REPLACEMENT OF HEPA FILTERS AT THE LANL CMR FACILITY: RISKS REDUCED BY COMPREHENSIVE WASTE CHARACTERIZATION

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ABSTRACT

In March 2001, the Los Alamos National Laboratory (LANL) completed the replacement of 720 radioactively contaminated HEPA filters for $5.7M. This project was completed five months ahead of schedule and $6.0M under budget with no worker injuries or contaminations. Numerous health and safety, environmental, and waste disposal problems were overcome, including having to perform work in a radioactively contaminated work environment, that was also contaminated with perchlorates (potential explosive). High waste disposal costs were also an issue. A project risk analysis and government cost estimate determined that the cost of performing the work would be $11.8M. To reduce risk, a $1.2M comprehensive condition assessment was performed to determine the degree of toxic and radioactive contamination trapped on the HEPA filters; and to determine whether explosive concentrations of perchlorates were present. Workers from LANL and personnel from Waldheim International of Knoxville, TN collected hundreds of samples wearing personnel protective gear against radioactive, toxic, and explosive hazards. LANL also funded research at the New Mexico Institute of Mining and Technology to determine the explosivity of perchlorates. The data acquired from the condition assessment showed that toxic metals, toxic organic compounds, and explosive concentrations of perchlorates were absent. The data also showed that the extent of actinide metal contamination was less than expected, reducing the potential of transuranic waste generation by 50%. Consequently, $4.2M in cost savings and $1.8M in risk reduction were realized by increased worker productivity and waste segregation.

INTRODUCTION

The Chemistry and Metallurgy Research facility (CMR) has been operating since 1952, providing actinide analytical chemistry and materials characterization in support of stockpile surveillance, pit manufacturing, stockpile lifetime extension, and nuclear weapons certification (Figure 1).

During this time, perchloric acid has been fumed as part of performing actinide chemistry at the CMR facility. The laboratory exhaust system at the CMR does not provide a dedicated exhaust for perchloric acid fume hoods. The exhaust from glove boxes and fume hoods is discharged to a common duct and is filtered to remove airborne toxic and radioactive particulates before discharge. However, perchlorates are known to deposit in the ductwork of ventilation systems where perchloric acid is fumed and in 1997, perchlorates were found in the filter plenums in Wing 5 of the CMR.

Fig. 1. The CMR Facility

There are documented incidents from industry and academia where perchlorates have accumulated in exhaust ductwork and ignited or detonated in reaction to a strong initiating force. Some of these incidents have resulted in injury and death (1). As a result, the National Fire Prevention Association (NFPA) requires the use of methylene blue to detect the presence of perchlorates when work is performed on exhaust systems where perchloric acid has been fumed (2).

In 1994, the Oak Ridge National Laboratory (ORNL) developed a sampling method to determine the presence of perchlorate salt on ductwork surfaces (3). A sample is collected using a water-wetted cheesecloth measuring 4" by 4" and swiped over a one square foot area. The presence of the perchlorate ion causes methylene blue to change color at 750 parts per million (ppm).

In 1997, the CMR facility established a perchlorate safety action level of 150 ppm. This action level was based on the accuracy of the method of sample collection and analytical methodology, not the explosive characteristics of the various compounds of perchlorates used or found in chemical processes. (4)

Discovery of Perchlorate Salt Contamination in the CMR Laboratory Exhaust System

In August 1997, during routine maintenance in one of the laboratory exhaust filter plenums in CMR Wing 5, samples were collected and perchlorates were detected above 150 ppm. Consequently, the U.S. Department of Energy (DOE) directed LANL to replace perchlorate contaminated HEPA filters as a condition for authorizing the facility's Basis for Interim Operations in August 1998 (5), based on the concern that an explosion hazard may exist.

Preparation for a Condition Assessment of the CMR Laboratory Exhaust System

A condition assessment of the CMR laboratory exhaust filter plenums in Wings 2, 3, 5, and 7 was performed from December 1999 to November 2000 to determine the extent of perchlorate, toxic, and radioactive contamination present; and to determine how best to protect workers from radioactive contamination and the potential explosive hazard posed by perchlorates.

