Department of Energy Defense Programs
Integrated Contractors
Waste Minimization Program
Accomplishments
Fiscal Years 1990, 91 & 92

Return on Investment Document
The Department of Energy, Office of Defense Programs (DOE/DP) is a national leader in the development of technologies for eliminating and minimizing manufacturing related waste and hazards. Through the department's manufacturing and nuclear weapon production facilities, many of these technologies have been fielded and demonstrated to be both efficient and cost effective. This document provides brief statements concerning a number of ongoing projects whose primary purpose is to improve the overall quality of material processing operations, and include waste and hazard minimization. These brief statements are intended to communicate the broad-based approach employed and to indicate the commitment DOE/DP is making to the area of waste and hazard minimization. Accomplishments highlighted in this report are not comprehensive, but serve to describe the areas of technology development and the integrated nature of the department's waste minimization efforts.

In 1989, the Department of Energy initiated a formal waste minimization program that focused on the manufacture and production of nuclear defense components and systems. The goal was to eliminate or greatly reduce waste and hazards associated with the manufacture and reuse of individual nuclear weapon components. The program was initially sponsored jointly by the offices of Environmental Remediation and Waste Management (DOE/EM) and the Defense Programs (DOE/DP), and now receives continuing support from the DP Office. Waste minimization technology development is organized into 8 waste streams, which include both radioactive and toxic materials. The developments include process improvements, process change-outs, recycle, substitution, advanced instrumentation and control systems, automation, and systems analysis. Each of the 8 waste streams has a national expert (Waste Stream Manager) heading the development task selection process and tracking the progress in each area. These Waste Stream Managers also provide a coordination and integration role, both within the Department of Energy as well as with outside industry. DOE Program Managers, together with the Waste Stream Managers, represent a management team whose purpose is to guide developments and ensure proper emphasis on projects.

Outstanding progress has been made in a number of areas, many of which are discussed in this document. The reduction in the amount of waste generated within the DOE complex is significant and can be traced directly to these technology development efforts. In some areas, wastes have been reduced by >95%, while in others, such as chlorinated solvents, they have been entirely eliminated. The reduction in hazardous operations and potential hazards is noteworthy.

Numerous opportunities exist for applying both the technologies and overall waste minimization approaches to industrial concerns outside the DOE. If, after reading this document, additional information is desired, please contact John Marchetti (301) 903-3487 or Richard Cameron (505) 845-6361 at the Department of Energy, Office of Defense Programs.
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Sensors and Process Monitors

Accurate and timely control of processes and reagent conditions minimizes excess reagent usage, process volumes, and, in some cases, worker hazards.

- **Sensor Monitors Metals and Ions in Plating Rinse Tanks**
  A multi-ion detector system has been developed using micro-electrode sensor arrays for detecting both anions and cations in plating rinse tanks. The system has been proved to detect copper, cadmium, lead, and cyanide ions in the parts-per-million range. Techniques for monitoring chromium and nickel are under development. The sensor is an improvement over conventional conductivity meters because exact levels of different metals can be measured simultaneously. With such a sensor, the rinsing of electroplated parts can be optimized, ensuring adequate cleanliness with minimum water use and resulting in the lowest possible levels of metals in the rinsing waste stream. An estimated 500,000 gallons per year of dilute rinse waters can be saved across the weapons complex.
  
  \( \text{(R. Stoltz, ELECTRO-01)} \)

- **Ion-Selective Electrode Eliminates Titration with Silver and Chrome**
  Chrome and silver are RCRA-listed wastes that are used in chloride concentration determinations. The main processes for aqueous chloride purification are ion exchange and solvent extraction. Both are dependent upon the solution's chloride concentration for effective plutonium extraction. Chloride concentration was typically determined by titration with a standard silver nitrate solution and chrome indicator. Replacement of the titration with the use of an ion-selective electrode eliminated the mixed waste stream. The determination of chloride concentration is simplified and more accurate and the use of additional chemicals such as neutralizers, indicators, etc. has been eliminated.
  
  \( \text{(Christensen, PU-01)} \)

- **Detector Reduces Chlorine Gas and Equipment Corrosion**
  Chlorine gas is bubbled through molten calcium oxide to convert it to calcium chloride, a reagent necessary to reduce plutonium oxide to plutonium metal. A spectrophotometer incorporated into the off-gas system immediately detects the breakthrough of chlorine gas. This chlorine detection allows for a 50% reduction of chlorine in the off-gas system. Other benefits are improved process control, a reduction in caustic scrubber solution used in off-gas waste treatment, and reductions in chlorine gas, chlorine storage, equipment corrosion, and equipment cost.
  
  \( \text{(Christensen, PU-02)} \)
Sensors and Process Monitors (continued)

- **Airborne Contaminant Real-Time Workplace Monitor Developed**
  Airborne contamination monitors for uranium and beryllium are being developed that meet existing and proposed regulations. Data on these monitors indicate that the analytical sensitivity is sufficient to meet existing and proposed regulations. Implementation of these monitors will reduce worker exposure to airborne hazards, provide timely environmental sampling, reduce potential for unlawful environmental discharges, and reduce analytical expense. The estimated savings are $1.6 million per monitor compared to the alternative method of discrete sampling and laboratory analysis.
  
  *(D. Stoltz, MISC-01)*

- **Sensor Monitors High-Acid Concentrations in Real Time**
  An acid sensor has been developed and tested that monitors high-acid concentrations in-line. Many industrial operations depend on careful acid concentration control for their processing. In the past, no reliable method was available for monitoring acid concentrations over 1 molar acid without first removing the samples from the process line and then using titration. By incorporating the appropriate acid-sensitive polymers into a fiber optic flow cell, in-line acid concentrations can be measured rapidly and reversibly over the high-acid range of 0.5 to 12 molar acid. There are no commercial devices that can provide this function. The sensor allows for real-time control, much higher operating efficiencies, and better control of acid recovery and dissolution operations. The titration waste has been eliminated, and through process optimization, process waste has been reduced.
  
  *(Christensen, PU-03)*

- **Faster and More Accurate Environmental Analytical Methods Save Time and Money**
  Faster and more accurate analytical methods have been developed for nonradioactive materials. Methods have been developed to measure the concentration of methylenedianiline in printed circuit boards made from nonconductive laminate (i.e., prepreg) advertised as "methylenedianiline free". Ion chromatography and inductively coupled plasma-mass spectrometry methods for analyzing environmental and industrial waste samples have also been developed. Nondestructive x-ray fluorescence methods that minimize sample waste have proved effective. These new methods offer significant time and cost savings over existing regulatory agency approved methods.
  
