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**Development of Ultrafiltration and
Inorganic Adsorbents for Reducing
Volumes of Low-Level and Intermediate-
Level Liquid Waste: January-March 1978**

John W. Koenst, William R. Herald

and Raymond C. Roberts

April 27, 1978

Monsanto

MOUND FACILITY

Miamisburg, Ohio

operated by

MONSANTO RESEARCH CORPORATION

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for the

U. S. DEPARTMENT OF ENERGY

Contract No. EY-76-C-04-0053

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Foreword

Under the sponsorship of the DOE Division of Waste Management, Mound is responsible for the development and demonstration of separation methods for removing radionuclides from intermediate-level and low-level liquid processing wastes prior to introduction into a combined waste stream.

This report is submitted by W. T. Cave, Director, Nuclear Operations, and B. R. Kokenge, Manager, Nuclear Technology, from contributions prepared by members of the Nuclear Waste Technology Section, K. V. Gilbert, Manager, and the Volume Reduction Technology Group, W. H. Bond, Leader, under the technical direction of J. W. Koenst.

Previous reports on this project are listed below:

Development of Ultrafiltration and Inorganic Adsorbents for Reducing Volumes of Low-Level and Intermediate-Level Liquid Waste:

October-December 1977	MLM-2503
July-September 1977	MLM-2499
April-June 1977	MLM-2464
January-March 1977	MLM-2420

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Abstract

The exposure of noncellulosic ultrafiltration membranes to a radioactive environment simulating up to 24 months of exposure to a beta dose of $10 \mu\text{Ci}/\text{cm}^3$ and a gamma dose of $10^{-5} \mu\text{Ci}/\text{cm}^3$ did not show any conclusive evidence of membrane degradation. Viscosity measurements for control membranes and irradiated membranes indicate no changes in polymer molecular weight were caused by the radiation exposure. This, in turn, suggests no physical or mechanical degradation took place.

A continuous run on the UF pilot plant was completed. The run lasted 33.5 hr; during this period, the flux declined from 4 gal/min to 0.8 gal/min while rejection of alpha activity increased slightly. A total of 20,000 gal were processed through the UF system.

The small laboratory column tests were continued with uranium-233 and americium-241. Several new resins were being evaluated along with the same type of resin as used before with uranium-233 and plutonium-238. Tests were continued with the 2-in. Engineering Columns using ultrafiltration product spiked with uranium-233.

Membrane irradiation studies

J. W. Koenst

Ultrafiltration membranes have exhibited the ability to successfully treat some radioactively contaminated waste streams. The exposure of a polymeric membrane material to a radioactive environment for an extended time period may, however, lead to membrane degradation. This degradation may be manifested by membrane hardening, embrittlement, softening, cracking, discoloration, or performance characteristic (e.g., permeability) alteration. Because of this degradation potential, the performance characteristics and mechanical properties of two noncellulosic ultrafiltration membranes were assessed. The UF membranes tested were Abcor, Inc. types HFD and HFM. Both

membranes are noncellulosic and have a molecular weight cutoff of 20,000 amu.

A membrane is characterized by its permeability (water flux), removal efficiency (rejection) for specific species, and its physical and mechanical properties. The membrane's permeability is defined as the volume of liquid (permeate) produced per unit area of membrane in a specified time (e.g., gal /ft²-day). Membrane removal efficiency, r , for a given solute is expressed as

$$r = \frac{\text{Feed Conc.} - \text{Permeate Conc.}}{\text{Feed Conc.}} \times 100\% \quad (1)$$

The physical and mechanical properties of membranes include tensile strength, elongation, elasticity, solution viscosity, stiffness, and hardness. Most of these

properties depend primarily on polymer molecular weight and polymer molecular structure.

Radioactive degradation in polymers generally results in two types of reactions: chain scission and crosslinking. The former gives rise to the formation of lower molecular weight polymers, and the latter results in network structures that are tighter and insoluble. It can thus be predicted that if substantial chain scission occurs, membrane flux will increase and membrane solute rejection will decrease. On the other hand, if crosslinking takes place, one can predict membrane flux will decrease and membrane solute rejection will increase.

Nine type HFD membranes and nine type HFM membranes were irradiated at the Massachusetts Institute of Technology MITR-II, 5-MW research reactor. Three discs of each membrane type were exposed to beta and gamma irradiation to simulate 6, 12, and 24 months of field operation on low-level nuclear waste streams.

Following irradiation and retesting of the membranes for flux and rejection characteristics, the molecular weights of the irradiated and control membranes were determined.

