# Preparative Scale Mass Spectrometry: A Brief History of the Calutron

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Calutrons were developed in the laboratory of E. O. Lawrence at the University of California at Berkeley. They were a modification of the cyclotrons he had invented and used in his Noble Prize winning investigations of the atomic nucleus. At the time their construction was undertaken, calutrons represented the only certain means of preparing enriched uranium isotopes for the construction of a fission bomb. The effort was successful enough that every atom of the 42 kg of $^{235}U$ used in the first uranium bomb had passed through at least one stage of calutron separation. At peak production, the first stage separators, $\alpha$ tanks, yielded an aggregate 258-g/d $^{235}U$ enriched to about 10 at. % from its natural abundance level of 0.72 at. %. The second stage separators, $\beta$ tanks, used the 10 at. % material as feedstock and produced a total 204-g/d $^{235}U$ enriched to at least 80 at. %. The latter, weapons grade, material was used in fission bombs. Under typical operating conditions, each $\alpha$ tank operated at a uranium beam intensity at the collectors of approximately 20 mA and each $\beta$ tank at a beam intensity of approximately 215 mA at the collectors. Bulk separation of isotopes for bomb production ceased in 1945. Since that time calutrons have been used to separate stable isotopes, but on a more limited scale than wartime weapons production. Stable isotope separations since 1960 have taken place using one modified beta tank. (J Am Soc Mass Spectrom 1997, 8, 943–953) © 1997 American Society for Mass Spectrometry

The purpose of this Account and Perspective is to recount the story of the development and use of preparative scale mass spectrometers, the calutrons. The initial development of these electromagnetic isotope separators occurred as part of the Manhattan Project. Since this critical war effort, the Atomic Energy Commission and its successor, the Department of Energy, have used calutrons to separate isotopes that are used for physical and biomedical research. For example, calutrons have been operated, under ISO 9000 conditions, to separate an isotope for a cancer treatment protocol approved by the Food and Drug Administration.

Using calutrons for peaceful purposes yields tens to hundreds of grams per year of highly enriched, physically and biomedically significant isotopes which are often minor components of an element's natural isotopic distribution. However, this important and impressive contribution to research pales in significance to the magnitude of the accomplishments in the period of 1940–1945 [1]. The Y-12 project, the wartime name for calutrons, originated as a concept for large scale isotope separation in 1941, and produced 200 g of 12 at. % $^{235}U$ by February, 1942. While this separation represents more than a 15-fold increase in enrichment from the natural abundance level of 0.72 at. %, it was only about one seventh of the enrichment estimated at that time to be necessary for an atomic weapon. Remarkably, within 18 months, 43 kg of weapons grade, i.e., $\geq$85 at. % enrichment, $^{235}U$ had been produced. This amount of fissionable isotope required more than 5000 kg of natural abundance uranium to have passed through the calutrons!

Despite the fact that the events recounted below occurred more than 50 years ago, complete details of how this astounding feat was accomplished cannot be obtained by the public. We were initially surprised at our inability to have access to such materials pertinent to the work done during World War II. We found that while few, if any, of the individual aspects of the calutron development and production work are classified today, aspects of the wartime work that would provide detailed information about production rates and operational efficiency are not available to the public. When one realizes that during the recent Persian Gulf War, calutrons were found to be part of the Iraqi

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government's atomic weapons development program [2], the basic wisdom for such restrictions is apparent.

This account of the development and use of calutrons is a composite of both the history of a portion of mid-20th century physics and the history of the Manhattan Project. It differs from accounts of those areas because it considers events in either of them only as they bear on calutron development. In this sense, the following account is unique. For those interested in a broader picture of early 20th century physics or the Manhattan Project, an annotated reading list is given as an Appendix.

## Historical Background

Between 1927 and 1931 Ernest Lawrence invented the cyclotron in order to generate protons with sufficient energy to disrupt the atomic nucleus and explore interactions between those protons and the nucleus. Theoretical calculations at the time estimated that 1-MeV protons would be required for this task. In 1927 Lawrence saw reports of European work using a linear accelerator to generate high energy particles. Lawrence realized that to obtain 1-MeV protons from such devices would require prohibitively long tubes. In his biography, Herbert Childs describes Lawrence's next step in a manner that makes it clear that the step was pure inspiration [3, p. 139]. Lawrence realized that using a magnetic field could confine accelerating particles to circular trajectories, thereby giving all particles constant angular velocity. The radius of the particle trajectories would, however, depend on their energy. The particles underwent successive resonant acceleration through the application of radiofrequency voltage across the gaps of magnet pole pieces, the "Dees." In 1929 Lawrence and Niels Edlefsen, his first graduate student, assembled a 4-in.-diameter version of the device [4]. Initially this device produced 1300-eV protons. Use of a stronger magnet led to 80-kV protons. By July, 1931, Lawrence had designed and constructed a 1-MeV proton instrument.

In 1932 Cockroft and Walton reported that a Li target bombarded with high energy protons yielded a pair of $\alpha$ particles accompanied by the release of $8.6_2$ MeV [5]. Within a few months, the work had been replicated at the University of California at Berkeley [6]. The accelerator results were used by Kenneth Bainbridge in conjunction with mass spectrometric measurements to demonstrate the equivalence of mass and energy [7]. Bainbridge used his exact mass measurement of $^7$Li and F. W. Aston's measurements of the masses of hydrogen and helium [8] for the calculation. The mass difference of $0.018_1$ units on the $^{16}$O scale calculated by Bainbridge is equal, within experimental error, to a mass of 0.0182 mass units, equivalent to the energy release of the accelerator measurements.

