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AFCT/TFCT/ISFS PROGRAM

TECHNICAL PROGRESS REPORT
FOR THE PERIOD
OCTOBER 1, 1977 - DECEMBER 31, 1977

COMPILED BY
O. F. Hill

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Work Performed Under Contract EY-76-C-06-1830

BATTELLE
PACIFIC NORTHWEST LABORATORIES
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PREPARED FOR THE
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FUEL CYCLE PROGRAM OFFICE
UNDER CONTRACT EY-76-C-06-1830

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INTRODUCTION

This is the eighth in a series of quarterly progress reports on research and development studies performed by Pacific Northwest Laboratory (PNL) for the Alternate Fuel Cycle Technologies/Thorium Fuel Cycle Technologies/International Spent Fuel Receipt and Storage (AFCT/TFCT/ISFS) Program, formerly entitled the LWR Fuel Recycle Program. This program, sponsored by the Department of Energy (DOE), is designed to provide information needed by industry to close the back end of the power reactor fuel cycle. Included in the program are activities supporting specific design studies, as well as activities for general fuel cycle technology. The overall program is managed by Savannah River Laboratory (SRL) under the direction of the Fuel Cycle Program Office (FCPO) of the Savannah River Operations Office (SR) of the DOE.

During the past quarter, PNL conducted studies in the following tasks:

<u>Subtask</u>	<u>Project Title</u>
210.1	Survey Current Technology of Fuel Handling Techniques
340.3	Investigation of Air Cleaning Processes for Removing Tributyl Phosphate (TBP) from Off-Gas Streams
350.5	Study of Iodine Chemistry in Process Solutions
650.1 650.2	Electropolishing to Decontaminate Metallic Waste from Alternate and Thorium Converter Fuel Cycles
810.5	U.S. Scale Transport, Dispersion and Removal Mode Comparison
840.2	Safety Criticality Experiments

This quarterly report summarizes PNL activities during the months of October, November, and December, 1977. Previous reports in this series are BNWL-2052, BNWL-2080-1, -2, -3, -4, -5, and -6.

SPENT FUEL RECEIPT AND STORAGE

PROJECT TITLE: Survey Current Technology of Fuel Handling Techniques

PROJECT MANAGER: R. S. Kemper, Materials Development Section, Materials Department

PRINCIPAL INVESTIGATORS: K. R. Ames, Applied Engineering and Development Section, Physics Department

G. S. Allison, Materials Development Section, Materials Department

OBJECTIVE

The objective of this project is to identify and assess potential improvements for spent fuel handling in predissolver equipment. This will be done by evaluating the spent fuel handling process and the conceptual design development, as well as by evaluating the demonstration and operation of prototype equipment. Alternative processes will be developed where significant improvements are identified in either plant efficiency or waste management.

SUMMARY

- The order for the arc-saw has been placed with RETECH and delivery is planned in early March 1978.
- The fuel design catalog is nearly complete and will be issued in January 1978.
- The report of cutting trials on RETECH's arc saw will be issued in January 1978.
- Components for one GE BWR dummy fuel bundle are on hand and will be assembled for use in setting up the arc saw for full-scale end-fitting removal development. Orders for additional dummy bundles for end-fitting removal development are being processed.
- New lab-scale CO₂ blast equipment has been received, installed and is operating.

TRIPS AND VISITORS

November 9, 1977 - G. S. Allison and Wayne Weihermiller visited RETECH, Ukiah, CA.

November 28-December 2, 1977 - Wayne B. Weihermiller visited
Combustion Engineering, Windsor, CT
Babcock & Wilcox, Lynchburg, VA
General Electric, Wilmington, NC
Savannah River Laboratories, Aiken, SC

TECHNICAL PROGRESS

The order for the arc saw was released by DOE and placed with RETECH, Ukiah, California, in December 1977. Delivery is planned for March 1978, and plans are being made for installation in the 314 Building in the 300 Area.

Components for a dummy fuel bundle (GE BWR) have been received from the Chemical Technology Department for use in setting up the arc saw for full size cutting trials. Procurement action is underway for PWR and BWR dummy bundles and/or components to be used in developing the end-fitting removal techniques.

