# THE ARCHIMEDES FILTER PLANT: A NEW CONCEPT FOR REDUCING THE AMOUNT OF HLW AT HANFORD

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## ABSTRACT

Archimedes Technology Group is developing a plasma technology, called the Plasma Mass Filter[1], which can separate a nuclear waste mixture into mass groups and thus reduce the amount of radioactive waste. The process under development includes waste preprocessing, volatilization, and separation. The material is converted into a vapor and subsequently ionized by RF power. The Filter is a cylindrical device that employs an axial magnetic and a radial electric field to produce a low-pass mass filter for ions. Ions with mass above a tunable “cutoff mass” are expelled from the plasma. A full-scale demonstration unit of the Filter has been operating in San Diego since February of 2003. Experiments to date have utilized noble gases, noble metals and sodium-based plasma with densities of up to $10^{19}$ ions-$m^{-3}$ and magnetic fields up to 0.15 T. This technology could significantly reduce the volume of high-level radioactive waste at the Hanford Site in Richland, Washington. Introduction of the AFP into the current baseline assures DOE of meeting both deadlines at substantially lower cost and with significantly lower volumes of immobilized waste, both onsite and at Yucca Mountain.

## INTRODUCTION

From its initial formation in 1998 until today, the Archimedes Technology Group has focused on one goal – developing and deploying a unique technology to pretreat high-level tank waste (HLW) and reduce the fraction requiring HLW vitrification at Hanford by 75-85%. Today, more than $100 million of private financing has been invested to meet this goal. A full scale demonstration unit (referred to as DEMO) based on the plasma mass filter concept (Archimedes Filter[1]) has been designed and built in San Diego, and testing in 2003 and 2004 has proven the ability of the Filter to separate heavy and light atoms.

Analysis of the inventory contained in Hanford’s tanks indicates that material can be divided into two classes. The first type is low-activity and non-radioactive material (LAW) that is light in mass (AMU<90) and the second is heavy mass material (AMU>90) that is considered HLW. The *Filter* can separate these two classes utilizing electric and magnetic fields combined to create rotating plasmas. Material is vaporized and injected into the filter where it is ionized by radio frequency (RF) power. Heavy elements are spun out almost immediately, but light elements spin in confined orbits and are transported to the ends of the filter. The point of separation (light vs. heavy mass cutoff) is “tunable” by adjustment of the electric and magnetic fields. The heavy and light atoms are collected separately by actively cooled collectors. This breakthrough approach has the following important attributes: high separation efficiency, high throughput rate, attractive economics, and the ability to handle complex materials.

Testing to date has demonstrated the physics of the process using noble gas and metallic “waste” materials. Conceptual design for the plant has been completed and is discussed below. Testing on the DEMO unit during 2004 and early 2005 has been designed to further demonstrate the filter unit’s ability to provide separation in high-power, sodium-rich, rotating plasmas.

## How the Archimedes Separation Process Works

As a physical process (not a chemical one), the Archimedes Filter relies on the physics of rotating plasmas to establish what is called the “cut-off mass”. The equation to determine cutoff mass in the Filter is shown in equation 1. R is the plasma radius, B is the magnetic field, $V_0$ is the voltage applied to the central electrode (voltage profile is a parabola peaked at R=0), $m_p$ is the proton mass, Z is the charge state of the species and *e* is the electron charge.

$$A_{cutoff} = \frac{ZeR^2B^2}{8V_0m_p} \qquad \text{(Eq. 1)}$$

This process is indifferent to the complexity of waste input; elements with Atomic Mass Unit (AMU) above the mass cutoff are simply sent in one direction, while elements below the cutoff are sent in another. For example, for the Hanford “Envelope D” tank waste blend, we could achieve up to an 85% mass reduction by setting the device to a mass cutoff below Strontium 90. The physics underlying this separation process differs fundamentally from that of other rotating systems such as mechanical centrifuges and other plasma systems used for isotope separation.

