The American Gas Centrifuge
Past, Present, and Future

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By

Dean A. Waters
Chief Scientist and Technical Manager, USEC, Inc

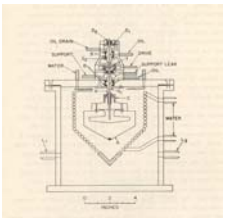
Introduction

The art of gas centrifugation was born in 1935 at the University of Virginia when Dr. Jesse Beams demonstrated experimentally the separation of chlorine isotopes using an ultra-high speed centrifuge. Dr. Beam's experiment initiated work that created a rich history of scientific and engineering accomplishment in the United States in the art of isotope separation and even large scale biological separation by centrifugation. The early history of the gas centrifuge development was captured in a lecture and documented by Dr. Jesse Beams in 1975[1]. Much of Dr. Beams lecture material is used in this paper up to the year 1960. Following work by Dr. Gernot Zippe at the University of Virginia between 1958 and 1960, the US government embarked on a centrifuge development program that ultimately led to the start of construction of the Gas Centrifuge Enrichment Plant in Piketon Ohio in the late 1970's. The government program was abandoned in 1985 after investing in the construction of two of six planned process buildings, a complete supply chain for process and centrifuge parts, and the successful manufacture and brief operation of an initial complement of production machines that would have met 15 percent of the planned capacity of the constructed process buildings. A declining market for enriched uranium, a glut of uranium enrichment capacity worldwide, and the promise of a new laser based separation process factored in the decision to stop the government program. By the late 1990's it had become evident that gas centrifugation held the best promise to produce enriched uranium at low cost. In 1999, the United States Enrichment Corporation undertook an initiative to revive the best of the American centrifuge technology that had been abandoned fourteen years earlier. This is an exciting story and one that when complete will enable the United States to maintain it's domestic supply and to be highly competitive in the world market for this important energy commodity.

The Early Days

Scientists first became interested in separating isotopes in the early 1900's when it became evident that the recent discovery that elements had stable and radioactive isotopes. The initial interest in isotopes was their potential use as biological and industrial tracers. Although many separation processes were suggested and attempted, none were successful until 1934 when Dr. Jesse Beams used an evaporative centrifuge to separate chlorine isotopes. The adjoining figure shows a 1975 picture of Dr. Beams and a drawing of the first successful evaporative centrifuge. The rotor was suspended by a stainless steel hypodermic needle. The rotor was partially filled with liquid CCl_4 and preferential evaporation allowed the lighter isotope to be drawn off through the hollow needle while the heavier isotopes were concentrated in the residual liquid. The rotor operated at a peripheral speed of 440 m/s (1550 rps) and was surrounded by a low pressure helium atmosphere (5 torr) helium for proper heat balance from rotor to casing. Complete equilibrium was not achieved in this machine but it achieved a separation that was about 50% of theory. The late 1930's was a fruitful development period at the university. The developments included: magnetic bearings that could both support part of the thrust load of a bearing at the other end of the rotor; the fully magnetically suspended centrifuge; air bearing supported air drive turbines; electric motors that drove centrifuges to 1.5 x 106 rev/sec and centrifugal fields as high as 10^9 G's (times gravity); specially shaped magnetically suspended (and damped) steel rotors that achieved peripheral speeds of 1500 m/s.[2] These developments have proven to be useful for the separation of biological material.

Dr. Jesse Beams



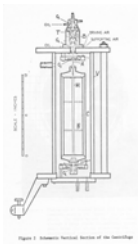
1935 Chlorine Isotope Separation

[1] Early History of the Gas Centrifuge Work in the USA; Jesse W. Beams; May 1975; Published by the University of Virginia, Charlottesville, VA, 22901

[2] This was only exceeded in the1970's when 2200m/s was obtained with a tapered carbon fiber rod rotor by professor Phillip Moon, Univ. of Birmingham, of the UK

Very soon it became evident that long tubular centrifuges would produce more separation even if operated in the evaporative mode. Within two years of the original work this belief led to the construction of an 11 inches long, 4 inch diameter steel rotor with Duraluminum end caps. The rotor weighed about 25 pounds and had a ½ inch thick wall. The central withdrawal tube for the evaporated gas was supported at two points within the tube to prevent it from seeing its flexural critical as it was spun up to speed.

