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Annual Report

**Mediated Electrochemical Oxidation Treatment
for Rocky Flats Combustible Low-Level
Mixed Waste**

Final Report to Rocky Flats Plant
FY92 Tasks under TTP SF 221207

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FY 92 Annual Report

Mediated Electrochemical Oxidation Treatment of Rocky Flats Combustible Low-Level Mixed Waste

Executive Summary

The Mediated Electrochemical Oxidation (MEO) process was studied for destroying low-level combustible mixed wastes at Rocky Flats (RFP). Tests were performed with nonradioactive surrogate materials: Trimsol for the contaminated oils, and reagent-grade cellulose for the cellulosic wastes. Extensive testing was carried out on Trimsol in both small laboratory-scale apparatus and on a large-scale system incorporating an industrial-size electrochemical cell. Preliminary tests were also carried out in the small-scale system with cellulose. The following operating and system parameters were studied: use of a silver-nitric acid versus a cobalt-sulfuric acid system, effect of electrolyte temperature, effect of acid concentration, effect of current density, and use of ultrasonic agitation. Destruction and coulombic efficiencies were calculated using data obtained from continuous carbon dioxide monitors and total organic carbon (TOC) analysis of electrolyte samples. For Trimsol, the best performance was achieved with the silver-nitrate system at high acid concentrations, temperatures, and current densities. Destruction efficiencies of 98% or greater and coulombic efficiencies close to 50% were obtained in both small- and large-scale systems. For the cellulose, high destruction efficiencies and reasonable coulombic efficiencies were obtained for both silver-nitrate and cobalt-sulfate systems.

1.0 Introduction

Mediated electrochemical oxidation (MEO) was originally developed for dissolution of difficult-to-dissolve forms of plutonium oxide but later was found to be effective for oxidizing nonpolymerized organic materials. Extensive development work on this technology has been done at Pacific Northwest Laboratory and at Lawrence Livermore National Laboratory (LLNL), in the United Kingdom, and in France.¹⁻⁴ MEO is an inherently safe process because the hazardous and radioactive materials are completely contained in the aqueous phase and operating temperatures and pressures of the system are low (well below 100°C and 30 psig).

The most commonly used mediator-electrolyte combination is silver in nitric acid. The process produces divalent silver ion, a strong oxidizing agent, which dissolves the radioactive components of mixed wastes and destroys the organic components. Other mediator-electrolyte combinations (e.g., cobalt in sulfuric acid, and iron and cerium in various acids) have also been investigated.

In the past, work at LLNL has focused on understanding the basic science and modeling the dissolution and destruction mechanisms. To this end, the reaction rates of water with Ag(II) were measured using spectrophotometric methods and the diffusivity of silver ions in nitric acid was estimated using a rotating disk electrode.⁵ The breakdown of

organics, such as ethylene glycol, was modeled in detail with the formation and eventual destruction of intermediate compounds.⁶⁻⁸ Dissolution of plutonium oxide was also modeled and system studies were conducted to optimize system operating parameters.^{9,10} Also, a full-scale system was built for plutonium oxide dissolution and tested with surrogate materials.¹¹

Part of last year's effort was directed toward studying the destruction of combustible Rocky Flats mixed wastes, specifically, wastes containing Trimsol and cellulosic material. Although a major part of the work involved small-scale laboratory apparatus, it was important to demonstrate destruction on large industrial-scale equipment so results could be confidently extrapolated to plant-size operations. Also, since Trimsol contains chlorinated organics and silver is precipitated by chlorides, an additional recovery step is needed. Hence, an alternate mediator, cobalt, was tested. Cobalt also has the advantage that it may be possible to use it in undivided cells, and its removal from sulfuric acid has been demonstrated at UCLA down to 2-ppm levels. Therefore, cobalt was also used for testing the destruction of cellulosic materials.

Based on the results of last year's experiments, a preliminary conceptual flowsheet was developed for the destruction of mixed wastes containing cutting oils. The flowsheet, which includes secondary processes, is presented in Appendix A of this report. This conceptual design is preliminary because the Trimsol destruction process will continue to be refined as part of this year's activities.

2.0 Objectives

The primary objective of this work was to evaluate the MEO process as an alternative to incineration of low-level waste oil and cellulose. The

experimental work was pursued on small laboratory-scale apparatus and also on a large bench-scale system equipped with an industrial cell. Enough experimental data was gathered so that destruction efficiencies (mass balances) and coulombic efficiencies (energy balances) could be determined for the process.