Figure 1 below depicts how the Archimedes separation process works. Waste is injected into a vacuum chamber. RF power ionizes the injected material, resulting in the creation of plasma (atoms transform into a plasma state when an electron leaves their atomic orbit). The resulting positively-charged ions in the plasma respond to electric and magnetic fields and begin to rotate quickly, much like the forces of these two fields spin an electric motor. When the magnetic and electric fields are adjusted to create a specific "cutoff mass", light ions are confined to the plasma while heavy ions are spun out (hence the name Archimedes “Filter”).

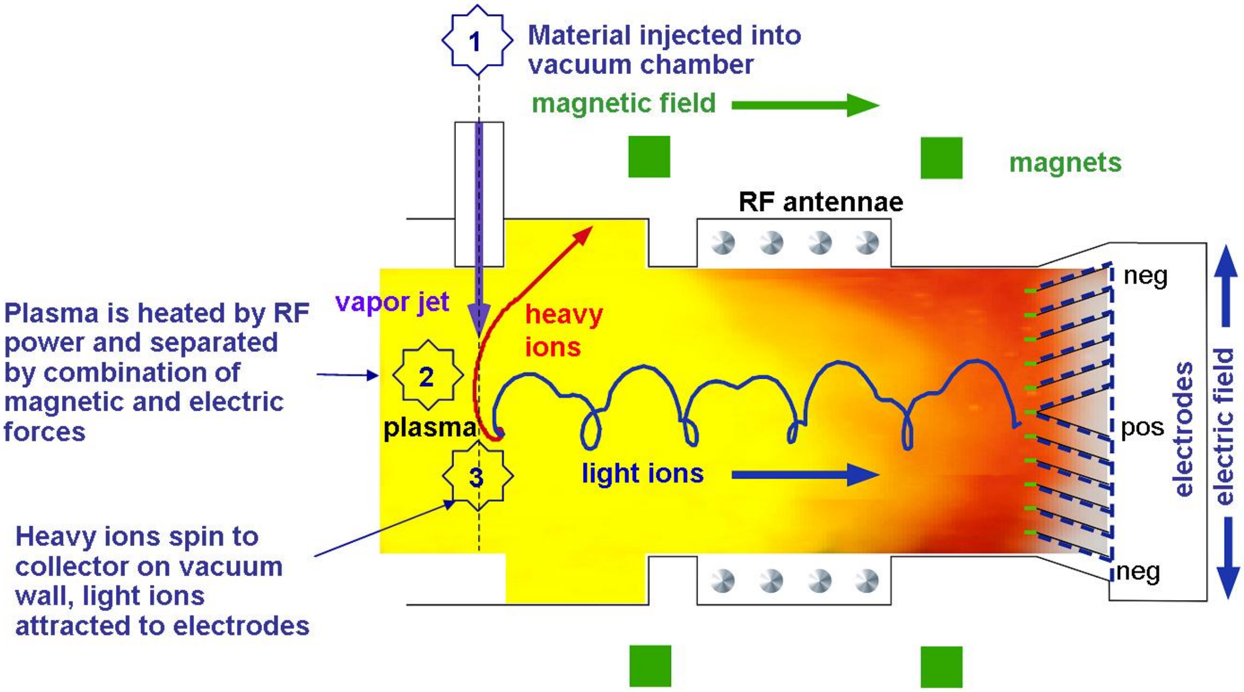


**Fig. 1. Schematic of Archimedes Separation Process**

## Archimedes Potential Role in the Hanford Process Flow

Archimedes engaged Battelle Northwest to gain a detailed understanding of the evolving tank waste process flow planned for Hanford. The scope of the engagement included modeling a current baseline process flow with mass balances. Battelle then proceeded to evaluate how to optimize the integration of a potential deployment of the Archimedes Filter.

Figure 2 (A) is a simplified process flow of the current Hanford baseline. The tank farm is represented in gray and there are two basic paths following solid/liquid separations. The path below (yellow) represents LAW (low activity waste); the path above (red) represents HLW sludge. Two key data points on the chart are: 1) the output of 9,320 canisters of HLW glass and 2) the addition of over 7,860 MT of sodium used for caustic washing of the HLW sludge.