In 1938 Otto Hahn and Fritz Strassman discovered nuclear fission. They found that uranium which had been bombarded with slow neutrons yielded small nuclear fragments and a great deal of energy. Hahn and Strassman's investigations allowed them to identify radioactive barium as a product, measure an energy release of about 200 MeV and observe the production of additional neutrons [9]. Their colleague Lise Meitner calculated that these results were entirely consistent with the equivalence of mass and energy [10]. Within a week of the publication of Hahn and Strassman's work, there was wide recognition that such results might lead to an atomic bomb [11, pp. 252–261; 12, p. 7].

In this same year, Nazi Germany expanded rapidly. Germany annexed Austria in March and the Czechoslovak Sudetenland in September. By March, 1939, the remainder of Czechoslovakia had been seized. The potential consequences of an atomic weapon in the hands of the Third Reich prompted grave concerns among a number of scientists who had fled the Nazi regime and settled in the United States. Prominent among this group were Leo Szilard, Enrico Fermi, Edward Teller, and Eugene Wigner. While the plans of German physicists were not known to this group, it was certain that the Germans, in principle, were very capable of developing an atomic weapon. The group began to plan ways to circumvent Germany's acquisition of such a weapon.

Planning by the group of concerned scientists resulted in a letter from Albert Einstein to President Franklin D. Roosevelt [11, pp. 305–315]. Dated August 2, 1939, but not delivered until October 11, the letter was presented to the President by his long-time informal advisor, Alexander Sachs, an economist trained in biology and interested in physics. The delay in delivering the letter was caused by the pressure of world events. Between the letter's writing and delivery, Adolph Hitler and Josef Stalin signed the German–Soviet Non-Aggression Pact, and Germany invaded Poland on September 1. The President's initial response to the letter and to Szilard's appended comments has been described as one of "skeptical interest" [12, p. 14]. Another report states that Roosevelt immediately called in his aide, General Edward M. "Pa" Watson, and told him that "this requires action" [11, p. 314]. In either case, Lyman Briggs, then director of the National Bureau of Standards, was directed to organize what became known as the Advisory Committee on Uranium. At the initial meeting of the Advisory Committee held on October 12, 1939, Army and Navy ordinance experts, Lt. Col. Keith F. Adamson and Cdr. Gilbert C. Hoover, were openly skeptical of the possibility of an atomic weapon or of its possibility of being used in the present war [11, pp. 315–317]. Their cautious attitude outweighed the more optimistic opinions of Sachs, Briggs, Wigner, Szilard, and Teller. Most likely, this resulted from the overall conservative nature of the military when confronted with novel possibilities offered by science. As a consequence, support for research on the feasibility of fusion was minimal. Fermi was granted $3000.00 to buy pure graphite and investigate its properties as a neutron moderator [12, p. 23].

Despite what must have been a disappointing official response, investigations into uranium fissionability continued. Late in 1939, Fermi and John Dunning at Columbia University asked Alfred O. Nier of the University of Minnesota to try separating and collecting the uranium isotopes. Since Nier had made the original measurements of the natural abundance isotope distribution of uranium several years earlier, the request was appropriate. Nier assembled a new mass spectrometer for the isotope collection, and by February, 1940, had collected samples of $^{235}U$ and $^{238}U$ on Ni foils. He accomplished this using the tetrachloride and tetrabromide salts after an early attempt to use the very volatile $UF_6$ salt led to a hopelessly contaminated instrument. Nier collected samples over a 2-day period and mailed them to Columbia by pasting the foils onto the margin of a handwritten letter. Less than two days later, Dunning completed the measurements. He showed that $^{235}U$ was the isotope responsible for slow neutron fission of uranium. Demonstration of the fissionability of the minor uranium isotope proved the need for isotope separation in order to produce a uranium atomic bomb.

In retrospect, it is astounding that, within 20 years of recognizing the existence of isotopes in nature, isolating bulk quantities of a particular minor isotope of a metallic element had become a necessity. The feasibility of performing such separations had been debated since about 1939, and Lars Onsager had argued that gaseous diffusion might be a way to effect such a separation. By early 1941, Lawrence began to think that he could adapt his cyclotrons to become isotope separators.

Simultaneously with the work on separating and identifying the fissionability of $^{235}U$, there was other fundamental work being done on the nature of reactions of the atomic nucleus. These studies were concerned with the interaction between the atomic nucleus and high energy protons or deuterons and led to the discovery of the transuranic elements. In the spring of 1940, Edwin McMillan and Philip Abelson at Berkeley identified element 93, which they named neptunium. The publication of their results in the July 15 issue of Physical Review [13] was the source of a formal protest by Britain to the United States. At war with Germany, the British felt that such information was an inappropriate revelation of what should have been considered "nuclear secrets" [11, p. 351]. By late 1940, the work had advanced to the point where Glenn Seaborg and McMillan had nearly identified $^{238}Pu$ on the basis of its $\alpha$-particle emission spectrum [14, 15]. Proof of the fissionability of the $^{239}Pu$ isotope followed rapidly [16], and thus, a use for the abundant, but nonfissionable, $^{238}U$ had been found. The lapse between the submission and publication dates of the last papers should be noted. The lapse was not a consequence of major problems in the editorial offices of Physical Review, but of the recognition of the strategic importance of the Berkeley discoveries. While, in retrospect, the German approach to an atomic weapon did not realize the significance of the McMillan paper of 1941, the British protest of its publication certainly must have hastened the decision to delay publication of the Pu discoveries.