To ensure that the assessment was performed safely and that samples would be collected according to current industry practice, Waldheim International of Knoxville, Tennessee (6) was contracted. Waldheim is nationally recognized for characterizing and decontaminating laboratory exhaust systems containing perchlorates.

WORKER SAFETY

To protect workers from an explosion from perchlorates accumulated in the plenums, whole body ballistic and fire retardant personal protective equipment (PPE) was used (Figure 2). The ballistic PPE alone weighs approximately 55 pounds. The ballistic plus fire retardant PPE resulted in adding approximately 65 to 70 pounds of clothing to workers equipped with supplied breathing air. This additional PPE significantly increased the likelihood of worker stress, exhaustion, and collapse requiring emergency rescue.

WASTE MANAGEMENT IMPLICATION

The U.S. Environmental Protection Agency (EPA) regulates waste capable of detonation at standard temperature and pressure, or by a strong initiating force through the Resource Conservation and Recovery Act (RCRA) as a reactive waste per 40 CFR § 261.23. However, the presence of radioactive contamination in the filter media coupled with the technology required to treat the reactive hazardous characteristic, according to RCRA, created daunting worker safety and engineering challenges.

Because the LANL action level of 150 ppm is not based on the explosivity of perchlorates, and because the precautions for worker safety challenge sound safety management, it was essential to establish a reaction threshold for perchlorates based on scientific evidence. In the event that the reaction threshold is found to be greater than the current action level, then burdensome PPE could be eliminated and worker risk would decrease. At the same time, a clear disposal path for a significantly smaller volume of waste would also be created.

Besides the perchlorates, numerous toxic organic compounds and metals are also used at the CMR facility. No RCRA waste treatment is performed in the CMR. Therefore, only toxicity characteristic metals and organic compounds found in 40 CFR § 261.24 may cause waste filters to be generated as hazardous waste.

Fig. 2. Preparing a worker for entry into the filter plenum.

CONDITION ASSESSMENT

The exhaust portion of the CMR laboratory ventilation system contains two confinement zones. The laboratory zone serves all the radiological areas, including laboratory areas, the wing spinal corridor, and the basement. The non-laboratory confinement zone serves the uncontrolled perimeter offices and hallways; and was not part of this assessment because no perchloric acid has been fumed through this exhaust system.

In the laboratory confinement zone, exhaust is drawn from the laboratories through two ducts located in the basement; then to two filter plenums that serve the north and south sides of a wing. The two ducts are interconnected before reaching the plenums. The plenums in Wings 2, 5, and 7 contain two stages of nuclear-grade HEPA filters and consist of four compartments, including three filter stages (Figure 3). The first filter stage contains stainless steel, high-velocity panel filters, which protect the HEPA filters from fire and large particles. The second and third filter stages consist of nuclear-grade HEPA filters in a 5 by 12 array.

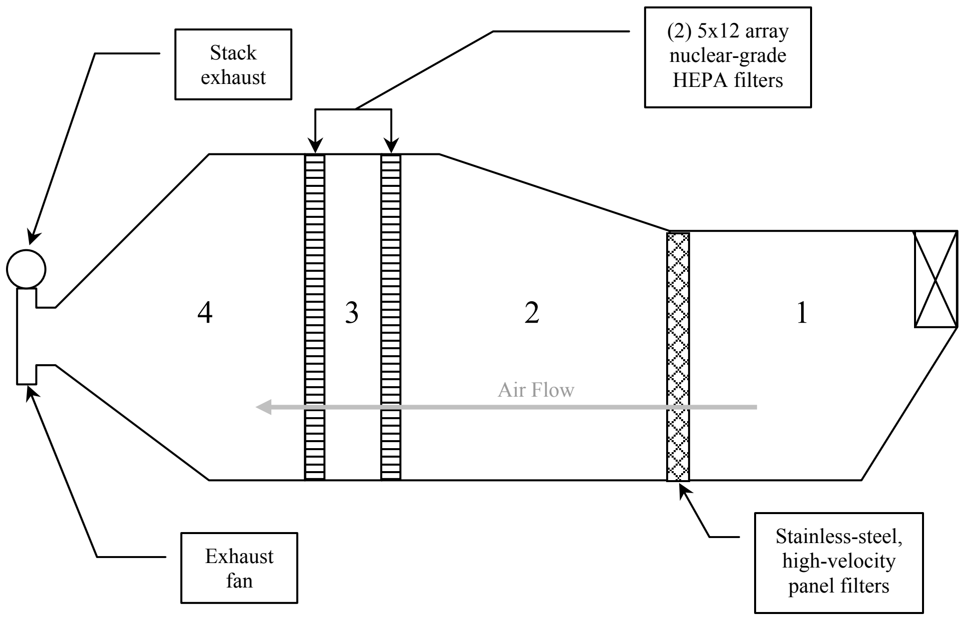

Fig. 3. Typical HEPA filter plenum.