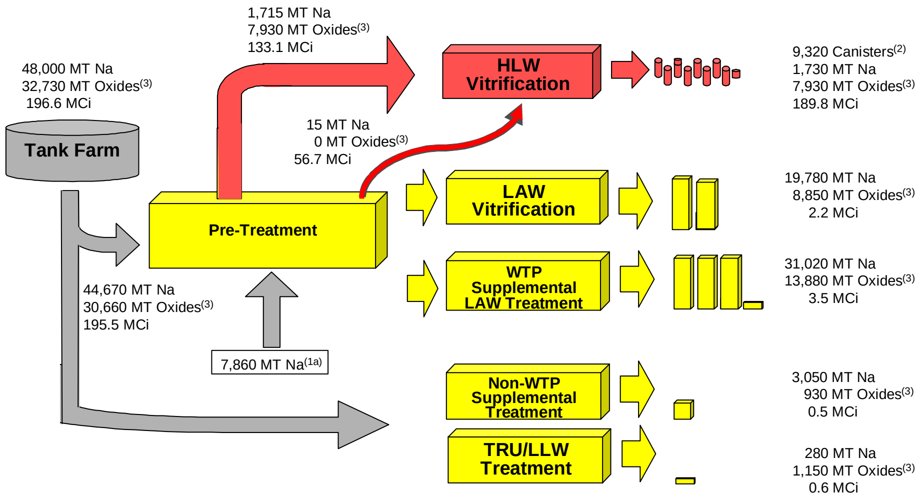
In Figure 2 (B), the Archimedes Filter Plant (AFP) (blue) would be inserted in the HLW path in order to separate up to 85% of the mass, the non-radioactive elements, and send the heavy elements (as little as 15% of the mass) to the HLW vitrification facility. Due to the removal of the non-radioactive elements, DOE could theoretically avoid making over 6,600 of the 9,320 canisters in the current baseline. The light elements, or up to 85% of the incoming mass, would qualify as LAW and could be immobilized with LAW glass or any of the supplemental technologies currently under consideration. In addition, for any sludge treated by Archimedes, DOE could eliminate the caustic washing step in the Pretreatment Building and thus avoid adding sodium – hence the 14% reduction in the total LAW or 24% of material destined for the LAW supplemental technologies.

Since there are significant variations in the sludge composition, not all batches of waste will benefit equally from the Archimedes mass separation process. Under the next phase of work currently underway by Battelle, we are evaluating the specific Hanford tanks that would receive the greatest benefit from treatment with the Archimedes technology to reduce the number of HLW glass canisters required to immobilize the HLW sludge in those tanks. Preliminary information indicates that deploying only two Archimedes Filters at Hanford could result in avoiding production of a significant percentage of the HLW glass by selecting those tanks for treatment that would receive the greatest mass reduction from using our technology to separate heavier radioactive elements from lighter non-radioactive elements. Our implementation plan will be refined to propose an optimal number of filters as the further analysis by Battelle and Archimedes progresses. The conceptual design already completed by Archimedes is for a 2-unit plant.