3.0 Experimental Work

The experimental work on organic destruction was conducted in two phases. In the first stage, small laboratory-scale experiments were carried out where it was relatively easy to vary system temperature, acid concentration, and mediator-electrolyte combination. Small-scale experiments were also performed to test the effects of ultrasonic agitation in emulsifying and dispersing insoluble oils. The experiments were conducted with Trimsol as a surrogate for the low-level mixed waste oils at RFP. Preliminary testing of cellulosic wastes was also carried out using reagent-grade cellulose. All small-scale experiments were run in a batch-feed mode. That is, a measured amount of organic material was introduced into the anolyte prior to turning on the cell.

In the second phase, organic destruction was demonstrated in a bench-scale system using a commercially available industrial-size cell. Experiments were performed on this system with Trimsol at different acid concentrations and temperatures. In these experiments, the organic was fed and metered continuously to the anolyte during the run. The full set of experiments are described in the following subsections.

3.1 Small-Scale Experiments with Trimsol

Small-scale experiments were performed in H-shaped cells, which could be fitted with an ion-selective membrane separating the two cell compart-

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Figure 1. Schematic of small-scale apparatus in closed container with carbon dioxide monitor.

ments. In most of the experiments conducted for organic destruction, the cell was placed in a closed container and the gas within continuously sampled for carbon dioxide using a Horiba Model 2000 Infrared Gas Analyzer. With this technique, it is possible to determine the instantaneous generation rate of carbon dioxide, which is the desired end-product in the oxidation of organic carbon. A schematic of the setup is shown in Figure 1. Details of the container and the H-cell are shown in Figure 2. One compartment of the cell was fitted with a rotating platinum cylinder for the anode, while the other contained a platinum strip for the cathode. At the end of most of the experiments, samples of the catholyte and anolyte were removed and sent for

TOC analysis. For experiments above ambient temperatures, the whole cell was wrapped with heating tape hooked up to a temperature controller. Initially, nonuniform temperature distributions in the cell resulted in various problems, especially in the destruction of the membrane. These have largely been resolved by the judicious use of insulation, although nonuniformities of about $\pm 5^\circ\text{C}$ are still present. In the future, the cells will be placed in an adjustable thermostat bath.

Using the continuous carbon dioxide monitor, experiments with Trimsol were performed at different conditions to determine the effect of various system and operational parameters. The parameters that were studied were mediator-acid combination,

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Figure 2. Schematic of closed container and H-cell.

cell current, acid concentration, and electrolyte temperature. The experimental matrix is given in Table 1.

A few experiments were also performed with Trimisol in a larger H-cell, using an ultrasonic probe to keep the oil emulsified in the strong acid solution. In this experiment, the carbon dioxide generated could not be measured. Instead, samples were drawn periodically from the electrolytes for subsequent TOC analysis. Temperature was the only parameter varied in this study. Table 2 gives the experimental matrix for the ultrasonic tests.

3.2 Small-Scale Experiments with Cellulose

Preliminary experiments in a small H-cell were conducted with reagent-grade cellulose, using the continuous carbon-dioxide-monitoring system described above. No TOC analyses were performed for these tests. The parameter studied here was the acid-mediator combination. Table 3 gives the test matrix for this set of experiments.

3.3 Large-Scale Experiments with Trimisol

The large-scale system was built with a commercially available industrial electrochemical cell,

Table 1. Small-Scale Trimsol Experiments in Closed Volume with CO₂ Detector

Run No.	Mediator	Acid	Cell Current (mA)	Temp. (°C)	Trimsol (g)
82	0.5 M CoSO ₄	1.63 M H ₂ SO ₄	673	no heating (~30)	0.4467
103	0.5 M AgNO ₃	3.25 M HNO ₃	673	no heating (~30)	0.4068
105	0.5 M AgNO ₃	3.25 M HNO ₃	1020	no heating (~40)	0.4036
141	0.5 M AgNO ₃	8 M HNO ₃	1020	40	0.4067
142	0.5 M AgNO ₃	8 M HNO ₃	1020	50	0.3835
143	0.5 M AgNO ₃	8 M HNO ₃	1020	70	0.3191
144	0.5 M AgNO ₃	8 M HNO ₃	1020	70	0.3879