1937 Centrifuge



Disagreement between theory and test results suggested that in addition to the evaporative component of separation there was a synchronous "whirlwind" occurring within the rotor with radial and axial components that affected the separation as a function of the withdrawal rate of the gas from the rotor. In order to prevent the whirlwind a "spider" was introduced that divided the rotor into six axially oriented chambers. With this design, the gas was forced to rotate at the same speed of the rotor, which greatly increased the overall separation at high withdrawal rates. Shortly after this result was obtained R. F. Humphreys[3] demonstrated the separation of bromine isotopes. Karl Cohen developed a theory that took into account the case of an evaporative centrifuge wherein the vapor is drawn off at such a high rate that equilibrium conditions are not obtained. Cohen later developed the theory that took into account both the basic evaporative separation factor and the length of the centrifuge and followed with developing the basic relationship for any gas centrifuge process - the familiar

$$\delta U = \pi \rho D Z/2 \{ (M_2-M_1) r^2\omega^2 /2RT\}^2 E$$

where $E \leq 1$ is a measure of the flow pattern and magnitude of flow into/out of the centrifuge, (M_2-M_1) are the isotopic molecular mass difference, $r^2\omega^2$ is the squared peripheral speed of the rotor, R is the gas constant, T is Temperature, Z is the separation length, D is the diffusion coefficient, and is ρ the density.

The fact of early success with evaporative centrifuges was to influence US centrifuge design up to the end of the World War II programs. It was recognized that that evaporative centrifuges had a major drawback even though they could be cascaded. Evaporative centrifuges were a batch process and the liquid adds to the stress in the rotor tube. Consequently by 1937 work focused on long tubular centrifuges within which either gases or liquids could be circulated but the major effort was focused on gas centrifuges. The first effort was on flow through or Concurrent centrifuges where the light fraction was collected near the axis and the heavy fraction was collected near the wall. The machine was designed to operate in both the concurrent and countercurrent mode. The tubular steel rotor was 12 inches long, operated at 1060 rps, had an inside diameter of 7.62 ID, and had duraluminum end caps. Tests were conducted using ethyl chloride, N_2 and CO_2 gas. Cohen and E. V. Murphree worked out the theory for concurrent flow (1938). Urey suggested center feed, end extraction, the use of a temperature gradient to cause countercurrent flow and also suggested using what we would call scoops today to use the impact pressure to extract the gas. These ideas were not pursued in the physics experiments because it was thought that they would cause too much interference with the internal flow.

"Spider Baffle" End View

[3] R.F. Humphreys, Phys. Rev.56 684 (1939)

Soon after the March 1939 announcement of uranium fission by neutrons, it became clear to many that because of the huge release of energy through fission that a bomb might be created using the uranium 235 isotope. Dr. Beams and his co-workers at the University of Virginia became interested in the separation of uranium isotopes and uranium hexaflouride (UF_6) was identified as the best gas for the process.

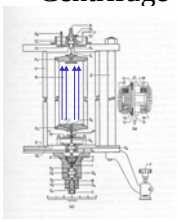
L.B. Snoddy, a University of Virginia chemist and physicist undertook making his own UF6 to study the material/ corrosive properties. He concluded that if pure it could be used in the current materials used in the gas centrifuge experiments if the materials were dry and operation was near room temperature.

At the national level, in 1940 the Uranium Committee was set up under the direction of Dr. J. L Briggs to coordinate the efforts of the many researchers that had become involved in exploring the potential use of uranium for the military. The assignments were:

- •Theory and overall coordination group-Columbia University.
- • Centrifuges for pilot plant - Westinghouse Electric Co.
- • Pilot plant/Enrichment plant - Standard Oil Co (now Exxon)
- • Test theory by experiment – University of Virginia(started in late 1940)

UF6 was in short supply at that time but by then end of 1941 test data was obtained that gave excellent agreement with the Cohen theory for a single machine and for a 2 machine re-enrichment or cascade. Meanwhile, although several theorists suggested methods for circulating gas it was a team including H.C. Urey, Karl Cohen, C. Skarstrom, and P.A.M. Dirac that worked out the mathematical theory and proposed the most efficient means to go about separating isotopes by gas centrifugation in 1941.