**(A)**

**Process Flow & Mass Balance**

**Hanford Sept 04 Baseline (1) without Archimedes Filter**



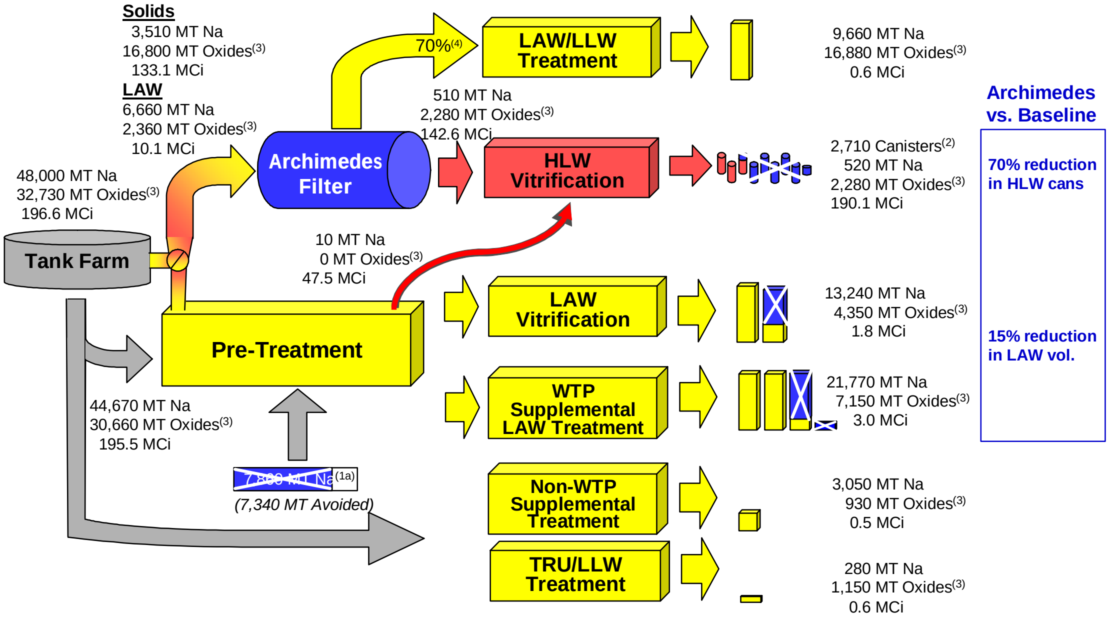
Source: Assessment of the Archimedes Filter for Use on Hanford Tank Waste, PNNL, Sept 2004

Note: *(1) Baseline = Target Case per RPP System Plan Rev 2*
*(1a) 6,080 MT Na addition required for caustic washing. 1,780MT Na added for pH adjustment (neutralization)*
*(2) Assumes immobilized waste form achieves average 35 wt% waste loading*
*(3) Excludes sodium oxide ($Na_2O$)*

**(B)**

**Process Flow & Mass Balance**

**Hanford Sept 04 Baseline (1) with Archimedes Filter**



Note: *(1) Baseline = Target Case per RPP System Plan Rev 2 (1a) Na addition required for caustic washing avoided with AFP; Na added for pH adjustment (neutralization) partially avoided with AFP (2) Assumes immobilized waste form achieves average 35 wt% waste loading (3) Excludes sodium oxide ($Na_2O$) (4) Fraction of total oxide mass that originally went to HLW vitrification in the Target Case and which now by-passes HLW vitrification as a result of the Archimedes Filter*

**Fig. 2. Hanford Process Flow and Mass Balance without (A) and with Archimedes Filter (B)**

Archimedes has engaged a team of industry leaders to create the Conceptual Design for the AFP. Figure 3 is a schematic of the AFP process flow with the subsystems highlighted by color for each design team. There are 24 subsystems in the AFP; four are based on the fundamental technologies that are the focus of the DEMO (i.e., plasma torch for calcinations, inductively coupled plasma (ICP) torch for injection, the Filter and the collectors/removal process). The remaining twenty are systems that have been utilized in other commercial or research nuclear facilities.