Anolyte volume: 40 mL
 Catholyte volume: 40 mL
 Anode: Rotating Pt cylinder 1.2-cm diam. × 1.78-cm long
 Anode rotational speed: 1500 rpm
 Separator membrane: Nafion 117

Table 2. Small-Scale Trimsol Experiments with an Ultrasonic Agitator

Run No.	Temp. (°C)	Trimsol (g)
U-2	no heating (~57)	0.4318
U-3	70–75	0.3462

Anolyte: 200 mL of 0.5 M AgNO₃ and 8 M HNO₃
 Catholyte: 200 mL of 8 M HNO₃
 Anode: Stationary Pt strip 3/8-in. wide × 1-1/8-in. long
 Cell current: 1082 mA
 Separator membrane: Nafion 117

Table 3. Small-Scale Cellulose Experiments in Closed Volume with CO₂ Detector

Run No.	Mediator	Acid	Cellulose (g)
126	0.5 M Ag NO ₃	3.25 M HNO ₃	0.5030
111	0.5 M CoSO ₄	1.63 M H ₂ SO ₄	0.675
128	0.5 M CoSO ₄	1.63 M H ₂ SO ₄	0.5001

Anolyte volume: 40 mL
Catholyte volume: 40 mL
Anode: Rotating Pt cylinder 1.2-cm diam x 1.78-cm long
Anode rotational speed: 1500 rpm
Cell current: 1020 mA
Separator membrane: Nafion 117

(a)

Figure 3. (a) The photograph above shows the large-scale system; (b) on the facing page is a schematic of the flow system.

the FM-21, built by Imperial Chemical Industries (ICI). Figure 3 (a) shows a photograph of the system and the cell stack. The cell has a plate-and-frame design, with expanded metal electrodes and turbulence promoters installed on the anodes. The electrodes are made of niobium, with the anodes coated with platinum. The cell stack presently has two anodes and three cathodes, with expansion capacity to accommodate more electrode pairs. Nafion 117 cation-selective membranes divide the electrodes between the anode and cathode compartments. The present system has the capacity of delivering up to 3000 A of limiting current to the mediator.

Figure 3 (b) shows a schematic of the flow system. Included in the figure are auxiliary carbon dioxide monitoring, gas scrubbing and acid regeneration systems, which have not yet been installed and are part of a future upgrade. In the experiments with Trimisol, the oil was continuously fed to the anolyte just downstream of the reservoir. Samples were taken periodically from the anolyte throughout the runs, and from the catholyte at the end of the runs, for post-test TOC analysis. The experimental parameters studied were acid concentration and electrolyte temperature. The test matrix for these experiments is shown in Table 4.

(b)

Table 4. Large-Scale Experiments with Trimsol

Run No.	Run Time (h:min)	Anolyte Acid	Temp. (°C)	Cell Current (A)	Trimsol Feed Rate (g/h)
ORGI	1:30	4 M HNO ₃	25	1500	100
ORGK	2:00	8 M HNO ₃	30	2060	113
ORGL	3:00	8 M HNO ₃	58	2055	106

Mediator: 0.5 M AgNO₃
 Anolyte volume: 15.5 L
 Catholyte volume: 17.8 L
 Anodes: Two Pt-coated Nb-expanded metal electrodes
 Anode area: 0.85 m² each
 Separator membranes: Nafion 117

Table 5. Elemental Composition of Trimsol

Element	wt%	Atomic Weight	Moles per 100g of Trimsol
C	68.37	12.011	5.69
H	10.79	1.0079	10.71
O	7.50	15.9994	0.47
Cl	11.1	35.453	0.31
S	1.0	32.06	0.03
N	0.86	14.0067	0.06

Table 6. Results of Small-Scale Trimsol Experiments with CO₂ Detector.

Run. No.	Mediator	Acid	Cell Current (mA)	Temp. (°C)	Post-test Anolyte TOC (mg/L)	Post-test Catholyte TOC (mg/L)	Destruct. Efficiency (%)	Coulomb Efficiency (%)
82	0.5 M Co SO ₄	1.63 M H ₂ SO ₄	673	~30	-	-	15 ^a	2
103	0.5 M Ag NO ₃	3.25 M HNO ₃	673	~30	-	-	35 ^a	5
105	0.5 M Ag NO ₃	3.25 M HNO ₃	1020	~40	-	-	57 ^a	10
141	0.5 M Ag NO ₃	3.25 M HNO ₃	1020	40	14	13	99.6 ^b	20
142	0.5 M Ag NO ₃	3.25 M HNO ₃	1020	50	45	63	98.3 ^b	45
143	0.5 M Ag NO ₃	3.25 M HNO ₃	1020	70	17	19	99.3 ^b	55
144	0.5 M Ag NO ₃	3.25 M HNO ₃	1020	70	9	14	99.6 ^b	65

^a From CO₂ measurements

^b From TOC measurements

4.0 Results and Discussion

The results of the Trimsol and cellulose destruction experiments are discussed separately below.