Concurrent/Countercurrent Centrifuge



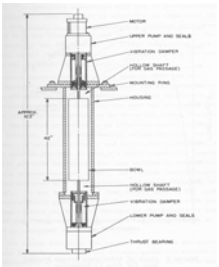
Concurrent / Countercurrent Centrifuge

(concurrent mode)

Interestingly during 1940 Dr. Beams was visited by Dr. Gunn, who at that time was the Director of the Naval Research Laboratory who was interested in using a Uranium reactor to drive a submarine (1940) – clearly a man with vision.

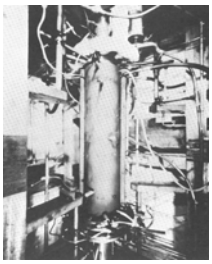
Since the prior work at the University of Virginia had verified the separation theory under equilibrium conditions, the next phase was aimed at verifying separation under flow conditions for both concurrent and countercurrent flow. This required the use of long tubular rotors. Two machines were used: The small or "short bowl"centrifuge was 42 inches long, had an inside diameter of 7.2 inches, a ½ inch thick wall thickness, and operated at 470 hz. The "Long Bowl"rotor was 11 ft - 4 inches long, had an inside diameter of 7.2 inches, a ½ inch wall thickness, and operated at 350 hz. The long bowl rotor passed through two rotor flexural critical speeds on the way up to operating speed. Both the short and the long bowl rotors were made of Duraluminum. No Scoops were used in either machine because of the desire to have undisturbed flow at the ends in order to confirm the theory. This meant that

WW II Machines 1942-1943



7.2 in ID and 8.2 in. OD Machine

Short Bowl



Westinghouse 132 in long machine

Long Bowl

flow into and out of the centrifuge had to be externally pumped. The total weight of the Long Bowl centrifuge was 3200 lb. It was driven by a steam turbine.

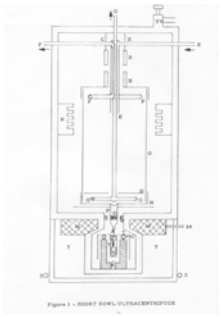
It soon became evident that countercurrent flow gave the best results for separation per unit length in accordance with the Cohen theory. The focus was to verify the theory so that a pilot plant could be built. The actual test used the machine as a stripper stage in order to verify the theory (one could get better data with U238) Both machines operated but the Long Bowl machine failed for undetermined reasons during tests. The Short Bowl machine ran for 93 days, separated 1,000 lbs of UF6 and 800 lbs were stripped and 200 lbs enriched to 5% assay. The separative capacity of the long bowl centrifuge was 1 SWU/year and the efficiency compared to theory was between 80-90 %. All of the WW II gas centrifuge work was terminated on January 34, 1944 in favor of the gaseous diffusion and calutron separation processes.

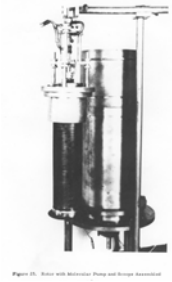
In the late 1940's work was reactivated at the University of Virginia to take advantage of higher strength materials. This work continued into the late 1950's when Dr. A. R Kulthau the director of the University of Virginia laboratory who kept abreast of reports coming out of Europe and Russia became aware of Dr.Gernot Zippe's Short Bowl work and invited him to the university to repeat the work he did in Russia in the US.

The US Government Program

Dr. Zippe came to the United States in 1958 and performed research at the University of Virginia at the request of the US Government over a two-year period. The results of his work were published in the well-known "Zippe Report" in 1959 before he returned to his homeland, Austria.