The Fuel Design Catalog is being prepared for issuance in January as a report entitled, "LWR Nuclear Fuel Bundle Data for Use in Fuel Handling." Additional data, such as assembly/disassembly information, final fuel tube closure design, and assorted general design details, were gathered during visits to Combustion Engineering, Babcock & Wilcox, and General Electric. These data were added to the design catalog draft, which was discussed with SRL personnel for final issuance.

The report of the September 1977 cutting trials is nearly complete and will be issued in January 1978.

The new lab-scale CO₂ blasting equipment was received in late October and installation was completed in early November. Even though the air supply was inadequate, it was possible to determine that the fluidized feed system at the bottom of the hopper was not working. New components must be fabricated to determine whether the concept of fluidizing dry ice granules to make them flow out of the bottom of the hopper will work.

In the meantime, experiments are in progress using a suction blast of particles swirled up out of the bottom of the hopper with jets of compressed nitrogen. A search is presently being made for another facility for hot lab-scale tests since the original facility will not be available on time.

PLANS FOR NEXT QUARTER

- The arc saw will be installed, debugged and cutting initiated. Procurement and assembly of dummy bundles for cutting trials will continue.
- Finalize location for hot lab-scale CO₂ blast testing.
- Continue development of lab-scale test equipment.
- Investigate potential for buying CO₂ blast equipment from Lockheed.

OFF-GAS TREATMENT

PROJECT TITLE: Investigation of Air Cleaning Processes for Removing Tributyl Phosphate (TBP) from Off-Gas Streams

PROJECT MANAGER: L. C. Schwendiman, Particulate & Gaseous Waste Research, Atmospheric Sciences Department

PRINCIPAL INVESTIGATOR: G. B. Parker, Particulate & Gaseous Waste Research, Atmospheric Sciences Department

OBJECTIVE

The objective of this project is to provide a suitable air cleaning process for removing low concentrations of tributyl phosphate (TBP) vapors from nuclear fuel reprocessing off-gas streams.

SUMMARY

- Loading of an alumina catalyst material with TBP vapor in a laboratory scale system is nearly complete, with a greater than 60% breakthrough measured after metering nearly 5 grams of TBP to the material. The material appears to be efficient in trapping TBP vapor.
- Construction is nearing completion on a bench-scale demonstration unit to measure the effectiveness of sorbent materials in removing TBP from a simulated process stream.
- Although there was considerable effort, little success was achieved in quantifying TBP vapors with an HP-5730 gas chromatograph. The vapor samples injected from a gas syringe were not reproducible. Work was terminated on the quantification of TBP vapor.
- A formal work plan outlining anticipated work in 1978 has been written. A schedule of tasks and milestones in the plan will be reviewed monthly by BNW management.

TRIPS AND VISITORS

None

TECHNICAL PROGRESS

An experiment to measure the TBP retention of a granular alumina catalyst material is continuing in FY-1978. The material is packed in a 1 in. diameter by 1.5 in. deep bed and is being loaded with TBP vapor in an air stream flowing at 1.9 ℓ /min. Bed temperature is 100°C and TBP concentration ranges from 1×10^{-4} to 2×10^{-4} g/ ℓ . After nearly 34,000 ℓ of air and 5 g TBP metered to the column, a breakthrough of 60% of the inlet concentration has been measured. The material has shown excellent retention of TBP. Final calculations will be made when 100% breakthrough is measured.

A bench-scale demonstration unit is being assembled and will be used to investigate TBP removal from a gaseous stream containing constituents in the process off gas. Off-gas treatment will be part of the column arrangements as represented in the fuel reprocessing flow sheet. TBP removal will be determined for the candidate alumina catalyst media with and without prior off-gas treatment. This work will parallel current experiments identifying TBP retention on other promising solids.

Attempts were made to quantify TBP vapor using a gas chromatograph and digital integrator. Samples of vapor above liquid were injected into the chromatograph using a gas-tight syringe under various conditions, using several techniques. The samples were not reproducible and a calibration curve could not be constructed. Work on the calibration has terminated. The gas chromatograph and integrator are now dedicated to measuring iodine in the bench-scale demonstration unit.

PLANS FOR NEXT QUARTER

Studies on sorbent materials for TBP removal will continue using the laboratory scale system. Materials from the experiments that show high retention of TBP will be tested on the bench scale demonstration unit in a simulated process stream.