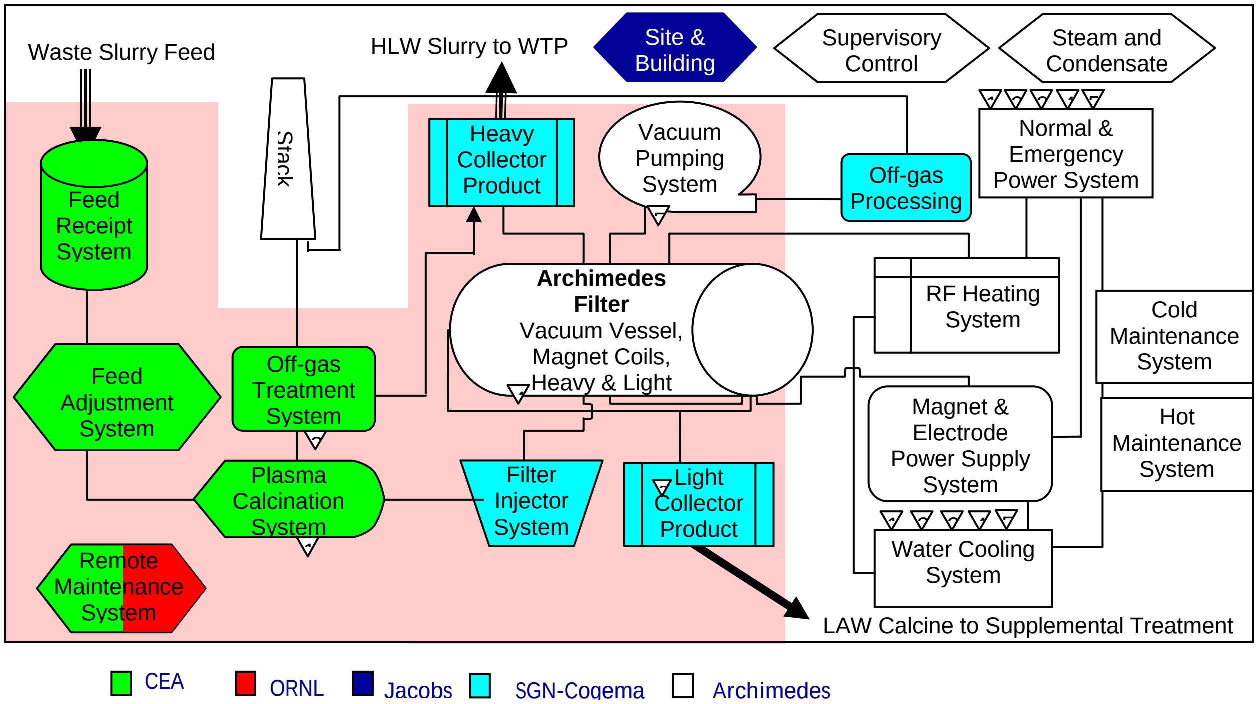


**Fig. 3. Schematic of AFP Conceptual Design and Design Team**

Figure 4 is a cutaway of the conceptual design for the Archimedes filter that we propose to deploy at Hanford. This view shows the internals of the Filter including the RF antennae, the two light (LAW) collectors at each end of the Filter the heavy (HLW) collector, and the point of injection in the lower center of the heavy collector. The Conceptual Design was completed in November of 2003 and a formal design review using outside reviewers was completed in December of 2003. A cost estimate and project schedule based on the conceptual design was completed in the first quarter of 2004.

The DEMO and the Conceptual Design of AFP have been guided by one central principle – to use proven and existing technologies for all systems that interact with or support the Archimedes Filter process. Not only will this reduce the risk associated with the performance of the Filter itself, but it will also reduce the risk of the integrated system as a whole and speed the transition from prototype to final design of AFP. Finally, these performance risks have been mitigated to the extent possible through our investment in full-scale demonstration of the key technology systems.