  *(D. Stoltz, MISC-02)*

- **Residual Explosive Detection in Water and Soil Developed**
  Improved purge and trap techniques for concentrating samples and analyzing by gas chromatography have proved effective in quantifying both common organic industrial compounds and explosives. Figure 3 shows the increased sensitivity. These methods have been used to characterize both water and soil samples for toluene, methanol, acetone, tetrahydrofuran, and dioxane.
  
  *(Humphrey, ENERG-01)*
Recovery, Recycle, and Reuse

Fig. 4 ENVIRO-CP process for the rejuvenation and recycling of chemicals used in electroless nickel plating

The recovery, recycle, or reuse of equipment, reagents, or side reaction products requires less secondary and tertiary waste handling and provides feed, consuming less resources.

- **Alloy Consolidation Reduces Volume of Radioactive Material**
  A full-scale consolidation of depleted uranium alloy components was implemented to reduce the volume of radioactive material requiring storage. Depleted uranium alloy components are being recovered and stored. A vacuum induction process that melts these components reduces the total volume of radioactive material requiring storage by more than 80%; thus improving storage efficiency. Depleted uranium alloy consolidation reduces storage requirements by 97% and storage costs by $93,500. Additional savings are realized by decreasing safeguards and security needs.

  (Koger, U-02)

- **Technique Increases Plutonium Recovery and Recycle**
  A new precipitation technique has been developed and proved on half-scale that successfully increases plutonium recovery and recycle. A homogenous precipitation technique is being developed to increase plutonium recovery efficiencies from 99% to 99.9999%. This technique uses the thermal decomposition of a urea/formamide mixture to produce hydroxyl ions that are evenly distributed throughout the solution. These hydroxyl ions precipitate the plutonium ions into an easily filterable cake with a directly discardable filtrate. No further precipitation or acid adjustment within the plutonium facility is required. This eliminates additional filtrate residue processing and reduces radioactive secondary waste production, reducing waste processing costs by 90%.

  (Christensen, PU-04)
Recovery, Recycle, and Reuse (continued)

- Conversion of Salts Into Original Acid and Base Components Reduces Toxic Waste
During recovery and processing of uranium and plutonium, large amounts of waste salts are generated. These nitrate salts, considered toxic by the EPA,

![Figure 5 Example of an electrochemical membrane for recovery and recycle of salts](image)

- Biological Digestion in Explosive Processing Enables Filter and Water Reuse
Biological digestion enables reuse of charcoal filters and process water in explosive processing. A three-step biological digestion process was developed that reduces the amount of charcoal and water required in the treatment of explosive-containing waste. First, the RDX (cyclotrimethylene trinitramine) explosive is adsorbed from the waste stream using activated charcoal filters. The RDX is then desorbed from the filters with warm water. Lastly, anaerobic biodegradation is used to break down the explosive compounds into nonhaz-

![Figure 6 Biological digestion process](image)
Recovery, Recycle, and Reuse (continued)

- **Process Eliminates Mixed Waste and Reduces Hazards**
A common plutonium recovery process involves leaching the metal with an acid solution. An alternative process uses hydrogen gas to convert plutonium metal into a hydride. The plutonium metal then breaks into chips and falls beneath the item being cleaned. The fragments are heated in place, freeing the hydrogen to be recycled to the item above, thus allowing for hydrogen recovery, recycle, and reuse. In addition, a dry bed of uranium hydride and powdered uranium has been developed for storing hydrogen gas between uses. These dry beds eliminate the discharge of thousands of liters of flammable hydrogen gas into the environment. The hydride/dehydride recycle process not only reduces the hazards of handling large quantities of hydrogen gas and pyrophoric plutonium hydride, but also eliminates the large hazardous mixed-waste stream generated by the acid dissolution.

  (Christensen, PU-07)

- **Extractant Removes and Recycles a Hazardous Chemical**
An organic extractant has been developed and synthesized that selectively binds fluoride anion in 7 molar nitric acid. The key to this selective binding is the cavity in the extractant. The fluoride fits closely in the cavity while other anions are too large or have the wrong shape to fit. Fluoride is commonly added to nitric acid to improve plutonium dissolution from various residues and is then complexed by adding aluminum before plutonium recovery. However, this new organic extractant eliminates the need to add aluminum solutions, and the bound fluoride anion can be removed from the organic cage at high pH and recycled to the dissolution process. Several laboratory-scale tests without plutonium and a single laboratory-scale test with plutonium have shown that the technology is viable for full-scale processing and can provide a 30% reduction in waste volumes. Fluoride recovery and recycling will minimize storage, handling, and the amount of fluoride required for processing. The molecular structure of the organic compound with an encapsulated fluoride is shown in Figure 7.

  (Christensen, PU-08)
A novel unit process reduces waste generation, current hazards, and resource usage by process substitution rather than reagent or product substitution.

**Dry Machining Eliminates Chlorinated Hydrocarbons**

In traditional machining, an oil must be applied to the machined parts to ensure that they remain cool during cutting and to eliminate potential fire hazards. Afterward, a RCRA-listed solvent is used to remove the oil. When machining plutonium, the oil removed results in radioactive waste, the solvents result in mixed waste, and if there is oxygen in the atmosphere, the plutonium chips result in a plutonium oxide stream for secondary recovery. For every kilogram of oxide generated during traditional machining, approximately 100 kilograms of tertiary waste are generated. Through the use and optimization of special cutting tools, controlled atmospheres, and controlled cutting parameters, the dry machining process has been proved safe on a full scale, and the plutonium oxide, cutting oils, and subsequent cleaning solvents have been eliminated. The implementation of dry machining eliminated 15,000 gallons per year of carbon tetrachloride from the biggest user in the country.

(Christensen, PU-10)

**Lithium Part Production Method Minimizes Hazardous Waste**

The new elastomer bag method is replacing the warm-pressing method currently used in lithium part production. The new method is capable of producing near-net-shape parts, thus reducing machining wastes and costs compared to the currently used warm-pressing method. Design modifications to the Hydrin rubber lids on the elastomer bag have eliminated failures that originally resulted in generation of hazardous lithium scrap. The increased process efficiency means less operator exposure to hazardous materials.