A very precise technique for assessing membrane degradation is comparison of membrane polymer molecular weights before and after beta and gamma radiation exposure. These results are discussed below.

Figure 1 presents the plot of efflux time as a function of polymer concentration for the control membranes. A similar plot is given in Figure 2 for six of the

HFD membranes which were irradiated. The remaining three membranes were eliminated from the analysis since weight increases (negative polymer concentrations) were recorded after membrane dissolution. The data in Figure 1 scatter around two straight lines which both intersect the time axis (i.e., zero polymer concentration) at the efflux time of the solvent. The reason for two lines, rather than one, is the performance of the viscosity measurements by two individuals. A reflex action is required to obtain the efflux time to the nearest tenth of a second and, therefore, a constant error is associated with each experimenter. The efflux time as a function of concentration lines identified by the control membranes are reproduced exactly in Figure 2. As can be observed, the data for the irradiated membranes correlate very well with the "control lines" indicating no degradation in membrane molecular structure.

The relationship between the efflux time and the polymer solution concentration for both the control and irradiated HFM membranes is shown in Figure 3. Similar to the data presented in Figures 1 and 2, the best straight line intersects the efflux time axis at the efflux time of the solvent (117 sec). This straight line relationship indicates that the molecular weight of the membranes remained unchanged by the beta and gamma radiation dosages applied.

The exposure of noncellulosic ultrafiltration membranes to a radioactive environment simulating up to 24 months of exposure to a beta dose of $10 \mu\text{Ci}/\text{cm}^3$ and an alpha dose of $10^{-5} \mu\text{Ci}/\text{cm}^3$ did not show any conclusive evidence of membrane degradation. Viscosity measurements for

FIGURE 1 - Efflux time t as a function of polymer concentration for control HFD membranes.

FIGURE 2 - Efflux time t as a function of polymer concentration for irradiated HFD membranes

FIGURE 3 - Efflux time t as a function of polymer concentration for control and irradiated HFM membranes

control membranes and irradiated membranes indicate no changes in polymer molecular weight were caused by the radiation exposure. This, in turn, suggests no physical or mechanical degradation took place.

Membrane pilot plant studies

R. C. Roberts

In January, 1978, a continuous test of the ultrafiltration pilot plant was begun. Feed for this test was taken from one of the 30,000-gal influent tanks in the Waste Processing building. The system was operated continuously for approximately 33 hr, at which time the flux had become so low that it was decided to terminate the test. During the course of the test, the flux dropped from approximately 4.1 gal/min to approximately 0.8 gal/min, and the rejection of activity fluctuated between 90% to 99.5% (see Table 1 and Figure

4 for additional data). A total of 20,000 gal had been processed by the UF system.

At the conclusion of the continuous run, the UF system was cleaned thoroughly by flushing with water and detergent. Two of the D type membrane tubes were removed and replaced with two tubes containing experimental polysulfane membrane. This membrane has a molecular weight cutoff (MWC) of approximately 5,000 amu compared to 20,000 amu for the D and M type membranes. Separate sample lines were installed from each of these tubes so that samples of the permeate could be taken from each one individually. These tubes were then labeled EX-1 and EX-2. A series of runs using WD influent was then made so that the performance of these membranes could be compared with the D and M membranes.

FIGURE 4 - Flux decline for continuous run.

As was expected, the flux obtained from these tighter membranes was much less than from the D or M membranes (generally the flux was only 10% to 20% of the flux of the D and M membranes). At first, the rejection of activity by membranes "EX-1" and "EX-2" was significantly higher than the D or M membranes; however this declined rather rapidly. After only a few runs, the rejection was no better than that of the D and M membranes. Because the flux obtained from these membranes is much less than that of the D and M membranes, and because the rejection of activity is no better than that of the D and M membranes, membranes EX-1 and EX-2 were not considered suitable for UF processing. (The results of these runs can be seen in Table 2 and Figure 5.)

Adsorbent tests

W. R. Herald

The small laboratory column (0.7-cm diameter) tests for removal of americium-241 were continued using the same kind of resins which were tested for removal of uranium-233 and plutonium-238. In addition, several new resins were tested with americium-241 and uranium-233. (See Table 3 for a list of resins being studied at Mound Facility.) Additional tests with the new resins will be conducted with uranium-233 and plutonium-238. These small column tests are being used to screen adsorbents for testing on the 2-in. Engineering Columns. The results of these small column tests are given in Tables 4 to 6.