**Table 1.** Fission bomb status—November 1, 1941

| |
|---|
| Critical mass of $^{235}U$ is 2–100 kg |
| 1–10 tons of $^{235}U$ expected to equal $5 \times 10^5$ tons TNT |
| No chain reaction achieved |
| No large quantities of uranium metal or moderators |
| No appreciable separation of $^{235}U$ |
| Only infinitesimal amount of Pu exists |

Simultaneous with the experimental work that led to the discovery of new elements, there were widespread attempts to estimate the mass of U or Pu necessary to establish a self-sustaining production of neutrons, the critical mass. In 1939 Rudolf Peierls, a German emigre to Britain, used the relationship between the surface area and volume of a mass, in conjunction with estimates of nuclear neutron capture cross sections, to calculate a 30-ton critical mass for natural uranium. Clearly this was an unwieldy amount of material. Demonstration of $^{235}U$ fissionability and early estimates of its neutron capture cross section allowed Peierls' values to be reduced about 200-fold for the fissionable isotope.

By the end of November, 1941 the feasibility of a fission bomb was accepted. The status of such a bomb is summarized in Table 1. Several significant conclusions can be drawn from this table. First, the estimates of the amount of fissionable isotope varied by a factor of ten. That the estimates are no more disperse than this is remarkable considering the state of knowledge at the time and the absence of any proof for the chain reaction needed for a bomb or reactor. Second, there was virtually no fissionable material in existence nor had any neutron moderators, necessary to control any chain reaction, been demonstrated. At that time, a report from the National Academy of Sciences, under the auspices of the Office of Scientific Research and Development (OSRD), said, "If all possible effort is spent on the program, fission bombs [might] be available in significant quantity in three or four years" [12, p. 32]. The National Research and Development Council (NRDC), a research division of the OSRD, was the committee of scientists closely involved with the questions surrounding the development of atomic weapons. The NRDC recognized that it or any existing private or government institution was unable to organize the construction and manufacturing of an atomic weapon. For this reason, it was decided, in consultation with President Roosevelt, to turn over the these tasks to the Army. The Army assigned the Corps of Engineers the job, and the latter created the Manhattan Engineering District [12, pp. 31–35].

By September, 1942, the Manhattan Engineering District had selected Oak Ridge, TN as the site at which to conduct uranium enrichment operations. This 54,000-acre site was isolated geographically and was far

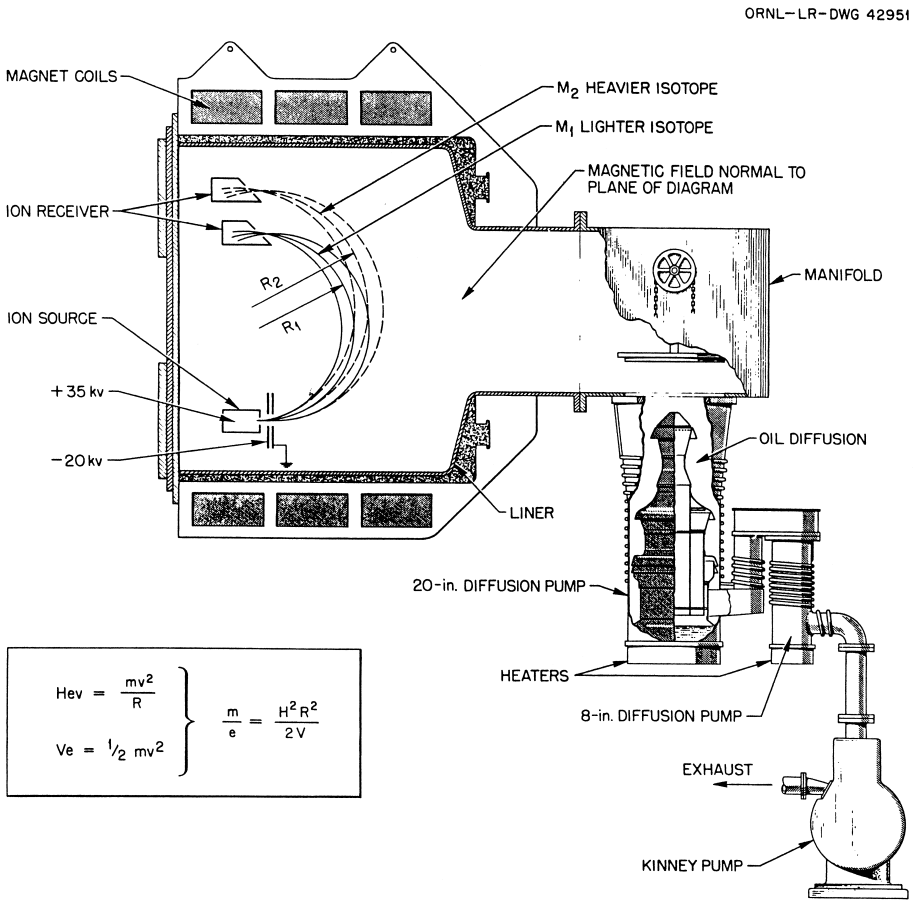


**Figure 1.** Schematic of second stage, $\beta$ unit, separator. ORNL Drawing 42951.

enough from the ocean that invasion threats were accepted as minimal. The area was sparsely populated; only 1,000 families had to be relocated. The Oak Ridge site had the additional geological advantage of being a series of isolated valleys that would limit damage in adjacent sites in case of plant failures. A final major advantage was the ability to supply large amounts of electrical power from the nearby Tennessee Valley Authority hydroelectric dams which had only recently been completed. The Oak Ridge reservation, or the Clinton Engineering Works, thus became the site of the Y-12 electromagnetic separation plant, the K-25 gaseous diffusion plant, and the X-10 graphite reactor for pilot plant plutonium production studies.