Work will be initiated in the development of an alternative method to measure TBP using laser techniques. We will work closely with engineers at BNW to assess the feasibility of laser analysis and explore the possibility of constructing a prototype unit.

Initial development work will begin to measure TBP vapors in a process stream from a pilot plant unit under construction at BNW to generate waste from reprocessing spent fuel.

PUREX PROCESS - SOLVENT EXTRACTION

PROJECT TITLE: Study of Iodine Chemistry in Process Solutions

PROJECT MANAGER: H. H. Van Tuyl, Applied Chemistry Section,
Chemical Technology Department

PRINCIPAL INVESTIGATOR: J. L. Swanson, Applied Chemistry Section,
Chemical Technology Department

OBJECTIVE

The objectives of this project are to study the behavior of iodine species that are not volatilized from the dissolver solution and to develop means of managing iodine in the various plant streams to minimize its release to the environment.

SUMMARY

Work this quarter again emphasized adsorption of iodine from dilute HNO_3 solutions simulating the excess water stream from a fuels reprocessing plant.

- In the use of MnO_2 -impregnated macroreticular polymeric adsorbents, comparisons were made of the nature of the polymeric adsorbent and of the conditions of initial MnO_2 -impregnation and subsequent reimpregnation. There was found to be little, if any, effect of the presence of dissolved organic material.
- In the use of a macroreticular anion exchange resin to remove iodide ion, some decrease in removal efficiency was observed during the ten completed cycles of loading and elution. Elution was readily accomplished with 1M HNO_3 .
- In the use of a macroreticular anion exchange resin to remove elemental iodine, a greater solution volume could be processed than when iodide ion is the adsorbing species. Elution was readily accomplished when 1M HNO_3 and 1M NaOH solutions were alternated.
- In the use of untreated macroreticular polymeric adsorbents with hydrogen peroxide added to the feed to stabilize elemental iodine, the iodine DF was decreased markedly as the solution flow rate increased.

TRIPS AND VISITORS

October 25, 1977 - J. L. Swanson visited SRL to discuss fuel reprocessing studies.

October 26-28, 1977 - J. L. Swanson visited ORNL to discuss fuel reprocessing studies and to attend the annual meeting of the Chemical Technology Division.

TECHNICAL PROGRESS

Emphasis is still to test and develop adsorption processes to remove iodine species from the excess water stream before it is discharged to the environment. Most of this work involves 0.01M HNO_3 solution since that is the likely composition of the excess water as it is obtained as overheads from the acid fractionator and/or the waste concentrators. Comparative data are presented in Figure 1 for four systems examined this quarter; the scattered data at iodine DF's in excess of 100 are probably largely due to counting uncertainties from the low activity levels in those samples. More detailed information on these four systems is contained in the following sections.

MnO_2 -Impregnated Polymeric Adsorbents

Work this quarter included study of: 1) the effect on iodine decontamination factor (DF) of the polymeric adsorbent used, 2) the conditions of MnO_2 impregnation, 3) exposure to light, and 4) the presence of dissolved organic material in the feed. Test conditions and results are summarized in Table 1. Typical behavior of these adsorbents, illustrated by Figure 1a, involves an extended period of operation with relatively little change in iodine DF, and then a sharp decrease in DF when the MnO_2 has washed off the adsorbent.

Comparison of the results of experiments M-7, M-10, and M-11 shows that impregnated XAD-2 and XAD-4 are both markedly superior in iodine DF capability to impregnated XAD-7. The XAD-4 is superior to XAD-2 in that the MnO_2 washed off more slowly, thus allowing longer operation before the bed had to be reimpregnated. The adsorbents XAD-2 and XAD-4 are both polystyrene-based materials, but they have different pore sizes and surface areas (XAD-4 has smaller pore size and higher surface area than does XAD-2). The XAD-7 adsorbent is an acrylic ester-based material having pore size and surface area similar to those of XAD-2.