Table 2 - COMPARISON OF NEW MEMBRANE TYPES (EX-1 AND EX-2) WITH D AND M MEMBRANES

Run No.	Flux (gal/ft ² /day at 77°F)				Rejection of Activity (%)				Suspended Solids (mg/liter)	Temperature OF	pH
	D	M	EX-1	EX-2	D	M	EX-1	EX-2			
1	23.9	24.9	6.5	3.3	71.7	72.5	79.0	87.7	75	77	-
2	21.7	21.7	4.5	1.0	68.9	68.8	72.7	83.1	100	77	7.8
3	21.3	24.5	7.6	2.9	74.6	76.1	80.1	76.4	35	77	6.8
4	18.4	22.3	4.1	1.7	81.2	85.6	92.3	86.2	30	77	8.4
5	22.9	28.6	6.6	2.8	93.0	94.0	94.5	92.8	25	77	8.0
6	28.2	32.3	8.3	3.5	91.8	92.2	90.4	73.4	30	77	6.9
7	26.6	30.3	7.3	3.1	91.2	90.1	91.0	88.1	30	77	6.9
8	34.2	43.4	11.0	6.9	97.1	97.3	97.5	95.2	35	77	6.9
9	37.5	46.2	12.1	7.2	94.9	94.8	94.9	93.3	30	77	7.3
10	33.2	47.9	11.0	6.9	93.4	93.8	94.0	69.2	50	77	8.2

Table 1 - CONTINUOUS RUN OF U.F. PILOT PLANT^a

Through Put Volume (gal)	Time (hr)	Flux (gal/min Corrected to 77°F)		Activity (dis/min/ml α)			Rejection of Activity (%)		Temperature OF	pH
		D Membrane	M Membrane	D	M	Feed	D	M		
0	0	1.96	2.13	4.05	4.84	64.78	93.7	92.5	66	8.2
100	~0.2	1.58	1.61	-	-	-	-	-	71	9.4
500	0.9	0.95	1.00	-	-	-	-	-	71	10.1
1,100	1.9	0.87	0.90	-	-	-	-	-	73	10.3
2,300	3.9	0.71	0.73	2.32	1.86	24.28	90.4	92.3	77	10.4
4,300	7.0	0.56	0.60	1.73	1.40	22.72	92.4	93.8	81	10.5
7,000	11.5	0.46	0.49	1.41	1.32	29.85	95.3	95.6	79	10.6
11,800	19.5	0.39	0.41	1.31	1.37	23.28	94.4	94.1	75	10.9
13,350	22.0	0.41	0.43	2.02	1.73	301.67	99.3	99.4	73	10.6
15,700	26.0	0.39	0.43	2.41	3.82	70.01	96.6	94.5	77	9.6
18,450	31.0	0.40	0.44	2.31	2.60	158.15	98.5	98.4	68	10.2
19,700	33.0	0.39	0.42	1.89	1.85	138.78	98.6	98.7	77	10.2
20,000	33.5	0.39	0.42	-	-	-	-	-	71	10.2

^aSuspended solids varied from ~30 mg/liter to ~70 mg/liter during the course of this run.

FIGURE 5 - Comparison of rejections of activity and average flux of 4 types of membranes for 10 runs.