By 1945, Oak Ridge, TN was a town housing approximately 64,000 workers and their families. The task of housing, feeding, and washing these people was substantial, including what may have been the first 24-h grocery store operation in the United States. Single family houses and dormitories were built. Serious efforts were made to make the surroundings pleasant by including theaters, bowling alleys, athletic fields, taverns, and churches [17, p. 17; 12, p. 445]. The extent to which this effort was successful is the degree to which many of the original homes in the center of the town are still valued for their location.

## Development and Operation of the Calutrons

By early 1942 Ernest Lawrence and his group at Berkeley were able to demonstrate the feasibility of using modified cyclotrons for isotope separation. These devices became known as calutrons. The origin of this composite word is from "CalU," i.e., Berkeley, and "tron," a Greek suffix meaning instrument.

The classic calutron is a 180° sector homogeneous magnetic field instrument with the source and collector internal to the magnetic field. It employs a side extraction ion source, produces a line image at the collector and has multibeam capabilities. Figure 1 is a schematic drawing of a second stage, beta unit, separator. With the magnetic field directed into the page, the schematic shows trajectories for two positively charged isotope ions. The schematic shows only one pair of collectors, also known as receivers. In practice, each ion source assembly employed either two or four pairs of receivers. Each vacuum system assembly, also known as a tank, held the ion sources and their associated collectors. The main portion of each ion source contained the number of slit assemblies required to produce separate ion beams for each receiver. Some concept of the scale of these devices can be obtained from the diffusion