Zippe Machine 1958





The machine that Dr. Zippe developed was a major departure from an engineering standpoint from the machines developed during WWII. The rotor was light and small, 13 inches long, 2.92 inches inside diameter, and the rotor wall was thin at 0.032 inch. This meant that the suspension systems could also be small and very efficient regarding power consumption. The upper suspension consisted of a flexibly mounted magnet that held the rotor upright and alleviated some of the rotor weight as seen by the lower suspension. The lower suspension utilized a small pivot bearing to support the remainder of the rotor weight. Gas was introduced into the rotor through a non-rotating center post and the product and waste gas was extracted through the use of scoops at the ends of the rotor; the gas impact pressure on the scoops was sufficient to drive the gas through the cascade piping so as to enable cascading the machines without the use of external pumps. Vacuum was maintained around the rotor with the aid of a molecular pump located near the top of the rotor. Finally, the rotor was driven to speed and maintained at speed through the use of a simple axial air gap hysteresis -synchronous motor locates at the bottom of the rotor. The motor armature was a thin steel plate that could be magnetized such that the motor operated synchronously once the rotor reached operating speed. The machine produced 0.45 SWU and consumed less than 10 watts in operation. All of these features suggested that the machine could be easily cascaded and with further development could produce meaningful enrichment at relatively low capital and operating cost.

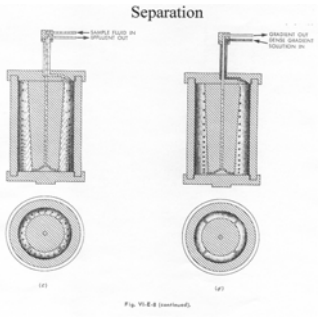
Following closely on the completion of the report, the United States Government initiated a bid process, open to US corporations, to build and evaluate a centrifuge cascade based on the Zippe machine.The work was awarded to the Union Carbide Corporation in 1960. At that time, UCC was the operating contractor for the gaseous diffusion plant located in Oak Ridge, Tennessee. The following year, a bid to develop an

advanced gas centrifuge machine was awarded to the AiResearch Division of the Garrett Corporation. Within a short timeframe, less than ten years, revolutionary development work by both the Union Carbide and the Garrett Corporations led to machines that had a productivity that was a factor of 100 more than the 1960 Zippe machine. During the revolutionary period reliability was extensively evaluated and improved but most important, it was learned how to scale machines to production size and thus optimize the cost of separative work.. The machine size scale-up was guided by cost and economic models throughout the 1960's and by the early 1970's it was clear that the larger size machines provided the best avenue toward low cost SWU.

Spin-off Technology – The Biological Centrifuge

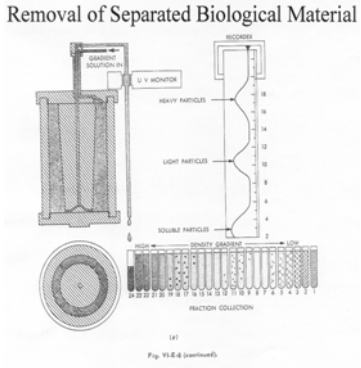
During the late 1960's, a significant spin-off from the US gas centrifuge program was the development of large-scale density gradient liquid biological centrifuges, of a type conceived by Dr. Norman Anderson. These centrifuges could be used to purify biological material for research purposes and eventually were used to produce high purity vaccines. Dr. Anderson, who was working in the Biology Division of the Oak Ridge National Laboratory at that time obtained grants from the National Institutes of Health for the research and a relationship was developed with the UCC centrifuge program to develop the rotors and the biological separation processes[4]. Between 1966 and 1973 a wide variety of centrifuges were developed for research purposes ranging in size from 12 inch diameter rotors that operated at 5000 RPM to one inch diameter magnetically suspended rotors that operated up to 400,000 RPM. The first drive system used in the MAN Program was built by the Spinco Division of the Beckman Corporation. Spinco made many of the developed research rotors commercially available in the early 1970's.

Isopycnic Banding Biological Centrifuge



Probably the most important development to come out of the program was the development of the process and production machine to purify influenza vaccine. Prior to 1970, vaccines were produced in a multi-step process that started by collecting thousands of eggs that had been produced at the same time by thousands of chickens. The eggs were then inoculated with a live virus and incubated for about two weeks. The eggs were then cracked and after the shells and other large scale debris was removed the virus was (or might be) killed and the vaccine was prepared for human inoculation. In this process the resultant vaccine was more than 98 % egg debris and only about 1 % virus. Any individual who was allergic to eggs could have either a mild or sometimes even a fatally violent allergic reaction. This meant that children under ten years old and adults over sixty years old could not be inoculated. In the case of influenza, these are the very population groups that are at the most risk.