4.1 Trimsol Results

Trimsol is a mixture of various oils and other organics. Table 5 gives the elemental composition of Trimsol. Also shown in the table is the number of moles of each element per 100 g of Trimsol. Hence, a pseudochemical formula for Trimsol, neglecting the small amounts of sulfur and nitrogen present, is $C_{5.69}H_{10.71}O_{0.47}Cl_{0.31}$, where it is understood that the subscripts refer to moles of each element per 100 g of Trimsol. The number of Ag(II) ions required to completely destroy 100 g of Trimsol is then given by

Hence, 5.69 moles of carbon dioxide are generated and 32.22 moles of electrons must be removed at the anode when 100 g of Trimsol are completely oxidized. The corresponding water generation occurs in the cathode compartment. Note that the chlorine ions will combine with Ag(I) to precipitate out as insoluble silver chloride from the solution.

In the small-scale experiments with Trimsol, where carbon dioxide evolution is continuously measured, it is possible from Equation (1) to determine the destruction efficiency with time from the percentage of organic carbon converted to carbon dioxide. The coulombic efficiency can also be determined by comparing the amount of charge delivered up to the time of complete destruction with the amount theoretically required from Equation (1). The final destruction efficiency can also be determined from TOC analysis of the post-test samples.

In general, the TOC results are more accurate, but errors can arise if organic components stick to the sides or float to the top of the chamber when samples are taken. The carbon dioxide measurements are susceptible to interference from NO_x collecting in the container, which causes the readings to be higher than actual, and from leaks, which have the opposite effect.

The results from the continuous carbon dioxide monitor are shown in Figures 4 (a) to (g) for the small-scale Trimsol destruction experiments given in Table 1. Table 6 summarizes the post-test sample TOC results, along with a summary of destruction and coulombic efficiencies for each run. The results in Table 6 show that coulombic and destruction efficiencies increase as the mediator-acid combination is changed from cobalt-sulfuric acid to silver-nitric acid, and as the current increases. The efficiencies increase dramatically when the concentration of nitric acid is increased. For all runs at the higher concentration of nitric acid, irrespective of temperature, the destruction efficiencies are high—in the 98–99+ range. However, the coulombic efficiency shows a marked dependence on temperature, increasing from about 20% at 40°C to between 55% and 65% at 70°C. Note that some of the organic material migrates through the membrane to the cathode compartment. The TOC remaining in the system after the test was used to calculate destruction efficiencies.

The results of the TOC analysis of samples taken during runs are shown in Figures 5 (a) to (c) for the large-scale Trimsol destruction experiments given in Table 4. The destruction and coulombic efficiencies calculated from the data are shown in Table 7. The destruction efficiencies were based on TOC values at the end of the runs. However, in the first run, where the acid concentration was low,

there was a buildup of a waxy material, which had separated out and floated to the top of anolyte reservoir. We estimated that material to be as much as 25% of the feed. This was accounted for in the destruction efficiency calculations. The surfactants in Trimsol, which keep the oils emulsified, are attacked by acids; but in subsequent runs at higher acid concentrations, the problem of separation was much less pronounced. A reason for this may be

that higher oxidation rates, corresponding to higher acid concentrations, result in the destruction of oil droplets before they have a chance to coalesce.

In general, the results from the large-scale system are qualitatively similar to the small-scale system. The coulombic efficiencies are higher for the large-scale system, as might be expected due to the higher turbulence, agitation, and shear that the oil is subject to in that system. The destruction efficien-

(a) Experiment No. 82.

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(b) Experiment No. 103.

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(c) Experiment No. 105.

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Figure 4. Results of small-scale experiment on Trimsol with CO₂ monitor. Results on this page are from runs (a) 82, (b) 103, and (c) 105; results on the facing page are from runs (d) 141, (e) 142, (f) 143, and (g) 144. Table 1 on p. 5, displays the experimental matrix for these runs.