Table 3 - RESINS BEING STUDIED AT MOUND

Resin	Mesh Size	Type	Form	Manufacturer
IRC-50	16-50	Weakly Acid, Cation	H ⁺	Rohm & Haas
XN-1010	20-50	Strong Acid, Cation	H ⁺	Rohm & Haas
IRA-430	16-50	Strong Base, Anion	Amine	Rohm & Haas
IRA-900	16-50	Macroreticular Strong Base, Anion	CL ⁻	Rohm & Haas
IRA-904	16-50	Strong Base, Anion	CL ⁻	Rohm & Haas
IRA-938	16-50	Macroreticular Strong Base, Anion	CL ⁻	Rohm & Haas
200	16-50	Macroreticular Strong Acid, Cation	Na ⁺	Rohm & Haas
XE-236	16-50	Weak Base, Anion	Amine	Rohm & Haas
XE-243	16-50	Macroreticular, Cation	Amine	Rohm & Haas
XE-270	16-50	Weak Base, Anion	Amine	Rohm & Haas
XE-279	16-50	Strong Base, Anion	Amine	Rohm & Haas
XAD-2	16-50	Hydrophobic Adsorbent	-	Rohm & Haas
XAD-7	16-50	Hydrophobic and Hydrophilic Adsorbent	-	Rohm & Haas
D-1X4	20-50	Strong Base, Anion	NO ₃	Dow
HCR-W	20-50	Strong Acid, Cation	H ⁺	Dow
MSA-1	20-50	Macroporous Strong Base, Anion	CL ⁻	Dow
MSC-1	20-50	Macroporous Strong Acid, Cation	H ⁺	Dow
MWA-1	20-50	Macroporous Weak Base, Anion	Amine	Dow
SAR	20-50	Strong Base, Anion	CL ⁻	Dow
SBR-P	20-50	Strong Base, Anion	CL ⁻	Dow
WGR	20-50	Weak Base, Anion	Amine	Dow
11	20-50	Weak Base, Anion	CL ⁻	Dow
50W-X8	50-100	Strong Acid, Cation	H ⁺	Dow
Bone Char (Calcium Phosphate)	100-<200	Inorganic Adsorber	-	Kerr-McGee
Titanium Phosphate	<300	Inorganic Adsorber	-	Bio-Rad
Zirconium Phosphate	<300	Inorganic Adsorber	-	Bio-Rad
Ammonium Molybdo- phosphate	<300	Microcrystalline, Cation	-	Bio-Rad
Sodium Titanate	<300	Inorganic Adsorber	-	Sandia

Several pairs of resins were run in series (see Table 7). Notable results were obtained with the pairs XAD-7/XN1010 (D.F. 83.2) and MSA-1/IRA938 (D.F. 56.18). Several resin pairs gave raffinate alpha concentrations higher than feed due to the change of pH caused by the first column and the subsequent elution of uranium-233 adsorbed on the second column.

Tests were continued with the Engineering Columns using ultrafiltration product as feed. This solution contains all the ionic species of waste from the Waste Processing Facility but has practically all suspended solids removed. This "ultrafiltered" solution was spiked with uranium-233 to give the alpha concentration as listed in Tables 8 and 9. These

Table 4 - RESULTS FROM THE LABORATORY COLUMN TESTS WITH URANIUM-233

pH	Feed		Raffinate Alpha (dis/min/ml)	Resin		D.F.
	Alpha (dis/min/ml)	Flow Rate (ml/min)		Type	Height (cm)	
3	12896	1.83	840	11	7	15.35
3	12896	1.83	2205	SBR-P	7	5.85
3	12896	1.83	1732	IRA-430	7	7.45
3	12896	1.83	821	IRA-938	7	15.71
3	12896	1.83	418	AG 1X4	7	30.85
3	12896	1.83	550	XE-236	7	23.45
3	12896	1.83	857	IRA-904	7	15.05
3	12896	1.83	421	IRA-900	7	30.63
7	780	2.0	367	MSC-1	7	2.13
7	780	2.0	1323	SBR-P	7	-
7	780	2.0	475	200	7	1.64
7	780	2.0	175	MSA-1	7	4.46
7	780	2.0	764	IRC-50	7	1.02
7	780	2.0	479	XN1010	7	1.63
7	780	2.0	1179	XAD-7	7	-
7	780	2.0	817	IRA-938	7	-
7	780	2.0	1142	XAD-2	7	-
7	780	2.0	105	11	7	7.43
7	1350	1.83	1251	MSC-1	7	1.08
7	1350	1.83	451	SBR-P	7	2.99
7	1350	1.83	2039	200	7	-
7	1350	1.83	141	MSA-1	7	9.57
7	1350	1.83	820	IRC-50	7	1.65
7	1350	1.83	1222	XN1010	7	1.10
7	1350	1.83	735	XAD-7	7	1.84
7	1350	1.83	170	IRA-938	7	7.94
7	1350	1.83	1007	XAD-2	7	1.34
7	1350	1.83	181	11	7	7.46

tables show that at pH 3, bone char was by far the better of the three adsorbents tested (average D.F. of 130 vs <8), but at pH 9.8, MSA-1 performed better giving an average D.F. of 39 vs <6 for the other two resins.

The Engineering Column system (Figures 6 through 14) was shut down for several weeks to repair a leak on the bottom of the plastic 500-gal raffinate tank (Figure 8). An additional week of downtime was required for the installation of a 6-in. diameter glass column. This

column will contain a mixed bed of various resins and adsorbents. The column was designed, fabricated, and installed for the removal of radioisotopes from the raffinate streams of the 2-in. Engineering Columns. This column will reduce the levels of plutonium, americium, neptunium and uranium in the Waste Process stream from future experiments. The alpha concentration of the raffinate has been reduced to <1 dis/min/ml for the first 50 gal. of solution processed through this column.