FIGURE 1. Removal of Iodine from 0.01 M HNO_3

TABLE 1. Results with MnO₂-Impregnated Polymeric Adsorbents (first cycle)

Column Preparation Conditions

- Bulk of the KMnO₄ solution rapidly flowed upwards to displace water
- Flow stopped for ~hr to allow reaction to proceed
- Remainder of the KMnO₄ solution rapidly flowed upwards
- Another ~hr allowed for reaction to proceed
- KMnO₄ solution washed out
- Small bed (generally one-fourth the size of the impregnated bed) of untreated polymeric adsorbent placed above the MnO₂ - impregnated bed

Iodine Adsorption Conditions

- Feed composition = 1×10^{-5} M added I₂ in 0.01 M HNO₃
- Feed flow = 1 to 10 column volumes/hr
- Exposed to light (except for Expt M-9)

Expt	Polymeric Adsorbent	Impregnation Solution		MnO ₂ Impregnated Millimole/ml	Nominal DF ^(b)	Length of Operation Till DF=10	
		KMnO ₄ , M	Volume, CV ^(a)			Time, Days	Volume, CV
M-11	XAD-7	0.01	8	0.065	~3	1	140
M-10	XAD-2	0.01	8	0.048	~100	9	900
M-7 ^(c)	XAD-4	0.01	8	>0.052	~200	>23	>1900
M-6	XAD-4	0.01	6	0.039	~200	16	1300
M-9 ^(d)	XAD-4	0.01	8	0.033	~200	19	1700
M-12	XAD-4	0.03	9	0.085	~100	30	2600
M-13 ^(e-f)	XAD-4	0.03	9	>0.117	~60	>24	>2100

(a) CV = column volumes

(b) DF = (concentration of iodine in feed) ÷ (concentration of iodine in effluent)

Nominal DF is a typical value obtained during the majority of the experiment

(c) Experiment was terminated while MnO₂ remained (estimated to be <10% of total)

(d) Iodine adsorption conducted in the absence of light

(e) Feed solution nearly saturated with respect to 30% TBP-NPH

(f) Experiment not yet complete

The conditions of impregnation are important to the effectiveness of the bed in giving a high iodine DF. The data of Table 1 show that higher iodine DFs were obtained with beds impregnated using 0.01 M KMnO_4 solution than with beds impregnated with 0.03M KMnO_4 solution. The reason for this is likely the oxidation of a portion of the iodine to iodate, as was observed earlier with more heavily impregnated beds. The data of Table 1 also show a considerable range of impregnation occurring under supposedly identical conditions; evidently closer control of flow rate and reaction time is required to obtain reproducible degrees of impregnation.

The iodine adsorption portion of experiment M-9 was conducted in the dark. The results obtained here were comparable to the others; it is thus concluded that exposure to normal laboratory light has little or no effect on the removal of iodine by MnO_2 -impregnated adsorbents.

Experiment M-13 is being run using feed solution which is nearly saturated with 30% TBP-NPH (the solvent normally used in Purex process operations). The iodine DF is not as high as was obtained in experiment M-12 with a similarly prepared bed without organic material in the feed. The difference, however, could well be due to the higher extent of MnO_2 -impregnation in experiment M-13, rather than to the presence of the dissolved organic material. If there is an effect of the dissolved organic material, it is not very large.

The rate at which the MnO_2 washes off the columns appears to generally (but not always) be more a function of time than of flow rate; if the experiments had been run at a feed flow rate of 10 column volumes/hour during the entire time span of the experiments, the volumes processed would have been 2 to 3 times greater than the values listed in Table 1. More effort will be required, however, to better define the total volume which can be processed before iodine breakthrough occurs.

Whether or not it would be practical to discard the iodine-loaded adsorbent after the MnO_2 has all washed off and iodine breakthrough has occurred depends on such factors as: 1) the cost of the adsorbent itself, 2) the cost of reimpregnating a spent adsorbent bed relative to the cost of impregnating a fresh bed, and 3) the cost of treating and/or discarding the waste. The cost of the adsorbent itself would only be about \$25,000 per year for an Amberlite XAD-4 adsorbent (when discarded after 5,000 column volumes of solution have been

processed at a rate of 10 column volumes/hr).

The results of recent tests on reimpregnation of spent adsorbent beds are presented in Table 2. Comparison of the results of experiment M-7-2 with those of experiment M-7 (Table 1) shows that neither the degree of impregnation nor the operational capacity is as high when reimpregnation is done using the same procedure as was used for the initial impregnation.