(D. Stoltz, MISC-03)
**Novel Unit Processes (continued)**

- **Plasma Process Effectively Decontaminates Items and Recovers Plutonium**
  When standard decontamination procedures are used to remove plutonium from contaminated items, considerable quantities of waste are generated. However, the plasma decontamination process recovers plutonium and plutonium oxides from various substrates without generating additional waste. This process uses plasma to generate a reactive chemical intermediate from an inert and harmless feed gas. This intermediate reacts with the plutonium contamination (usually an oxide of plutonium) to form a volatile, gaseous product, which is pumped off from the item, leaving a clean decontaminated substrate. The off-gas is then filtered, and the residual plutonium species are trapped and recovered. Plasma decontamination of uranium would eliminate tens of thousands of liters of radioactive (potentially mixed) waste, the largest waste stream in weapons disassembly, and will also result in a reduction in process times and near elimination of personnel radiation exposure. This process has the potential to recover plutonium from soil or incinerator ash, to aid in site cleanup and decommissioning, and to decontaminate tools used in radioactive environments. This allows for their reuse and prevents their disposal as waste.

  *(Christensen, PU-11)*

- **In Situ Chlorination Eliminates Phosgene and Caustic Waste**
  Plutonium trichloride is required in the molten salt extraction process used to purify plutonium metal. The chloride is created by a reaction of plutonium oxide with hazardous phosgene gas and is then added to the extraction process. The neutralization of the phosgene off-gas requires large amounts of caustic scrubber waste solutions. However, by introducing chlorine gas into the molten plutonium metal and generating the chloride in situ, approximately 200 liters of radioactive caustic scrubber waste solutions are eliminated. Because the chlorine gas reacts 100% with the metal, no off-gas scrubber solutions are generated. Consequently, phosgene use has been totally eliminated in favor of a less hazardous chlorinating agent, and radiation exposures to personnel have been reduced.

  *(Christensen, PU-12)*
Novel Unit Processes (continued)

- **New Processes Identified as Potential Replacements for Fluoride Processing**

  Three processes have been successfully demonstrated and are under examination as potential replacements for the fluoride reduction process. One of the major concerns with uranium processing is the current fluoride reduction method that generates large waste streams (one of which is a mixed waste stream), and is a potential hazard to workers and the general public. Saltless Direct Oxide Reduction, currently under examination as a potential replacement, has had considerable success in the developmental stage. Two competing processes, photochemical and electrochemical reduction of uranyl nitrate, have also been successfully demonstrated. In these processes, the uranium powders are melted in calcium oxide crucibles and consolidated into buttons. At the beginning of the project, the success of these containment crucibles was considered to be one of the technical challenges. The replacement processes significantly increase safety and reduce cost.

  (Koger, U-04)

- **Reverse Blow-Forming Techniques Reduce Waste**

  Reverse Blow Forming uranium part production offers the opportunity to produce near-net shape parts and reduce the waste generated when machining a part to shape. This technique was successfully demonstrated using a lead tin alloy. Reverse Blow Forming is an improvement to the traditional superplastic forming method and is expected to reduce machining chips by 35%.

  (Koger, U-05)

- **Centrifugal Contactors Eliminate Large Amounts of Solvents and Hazardous Chemicals**

  Centrifugal contactors are being examined as a replacement for the current two-cascade system of pulse columns used in uranium purification. The columns require large amounts of solvents and an aluminum nitrate salting agent that must be disposed of or recovered. Experiments were performed using tri-butyl phosphate as a single solvent, and a minimum uranium loss of 5 ppm was obtained.

  (Koger, U-06)

- **Nonfluoride Sintering Method Eliminates Hazardous Additive and Radioactive Waste Stream**

  A nonfluoride sintering method was investigated as an alternative to the sintering step currently used in uranium purification. With this new method, approximately 80% of the uranium will be recovered, a very large radioactive caustic waste stream will be eliminated, and the additive aluminum nitrate, a major contributor to the waste stream, will no longer be necessary.

  (Koger, U-07)
Novel Unit Processes (continued)

- **Chipless Method for Machining Thorium Developed**
  A method for machining thorium that does not produce chips has been developed and successfully demonstrated. From a waste and hazard viewpoint, chip production during thorium machining is undesirable. A chipless method has been developed and successfully demonstrated on surrogate materials. The cutter is pressed into the surface of the material while the material is rotated. This process produced only a few flakes of material and no chips.  
  *(Koger, U-08)*

- **RCRA Waste Eliminated in the Plating of Copper onto Stainless Steel**
  The standard procedure for electroplating thin layers of copper onto 304L stainless steel requires eight aqueous steps, several of which generate RCRA-hazardous wastes. An alternative vacuum deposition requires only four environmentally benign steps and produces noncolumnar, fine-grain deposits of copper with superior adhesive strengths. It is being implemented as an alternative to electro-deposited copper in selected applications. The estimated waste reduction is approximately 10,000 gallons per year of medium concentration wastes across the complex.  
  *(R. Stoltz, ELECTRO-03)*

- **Supercritical Carbon Dioxide is a Compatible Replacement for Chlorinated Hydrocarbons**
  An alternative cleaning technology to chlorinated hydrocarbon solvents, which employs supercritical fluid carbon dioxide (SCF), was identified and investigated. SCF has excellent solvent properties for organics, is attained at moderate conditions, and has minimal environmental, safety, and health risks. The major concern of supercritical carbon dioxide’s chemical compatibility with freshly burnished plutonium metal has been eliminated. Additionally, the cleaning efficiency has been demonstrated as adequate, thus permitting design of a pilot facility. Implementation of the carbon dioxide cleaning process eliminates a major source of mixed waste in fabrication and an equally large discharge of ozone-depleting vapors to the environment. In addition, the development of carbon dioxide recycle capability minimizes total waste generation.  
  *(Stiefeld, SOLV-01)*

- **High-Pressure Water Jet Successfully Disassembles Weapon Components**
  Figure 10 shows a high-pressure water jet used successfully to disassemble weapon components containing explosives. A coherent jet of high-pressure water successfully removed explosive components from metal housings. The water jet, directed along the adhesive interface between the case and the explosive, cuts the explosive and removes it in one large piece with minimal contaminated slurry or breakage.  
  *(Humphrey, ENERG-03)*
Novel Unit Processes (continued)