Table 5 - RESULTS FROM THE LABORATORY COLUMN TESTS WITH AMERICIUM-241

pH	Feed		Raffinate Alpha (dis/min/ml)	Resin		D.F.
	Alpha (dis/min/ml)	Flow Rate (ml/min)		Type	Height (cm)	
7	14430	2	7096	Bonechar	7	2.03
7	14430	2	8107	XE-270	7	1.78
7	14430	2	7861	WGR	7	1.84
7	14430	2	12682	AG50WX8	7	1.14
7	14430	2	9654	XE-236	7	1.49
7	14430	2	8774	MWA-1	7	1.64
7	14430	2	6218	XE-243	7	2.32
7	14430	2	13046	HCR	7	1.11
7	14430	2	6380	D 1X4	7	2.26
7	14430	2	8492	IRA-430	7	1.70
7	14430	2	7243	IRA-900	7	1.94
7	14430	2	4422	IRA-938	7	3.26
7	14430	2	7220	MSC-1	7	2.00
7	14430	2	10820	XN1010	7	1.33
7	14430	2	6480	IRA-904	7	2.23
7	14430	2	9888	SAR	7	1.46
7	14430	2	4250	XE-279	7	3.40
7	14430	2.3	6342	11	7	2.28
3	21952	2.3	14602	IRC-50	7	1.50
3	21952	2.3	716	XN1010	7	30.66
3	21952	2.3	1260	200	7	17.42
3	21952	2.3	14223	IRA-904	7	1.54
3	21952	2.3	1213	MSC-1	7	18.10
3	21952	2.3	15244	MSA-1	7	1.44
3	21952	2.3	1348	AG 1X4	7	16.28
3	21952	2.3	1587	AG 1X4	7	13.83
3	21952	2.3	1329	D 1X4	7	16.52

Table 6 - RESULTS FROM THE LABORATORY COLUMN TESTS WITH AMERICIUM-241

pH	Feed		Raffinate Alpha (dis/min/ml)	Resin		D.F.
	Alpha (dis/min/ml)	Flow Rate (ml/min)		Type	Height (cm)	
3	21952	2.3	630	AG50WX8	7	34.84
3	21952	2.3	6641	XE-279	7	3.31
3	21952	2.3	330	WGR	7	66.52
3	21952	2.3	888	HCR	7	24.72
3	21952	2.3	1002	MWA-1	7	21.91
3	21952	2.3	149	XE-270	7	147.33
3	21952	2.3	17054	SAR	7	1.29
3	21952	2.3	777	XE-243	7	28.25
3	21952	2.3	6138	XE-236	7	3.58
3	21952	2.3	18825	XAD-2	7	1.17
3	21952	2.3	19241	IRA-900	7	1.14
3	21952	2.3	20856	XAD-7	7	1.05
3	21952	2.3	19040	11	7	1.15
3	21952	2.3	14308	SBR-P	7	1.53
3	21952	2.3	19956	XE-340Ag	7	1.10
3	21952	2.3	18916	IRA-430	7	1.16
3	21952	2.3	16219	IRA-938	7	1.35
3	21952	2.3	3	Bonechar	7	7317.33

Table 7 - RESULTS FROM THE LABORATORY COLUMN TESTS WITH URANIUM-233
AND TWO COLUMNS IN SERIES

pH	Feed		Raffinate Alpha (dis/min/ml)	Resins		D.F.
	Alpha (dis/min/ml)	Flow Rate (ml/min)		Type	Height (cm)	
7	1664	1.96	9204	200/XN1010	7 + 7	-
7	1664	1.96	4235	MSC-1/XN1010	7 + 7	-
7	1664	1.96	64	MSA-1/XN1010	7 + 7	26.0
7	1664	1.96	1185	IRC-50/XN1010	7 + 7	1.4
7	1664	1.96	57	SBR-P/XN1010	7 + 7	29.2
7	1664	1.96	1827	XAD-7/XN1010	7 + 7	-
7	1664	1.96	2413	XN1010/XN1010	7 + 7	-
7	1664	1.96	20	XAD-7/XN1010	7 + 7	83.2
7	1664	1.96	2260	IRA-938/XN1010	7 + 7	-
7	1664	1.96	384	11/11	7 + 7	4.3
7	618	1.87	87	MSA-1/MSA-1	7 + 7	7.10
7	618	1.87	81	MSA-1/MSA-1	7	7.63
7	618	1.87	16	11/IRA-938	7 + 7	38.63
7	618	1.87	11	MSA-1/IRA-938	7 + 7	56.18
7	618	1.87	59	11/11	7 + 7	10.47
7	618	1.87	75	11/MSA-1	7 + 7	9.51
7	618	1.87	126	11/11	7	4.9
7	618	1.87	21	IRA-938	7 + 7	29.43
7	618	1.87	103	IRA-938/IRA-938	7 + 7	6.0