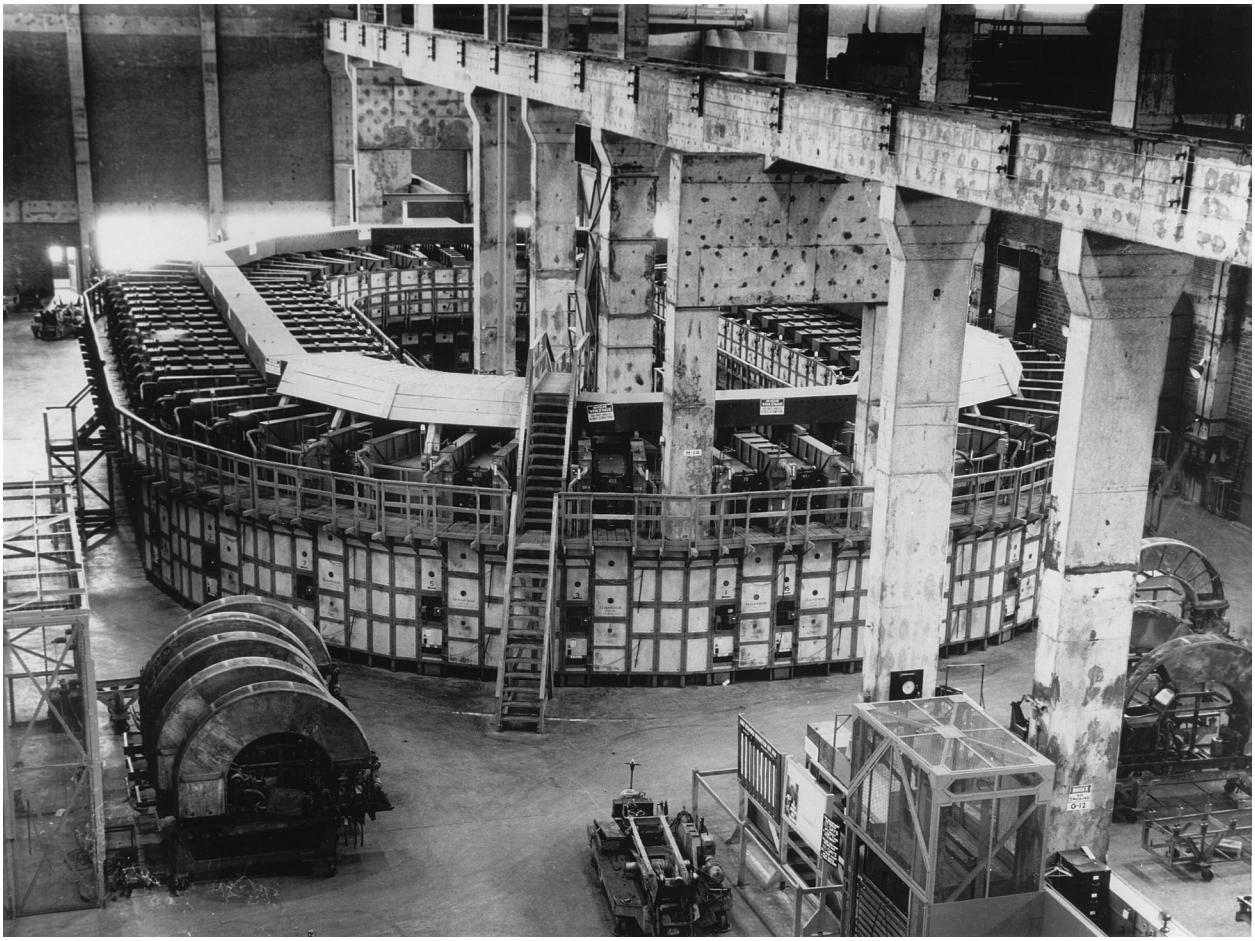

**Figure 2.** Photograph showing $\alpha$ unit "race track" assembly of calutrons. Photo source: ORD-PRO-2031.

pump dimensions. Each tank was evacuated using a 20-in. diffusion pump backed by an 8-in. diffusion pump backed in turn by a roughing pump. The diffusion pumps were backed by dry-ice cooled traps that were approximately as effective as the pumps themselves in achieving the operational vacuum. Working pressures were in the region of tens of millitorr.

Tanks were grouped into large assemblies. Initially, the large first stage separators, $\alpha$ units, were grouped into an oval assembly of 96 tanks, each tank separated from the others by their coils and magnet pole pieces. In this original configuration each tank had two opposing separators each operating with two ion beams and receiver pairs. The shape of these assemblies led to them being called "racetracks," or "track." A sense of the overall scale of these tank assemblies is given in the photograph of an $\alpha$-1 racetrack shown in Figure 2. The tanks are located down and between the higher structures which contain the oil cooled magnet coils. The walkway over the top was necessary to provide access to the source and collector assemblies in the rear center portion of the track.

The $\alpha$ units were first stage separators that enriched natural uranium to >10 at. % $^{235}$U. Material obtained from this approximately 20-fold enrichment from the natural abundance level was used as feed for the second stage separators. The $\beta$ units yielded $^{235}$U of weapons grade enrichment, $\geq$88 at. %. While it would have been desirable to have achieved the entire separation in a single stage operation, this feat was accomplished only after the time when calutrons were used for large scale $^{235}$U production. Initial versions of the $\alpha$ units, as well as all the $\beta$ units, operated with two ion beams from a single source. Later $\alpha$ units operated with four ion beams per source. All $\beta$ units operated with 36 tanks per track while the $\alpha$ units were kept at 96. Operating conditions for the calutrons under conditions for uranium separations are summarized in Table 2. The total of 864 $\alpha$ tanks that were ultimately in operation at the Y-12 site consisted of five tracks, 96 tanks per track, of the double beam $\alpha$-1 units and four tracks 96 tanks per track, of the quadruple beam $\alpha$-2 units. The 288 $\beta$ calutrons ultimately in operation consisted of eight tracks of 36 dual beam units per track. Only 216 of the 288 units ever operated.

Figure 3 is a photograph of one of the double beamed beta sources. Samples of $UCI_4$ were loaded into a charge bottle and placed into an oven. This is the rectangular

**Table 2.** Calutron operating conditions (a) and estimated calutron efficiency (b)

(a)

| | $r$ (cm) | $B$ (G) | $2\Delta r$ (mm) | $n$ |
|---|---|---|---|---|
| *alpha* | 122 | 3200 | 15.6 | 864/96 (5 $\alpha$-1, 4 $\alpha$-2) |
| *beta* | 61 | 6400 | 7.8 | 216/34 |

Accelerating voltage = 35 kV
Magnet power/tank ~4500 kW, 7500 A at 600 V
Pumping capacity ~7.5 $m^3/s$
$n$ = number of units = tanks/tracks

(b)

Change ~100-g $UCl_4$
Sample rate: 1–4 g/h
Peak production rate ~200 g/day of ~88 at. % $^{235}U$
(42-kg, 88-at. % $^{235}U$ in 6 months)
~20-mA beam current in $\alpha$ unit
~215-mA beam current in $\beta$ unit
Only 10% of charge reaches collectors

container seen in the center of the source. After bolting the source flange into place and pumping down, the sample was heated. The ovens were heated resistively to volatilize the salt in the charge bottles at a rate of 1–4 g/h of $UCl_4$. Electron ionization, using two heated 11/64-in.- (4-mm)-diameter tantalum rods, produced beams that were focused onto the solid graphite collectors. Filaments were operated about 50 eV below the 35-kV potential applied to the source. The electrostatic focusing electrodes were used to maximize ion intensity to the collector. The size of these collector assemblies in the $\alpha$ units may be seen in Figure 4. Several charge bottles were typically used before removing the collectors. Uranium was recovered by burning the graphite receivers and extracting the metallic uranium from the ash.

Vacuum system liners were removed for cleaning at approximately the same time as the collectors. This was necessary in order to recover the approximately 90% of the charge of a given run that was deposited along the sides of the liner. This transmission efficiency was about the same as that of a typical mass spectrometer. The major loss could be accounted for by the low ionization efficiency of vaporized $UCl_4$. Neutral vapors then escaped from the source and deposited onto analyzer walls. A second source of loss was due to dissociative fragmentation of $UCl_4$ yielding species other than $U^+$. Tank liners as well as the source and collector assemblies were removed from the tracks using special gantries designed for the task. The liners were cleaned, vacuum tested, and recycled for use. Figure 5 is a photograph of part of the cleaning operation. Cleaning the tanks was not a delicate job. Hand scrapers and wire

**Figure 3.** $\alpha$ one calutron source showing charge box heater and two sets of filament heater ceramic standoffs. ORNL Photo 24574.