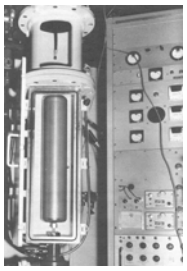
Isopycnic Banding Biological Centrifuge



[4] ORNL-3978 The Molecular Anatomy of Cells and Tissues, (The MAN Program), Annual Report for July 1, 1965 to June 30, 1966.

The initial isopycnic banding separation process was developed using a Spinco rotor that was 5 inch diameter, 12 inches long and operated at 30,000 rpm. In this process a sucrose and water density gradient was set up inside the rotor wherein the density gradually increased with increasing radius. Although a density gradient would form simply by spinning a sucrose solution at high speed the gradient was usually created by backfilling the rotor (from the wall to the center) with solution of increasing density by meaqns of a central feed and removal tube. Biological material is then introduced at the center of the rotor along the full rotor length. The biological material diffuses radially under centrifugal force created until it's density is equal to the density of the sucrose solution. The rate of separation and consequent banding of individual types of biological material depends on density of material and it's sedimentation rate. Sedimentation rate depends upon the size of discrete types of biological material and the density of the medium into which the material is diffusing. The material forms a discrete band at the point where isodensity is reached. This is called the isopycnic point for the biomaterial (equal density with the Sucrose solution). Removal of the discrete bands of material simply involves backfilling the rotor with a high density sucrose solution at the rotor wall. The discrete bands of biological material is forced out at the center of the rotor and collected. The initial experiments proved the process worked but in order to have a drug approved the machinery used in production had to be also approved and the experimental machines were too small for a practical process.

K2 Continuous Flow Isopycnic Banding Biological Centrifuge



In less than one year, in order to be able to have a machine ready for drug trials in the 1970 influenza season, the K-2 production centrifuge was designed, built and tested in a collaboration between Dr Anderson's Zonal Centrifuge Development project, Union Carbide Corporation, and the Eli Lily Corporation. The rotor was six inches in diameter, 30 inches long with about a ½ inch wall thickness and operated between 30,000 RPM (Aluminum rotor) to over 40,000 RPM (Titanium rotor). The K-II machine was successful in purifying influenza vaccine to a degree never before achieved commercially and the purity of the vaccine allows it to be administered without adverse allergic reaction. The lack of reaction meant that the vaccine could be administered to very young children and adults over the age of 60. Since the successful demonstration of the Anderson process it has been estimated that vaccines of the type produced then and now -- using the same K-II machine -- have saved hundreds of thousands lives throughout the world. The rights to build and sell the K-II centrifuge were given to ElectroNucleonics Corporation.

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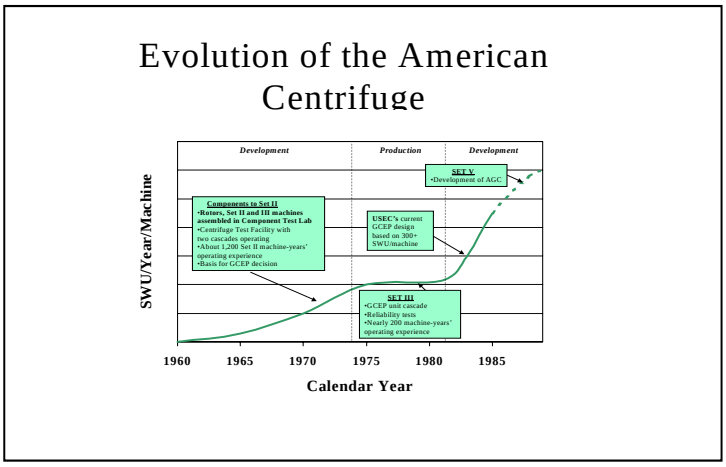
Production Gas Centrifuges

Several improved production sized machines were tested between 1970 and 1976. These were built buy AiResearch and UCC and involved six different machine designs that were operated in three groups in reliability cascades. In 1977 President Carter made the decision to build the Gas Centrifuge Enrichment Plant at the Piketon, Ohio site, and the UCC design was selected. From that point forward until 1982 all research and development ceased as all the programmatic focus was on GCEP.