- **Elastomer Bag Method Reduces Waste**
  Concerns that parts formed by the elastomer bag method will fail physical property tests have been dispelled. Near-net-shape parts created by pressing using an elastomer bag were formed and the finishes machined. Part cracking was not exhibited. These parts were fully characterized for chemical, physical, and mechanical properties. Originally, it was suspected that these properties varied when measured along different directions; however, this was not observed. The success of these formed parts has reduced lithium machining waste and the number of failed parts which have to be reintroduced into the recovery process.  
  (D. Stoltz, MISC-04)

- **Solid Oxide Electrolysis Chosen for Safe Tritium Gas Regeneration**
  Solid oxide electrolysis is the prime candidate to replace the sacrificial uranium beds used in the glovebox stripper regeneration system to decompose tritiated water. This process features negligible tritiated water vapor content in the exhaust oxygen stream. A similar system was used previously by the National Aeronautics and Space Administration.  
  (Woods, TRIT-01)

- **Gas Permeable Membranes May Help Recover Tritium**
  Gas permeable fibers and membranes that can separate the gases in a mixture have long been available. Commercial separators are also available. The feasibility of using polymer capillary bundles to separate tritium from glovebox-line gases was investigated. Hydrogen and deuterium separation was demonstrated, and the application of this technology to tritium looks very promising. When proved, this technology will be coupled with metal-getter technology to form a sophisticated tritium recovery/recycle system. The tritium recovery technologies reduce potential for worker exposure and eliminate contaminated waste handling and disposal costs. The recycling of tritium reduces exposure to the environment.  
  (Woods, TRIT-02)

- **Developments in Diamond-Like Carbon Coating Reduce Waste**
  Diamond-like carbon (DLC) films, composed of carbon and hydrogen, have been developed to provide smooth, corrosion resistant coatings for use in a variety of applications. An undercoating system for diamond-like carbon has been developed that expands its utility to a wider variety of substrates. Previous work indicated lack of adherence to iron and steel because of mechanical and chemical mismatch between the films and substrate. By developing a silicon layer between the film and the substrate, the adherence of diamond-like carbon to iron and steel has been increased. DLC films can now be substituted for electrolytic and electroless plating systems and for lubricating films that contain volatile organic hydrocarbons. Toxicity elimination and waste reduction are simultaneously enhanced because the DLC process occurs in an enclosed chamber and uses only methane and hydrogen as feed gases.  
  (R. Stoltz, ELECTRO-04)
Novel Unit Processes (continued)

- Testing Shows Metal Getters Safely Remove Tritium
  The DOE sites that process tritium typically convert waste gas tritium to water, thereby increasing the potential radiation exposure hazard to workers by a factor of at least 10,000 (based on a toxicity comparison of molecular gaseous tritium to tritiated water). An apparatus was completed for conducting small-scale tritium stripping tests with metal getters. Tests with one getter material demonstrated the getter’s ability to remove deuterium from a flowing nitrogen stream, simulating a tritium process waste stream. Data from this new system, along with developed models, will be used to design a getter-based tritium stripping system that significantly improves the safety of tritium recovery operations and reduces the amount of tritium contaminated waste for burial.  
  (Woods, TRIT-03)

- Near-Net-Shape Technology Reduces Waste in High-Explosives Processing
  Laboratory-scale parts of the LX-17-1 high explosive have been manufactured using near-net-shape forming and isostatic pressing. Density gradients within the matrix have been adjusted by using dynamic punching with aluminum alloy plugs. This technology provides potential significant reduction in the amount of high explosives waste generated. See Figure 11.  
  (Humphrey, ENERG-04)

- Processes Successfully Clean Uranium Chips and Eliminate Freon Use
  Approximately 80,000 pounds of freon are currently released to the atmosphere every year in uranium chip-cleaning operations. Possible replacements include aqueous cleaning and semiaqueous cleaning of the chips. Both of these techniques reduced the boron contamination to an acceptable level and, in combination with a vacuum drying system, are viable alternatives to freon. The elimination of freon also saves $284,000 per year in excise taxes.  
  (Koger, U-09)

- Aqueous Cleaning Technology Reduces Trichloroethane Usage
  Use of a chlorinated hydrocarbon as a vapor degreaser in hybrid microcircuit assemblies has been reduced by substituting a successfully tested aqueous cleaning technology. Test panels of Leadless Chip Carrier were soldered to test circuits on a transparent substrate for evaluating d-limonene and an aqueous/saponifier spray as alternative cleaning technologies. The aqueous/saponifier spray cleaning removed all solder flux residue; therefore, it will replace vapor degreasing in Leadless Chip Carrier cleaning. The use of 1,1,1 trichloroethane (a RCRA-listed chlorinated hydrocarbon) was reduced at one site by 37%.  
  (Stiefeld, SOLV-02)
Systems Analysis

Models of processes provide methods to predict and reduce waste generation and optimize process parameters without actually having to generate the waste.

- **Reaction Heat Effects Model Improves Process Efficiency**
  The discovery and modeling of heat effects in surface reactions significantly improves understanding and process efficiencies in a wide variety of industrially important surface chemistries. A conceptually simple theoretical model of heat effects in surface reactions has been formulated that accurately describes the generation and transport of heat in a wide array of important surface chemical systems. For the first time, a single model has been used to explain and predict many puzzling phenomena in reactive surface chemistries. Application of this technique has importance in such diverse fields as the semiconductor manufacturing industry, environmental restoration, and plutonium processing. By modeling the thermal feedback between heat of reaction and reaction kinetics, operating conditions can be identified that increase process efficiency by several hundred percent. Alternatively, the model clearly shows how to avoid process conditions that result in overheating and subsequent degradation. This model has enormous value for plasma etching and other surface chemical systems. (Christensen, PLI-13)

- **Computer Simulation Models Nuclear Weapons Processes**
  The model uses a material flow mass-balance to predict product throughputs, residue generation and recycle amounts, and waste generation amounts and types. The model makes it possible to predict waste generation changes for the entire system as the process flow sheet changes or specific process parameters change. Improving a single process may actually cause downstream inefficiencies by changing the residue types and the waste generated; thus, the system as a whole may be negatively affected. The simulation provides the analysts and technologists with process information without actually generating the wastes in an experimental setting. Comprehensive material data bases have been compiled by technology groups and experts for the various processes and material types. Various theoretical cases are fed to the model to assess what the impacts of substituting alternative technologies, scaling-up production, operating at less than optimum efficiencies, and recovering stockpile returns and new weapon designs on waste generation, worker exposure, production capacity, and equipment requirements. (Christensen, PLI-14)
- **Matrix for Cleaning Solvents Alternatives Developed**
  This matrix is a users guide of alternative cleaning solvents that lab results indicate have potential applications for removing contaminants, oils, greases, etc. It will be distributed to plant personnel for education and use in solvent substitution. The emphasis on solvent substitution and the availability of information to plant personnel should greatly reduce the use of chlorinated hydrocarbons and chlorinated fluorocarbons.  
  *(Stiefeld, SOLV-03)*