Table 8 - RESULTS FROM THE ENGINEERING TEST ION EXCHANGE
SYSTEM WITH ULTRAFILTRATION PRODUCT-URANIUM-233

Resin	One Bed Volume (844 ml) Weight (g)	Flow Rate (ml/min)	Initial Feed		Product (dis/min/ml)	Temperature (°F)	D.F.
			pH	Alpha (dis/min/ml)			
MSA-1	719.0	50	9.8	7428	205	72	36.23
MSC-1	804.7	50	9.8	7428	1346	72	5.52
XN1010	470.0	50	9.8	7428	961	72	7.73
MSA-1	719.0	50	9.8	2052	81	72	32.74
MSC-1	804.7	50	9.8	2652	1091	72	2.43
XN1010	470.0	50	9.8	2652	805	72	3.29
MSA-1	719.0	50	9.8	4878	83	72	58.77
MSC-1	804.7	50	9.8	4878	1065	72	4.58
XN1010	470.0	50	9.8	4878	779	72	6.26
MSA-1	719.0	50	9.8	3722	89	72	41.82
MSC-1	804.7	50	9.8	3722	1037	72	3.59
XN1010	470.0	50	9.8	3722	742	72	5.02
Bonechar	906.7	100	3	3375	30	72	112.50
AG 1X4	732.1	100	3	3375	552	72	6.11
IRA-904	744.7	100	3	3375	547	72	6.17
Bonechar	906.7	100	3	3655	74	72	49.39
AG 1X4	732.1	100	3	3655	489	72	7.47
IRA-904	744.7	100	3	3655	426	72	8.58
Bonechar	906.7	100	3	3390	57	72	59.47
AG 1X4	732.1	100	3	3390	323	72	10.50
IRA-904	744.7	100	3	3390	437	72	7.76
Bonechar	906.7	100	3	3362	24	72	140.08
AG 1X4	732.1	100	3	3362	577	72	5.83
IRA-904	744.7	100	3	3362	535	72	6.28

Table 9 - RESULTS FROM THE ENGINEERING TEST ION EXCHANGE
SYSTEM WITH ULTRAFILTRATION PRODUCT-URANIUM-233

Resin	One Bed Volume (844 ml) Weight (g)	Flow Rate (ml/min)	Initial Feed		Product (dis/min/ml)	Temperature (°F)	D.F.
			pH	Alpha (dis/min/ml)			
Bonechar	906.7	100	3	3023	19	72	159.11
AG 1X4	732.1	100	3	3023	487	72	6.21
IRA-904	744.7	100	3	3023	328	72	9.22
Bonechar	906.7	100	3	2953	28	72	105.46
AG 1X4	732.1	100	3	2953	489	72	6.04
IRA-904	744.7	100	3	2953	327	72	9.03
Bonechar	906.7	100	3	3018	11	72	274.36
AG 1X4	732.1	100	3	3018	455	72	6.63
IRA-904	744.7	100	3	3018	373	72	8.09
Bonechar	906.7	100	3	3045	21	72	145.00
AG 1X4	732.1	100	3	3045	464	72	6.56
IRA-904	744.7	100	3	3045	329	72	9.26

FIGURE 6 - Laboratory column test system with Engineering Column filters on left.

FIGURE 7 - Hoods containing Engineering Columns (center), liquid waste drumming (right), and laboratory columns (left).

FIGURE 8 - Storage tanks (500 gal) for engineering test system, raffinate (left) and feed (right). Transfer and mix pump (center).

FIGURE 9 - Chemical mix tank (left) and column feed tank (right) located on top of WD107.

FIGURE 10 - Column waste tanks and valves above TRU drum.

FIGURE 11 - TRU waste drumming hood.

FIGURE 12 - Engineering Columns pumps, pressure and temperature gauges (bottom). Laboratory columns (above).

FIGURE 13 - Two-inch column (top half) with associated flowmeters, gauges and distribution pots.

FIGURE 14 - Two-inch column (bottom half) and 20-liter overflow tank from pressure relief valves (bottom half).

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