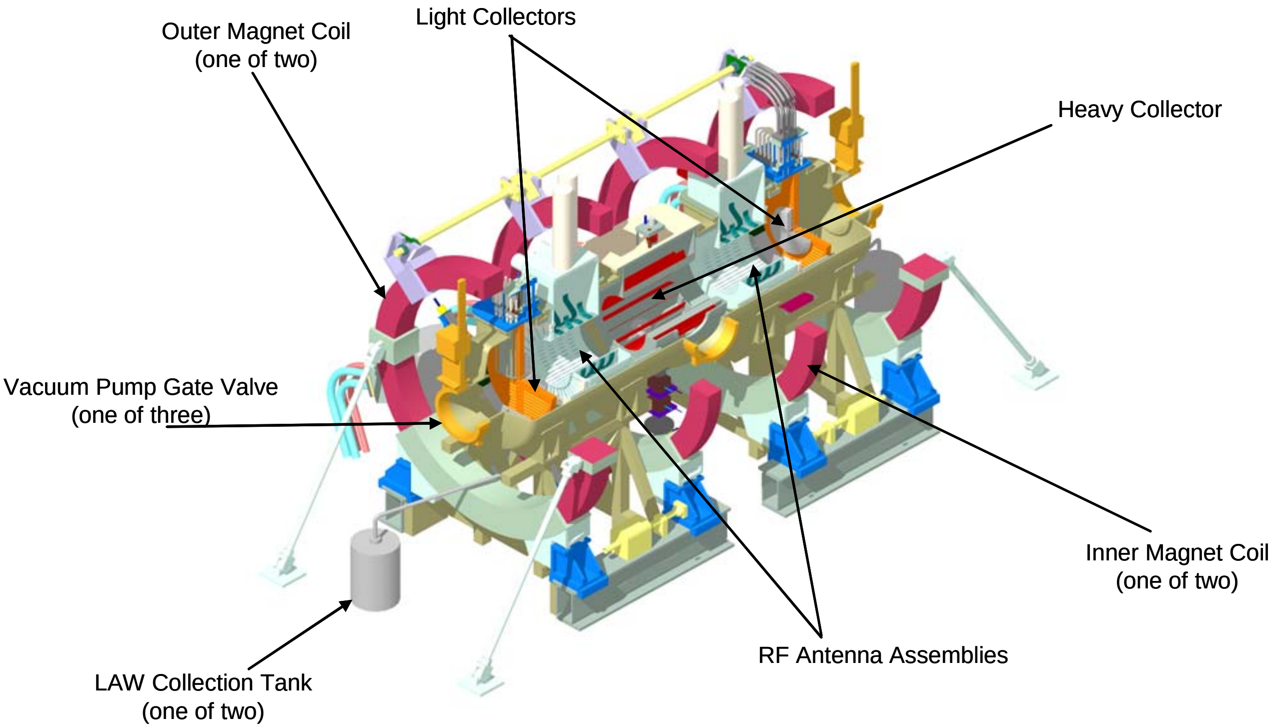


**Fig. 4. Conceptual Design of Commercial Filter**

### Results of DEMO Testing

Archimedes began assembling the DEMO (Figure 5) in San Diego during November 2002 and within just four months achieved its first plasma. Major components visible in this current picture are the vacuum vessel, the vacuum pumping system, the RF transmission lines, and the magnet coils. Plasma densities of approximately $10^{19}$ ions-m$^{-3}$ in magnetic fields greater than 1kG (0.1T) have been achieved in noble gases. As rotating plasmas are the mechanism for the filter process, the ability to spin ions to over 70,000 rpm has been a great accomplishment. Archimedes met a major milestone in the summer of 2003 when we achieved mass separation by tuning the Filter to separate xenon from argon. In October and November of 2003, we demonstrated separation of the noble metals copper, silver and gold in an argon based plasma.

Using Monte Carlo analysis of the expected orbits of the ions, we expect DF's of >1000 for most of the heaviest radioactive elements, but elements near the cut-off mass, like strontium 90, can have a reduced DF due to second ionization since the separation depends on M/Z. The DF estimated for strontium due to second ionization is 185 at the expected plasma parameters.

After demonstrating separation of noble gases and with trace metals in 2003, the DEMO underwent several component upgrades. The purpose of the first set of upgrades was to increase the power handling capabilities, and hence, the density and density profile of the DEMO plasmas. The upgrades included:

- Implementing phase control on the RF system in order to control the density profile of the plasma.
- Enclosing the antennas in chambers separated from the main plasma in order to achieve higher RF power, and thus higher plasma density, without arcing.
- Commissioning new electrode power supplies capable of supplying the high currents required to rotate the higher density plasmas.
- Installation of new electrodes and a new heavy collector designed to withstand the high heat loads associated with high power, steady state operation.
- These upgrades were commissioned with argon plasmas from January to August, 2004.