- **Method Developed to Identify and Record Hazardous Materials**
  Waste minimization during weapons dismantlement depends on accurate characterization of all materials used during weapons production. Many of the commercial materials employed are proprietary. Engineering drawing searches supplemented by nondestructive and chemical analyses have been used to create a materials data base. The data base is expandable. Knowing the makeup of each system has permitted segregation of hazardous materials from both nonhazardous and reusable components during disassembly, and it is expected that $500,000 per year in precious metals can be recovered.  
  *(D. Stoltz, MISC-05)*

- **Method Developed for Process Waste Assessments**
  Process Waste Assessments provide a systematic way to evaluate materials used in a process, identify waste leaving the process, and generate and evaluate options for pollution prevention. Guidance documents have been published and distributed to DOE sites and to selected private industries (e.g., electroplating and metal finishing). A training class was developed to teach personnel the methodology. A graded approach has been formulated based on the hazardous materials used and the quantity of waste generated which can be applied to manufacturing, non-manufacturing, and laboratory processes. This methodology is simpler than Environmental Protection Agency baseline data and integrates regulatory reporting requirements. The industrial hygiene baseline data collection total cost savings is $5,850,000.  
  *(D. Stoltz, MISC-06)*

- **Water Jet Technology Modeled**
  Little was known about the fundamental mechanics of using ultrahigh-velocity water jets to cut materials. A comprehensive model of the mechanics of water-jet machining was completed. This model has been used to evaluate the safety of using water jets to disassemble nuclear weapons.  
  *(Humphrey, ENERG-05)*

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**Fig. 12 Process waste assessments**

<table>
<thead>
<tr>
<th>Feeds</th>
<th>PROCESS</th>
<th>Product</th>
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<tbody>
<tr>
<td>Waste to Air</td>
<td>Waste to Soil</td>
<td>Waste to Water</td>
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</tbody>
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**(Systems Analysis (continued))**

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• Method Developed to Evaluate, Prioritize, and Minimize Waste
A methodology was developed to evaluate and prioritize waste minimization activities. A systematic and defensible method was developed for the DOE Waste Stream Managers to select waste minimization proposals that maximize the benefits to DOE while maintaining costs within budget. The method is composed of a structured set of evaluation criteria to characterize proposals; techniques for documenting anticipated costs, risks, and benefits; and a method for translating disparate data into a figure of merit. Figure 13 shows an example worksheet. The effectiveness of the process was demonstrated and provided a defensible budgeting process.

(D. Stoltz, MISC-07)

• Data Base Evaluates Carcinogen Replacements
A data base is being expanded that evaluates replacements for the carcinogen-containing polymer currently used in printed wire boards. The polymer currently used contains methylenedianiline, a suspected carcinogen, and replacements are being investigated. A standard test panel was created that contributes to uniform test data. Tests have been conducted on the tensile and flexure strength, thermal expansion, glass transition temperature, and delamination resistance of printed wire boards. These results have been added to the data base developed four years ago to evaluate replacement materials for polymers containing carcinogens. The identification of a replacement minimizes worker exposure to carcinogens.

(Swartz, POLY-01)
A reduction in the threats presented by hazardous chemicals, dangerous materials, or radiation may be accomplished by using less than was previously thought to be required, or by simply improving existing processes.

- **Changes in Analytical Fluid Suspension Eliminates Organic Waste**
  Powder samples are suspended in a fluid before analysis for particle size characterization. A suspension method was identified that uses water to adequately suspend the powder for accurate size analysis, eliminating the organic suspension aid, ethylene glycol. As a result, the volume of suspension fluid is reduced by 50%. Disposal of the organic waste required cementation, so this change resulted in significant disposal cost savings. *(Christensen, PU-15)*

- **Casting Improvements Reduce Feed Required and Eliminate Waste**
  Many improvements have been made to the plutonium-casting operation. Plutonium metal no longer needs to be rolled and formed after casting, and the need for machining after casting has been reduced. These improvements have been proved on subscale and some full-scale plutonium parts, eliminating graphite molds and the resultant waste from the wrought processing as well as greatly reducing the required amount of starting material. The amount of plutonium oxide generated by the redundant fabrication steps previously used resulted in a significant waste stream requiring secondary processing. For every kilogram of oxide eliminated during fabrication, approximately 100 kilograms of tertiary waste have been saved. *(Christensen, PU-16)*

- **Process Developed to Remove Classified Characteristics**
  Laboratory-scale methods and processes were developed to remove classified characteristics from water-soluble toxic and nontoxic materials. Removal of classified characteristics from waste items will be incorporated as part of the production process. Mechanical as well as chemical methods were employed to minimize the classified waste stream, greatly reducing the cost and security requirements of handling this stream. See Figure 14. *(D. Stoltz, MISC-08)*

- **Changes in Printed Wire Board Manufacturing Reduce Waste**
  Equipment changes in the flex circuit printed wire board manufacturing process have resulted in significant liquid waste stream reductions. At one DOE site, an etchant regeneration system has been installed and will reduce waste from 3,200 gallons per year to 170 gallons. Developer regeneration equipment was purchased that will reduce sodium carbonate contaminated waste water from 2,600 gallons per year to 250 gallons. Rinse system modifications will save 111,000 gallons of incoming water per year. *(D. Stoltz, MISC-09)*
Source or Hazard Reduction (continued)

- **Safety Enhanced in Lithium Processing Recovery Method**
  Hardware and control changes in lithium processing have optimized process monitoring, resulting in increased process efficiency and decreased process waste. The lithium chloride electrolytic process for generating lithium has been modified to improve lithium recovery. The cell uses chlorine gas and molten lithium. Hardware and control improvements were installed that include temperature monitoring throughout the cell and safety interlocks to prevent overheating hazards and to ensure gas flow. Preliminary equipment checkout has been successful. Process efficiency is increased, worker exposure to hazardous material is reduced, and hazardous waste generated is minimized.
  
