marriage, his wife, Esther, dying at a young age. His son, Lawrence, who was a United States Army World War II veteran, obtained a PhD in 1950 from Columbia University and ended his professional career as Dean of the School of Business, University of Colorado at Boulder. His second wife, Dorothy, was a nurse whom he had employed to help his mother look after his two children, following his wife's death. They married within the year. There were no children from this marriage.

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