The laboratory confinement zone filter plenums in Wing 3 contain one stage of non-HEPA filters and consist of five compartments (Figure 4). The Wing 3 plenums were originally designed to perform wet filtering of the contaminated exhaust. In the early 1970s, the wetting systems were disconnected and replaced by a dry filtration system. The first compartment contains an inactive wet wash system. A sump is located in this compartment to remove the contaminated water. The second compartment contains a stage of stainless steel, high-velocity panel filters. The third compartment contains a passive, chevron moisture separator and sump, which were designed to remove water when the plenum operated wet. The fourth compartment contains a combination cartridge/box filter stage in a 4 by 9 array.

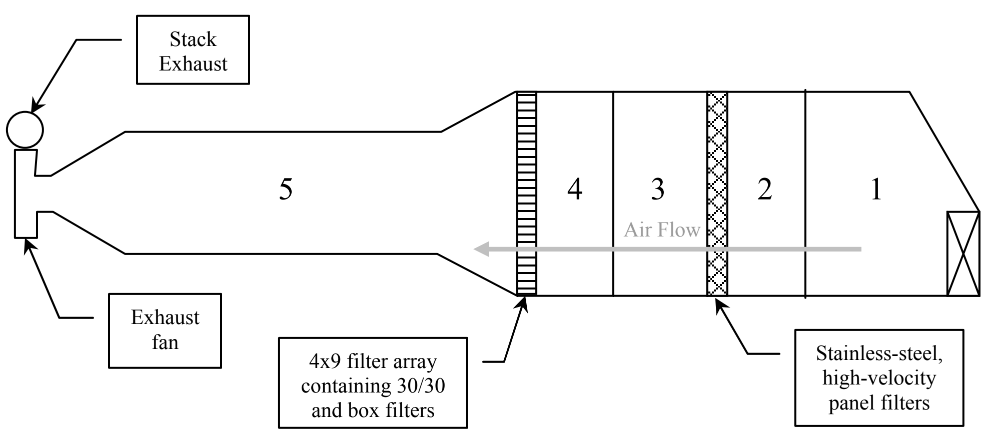

Fig. 4. Typical non-HEPA filter plenum.

Sample Collection

From December 1999 to February 2000, samples were collected for Ion-Specific Electrode (ISE) analysis of perchlorates from the laboratory zone exhaust filter plenums in Wings 2, 3, 5, and 7. In addition, four HEPA filters from each stage of 60 filters from Wing 5 were removed and cored for detailed perchlorate, toxic metal, and gross alpha-beta radiation analyses. Grab samples of floor residue were also collected from three plenums for X-ray diffraction (XRD) and gross alpha-beta radiation analyses. The purpose of XRD analysis was to characterize inert elements in the residue (e.g., Fe, Zn, and Si), which may sensitize perchlorates.

The HEPA filter samples were tested for perchlorates using ISE. Toxic metals, if present, were extracted from each HEPA filter sample by the toxicity characteristic leaching procedure (TCLP) and tested using EPA SW-846 standard methods for toxic metals listed in 40 CFR § 261.24.

Perchlorates Found on Plenum Surfaces

The highest perchlorate concentration found on the surface of the laboratory exhaust filter plenums was 0.84% and occurred in Wing 5 in compartment 2 of FE-28 (Table I). No perchlorate contamination was found below the 150 ppm action level in compartments 3 and 4 of the HEPA filter plenums. Therefore, no evidence was found to show that perchlorate contamination extended beyond the first stage of HEPA filters.

Table I. Perchlorate Concentration in Plenums (6).