**Figure 4.** $\beta$ unit collector assembly with labeled collector slits for one isotope pair. ORNL Photo 74250.

brushes were used on the liner inner surfaces. This work was done over a large sink in order to recover the metal sputtered on the liner surfaces for conservation of critical material. Such conservation was necessary, particularly for the $\beta$ units, since the material on the liners was already appreciably enriched. After the cleaning operation, liners, sources, and collector assemblies were leak tested in a special so-called "dry dock" vacuum manifold in order to minimize possible production down time. The possibility of radiation hazard to the workers was not a major consideration because the chemical toxicity of uranium is a far more substantial risk than its radiation hazard. The chemical risk is associated with kidney failure, but, in acute exposures at least, can be reversed through flushing with bicarbonate salts.

Figure 6 shows a shift change on August 11, 1945, 2 days after the Nagasaki bomb, at an entrance to the Y-12 plant. While the photograph is not necessarily indicative of the age and gender composition of the Y-12 workforce, women were generally more available than men as calutron operators. Operators were taken from the labor pool present in the nearby cities of Knoxville and Clinton, TN. Women were a major component of the work force at Y-12 because men were away in uniform. The men employed at Oak Ridge worked in the more skilled positions associated with machine trades. Typically, only high school educated women calutron operators were preferred to physicists because they could be relied upon to keep their eyes on the measured beam currents and make only minimal adjustments to operating voltages and tank pressures. Physicists, on the other hand, had a reputation for trying to make the system perform better by making constant adjustments to the controls. Of course, there were exceptions to the use of young women. Dr. Albert Myers, from whom an oral history was obtained at the outset of this project, was briefly an operator, but later became an instructor of new operators.

The Y-12 plant was operated full time, 7 days a week at its peak. By August, 1945, sufficient $^{235}U$ had been separated to produce a bomb. The amount of fissionable uranium produced is summarized in Table 3. This material shown in this table includes some material that had undergone an initial stage of separation by gaseous diffusion. Nevertheless, every atom of uranium in the first atomic bomb had gone through at least one stage of enrichment by the calutrons.