The results of experiments M-9-2 and M-12-2 indicate that it is beneficial to wash the exhausted adsorbent with a dilute ethanol solution prior to performing the reaction with the KMnO_4 solution. The goal here is to adsorb the ethanol onto the adsorbent so that it will act as an in-situ reductant for the permanganate.

Anion Exchange Resin and Iodide Ion

Typical behavior of the anion exchange resin and iodide ion system, illustrated in Figure 1b, involves a continual, rather rapid decrease in iodine DF as the volume of solution processed increases. Because of the relatively low volume which can be processed before iodine breakthrough occurs, the use of successive loading and elution cycles would appear to be a necessity in this system. Elution can be readily accomplished with about 30 column volumes of 1M HNO_3 , as was shown last quarter.

Continued cycling of the resin (Amberlite IRA-900) through loading and elution cycles resulted in some deterioration of the iodine DF behavior, but the DF was still quite good after a number of cycles. The instantaneous DF after passage of 350 column volumes of feed was about 40 in the first cycle, about 20 in the second cycle, and about 12 in the tenth cycle. The overall DF for the tenth cycle, in which 362 column volumes of feed were processed, was 50. This work was performed in the dark, and the results are comparable to those obtained last quarter during exposure to normal laboratory light.

Anion Exchange Resin and Elemental Iodine

Typical behavior of the anion exchange resin and elemental iodine system, illustrated by Figure 1c, also involves a continual decrease in iodine DF as the volume of solution processed increases. Breakthrough, however, does not occur

TABLE 2. Results with MnO₂-Impregnated Adsorbents (later cycles)
Conditions as Listed in Table 1.

<u>Expt</u>	<u>Pre-impregnation Wash</u>	<u>Impregnation Solution</u>			<u>MnO₂ Impregnated, Millimole/ml</u>	<u>Length of Operation till DF=10</u>	
		<u>KMnO₄,M</u>	<u>NaOH,M</u>	<u>Vol.,CV</u>		<u>Time, days/Vol.,CV</u>	
M-7-2	10 CV of 0.01 M NaOH followed by 10 CV of H ₂ O	0.01	--	8	0.025	12	1000
M-7-3	10 CV of 0.05 M NaOH	0.01	0.05	8	0.021	6	500
M-9-2 ^(a)	20 CV of 0.01 M ethanol in 0.05 M NaOH	0.01	0.05	8	0.026	20	1800
M-12-2	20 CV of 0.01 M ethanol in 0.05 M NaOH followed by 5 CV of 0.05 M NaOH	0.03	0.05	9	0.060	19	1500

^(a)This experiment had no iodine present in the feed.

as rapidly as when the iodine species is iodide ion (Figure 1b). This system must involve adsorption of elemental iodine on the resin polymer, as well as adsorption of iodide ion at the anion exchange sites. The DF controlling species appears to be iodide ion, presumably formed by reduction of elemental iodine by the resin. This conclusion is based on the behavior of the iodine species in the effluent about halfway through the experiment shown in Figure 1c. This effluent sample was extracted first with toluene and then with 10^{-4} M I_2 in toluene. The first extraction removed very little iodine (showing that the species was not I_2), and the second extraction removed essentially all of the iodine (showing that the species exchanges rapidly with I_2 , as does I^-).

The results in Figure 1c were obtained with nitrate-form Amberlite IRA-900 resin after four previous loading and elution cycles and were obtained in the dark. These data indicate an inverse relationship between DF and flow rate; however, the magnitude of this effect is relatively small (perhaps a factor of two in DF for a factor of ten in flow rate). Comparison with other results indicates that there is little, if any, effect of normal laboratory light. There is also little, if any, deterioration of iodine DF behavior through four cycles of loading and elution.

Data obtained during elution tests of the anion resin following adsorption of elemental iodine are summarized in Table 3. The most important observation is that elution of the adsorbed iodine was much more effective when HNO_3 and NaOH solutions were alternated than when either of these solutions was used alone. Possible explanations for this effect include: 1) the disproportionation of elemental iodine to iodide and hypiodite ions in the NaOH solution, which are then washed out by the HNO_3 solution, and 2) the release of trapped iodine during the cycling of the resin between the nitrate and the hydroxide forms. Whatever the reason, essentially all of the iodine was eluted using about 40 column volumes each of 1M NaOH and 1M HNO_3 .