			Perchlorates Detected per Plenum Compartment (ppm)				
Wing	Floor	Plenum	1	2	3	4	5
2	1	FE-14	25.9	60.6	7.2	2.8	
2	2	FE-15	21.5	19.2	107.7[a]	6.0	
5	1	FE-28	3,511.2	8,379.0	38.3	20.3	
5	2	FE-29	997.5	4,069.8	6.0	6.0	
7	1	FE-32	2,222.4	442.9	3.6	4.0	
7	2	FE-33	156.4	375.1	16.8	14.8	
3	1	FE-19	NS	91.8	75.8	111.7	43.9
3	2	FE-20	NS	NS	3,990.0	331.2	351.1

[a] Determined to be false
Blank = Not applicable
NS = Not sampled

During sample collection in Wing 3, compartment 1 in FE-19 and compartments 1 and 2 in FE-20 could not be accessed. Of the locations sampled, only one sample in compartment 3 of FE-20 was found to have a significant perchlorate salt concentration (i.e., 0.4%). Unlike the HEPA filter plenums, perchlorates were found beyond the first filter stage in significant concentrations.

Toxic Metals and Perchlorates Found on HEPA Filters from FE-28

The four HEPA filters that were removed from each stage of 60 filters from Wing 5, FE-28 were tested for RCRA toxicity characteristic (TC) metals, perchlorates, and gross alpha-beta radiation. Samples of the filter media and the frame were collected from each HEPA filter.

A nuclear-grade HEPA filter consists of four components: fiberglass filter media, fire retardant plywood (frame), aluminum pleat separators, and galvanized steel screens (front and back of the filter). A clean HEPA filter from the same production batch installed in the plenums was dismantled and its components weighed to determine the contributing proportion of each media in a HEPA filter. The fiberglass filter media was found to contribute 15% of the total weight of the filter. This proportion was used to determine the actual concentration of TC metals found on each filter. The fire retardant plywood contributes over 80% and the remaining two components contribute less than 5% of the total weight of the filter.

Table II shows the results for TC metals analysis from the HEPA filter samples. Cadmium (Cd) was detected at 2.29 ppm on the fiberglass filter media of the HEPA filters removed from compartment 2. This appears to exceed the RCRA regulatory level; however, by accounting for the contributing proportion of the fiberglass filter media, the actual concentration for Cd was extrapolated to 0.34 ppm, and thus below the RCRA regulatory level. No other TC metals were detected above the regulatory level. Additionally, no TC metals were found to have accumulated in significant concentration on the filter frames.

Table II. RCRA toxic metals detected on HEPA filters from FE-28.

			Concentration of Toxic Metals (ppm)							
Compartment	Location	Media	As^{+3}	Ba^{+2}	Cd^{+2}	Cr^{+6}	Pb^{+2}	Hg^{+2}	Se^{+4}	Ag^{+1}
2	3-10	Filter		0.92	2.29	0.83	1.90	0.04		
2	3-10	Frame		0.36						
2	4-7	Filter		0.80	1.62	0.62	3.44	0.020		
2	4-7	Frame		0.59						
2	4-9	Filter		0.42	2.06	0.72	1.90	0.01		
2	4-9	Frame		0.48						
2	5-6	Filter		0.66	1.68	0.54	1.82	0.01		
2	5-6	Frame		0.48						
3	3-10	Filter		1.08	0.05	3.58	0.60	0.03		
3	3-10	Frame		0.40						
3	4-7	Filter		0.89	0.05	0.76		0.03		
3	4-7	Frame		0.36						
3	4-9	Filter		0.90	0.02	3.56		0.02		
3	5-3	Filter		0.81	0.02	2.55		0.01		
3	5-3	Frame		0.35						

Blank = Not detected

Perchlorate Salt Found on HEPA Filters

The samples collected from the FE-28 HEPA filters were also analyzed for perchlorates utilizing ISE (Table III). The data shows that the highest contamination detected was 0.6%. The data also correlate with the sample analyses of the plenum compartments by showing that the HEPA filters are very effective at removing perchlorates, which appear to behave like particulates, from the exhaust air stream.

Table III. Perchlorates found on HEPA filters from FE-28.