The testing of centrifuges between the early 1970's to 1985 involved thousands of commercial size gas centrifuges. These were built and tested individually and in cascades to evaluate reliability, operability, and performance over a wide range of conditions. Until 1978 all of the machines were built by Airesearch or UCC. Three companies built government designed machines to fill the GCEP: Boeing Corporation, Goodyear Aerospace Corporation, and Allied Signal Corporation (Garrett AiResearch).

By 1980 and after the Three Mile Island reactor accident it became apparent that the market for enriched uranium was rapidly declining, there was a glut of uranium enrichment capacity worldwide, and a new

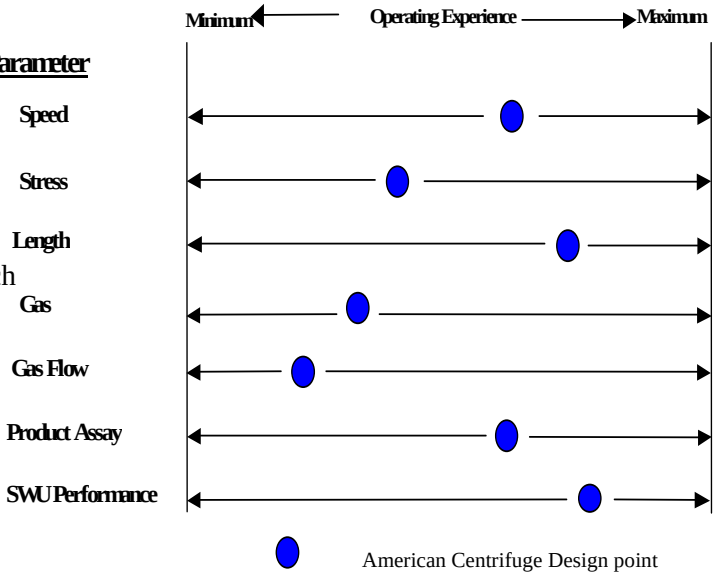
Atomic Vapor Laser Isotope Separation (AVLIS) process was beginning to show promise in the laboratory. These elements helped call to question whether the GCEP should be completed as planned or whether a new more advanced machine should be developed that would lower the cost of separative work for GCEP. By 1982 a decision was made to develop the more advanced machine. Retooling of the development laboratories was required to enable the development of the more advanced machine but only a modest redesign was required of the machine itself. By mid 1984 the retooling was complete and by April 1985, after less than six months of testing, an improvement of about 85 % in separative capacity over the GCEP machine had been demonstrated and it was believed there was significant potential for further improvement. Nevertheless, the decision was made by the US government to abandon all centrifuge work on June 5, 1985.



Program Termination Aftermath and the American Centrifuge

Following the U.S. Government cancellation of the GCEP project and all activities associated with gas centrifuge research and development all US government R&D was focused on Atomic Vapor Laser Isotope Enrichment Separation (AVLIS) technology. However, while the centrifuge program was being phased out, three important actions were taken that has made it possible for the gas centrifuge to become the best choice for new enrichment capacity for the next millennium. First, the DOE funded the retention of all of the key documentation from the government program including all of the R&D data and documentation for the GCEP plant as well as all of the centrifuge manufacturing documentation. Second, all of the equipment to manufacture, assemble, and test both GCEP and advanced centrifuges was retained. Third, and most important, a nucleus of key centrifuge R&D and manufacturing staff was retained in Oak Ridge with the objective of applying the centrifuge technology to other programs of national interest. The ultimate benefit of these actions is that when it became clear that gas centrifugation is the technology of choice, the information, facilities, equipment, and experienced staff were available.