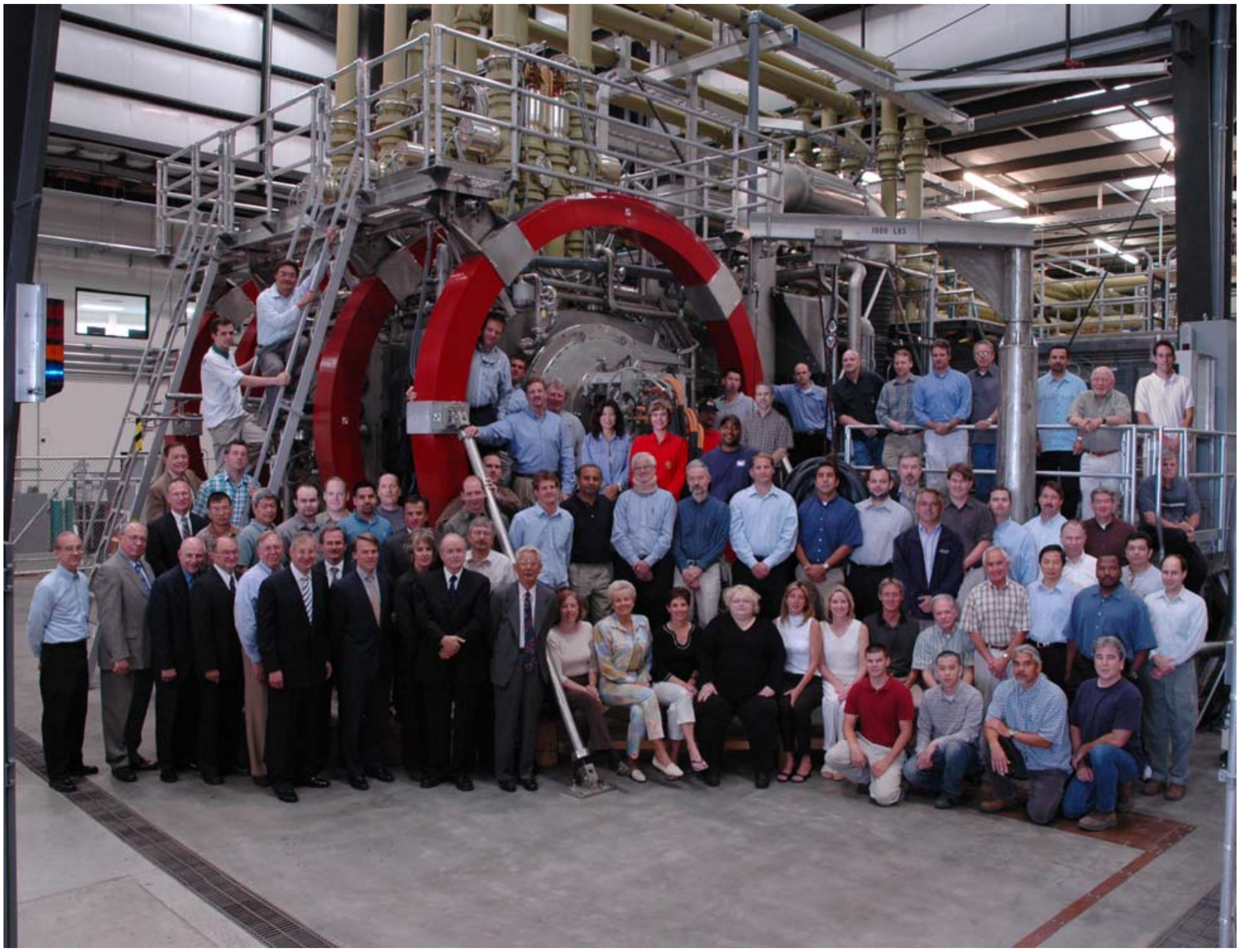


**Fig. 5. Archimedes Filter (and staff) in the San Diego Demonstration Facility**

Implementation of the high power upgrades significantly improved the performance of argon plasmas in the DEMO. Figure 6 shows the increase in plasma density that resulted from the upgrades. The red curve shows the highest density achievable before the upgrades, while the blue curve shows a typical density profile after the upgrade. The magnitude of the density has increased by a factor of 10 - higher density allows running at high throughput. The density profile is also more uniform than before, transitioning from an edge to core ratio of 4 to one that is less than 1.5.