Compartment	Location	Media	Perchlorates (ppm)
2	3-10	Filter	5,985.0
2	4-7	Filter	2,761.1
2	4-9	Filter	4,919.7
2	5-6	Filter	3,223.9
3	3-10	Filter	99.8
3	4-7	Filter	67.8
3	4-9	Filter	67.8
3	5-3	Filter	99.8

X-Ray Diffraction Analysis of Plenum Floor Residue

Inert material found in the plenum may sensitize perchlorates and lower the reaction threshold. Therefore, three floor residue samples were collected from Wings 3, 5, and 7 to better understand the matrix of inert material entrained on the filters. XRD was used to determine whether there were any inert substances present in the matrix, which are capable of sensitizing perchlorate salt. The elemental composition of each sample detected by XRD is shown in Table IV. The data acquired from these analyses were provided to the Energetic Materials Research and Testing Center (EMRTC) at the New Mexico Institute of Mining and Technology in Socorro, New Mexico to use in creating surrogate samples containing various concentrations of perchlorate salt.

Table IV. Inert elements detected in plenum floor residue using XRD.

	Concentration (ppm)							
Specie	Wing 2	Wing 2	Wing 2	Wing 5	Wing 5	Wing 5	Wing 7	Wing 7
Al^{+3}	0.23	0.50	1.21			0.16		
Br^{-1}	0.11		3.77			0.35		
Ca^{+2}	29.41	0.22	10.80	1.58		3.27	2.24	1.92
Cl^{-1}	1.25	12.22	3.82	13.19	9.13	9.09	1.18	7.44
Co^{+3}						0.11		
Cr^{+3}	0.21	0.46	1.57	0.15		3.94	0.49	0.13
Cu^{+2}	0.43	0.98	2.18			0.59	0.37	0.18
Fe^{+3}	10.88	67.54	20.93	6.47	24.56	60.15	9.97	75.86
K^{+1}	3.01	0.08	4.15	0.33		0.44	0.89	0.37
Mg^{+2}	1.03		0.17			0.20	0.39	
Mn^{+4}	0.14	0.27				0.63	0.11	0.61
Mo^{+6}	0.29		0.45			0.35		
Na^{+1}							56.94	
Ni^{+3}		0.25	0.51			4.30	0.38	
P^{-3}					0.29	0.13	1.29	
Pb^{+2}		0.22	0.77	0.67	1.19	0.14		
S^{-2}	0.63	6.49	3.19	0.91		1.31	21.18	0.25
Si^{-4}	48.45	4.08	42.10	6.75		10.00	3.81	1.59
Sn^{+2}	0.11		0.15					
Sr^{+2}	0.31		0.25		0.29			
Ti^{+4}	2.50		0.53	0.47	0.15	0.41	0.40	
U^{+5}			1.38	0.15		2.76		
W^{+6}			0.74					
Zn^{+2}	1.02	6.66	1.12	69.08	64.39		0.18	11.63
Zr^{+4}		0.04	0.22			1.59		

TCLP Toxic Metals and Organic Compounds Found on Filters

From October through November 2000, a second round of sample collection and analyses were performed for all the plenums in Wings 2, 3, 5, and 7 to determine the extent of TCLP metal and organic compound contamination. A statistical model was developed for a typical HEPA filter plenum to determine the location and the proper number of HEPA filter samples necessary to achieve 2σ or 90% confidence (7). This model determined that sixteen HEPA filter samples were required from each filter stage. No model was developed for the Wing 3 filter plenums as one-fourth of the filters were sampled from each filter stage – a sample size deemed to ensure high confidence.

Because the evidence from the Wing 5 filter samples collected the previous winter showed that particulate matter was efficiently removed from the first stage of HEPA filters, samples for TCLP metals and organic compounds were only collected from the first stage. However, samples were collected from both filter stages in the Wing 3 plenums.

As shown in Table V, TCLP organic compounds were virtually absent from the samples collected. Only Cd was found above the toxicity characteristic limit. As before, the presence of Cd in Wing 5 was discounted when the entire mass of a HEPA filter was taken into account. Therefore, none of the waste resulting from the replacement of filters in Wings 2, 3, 5, and 7 would require handling as toxicity characteristic hazardous waste because regulatory levels of metals or organic compounds were absent.

Table V. TCLP metals and organic compounds detected in Wings 2, 3, 5, and 7.