  *(D. Stoltz, MISC-10)*

- **Two Process Steps Involving Toxic Materials Eliminated**
  In metal finishing operations, two steps in passivation use toxic materials. Vapor degreasing uses trichloroethylene as a solvent, and alkaline cleaning uses sodium cyanide as a descaler. Tests for cleaning effectiveness and corrosion resistance on wrought and stainless steel parts showed that these two steps could be eliminated without compromising quality. As a result, the vapor degreasing step has been totally eliminated, and the number of parts requiring alkaline cleaning has been reduced by 75%.
  
  *(Stiefeld, SOLV-04)*
Material Substitution

Finding acceptable substitutes for current hazardous materials is the best alternative to dealing with them.

- **Material Substitution Eliminates Cyanide in Plating Baths**
  Process Waste Assessments were completed at two DP plating facilities and cyanide was identified as a large waste problem. Cadmium sulfate successfully replaced cadmium cyanide, and copper pyrophosphate was validated and implemented to replace copper cyanide. Plating bath stability, functional characteristics of the coating, and the plating procedure were all optimized. These substitutions have resulted in cyanide-free plating operations in at least four DOE facilities. Through meetings and video-based seminars, U.S. industry and other government facilities have been informed of the cyanide substitution activities. These facilities are implementing the substitutions in their plating operations. Cost savings is estimated at $3,000,000 per year based on a reduction in handling, control, and waste treatment costs. Potential hazards of cyanide exposure to workers are eliminated.  
  (R. Stoltz, ELECTRO-05)

- **Substitute for Tetrachloroethylene Identified and Demonstrated**
  The organic diluent used for tributyl phosphate in chloride solvent extraction of plutonium has been tetrachloroethylene (a RCRA-listed waste). Dodecane with ethanol has proved an acceptable substitute diluent, permitting the continued operation of chloride solvent extraction without generating a mixed waste. This has eliminated approximately 10,000 liters of hazardous mixed waste per year.  
  (Christensen, PU-17)

- **Material Replacements Reduce Mixed Waste**
  Every material that enters the uranium facility must be processed for uranium recovery. Examples of these materials are filters, wipes, and wooden pallets. The recovery process consists of burning these items to ash and then chemically processing them. By replacing high-ash materials with low-ash materials, the amount of mixed residues from the process is reduced. Replacement of wet filter media with polypropylene felt has reduced a major source of intractable uranium-bearing residues. Recommendations have been issued for replacing polyvinylchloride bag filters and shredder bags with low-ash alternatives. This will reduce the residues as well as the chemicals required for processing these materials.  
  (Koger, U-10)
Material Substitution (continued)

- **Alternative Cleaning Methods Minimize Hazardous Chemicals**
  Alternative cleaning solvents and processes were investigated that will reduce or eliminate chlorinated hydrocarbon and chlorinated fluorocarbon use. D-limonene was developed as an alternative cleaning solvent to trichloroethylene and chlorinated fluorocarbons for certain applications. For other components, successful alternative cleaning technologies that were identified and tested included aqueous cleaners, Actrel 4493L, soda blast, isopropyl alcohol, d-limonene, Bioact EC-7, and Citradet. Extensive cleaning efficiency tests and compatibility studies have been conducted, and investigation into cleaning avoidance techniques is ongoing. In December 1992, a final report will be distributed that summarizes the solvent substitution work conducted during the last three years. This report summarizes work completed at both the production plants and design labs in the following areas: alternative solvents, contaminants, materials compatibility studies, and accelerated aging studies.
  
  *(Stiefeld, SOLV-05)*

- **Solvent Substitution Eliminates Two Hazardous Materials**
  The nonhazardous solvents, d-limonene and BioAct EC-7, were selected as base line alternatives for many production processes. These selections were based on cleaning efficiency trials and processing optimization, cleaning specification revisions, component and component material compatibility tests, and, when applicable, functional component evaluation. As a very large user of chlorofluorocarbons (Freon 113), a machining facility was successfully converted to d-limonene cleaning, and a total elimination of Freon 113 was achieved. By converting to Bioact EC-7 for cleaning, a large ceramic manufacturing facility successfully achieved total elimination of a chlorinated hydrocarbon (dichloromethane).
  
  *(Stiefeld, SOLV-06)*
Alternative Solvents and Technologies Eliminate Chlorinated Fluorocarbons and Hydrocarbons

Alternative technologies developed at the laboratories and plants and funded by DP are actively being transferred to small- and medium-sized businesses. Methylene chloride was eliminated from mold-cleaning operations and replaced with nickel-Teflon coated molds and/or mechanical abrasion with plastic bead blasting, thus eliminating 600 gallons of methylene chloride use per year. It is anticipated that Freon-113 will be eliminated because of process design improvements reducing Freon use by 200 gallons per year. Methylene chloride as a polymer cleaning agent may be replaced with N-methylprrolidinone and acetone, reducing methylene chloride use by 250 gallons per year. Trichloroethylene vapor as a degreaser in ceramics machining is anticipated to be replaced by Oakite Citradet (a semiaqueous process) and detergent processes, eliminating 230 gallons per year of trichloroethylene. An anticipated switch from Freon-113 blending of battery electrolyte to dry blending of powders would eliminate 15 gallons of freon per year. In one DP plant, 21 out of 36 areas originally identified as chlorinated solvent users have implemented substitutes such as Solvent 140, Water Chaser 140, terpenes, and aqueous processes (e.g., vapor degreasers using perchloroethylene were replaced with ultrasonic cleaning using water). Another DP plant reduced the annual use of chlorinated hydrocarbons from 6,540 gallons in FY91 to 3,953 gallons in FY92 and reduced the annual use of chlorinated fluorocarbons from 33,650 pounds in FY91 to 17,640 pounds in FY92. These reductions were a result of the following changes: aqueous spray cleaning was substituted for halogenated solvents, trichloroethylene immersion cleaning was eliminated, aqueous volatile cleaner was substituted for Freon-113, and methylene chloride and trichloroethane were eliminated by converting to aqueous photolithography processing.