Untreated Polymeric Adsorbents

Earlier work on the removal of elemental iodine from a simulated excess water stream by adsorption on polymeric adsorbents showed that an oxidant (such as hydrogen peroxide) must be added to reoxidize the iodide ion produced by reaction of elemental iodine with the adsorbent. Work this quarter with 0.3M H_2O_2 and

TABLE 3. Elution after Adsorption of I_2 on Anion Exchange Resin

<u>Cycle</u>	<u>Solution Composition</u>	<u>Solution Volume, CV</u> ⁽¹⁾	<u>Iodine Removed, %</u> ⁽²⁾	
			<u>Incut</u>	<u>Total During Elution</u>
1	0.1 <u>M</u> NaOH	10	20	
	0.1 <u>M</u> NaOH	40	12	
	0.1 <u>M</u> HNO ₃	30	27	
	0.1 <u>M</u> NaOH	30	7	
	0.1 <u>M</u> HNO ₃	30	13	78
2	0.1 <u>M</u> NaOH	10	17	
	1.0 <u>M</u> NaOH	10	13	
	0.1 <u>M</u> NaOH	10	2	
	0.1 <u>M</u> HNO ₃	15	18	
	0.1 <u>M</u> HNO ₃	16	24	
	0.1 <u>M</u> NaOH	15	6	
	0.1 <u>M</u> HNO ₃	15	4	
	1.0 <u>M</u> HNO ₃	16	19	
	0.1 <u>M</u> NaOH	30	3	
	0.1 <u>M</u> HNO ₃	32	4	110
				93
4	1.0 <u>M</u> NaOH	21	32	
	1.0 <u>M</u> HNO ₃	20	66	
	1.0 <u>M</u> NaOH	20	2	
	1.0 <u>M</u> HNO ₃	19	4	
	1.0 <u>M</u> NaOH	21	0.2	104
5	1.0 <u>M</u> HNO ₃	20	18	
	1.0 <u>M</u> NaOH	21	24	
	1.0 <u>M</u> HNO ₃	20	68	
	1.0 <u>M</u> NaOH	21	2	
	1.0 <u>M</u> HNO ₃	22	4	
	1.0 <u>M</u> NaOH	20	0.1	
	1.0 <u>M</u> HNO ₃	19	0.8	118

(1) CV = column volumes

(2) % of that adsorbed during the corresponding loading cycle

Amberlite XAD-4 adsorbent, shown in Figure 1d, emphasizes the importance of solution flow rate in a kinetically-limited system such as this. Under the conditions used here, the iodine DF exhibited a negative second power dependence on solution flow rate. None of the other systems studied have shown a marked effect of flow rate on DF, as seen in Figure 1.

PLANS FOR NEXT QUARTER

Experimental efforts will continue in the areas discussed above. The interim report begun this quarter will be completed.

WASTE MANAGEMENT

PROJECT TITLE: Electropolishing to Decontaminate Metallic Waste from Alternate and Thorium Converter Fuel Cycles

PROJECT MANAGER: R. D. Nelson, Metallurgy Research Section, Materials Department

PRINCIPAL INVESTIGATORS: R. P. Allen, H. W. Arrowsmith, Metallurgy Research Section, Materials Department

OBJECTIVE

The objectives of this work are to develop and provide the concepts and data needed to design and operate electropolishing facilities for the decontamination of surface-contaminated solid metallic waste. Major program tasks include:

- transfer of compatible technology from the commercial electropolishing industry;
- development of solution treatment procedures to extend electrolyte life and minimize waste volume; and
- development of removal techniques for entrained contamination.

SUMMARY

- Technology transfer activities continued with visits to electropolishing facilities and manufacturers of electropolishing equipment, plasma arch torch cutting equipment, and solution processing systems.
- Encouraging results have been obtained using a titanium basket to hold components for electropolishing. After several decontamination runs the titanium basket showed no detectable radiation.
- Ion exchange (acid adsorption using ion exchange resins) has been identified as the most promising technique for our decontamination program, and an acid processing unit is being ordered. It was chosen over solvent extraction because of the greater complexity and safety problems involved in solvent extraction.
- Tests using a vibratory finisher with a plastic abrasive media and a chemical cleaning compound showed that this method would not be effective for removal of a contaminated recast layer.