(d) Experiment No. 141

(e) Experiment No. 142.

(f) Experiment No. 143.

(g) Experiment No. 144.

(a) Experiment ORGI.

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(b) Experiment ORGK.

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(c) Experiment ORGL.

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Figure 5. Results of TOC analysis of samples from Trimsol test on large-scale system. The three runs are (a) ORGI, (b) ORGK, and (c) ORGL. Table 7, on the facing page, summarizes the results for the three runs.

Table 7. Results of Large-Scale Experiments with Trimsol

Run No.	Anolyte Acid	Temp. (°C)	Destruction Efficiency	Coulombic Efficiency (%)
ORGI	4 M HNO ₃	25	~50 ^a	29
ORGK	8 M HNO ₃	30	86	41
ORGL	8 M HNO ₃	58	98	44

^a Takes into account 25% hold up of lighter insoluble organics in anolyte reservoir.

Table 8. Results of Small-Scale Cellulose Experiments with CO₂ Detector

Run No.	Mediator	Acid	Destruction Efficiency	Coulombic Efficiency (%)
126	0.5 M Ag NO ₃	3.25 M HNO ₃	99.7	80
111	0.5 M CoSO ₄	1.63 M H ₂ SO ₄	96.9	80
128	0.5 M CoSO ₄	1.63 M H ₂ SO ₄	99.2	70

(a) Experiment U2.

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(b) Experiment U3.

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Figure 6. Results of TOC analysis of samples from Ultrasonic tests with Trimsol (a) experiment U2, and (b) experiment U3. Table 2 summarizes the experimental matrix for these runs.

cies are a little lower in the larger system, probably due to the continuous feed process used rather than the batch feed mode used in the smaller scale system. For both the small rotating anode and the large expanded metal electrodes, the limiting current was calculated, and the cell current in these experiments was always maintained well below the limiting current. Hence, coulombic inefficiencies are due to slow reaction kinetics, especially slow surface kinetics for insoluble organic components, and parasitic parallel bulk reactions, rather than inefficiencies resulting from oxidation of water at the anode.

For the experiments using ultrasonic agitation given in Table 2, the results of the TOC analysis of samples taken during runs are shown in Figures 6 (a) and (b). These results would indicate extremely high destruction efficiencies: 75–80% in the first hour, 80–90% in the second hour, and above 90% beyond the third hour. These results would also indicate well over 200% coulombic efficiency in the first hour. Although ultrasonic agitation is capable of enhancing organic breakdown, these results should be considered very tentative until sources of

error (e.g., oil sticking to the sides of the cell walls) are eliminated.

4.2 Cellulose Results

Cellulose consists of a chain carbohydrate molecule with a chemical formula $(C_6H_{10}O_5)_x$. The basic unit, $C_6H_{10}O_5$, has a molecular weight of 162 g/mole, and the amount of Ag(II) required to completely oxidize it is given by

Hence, the complete destruction of 162 g of cellulose will require 24 moles of Ag(II), which will be generated by 24 moles of electrons removed from the anode. During this process, 6 moles of carbon dioxide will be released.

In the small-scale experiments with cellulose, the carbon dioxide evolution was continuously measured. From Equation (2), the instantaneous destruction efficiency can be calculated from the percentage of organic carbon converted to carbon dioxide. Figures 7 (a) through (c) show the results

(a) Experiment No. 126.

(b) Experiment No. 111.

(c) Experiment No. 128.

Figure 7. Results of small-scale experiments on cellulose with CO₂ monitor. The three runs are (a) 126, (b) 111, and (c) 128. Table 3 shows the experimental matrix for the three runs.

from the carbon dioxide monitor corresponding to the tests in Table 3. Table 8 summarizes the overall destruction and coulombic efficiencies of those tests, estimated from carbon dioxide generation plots. Results indicate that reasonably good destruction and coulombic efficiencies can be ob-

tained for cellulose destruction with both cobalt-sulfuric acid and silver-nitric acid systems.