USEC Design Targets and U.S. Centrifuge Program Operating Experience

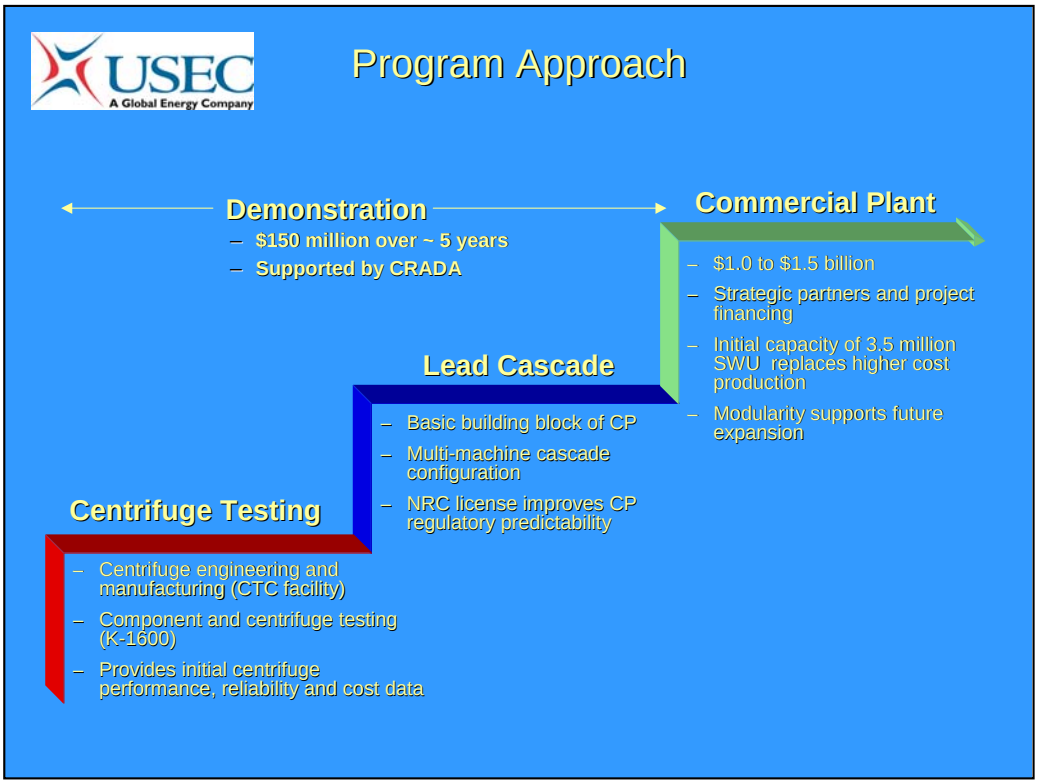


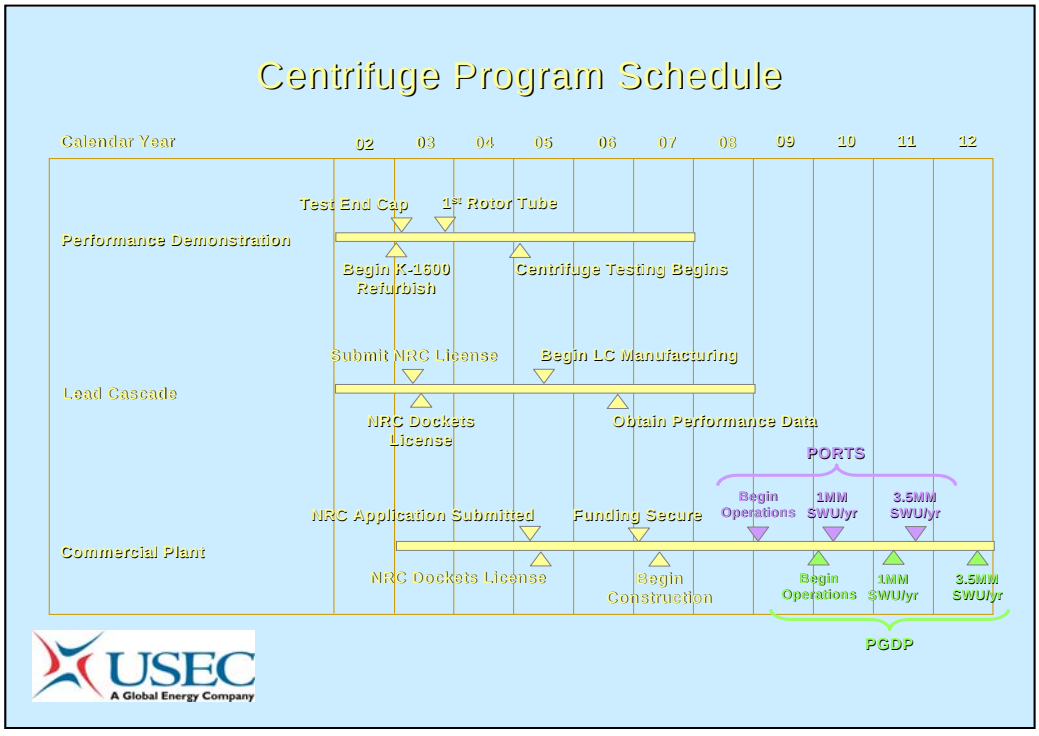
The US government funded AVLIS R&D from 1985 to the late 1990's. Further work was funded by USEC until it was determined that AVLIS could not be economically competitive. In June 1999, USEC suspended development of AVLIS technology and launched a worldwide search to evaluate advanced enrichment technologies. The search led to the Department of Energy's (DOE) gas centrifuge program and Oak Ridge centrifuge experts. In September 1999, USEC signed an agreement with the DOE granting limited access to gas centrifuge uranium enrichment technology.