TRIPS AND VISITORS

- October 5, 1977 - J. L. Crandall (SRL), L. H. Meyer (SRL), and R. B. Naylor (DuPont) reviewed program activities with R. P. Allen and H. W. Arrowsmith.
- October 11, 1977 - H. Kraus and A. Madwed of MacDermid Company, Waterbury, CT, discussed electropolishing equipment with H. W. Arrowsmith and R. P. Allen.
- October 12-13, 1977 - Program consultants L. S. Winter and D. Skvara, Hydrite Chemical Company, visited PNL.
- October 18, 1977 - R. P. Allen and H. W. Arrowsmith visited Union Carbide Corporation, Florence, SC, to discuss plasma torch cutting technology with D. G. Anderson, W. F. Dorsey, and T. E. Gittens.
- October 19, 1977 - R. P. Allen and H. W. Arrowsmith visited National Plastics and Plating Supply Company, Inc., Terryville, CT, to discuss the design of purification, storage, and waste disposal systems for spent electrolyte and rinse solutions with F. Coscina, N. Campbell, R. McGathen, and K. Hopfensperger.
- October 19, 1977 - R. P. Allen and H. W. Arrowsmith visited Wastesaver Corporation, Bristol, CT, to talk with J. T. MacDermid about distillation techniques for purification and recycling of rinse solutions.
- October 20, 1977 - R. P. Allen and H. W. Arrowsmith discussed distillation techniques with R. Pike, Pfaudler Company, Rochester, NY.
- November 1, 1977 - R. P. Allen and H. W. Arrowsmith reviewed program progress with R. E. Erickson and W. M. Shaffer at Savannah River and discussed electropolishing technology and decontamination applications with E. L. Albenesius, P. H. Permar and 20 other technical people representing both SRL and SRP.

- November 2, 1977 - R. P. Allen and H. W. Arrowsmith discussed design of electropolishing systems for decontamination applications with the DuPont Engineering Dept., Newark, DE.
- November 9, 1977 - P. H. Permar, T. J. Pazik, R. G. Baxter, and B. D. Helton of SRL and J. D. Anderson and J. Scafaria of DuPont Engineering Dept. visited PNL to continue design discussions.

TECHNICAL PROGRESS

Electropolishing is a well-established industrial process widely used to clean, deburr, and surface finish a variety of metals and alloys. One of our major program objectives is to utilize existing commercial electropolishing and electroplating technology and equipment wherever possible in the design, construction, and operation of electrochemical decontamination systems.

Technology Transfer

Technology transfer activities continued during this reporting period with visits to and from electropolishing equipment manufacturers. Large commercial electropolishing facilities were visited and distillation and solution processing techniques were discussed with other industry experts. Plasma torch cutting technology was also discussed with a major manufacturer.

Evaluation tests of titanium continued this quarter with the construction of a small 1 ft² basket (930 cm²) from expanded titanium sheet with diamond-shaped openings and stainless steel support structures. The basket was designed so that the titanium surface was electrically insulated from the stainless steel support structure to reduce the current drawn by the support structure itself. Nine mild steel connector rings were placed in the basket and electropolished at 12 V (dc) for 3 min (3 A/in.² on the connector rings). The radiation level of the rings went from 2 mrad/hr (beta) to background, except where rust had built-up. (The heavily rusted edges of the rings sometimes required additional pre-treatment and electropolishing.) This configuration permitted both sides of the rings to be decontaminated at once. After several decontamination runs the titanium basket showed no detectable radiation.

The titanium basket was also used to decontaminate stainless steel pieces of a plutonium-contaminated ($>10^6$ dis/min/100 cm²) demister. After electropolishing for 15 min at 100 A and 23.5 V, contamination on the pieces was reduced by a magnitude of 10, except where the pieces were in contact with the titanium mesh of the basket. Here, no measurable decontamination occurred. When the pieces were reoriented so that the surface area in contact with the titanium mesh was different than in the initial electropolishing, contamination levels were reduced to 40,000 dis/min/100 cm² fixed and <500 dis/min/100 cm² smearable. The basket had become contaminated to 40,000 dis/min/100 cm² with small pieces of residue visible on the mesh. Rinsing in the rinse tank did not remove this residue. The basket was submerged in the clean acid tank for 6 days, after which it showed no detectable radiation.