5.0 Conclusions

The MEO process is capable of achieving high destruction efficiencies and reasonable coulombic

efficiencies for both Trimsol and cellulose. For Trimsol, the tests show that high currents, acid concentrations, and temperatures enhance the destruction efficiencies. The silver-nitric acid combination is preferred since it is a more powerful oxidizing system than cobalt in sulfuric acid. Also, high shear rates appear to increase destruction rates. Since Trimsol is composed of many insoluble oils kept in emulsion by surfactants, which break down in acids, the oil has a strong tendency to coagulate and

separate out from the electrolyte. Hence, it is important to have a highly oxidizing, high-shear environment when Trimsol is fed into the electrolyte so the destruction processes have a chance to attack the large initial surface area available before the droplets start to coalesce. On the other hand, cellulose does not coalesce and appears to break down easily, thus allowing the use of less powerful oxidizing agents.

Appendix A

Preliminary Conceptual Design for MEO System

A preliminary flowsheet was developed for destruction of RFP low-level wastes consisting of contaminated cutting oils. The flowsheet, shown in Figure A-1, is based on our current experience with Trimsol in a silver-nitric acid system. The conceptual design includes a preliminary assessment of the auxiliary equipment required for recycling and minimization of waste streams. These are subject to change as we refine the process, and especially so if we alter the mediator-acid system.

- A** The basic electrochemical oxidation will be carried out by a group of four cells, each with its own anolyte and catholyte flow loops, with pumps capable of flowing 40 gal/min per loop. Each cell will have eight electrode pairs separated by cation-selective membranes. The anolyte will be 0.5 *M* silver nitrate in 8 *M* nitric acid. The catholyte will be 8 *M* nitric acid. The amount of electrolyte in each loop will be about 25 L.
- B** The cells will be electrically connected in series using a 100-kW power supply capable of supplying 12.5 kA to each cell with a 8-V total estimated voltage drop.
- C** At a coulombic efficiency of 43%, this system should destroy a total of 2.5 L/h of Trimsol and Trimsol-like material, thus eliminating the inventory of contaminated cutting oil wastes at RFP in five years. The

waste is fed directly into the anolyte flow loops.

- D** On the anode side, the gaseous effluent will be a mixture of approximately 3180 L/h of carbon dioxide and 5960 L/h of oxygen. The mixture will pass through a condenser and a bed of activated charcoal, ensuring a dry, organic-free discharge of nontoxic gases into the atmosphere. Since the mixture contains oxygen, it can also be used in regenerating nitric acid in the catholyte (see item H below).
- E** The chlorine released during the destruction of Trimsol will combine with silver to form insoluble silver chloride at a rate of 1.1 kg/h. Silver can be recovered from silver chloride electrolytically in an ammonium hydroxide solution. The power consumption is small—approximately 400 W. About 87 L/h of chlorine gas will be produced during this process, and must be converted to liquid or solid waste, if it is not permissible to discharge this small amount into the atmosphere.
- F** The anolyte will gradually build up dissolved solids and radioactive materials, which will have to be removed periodically. The frequency of this operation will depend upon the amount of foreign material in the waste cutting oils at RFP. The numbers given here assume that the anolyte will have to be refurbished every week. Hence, 100 L/wk of

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Figure A-1. Preliminary MEO conceptual design.

anolyte will pass through an electrolytic silver recovery step to remove 5.4 kg of silver. The cell power consumption will on average be less than 20 W. The contaminated acid will then go to a still, where the distillate, comprising approximately 90% of the original volume, will be recycled back into the cells. The still bottoms, containing about 10% or 10 L of 16 M nitric acid and radioactive wastes, will then be neutralized by caustic soda. Most of the radioactive wastes will precipitate out at this point and will be separated. The sodium nitrate can be reconstituted into nitric acid via salt splitting, if desired. If it is dried and discarded, about 14 kg of additional low-level solid waste per week will be generated.

- G** The catholyte acid concentration gets weaker with time, due to production of 400 L/day of water at the cathode. Five hundred liters per

day of the acid will be continuously passed through a still to remove the additional water, of which 50 L/day will be discarded and 350 L/day will be transported to the anode compartments to make up for water consumption in the anolyte.

- H** In addition to the water producing reactions at the cathode, the nitric acid is reduced to nitrous acid and must be regenerated. An acid regeneration column will perform this task requiring an input of 10,440 L/h of oxygen gas. More than half of the oxygen required is present in the anolyte exhaust (see item D above), which can be diverted for use here.
- I** Due to acid regeneration, the amount of NO_x produced in the catholyte will be minimal. However, a catalytic converter may be necessary to eliminate all possible NO_x emissions.

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