DOE had spent more than $450 million developing and demonstrating the technology over 20 years and more than $3 billion developing and deploying the technology by 1985. In 2002 USEC entered into an agreement with the Oak Ridge National Laboratory for the purpose of performing R&D and helping USEC replicate the machine that had performed so well in the 1980's. The resulting new/old centrifuge, branded the American Centrifuge™, is expected to be the world's most cost efficient uranium enrichment technology.

The parameters that affect the performance of the American Centrifuge™ have been selected to be well within the design and operating experience of the prior US government program as depicted in the accompanying figure. This deliberate choice was made to minimize any R&D necessary to prepare the machine for plant operation. In essence, the machine chosen does not have any components that had not already been tested (usually quite extensively for reliability) in the 1970 to 1985 timeframe. Advantage has been and will be taken of advances in the past fifteen years in electronics, software, manufacturing, and control systems to lower the cost of the machine and the balance of the enrichment plant without venturing into areas that would require research or development. In essence the American Centrifuge™ will look like and be a machine that had been built for use in GCEP in the 1980 timeframe. The challenge for USEC is to replicate what has already been demonstrated.

The approach being taken and the schedule for the demonstration, lead cascade and the commercial plant is shown in the accompanying figures. The intent of the centrifuge testing is to confirm that the USEC design as a minimum replicates what has already been demonstrated in the 1970's to 1980's with machines that have been manufactured by USEC in 2003 and beyond. The lead cascade is in reality a building block for the commercial plant that will enable evaluation of both the machine and a plant cascade operated with modern operational control systems. The schedule for deploying the commercial plant is to some extent dependent upon the location of the plant.. The Lead Cascade will be built at the Piketon, Ohio site while the commercial plant will be built either at that site or in Paducah, KY. All activities including the licensing of the Lead Cascade and the commercial plant are on schedule. USEC is confident in meeting the objective of deploying a 3.5 million SWU plant and beginning operation starting by 2010.


USEC
A Global Energy Company
Program Approach
Demonstration
– $150 million over ~ 5 years
– Supported by CRADA
Commercial Plant
– $1.0 to $1.5 billion
– Strategic partners and project financing
– Initial capacity of 3.5 million SWU replaces higher cost production
– Modularity supports future expansion
Lead Cascade
– Basic building block of CP
– Multi-machine cascade configuration
– NRC license improves CP regulatory predictability
Centrifuge Testing
– Centrifuge engineering and manufacturing (CTC facility)
– Component and centrifuge testing (K-1600)
– Provides initial centrifuge performance, reliability and cost data


Centrifuge Program Schedule
Calendar Year
02
03
04
05
06
07
08
09
10
11
12
Test End Cap
1st Rotor Tube
Performance Demonstration
Begin K-1600 Refurbish
Centrifuge Testing Begins
Submit NRC License
Begin LC Manufacturing
Lead Cascade
NRC Dockets License
Obtain Performance Data
PORTS
Begin Operations
1MM SWU/yr
3.5MM SWU/yr
NRC Application Submitted
Funding Secure
Commercial Plant
NRC Dockets License
Begin Construction
Begin Operations
1MM SWU/yr
3.5MM SWU/yr
PGDP
USEC
A Global Energy Company