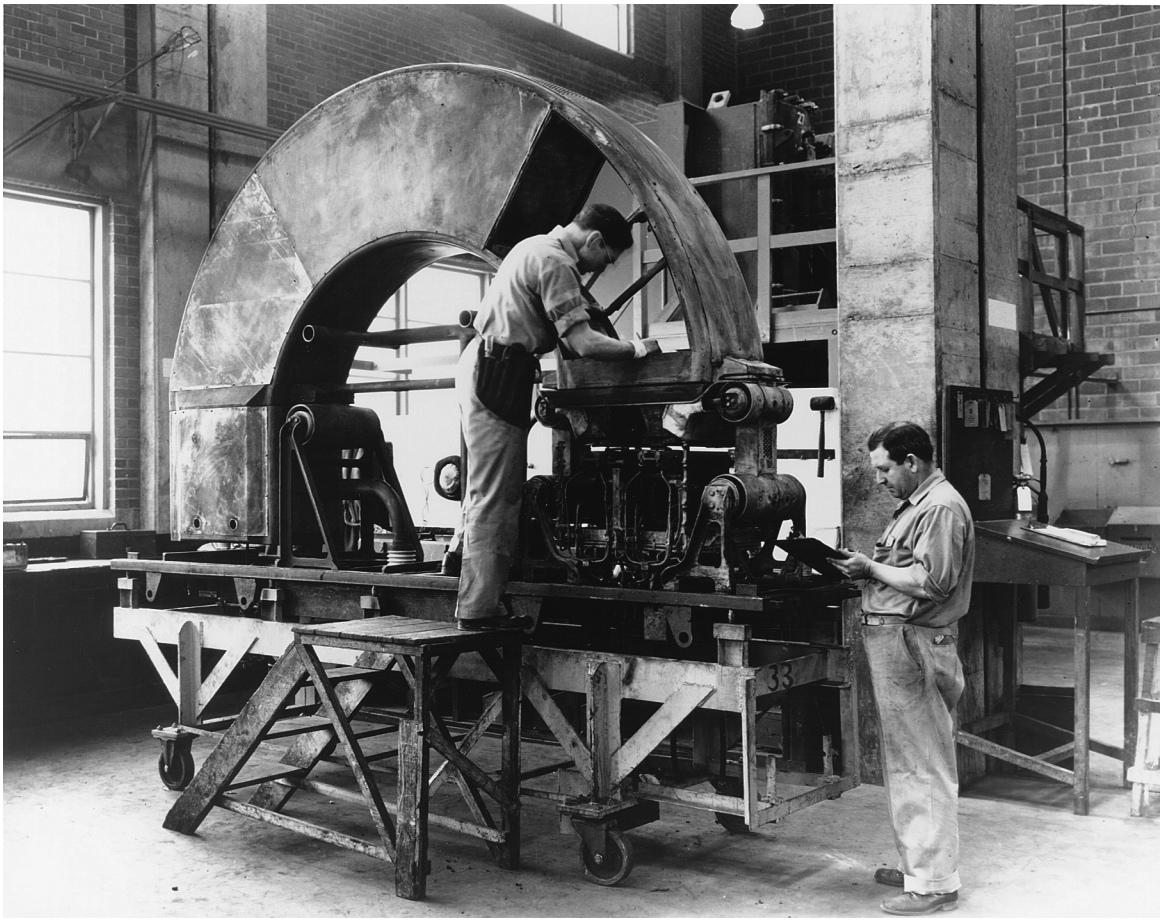

**Figure 5.** Tank liner during cleaning process. Photo source: Y-12 154.


**Figure 6.** Y-12 shift change on August 11, 1945. Photo source: PRO 936.

**Table 3.** Summary of wartime uranium-235 production

| |
|---|
| February, 1944: total of 0.2-kg $^{235}$U of 12 at. % produced |
| August, 1945: 42-kg weapons grade $^{235}$U produced |
| This required: |
| 5100-kg natural uranium |
| ~50-kg natural uranium through each of 864 $\alpha$ units |
| 2-kg 12-at. % $^{235}$U through each of 216 $\beta$ units |

Note: natural abundance $^{235}$U is 0.72%.
Weapons grade $^{235}$U is ~88 at. %.

## Calutrons Since 1945

By late 1945 $^{235}$U production using the essentially brute force calutron separation method had become obsolete and the use of calutrons for producing weapons grade uranium was phased out. In late 1945 a program for using the calutrons for separating stable isotopes was begun. Initially this program used two $\beta$ and two $\alpha$-2 calutrons that were located in the calutron pilot plant. In 1960, the stable isotope program expanded to the use of an entire $\beta$ track. The stable isotope separation program has been used for the enrichment of isotopes used in research, medicine, and industrial applications. This conversion of weapons technology into peaceful uses represents an important example of such a change, similar to the advent of commercial jet aviation, space exploration, and antibiotics.

There are a number of anecdotes about shutting down the calutrons. Love reports [1] that in order to assure a supply of spare parts one had to "recover" surplus material by passing it from a dump site back inside the restricted operating area and return it to storage. This approach was so effective that, to the present day cases containing source and collector insulators are still in the operating building and in packing cases addressed to the Clinton Engineering Works. Needless to say, such insulators would be prohibitively expensive to obtain today.

However, perhaps the most interesting anecdote related to the calutrons is the story of the silver magnet coils (Figure 7). As a result of war time shortages, most of the $\alpha$ and about half of the $\beta$ unit magnet coils were made of silver rather than copper. During the calutron construction period, 1942–1945, copper in brass shell casings received a higher priority than calutron construction. Scientists involved in construction of the coils needed another metal. Research indicated that there were large stores of silver, an excellent electrical conductor, in the federal treasury repository at West Point,

**Figure 7.** Calutron silver coils before return to U.S. Treasury. Photo source: Y-12 126949.

**Table 4.** Total stable isotope separations

| | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| H | | | | | | | | | | | | | | He | | | | | | | | |
| Li | 2985<br>35.9 | Ba | 0.003<br>1.3 | B | 65<br>9.5 | C | 150<br>10.3 | N | 41<br>2.5 | O | 0.022<br>0.5 | F | | Ne | | | | | | | | |
| Na | | Mg | 2889<br>47.7 | Al | | Si | 5757<br>146 | P | | S | 3447<br>127 | Cl | 451<br>26.1 | Ar | | | | | | | | |
| K | 2200<br>45.5 | Ca | 46,342<br>355 | Sc | | Ti | 2561<br>41.5 | V | 186<br>5.8 | Cr | 4088<br>55.3 | Mn | | | | Fe | 30900<br>224 | Co | | Ni | 11,106<br>123 | |
| Cu | 3517<br>43.6 | Zn | 1628<br>18.2 | Ga | 713<br>14.6 | Ge | 1663<br>22.1 | As | | Se | 784<br>31.0 | Br | 572<br>22.8 | Kr | | | | | | | | |
| Rb | 658<br>15.2 | Sr | 8985<br>78.8 | Y | | Zr | 2314<br>59.7 | Nb | | Mo | 9603<br>150 | Tc | | | | Ru | 64<br>7.1 | Rh | | Pd | 97<br>12.2 | |
| Ag | 801<br>12.4 | Cd | 2163<br>30.5 | In | 513<br>7.1 | Sn | 4932<br>109 | Sb | 384<br>5.4 | Te | 2271<br>27.9 | I | | Xe | | | | | | | | |
| Cs | | Ba | 1963<br>40.9 | La | 294<br>8.6 | Hf | 602<br>24.5 | Ta | 1427<br>27.9 | W | 9576<br>92.9 | Re | 370<br>6.7 | | | Os | 48<br>2.8 | Ir | 6.7<br>3.7 | Pt | 73<br>4.8 | |
| Au | | Hg | 648<br>122 | Tl | 2539<br>17.0 | Pb | 5280<br>105 | Bi | 51<br>0.6 | Po | | At | | Rn | | | | | | | | |
| Fr | | Ra | | Ac | | | | | | | | | | | | | | | | | | |
| Ce | 2123<br>61.1 | Pr | | Nd | 2571<br>58.9 | Pm | | Sm | 2666<br>39.5 | Eu | 627<br>14.7 | Gd | 1911<br>80.4 | Tb | 2.1<br>0.8 | Dy | 1176<br>32.2 | Ho | | Er | 1664<br>40.0 | |
| | | Tm | | Yb | 2487<br>63.2 | Lu | 376<br>9.7 | Th | 35<br>1.5 | Pa | | U | 6653<br>51.7 | Pu | 1506<br>24.3 | Am | 2<br>0.1 | Cm | 0.5<br>0.3 | | | |

Upper numbers: Total weight separated (g); lower numbers: Thousands of tank hours. Source: Stable Isotope Program, ORNL.