During the next round of upgrades that were recently completed, components were installed for injecting waste surrogate vapor into the DEMO plasma. These components included:

- A vacuum furnace for melting the waste surrogate.
- A melt delivery system for transporting the molten surrogate to the vessel.
- A high temperature nebulizer for converting the melt to droplets.
- An inductively coupled plasma (ICP) torch for vaporizing the droplets and injecting the vapor into the plasma.
- A high temperature evaporator for sodium plasma studies.
- Preparations for an 8 kW $CO_2$ laser system for laser ablation studies

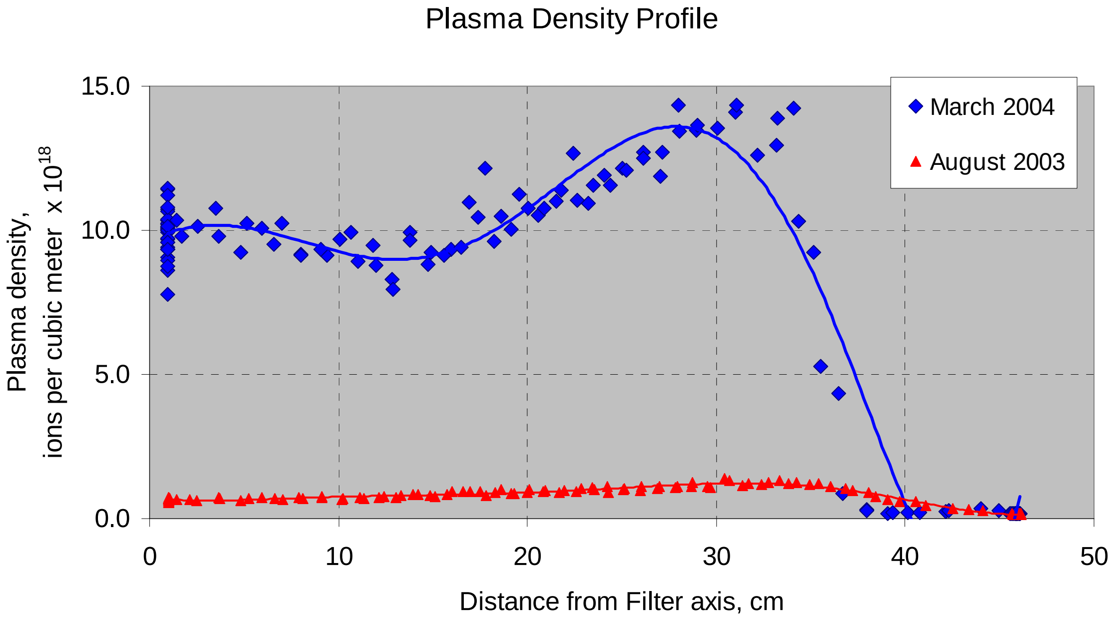


**Fig. 6. Density profiles before and after the hardware upgrades**

Major improvements in RF antenna and collector assemblies enabled increased plasma power and duration of stable plasma operations. In addition, advanced diagnostics, high temperature vapor injectors, electrode power supplies and automated control systems led the way to additional, more aggressive testing in late 2004. These tests used NaOH as the basic plasma feed material because sodium is the major constituent in the untreated HLW at Hanford in the form of nitrates, nitrites, oxides and hydroxides. Testing with NaOH is establishing modes of filter operation that will be used to test non-radioactive surrogates for HLW. Additional surrogates are planned to test and develop specific filter components such as the injector and collectors. These surrogates are selected for their ability to stress certain component design features and to qualify these components for the wide variations in performance conditions anticipated with Hanford HLW.

The DEMO mission is currently in transition from proof-of-principle and basic filter testing to a deliberate Engineering Development Program (EDP) that systematically designs, procures, tests, optimizes and validates key filter components and functions until they are judged suitable for HLW processing. The first phase of engineering development (EDP-1) has the primary objective of defining reference designs for all filter components. Reference designs are already available at the conceptual level, but known limitations for performance characteristics such as mass throughput, product removal and other engineering features require further development prior to preliminary design of Hanford-specific filter components.

## CONCLUSION

The current WTP baseline assumes the HLW sludge mission will be completed by 2028; however, it will cost billions of dollars and produce more glass logs than the proposed Nevada disposal site at Yucca Mountain has allocated to defense waste. There is also a commensurate challenge to complete LAW processing and disposal by 2028. Introduction of the AFP into the current baseline assures DOE of meeting both deadlines at substantially lower cost and with significantly lower volumes of immobilized waste, both onsite and at Yucca Mountain.

## REFERENCES

[1] T. Ohkawa, "Plasma Mass Filter", U.S. Patent 6 096 220, August 1, 2000