Changes in Vapor-Phase Soldering Operations Eliminate Hazardous Chemicals

Alternative solvents and technologies were identified and investigated to eliminate chlorofluorocarbon use in vapor-phase soldering operations. As a short-term solution to the chlorofluorocarbon problem, Freon 113 is being replaced with the less harmful SF-2 as a secondary vapor blanket on vapor-phase reflow soldering equipment. As a result, Freon 113 use was reduced by 6,000 pounds per year. As a long-term solution, three alternative technologies were analyzed: infrared, a new vapor phase, and convection soldering systems. Based on this analysis, a convection system was selected for installation and characterization to eliminate chlorofluorocarbon use.
Material Substitution (continued)

- **Replacement for Carcinogen in Printed Wire Boards Identified**
  Replacements have been identified for methylenedianiline (MDA), a suspected human carcinogen, as a curing agent for encapsulation processes and as a component in printed wire boards. Programs currently under way replace all MDA processes with materials that eliminate production worker exposure, yet do not sacrifice weapon quality and reliability. Organic anhydrides are being characterized as the primary replacement candidate for curing epoxy encapsulants. The anhydrides are noncarcinogenic with a toxicity comparable to table salt. Cycloaliphatic amines, noncarcinogenic materials with moderate toxicity, are being characterized as the secondary replacement candidate for MDA. Printed wire boards that do not contain MDA have been identified as replacements. MDA replacements eliminate worker exposure to the suspect carcinogen.

(Swartz, POLY-02)

- **Replacements in Foam and Elastomers Eliminate Carcinogen Exposure**
  Replacements have been identified and are being incorporated for toluene diisocyanate (TDI), a suspected human carcinogen that is employed in foams and elastomers. Materials that are either noncarcinogenic or less toxic are being investigated. Two foam formulations have been developed employing polymeric isocyanates, materials with a much higher vapor pressure than TDI, that minimize production worker exposure to the suspected human carcinogen. All foams in weapons systems will be replaced with one of these two formulations, depending on the specifications of the particular application. A curing agent with moderate toxicity but no carcinogenicity has been identified as a replacement for the TDI used to cure elastomers.

(Swartz, POLY-03)

- **Technology Transfer Effort Identifies Substitute for Hazardous Polymer**
  A contract was initiated to develop an alternative for the dry film photoresist currently used in flexible circuit manufacturing. The candidate replacement system is a complex of polymers and copolymers. This effort is supported by private industry, government agencies, and a consortium of universities.

(D. Stoltz, MISC-11)

- **Substitute Explosives Component Reduces Hazardous Waste**
  Dimethylformamide is a highly toxic component used in explosives manufacturing. Initial laboratory-scale tests indicate the possibility to significantly reduce hazardous waste by substitution of acetone, which is less toxic, for dimethylformamide. Pilot plant-scale tests have shown that a 55% reduction in hazardous waste is achieved by this substitution during the formulation of the explosive compound hexanitrostilbene.

(Humphrey, ENERG-06)
Substitutes for Chrome in Energetic Materials Identified and Tested

Boron/calcium chromate is an energetic material used in the DOE complex that contains chrome, a RCRA-listed waste. An extensive literature search produced many different boron-based compositions that were subsequently assessed for a variety of properties. Aluminum/copper oxide could replace boron/calcium chromate in certain pyrotechnic applications except that it is difficult to ignite. In Figure 16, differential scanning calorimetry shows that boron/copper oxide is much easier to ignite, yet produces a similar amount of heat. Based on the analytical results, boron/copper oxide was the preferred candidate. Safety and ignition sensitivity tests were successful, but low resistance-after-fire concerns are still being investigated. The replacement will eliminate the use of chrome in this operation. (Humphrey, ENERG-07)

Alternative Solvent Dissolves Explosives

Initial experiments have been successful in determining if supercritical carbon dioxide can be used as a nonsolvent substitute for dissolving explosives. The explosive PETN was dissolved in supercritical carbon dioxide; the solution was then expelled through a depressurization nozzle into a collection vial, isolating the explosive. Analysis showed the PETN was not chemically altered by this procedure. Solubility studies of the explosive in supercritical carbon dioxide showed that the solubility is a function of pressure and that a useful solubility is seen at higher pressures. Using supercritical carbon dioxide eliminates the use of hazardous solvents. (Humphrey, ENERG-08)

Nontoxic Replacement for Hexavalent Chromium Found

In aluminum finishing the deoxidizer potassium dichromate is used for cleaning before welding. It is a hexavalent chromium that is a RCRA-listed toxin. After tests were conducted on the bonding strength of epoxy materials to deoxidized aluminum surfaces, a nontoxic deoxidizer was identified and proved to be an acceptable replacement. (Stoltz, ELECTRO-06)

Ink Free of Volatile Organic Compounds Found

An ultraviolet-curable ink that has no volatile organic compounds has been shown to resist d-limonene, the selected replacement for the current hazardous solvent cleaning systems. Ultraviolet cure cabinets have been built to protect personnel from exposure to high levels of ultraviolet radiation. (Stiefeld, SOLV-09)
• Trivalent Chromium Plating System Replaces Carcinogen
A simple, optimized, and effective trivalent chromium-plating bath has been
developed to replace the hazardous hexavalent chromium system. The Depart-
ment of Commerce National Institute of Standards and Technology and the
DOE jointly sponsor this program. The bath uses only one plating tank,
-  exhibits higher efficiency than other trivalent formulations, and results in a
-  heat treatable coating. Replacement of hexavalent chromium with a noncarci-
nogenic trivalent will significantly reduce worker hazard in chromium-plating
operations and reduce the cost of protective systems and air monitoring.
(R. Stoltz, ELECTRO-07)

• Zinc-Nickel Plating Performance Optimized
Alkaline zinc-nickel baths are now becoming the industry standard for replac-
ing cadmium, a known heavy metal poison in plating operations for screws,
fasteners, and other functional connectors. The plating parameters have been
explored, and the optimum ranges for producing a uniform, corrosion resistant
electro-deposited alloy coating have been determined. Operation of the bath
in this optimum range will increase the use of zinc-nickel and accelerate the
elimination of cadmium plating in DOE and U.S. industry significantly reduc-
ing worker exposure to cadmium.
(R. Stoltz, ELECTRO-08)

• Resin-Sealing System Eliminates Use of Chrome
Boiling dichromate sealing baths and chromic acid deoxidizer systems are two
large sources of chromium in waste waters and in air effluents. At one DOE
plant, an organic resin system has been installed and has proved to be an
effective substitute. Significant reductions in fugitive air emissions of chro-
mium and in the levels of chromium in rinse wastes have resulted. It has also
resulted in cost savings in monitoring systems, air handling, and reporting.
(R. Stoltz, ELECTRO-09)


Automated Systems

Increasing the distance between the worker and the hazard or allowing an automated system to perform a hazardous job minimizes danger to personnel. Automated systems also allow for very tight control on process parameters, reducing waste generation.