	Concentration (ppm)			
TCLP Contaminant	Wing 2	Wing 3	Wing 5	Wing 7
1,1-dichloroethene	-	-	-	-
1,2-dichloroethane	-	-	-	-
1,4-dichlorobenzene	-	-	-	-
1,4-dichlorobenzene	-	-	-	-
2,4,5-trichlorophenol	-	-	-	-
2,4,6-trichlorophenol	-	-	-	-
2,4-dinitrotoluene	-	-	-	-
2-butanone	0.05	0.53	-	-
2-methylphenol	-	-	-	-
3- / 4-methylphenol	0.02	-	-	-
Arsenic	0.40	2.77	0.94	0.29
Barium	0.33	0.36	0.76	0.56
Benzene	-	-	-	-
Cadmium	0.07	0.54	4.42	0.31
Carbon tetrachloride	-	-	-	-
Chlorobenzene	-	-	-	-
Chloroform	-	-	-	-
Chromium	0.22	0.89	0.49	1.55
Hexachlorobenzene	-	-	-	-
Hexachlorobutadiene	-	-	-	-
Hexachloroethane	-	-	-	-
Lead	0.41	0.43	4.08	1.37
Mercury	0.00	0.10	0.05	0.02
Nitrobenzene	-	-	-	-
Pentachlorophenol	-	-	-	-
Pyridine	-	-	-	-
Selenium	0.16	1.10	-	-
Silver	0.06	0.04	0.11	0.04
Tetrachloroethylene	-	-	-	-
Trichloroethylene	-	-	-	-
Vinyl chloride	-	-	-	-

ENERGETIC MATERIALS RESEARCH AND TESTING CENTER

The EMRTC performed a series of tests on perchlorates to simulate the compositions found in the CMR laboratory exhaust system. These tests were conducted to establish a reaction threshold for perchlorates.

Two types of tests were performed on perchlorate salt: 1) Drop Hammer Test - to establish contact sensitivity, and 2) Cook-Off Bomb Test - to establish sensitivity under confinement and heat.

Perchlorates can have either organic or inorganic cations as part of the composition. These salts exhibit varying degrees of explosivity. LANL directed EMRTC to test available compounds most susceptible to explosion. EMRTC selected two inorganic and two organic perchlorates to determine which compound showed greatest sensitivity (8).

Iron, zinc, and silicon dioxide, in the proportions detected by XRD (i.e., Table IV), were included in the tested matrices to simulate the conditions present in the CMR plenums.

Hair, paper, and other organic constituents commonly found in duct dust are not detected by XRD; however, these substances may provide fuel in the event of a perchlorate reaction. EMRTC used sugar as the organic fuel to compensate for these missing organics.

Drop Hammer Test Results

EMRTC found that tetramethylammonium perchlorate (TMAP) is the compound most susceptible to detonation when subjected to the Drop Hammer Test (9).

TMAP was non-reactive between concentrations of 5.9% and 28% and only sporadic detonations were encountered at 28%, indicating that the reaction threshold was near. EMRTC reduced the concentration to 5.9% and found that no detonations occurred. Therefore, the reaction threshold for TMAP occurs at a concentration greater than 5.9%.

Cook-Off Bomb Test

Potassium perchlorate ($KClO_4$) was found to be most susceptible to violent decomposition when subjected to the Cook-Off Bomb Test (10).

A mixture of 89% $KClO_4$, 10% sugar (i.e., fuel), and 1% silicon dioxide was required to show decomposition under heat (194° centigrade) and confinement using the Cook-Off Bomb Test. Although no violent reaction was found below 89% $KClO_4$, the onset of off gassing was detected at 127° centigrade at a concentration equivalent to 28%. No explosive reactions were detected below 28% (11).

The highest concentration of perchlorates found in the Wings 2, 3, 5, and 7 filter plenums was 0.84% (see Table I). Therefore, on the basis of the EMRTC findings, no explosive concentration of perchlorates was determined to be present in the CMR filter plenums.