NY. A Treasury official was approached about the possibility of loaning silver to a wartime emergency project. When the official asked about the amount of silver required, he was told that the project would require about 15,000 tons of the metal. His response was "Sir, we measure our silver in ounces, not tons" [1]. Despite the official's chagrin, about 300-million Troy ounces of silver were loaned to the Manhattan Engineering District and shipped, under guard, to Detroit for drawing into silver buss. Guards were always present to pick up filings and scrap. After the war, the silver was returned to the Treasury with virtually no loss. The coils are shown in Figure 7 prior to being melted down for return to the Treasury.

In the 50 years since the end of World War II, about 250 isotopes of more than 50 elements have been separated. The total amounts for some of these elements has been very large, including kilogram quantities of calcium, for example. This was partially a consequence of preparation of large quantities of minor isotopes, in this case $^{48}$Ca, leading to large inventories of the other isotopes. These separations are summarized in Table 4. All of the stable isotope separations have been accomplished using only the four calutrons of the pilot plant and the one modified $\beta$ track. Figure 8 illustrates that three tanks on each side of the track have been removed to yield a track divided into four separately controlled segments, three with eight tanks each and a fourth with six. Independent operation is accomplished by using four dc current generators for the magnet coils in place of the original single generator. A further modification of the small segment into tanks having a 255° magnet geometry, an early post-war era development [1], al-

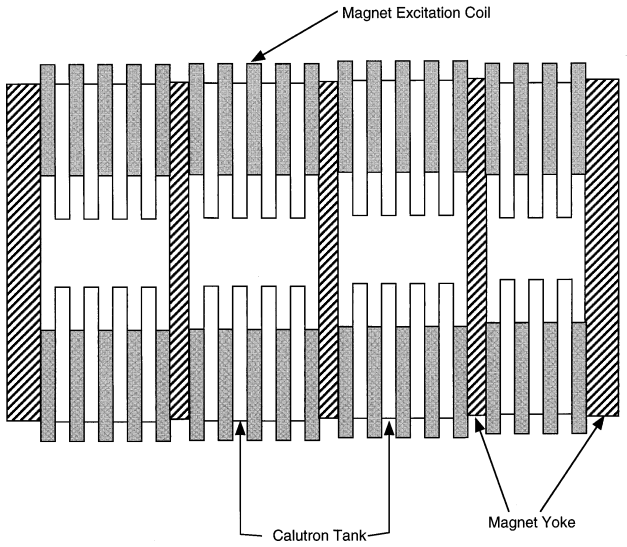


**Figure 8.** Schematic of $\beta$ track partitioned into segments for stable isotope separation. Source: J. Tracy, ORNL.

lows operation with a higher abundance sensitivity than possible in the original 180° separators.

At the present time, there are three large scale separations which serve as the financial basis for continued operation of the remaining $\beta$ track separations. These three separations are of substantial significance in medical imaging and treatment: 700 g/year of $^{203}Tl$ is prepared for use in cardiac imaging, 150 g/year of $^{68}Zn$ is separated for use in imaging of soft tissue tumors, and more than 25 g/year of $^{88}Sr$ is separated for use in treatment of metastatic bone cancers. Each of these isotopes requires subsequent irradiation in an accelerator or reactor to produce the high purity radioactive isotopes necessary for the final therapeutic application.

The use of the calutrons for medical purposes is a fitting conclusion to the history of these devices because it was one of Ernest Lawrence's dreams to use his cyclotrons for treatment of human disease. In this work, 50 years after their development, the major reason for their continued operation is their production of therapeutically important materials available by no other means.

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## Appendix

### *Reading List*

The emphasis of this Account and Perspective is on events of mid-20th century physics and the Manhattan Project as they bear on mass spectrometry and the development of calutrons. This era has been the subject of intensive study and there are a number of well written books that describe it in a broader fashion than undertaken here. Several of the books listed below were cited in this paper and all but one of them was read for background information.

1. Richard Rhodes. *The Making of the Atomic Bomb*; Simon and Schuster: New York, 1986. This history of 20th century physics won a Putlizer Prize. It is very readable and recent enough to be widely available.

2. Stephane Groueff. *Manhattan Project: The Untold Story of the Making of the Atomic Bomb*; Little Brown: Boston, 1967. This history emphasizes chemical aspects of the Manhattan Project.

3. Vincent C. Jones. *Manhattan: The Army and the Atomic Bomb*; U.S. Government Printing Office: Washington, D. C., 1985. This volume was prepared under the auspices of the U.S. Army Center of Military History and is part of their special studies of the United States Army in World War II. It is available from the Superintendent of Documents at the U.S. Government Printing Office.

4. R. G. Hewlett and O. E. Anderson. *The New World, 1939/1946, Volume I, A History of the United States Atomic Energy Commission*; Pennsylvania State University Press, State College, PA, 1962.

Volumes of a more specific nature are:

1. C. W. Johnson and C. O. Jackson. *City Behind a Fence*; University of Tennessee Press: Knoxville, TN, 1981. A history of the town of Oak Ridge Tennessee.

2. Herbert Childs. *An American Genius: The Life of E. O. Lawrence*; Dutton: New York, 1968.