- **Automated Alternatives to Manual Skimming Process Discovered**
  The current method used to extract molten lithium from electrolytic cells is manual skimming. This process places the operator in close proximity to a very high-temperature bath. Because of the nature of this bath, incidences of small fires and material splattering have occurred. Several potential solutions were modeled and tested in the laboratory using stereolithography. Two of these solutions are deemed as feasible alternatives. And one automated alternative has been successfully demonstrated that will remove the operator from this hazardous environment.  

  (Koger, U-11)

- **Automatic Dispensing Equipment Minimizes Worker Hazard**
  Automatic dispensing equipment has been identified to meter, mix, and dispense hazardous materials when it is impossible to substitute a less hazardous material. Many programs are under way to automate dispensing equipment for hazardous materials. Consequently, production worker exposure to these carcinogens or hazardous materials is minimized.

  (Swartz, POLY-04)

- **Remote Explosive Assembly Reduces Worker Hazard**
  In a joint project between weapons design personnel and production personnel, an automated system capable of dispensing titanium-subhydride explosive with a high reproducibility was demonstrated. Formal requirements and design documents have been developed. The integration of the pressing cell hardware and the initial version of the software has been completed. This remote explosives manufacturing cell reduces hazards to workers by eliminating personnel handling.

  (Humphrey, ENERG-09)

- **Automated Weapon Disassembly System Developed**
  A robotics system jointly developed by weapons design and production personnel performed well in laboratory tests. It successfully separated the high explosive from the mock nuclear assembly package, placed the mock nuclear assembly in the shipping fixture, and put the fixture in a shipping drum. To demonstrate the automated operations, hardware was fabricated and integrated with prototype software. The robotics system demonstrated excellent mechanical protection and electrical isolation features. This system greatly improves personnel safety by automating the disassembly and packaging.

  (D. Stoltz, MISC-12)
Engineering Controls

Physical controls such as gloveboxes, quality glovebox atmospheres, equipment shields, engineered air flows, and equipment configurations reduce worker hazards and may also be methods to improve process efficiencies.

- Air Filter Requirements Defined for Nuclear Material Processing Areas

Nuclear material processing areas use a HEPA filter system for filtering particulates from the air. When these large filter banks are replaced, radioactive waste is generated. Therefore, it is desirable to maximize the service life of these filters. It is also important that the filters do not become so full that particulates break through the filter bank contaminating the "clean" air. System performance requirements were defined for normal and abnormal processing conditions, and methods were developed to characterize filter performance. This site-specific plan minimizes radioactive waste generated while still insuring worker safety. (D. Stoltz, MISC-13)

- Cleaning System Eliminates Release of Chlorinated Hydrocarbons

A cleaning system has been developed that contains and recycles solvents used in radar manufacturing. Figure 19 illustrates an automatic, self-contained, sealed spray chamber loaded with the parts to be cleaned. After loading, the chamber is backfilled with nitrogen, the parts are cleaned with d-limonene or trichloroethylene, and the chamber is again backfilled with nitrogen. The parts are sprayed with alcohol, the chamber is purged with nitrogen, and the parts come out clean and dry. The system contains the vapors by trapping them in a carbon filter the size of a 55-gallon drum. Because the system is closed, no chlorinated hydrocarbons are released into the atmosphere and the solvent can be cleaned and recycled. (Stiefled, SOLV-10)

- Advanced Containment Design Reduces Hazardous Waste

A design study to select a new lithium machining enclosure has been completed. The design employs a stainless steel reactor vessel with glass viewing ports and a super high-purity cover gas. This reduces worker exposure to reactive lithium and saves an estimated $2 million per year from reduced need for removal and management of waste. (D. Stoltz, MISC-14)
Engineering
Controls

- Pneumatic Transfer of Radioactive Materials Minimizes
Wastes and Hazards

A significant number of operations in the Defense Complex require the
transfer of radioactive material outside glovebox lines. These transfers are
usually performed by removing the material from the glovebox in plastic bags
and hand carrying the bags to their destination. As an initial step to upgrade
the safety and productivity of this operation, two pneumatic sample transfer
systems were developed and successfully demonstrated, and a test-verified
computer model that accurately predicts operating parameters and limits on
the full practical range of pneumatic transfer systems was developed. This
model studies the effects of varying transfer distances, package sizes and
weights, air flow requirements, and pressure drops, etc. The prototype units
resulted in reductions in contaminated waste, decreased potential for contamina-
tion incidents, minimized radiation exposure, enhanced nuclear materials
safeguards, and increased efficiency of operation for distributing the relatively
small sample vials. It is anticipated that the same benefits will be proven on
larger scale transfers.

(Christensen, PU-18)
Waste minimization has the potential for reducing cost while providing a permanent and viable solution to most waste problems. Waste treatment and disposal consumes a significant portion of the Department's operating budget. In fact, if not reversed, this "end-of-the-pipe" concept of waste management will eventually consume the Department's entire budget. A combination of material substitution, modification of production operations, redesign of products, and recycling has the potential for significantly reducing the volume of waste generated as well as eliminating all hazardous and toxic constituents. It will move us toward the presidential goal to accelerate the phaseout of substances that deplete the Earth's ozone layer. A review of 13 Defense Program (DP) sites in 1992 indicated cost savings of more than $50 million due to avoided waste disposal and product purchase costs that resulted from material substitutions, process improvement, and recycling. Achieving such reductions throughout DOE will save the Department $10 billion in reduced waste treatment, storage, and disposal costs over a 15 to 20 year period.

The Waste Minimization Management Group continues to evolve with the changing needs of the Defense Complex. On August 27, 1992, a new mission statement was adopted. "In support of the enduring stockpile and downsizing of the nuclear weapons complex, the Waste Minimization Management Group will eliminate or reduce employee exposure to hazards in the nuclear weapon complex while fostering technology transfer opportunities."

A successful Pollution Prevention Technology Development Program, led by DP, will support DOE in achieving its waste reduction goals, but faster, more safely, and at a lower cost than would otherwise be possible. Technology development will provide significant benefits to government and U.S. industry through technology transfer. The investment in technology development will be recaptured through savings in operational and maintenance costs as well as in an improved quality of life.

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