FILTER REPLACEMENT

Filter replacement started in December 2000 and was finished in March 2001, approximately six months ahead of schedule. Because of the EMRTC findings, the plenum workers no longer were required to wear ballistic PPE. This decreased the weight of the required PPE by 80% and significantly improved safety and productivity. The original schedule had estimated filter replacement and plenum decontamination to require 15 working days per plenum because of poor productivity and concerns about worker exhaustion. The elimination of the explosive hazard resulted in plenums being completed an average of 4.5 workdays. No injuries or contamination events occurred during filter replacement.

The replacement was done in the wings with the least contamination first, thus ensuring that workers became thoroughly familiar with the work conditions before working in the most hazardous environments. There were three work crews performing the replacement. One crew was designated to prepare and demobilize the area by setting up and removing scaffolding and disposable plastic for contamination control. The other crews were similarly staffed teams of plenum workers, industrial hygienists, waste management technicians, and radiological control technicians. These teams worked eight-hour workdays in overlapping shifts. The first shift performed the first and third plenum entries, while the second shift performed the second and fourth plenum entries. This work schedule ensured that the work was performed during normal facility working hours.

To ensure that only HEPA filters containing transuranic radionuclide concentration (i.e., 100 nanocuries or greater of transuranic radionuclides) were packaged as such, each filter was removed from the plenum, and examined utilizing in situ gamma spectroscopy. The result of these individual, real-time analyses resulted in the equivalent of two filter stages of filters characterized and packaged as transuranic waste, approximately 50% less volume than planned. None of the filters from Wings 2 and 3 were found to be transuranic.

The remaining waste, which included filters, used PPE, plastic sheeting, anti-contamination barriers and disposables, were packaged as low-level radioactive waste and disposed in the low-level radioactive waste landfill at the LANL Technical Area 54 disposal site.

PROJECT COST ANALYSIS

As shown in Table VI, the condition assessment budget was exceeded by $384 thousand. There were three contributing factors to exceeding this budget:

1. Greater than expected cost of perchlorate salt contamination mapping;
2. Significant increase in the number of TCLP samples collected and analyzed; and
3. Work performed by EMRTC to determine the explosivity of perchlorates.

Although the condition assessment budget was exceeded, the better understanding of the extent and nature of perchlorates found in the filter plenums resulted in increased worker productivity and the cancellation of the construction of a perchlorate treatment system for the filters, wastewater, and resultant secondary waste. The condition assessment also provided the data necessary to efficiently characterize, segregate, and package the waste.

Table VI. Project Cost Summary

	Budgeted	Actual	Returned
Condition Assessment	$776,901	$777,901	
Design	501,203	500,119	$1,084
Construction	8,257,613	4,073,349	4,184,264
Management Reserve	657,753	384,084	273,669
Contingency	1,570,425		1,570,425
TOTAL	$11,764,895	$5,735,453	$6,029,442

Real-time in situ gamma spectroscopy performed during filter replacement also contributed to decreasing the construction phase of the project. By reducing the volume of transuranic waste by approximately 50%, an estimated $600 thousand cost savings was realized.

The success of the extensive characterization of the contaminants in the filter plenums and filters before starting replacement is therefore measured by the amount of money returned to the DOE at the end of the project less the savings realized by real-time gamma spectroscopy, as shown in Table VII.

Table VII. Monetary Quantification of Cost Savings from the Condition Assessment

	Thousands
A. Direct Project Cost	
Total direct project cost	$9,536
less Design costs	- 500
less Construction savings from gamma spectroscopy (approximate)	- 600
less Construction cost balance	- 3,473
subtotal Design and Construction cost savings	4,962
less Condition Assessment cost	- 777
Total cost savings resulting from waste characterization	$4,185
B. Contingency	
Total Contingency budget	$2,228
less Management Reserve used to cover Condition Assessment	- 384
Total risk reduction	$1,844

CONCLUSION

The replacement of filters in the CMR facility encountered similar problems as those found in decontamination and decommissioning projects involving radioactively contaminated equipment and structures. The experience at CMR was complicated by the presence of perchlorates, which are commonly used in actinide chemistry.

To minimize risk to workers and the environment, over twenty percent of the cost of this project resulted from the condition assessment of the filter plenums. The knowledge gained from collecting hundreds of samples and establishing a defensible and conservative threshold for perchlorate explosivity resulted in a significant waste reduction. Over $4.2M in cost savings and $1.8M in risk reduction are directly attributable to the expanded scope of the condition assessment.

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