Solution Treatment Studies

Solution treatment studies are in progress to extend electrolyte life and minimize secondary waste volume by developing techniques for removing dissolved metal and contamination from the electrolyte and rinse solutions. This work includes an evaluation of both energy separation (distillation, electrolysis) and mass separation (solvent extraction, precipitation, ion exchange) methods. Several possible solution treatment approaches are identified in Table 4.

TABLE 4. Solution Treatment Approaches

Ion Exchange	Precipitation
Solvent Extraction	Alcohol Precipitation
Distillation	Neutralization
Electrolysis	Dilution
Membrane Separation	Sulfide Precipitation
	Potassium or Barium Salt Precipitation

Ion Exchange

Standard ion exchange is not considered practical as a large-scale separation method. However, there are examples of strong acid cation exchangers being used in the purification of wet-process phosphoric acid, as well as phosphoric acid purification by the adsorption of the acid on

ion exchange resins. This latter technique (Figure 2) has been identified as the most promising technique for the electrolytic decontamination program. Its advantages over solvent extraction, which has been chosen as the backup technique, include:

- availability of a commercial, self-contained processing unit,
- no chemical additions and/or extensive secondary solution recycle schemes, and
- operational flexibility in the purified acid product.

FIGURE 2. Spent Electrolyte Purification by Reciprocating Acid Adsorption

Tests have been conducted by Eco-Tec Limited, Toronto, Canada, manufacturer of the reciprocating ion exchange acid purification unit for the decontamination program. These tests have demonstrated the unit's ability to remove dissolved metal from phosphoric-sulfuric electropolishing solutions. Good separations were obtained although it was necessary to dilute the solution by one-third and to heat it to reduce its high viscosity. Complete evaluation of this technique for acid purification, including its ability to remove radioactive contamination and to recycle the waste stream for further acid recovery, will begin as soon

as the acid purification unit is received. (Acquisition has been delayed due to foreign procurement problems.)

Solvent Extraction

The separation of impurities from phosphoric acid by solvent extraction (Figure 3) is generally based on the solubility of the acid in a water-immiscible organic solvent. Several individual extractions are summarized in Table 5. In Test 2 the impurity level of the acid had decreased by a factor of ten after reprocessing. For this particular test, the estimated recovery of acid from the feed was 60%. In Tests 3 to 6 the decrease of iron, chromium, and nickel impurities was less than expected since part of the impurity decrease resulted from dilution (makeup) with 75% phosphoric acid to the original feed volume. Acid recoveries in these tests varied from 54 to 70%. It is important to note that there was nearly total rejection of plutonium activity to the raffinate in these tests.

FIGURE 3. Spent Electrolyte Purification by Solvent Extraction

TABLE 5. Summary of Phosphoric Acid Extractions Using Methyl Isobutyl Ketone

Test No.	Aq. Feed Impurities (g/l)				Raffinate (g/l)				Purified Acid ^(a) (g/l)			
	Fe	Cr	Ni	Pu	Fe	Cr	Ni	Pu	Fe	Cr	Ni	Pu
1	23.4	5.8	2.9	0	43.8	10.8	6.0	0	16	4	2	0
2	54.0	13.3	6.7	0	74.8	17.9	8.8	0	5	2	1	0
3	22.3	5.5	2.7	0.2 ^(b)	30.6	6.7	3.3	0.3	7	5	1	trace
4	19.0	4.7	2.3	0.3 ^(c)	37.4	8.6	5.6	0.3	10	4	1	0 ^(d)
5	0	0	0	1.0 ^(e)	0	0	0	1.0	0	0	0	0 ^(d)
6	22.3	5.5	2.7	0.2 ^(b)	41.4	8.9	4.4	0.2	10	4	1	0 ^(d)

(a) These values are corrected impurity levels for the purified acid after extraction, concentration to ~75% H_3PO_4 and makeup to the original feed volume with impurity-free 75% H_3PO_4 .

(b) Plutonium impurity from electropolished Pu metal.

(c) Combination of plutonium oxide and plutonium ion.

(d) X-ray fluorescence analysis was checked by low-level radioactivity counting of these samples for plutonium.

(e) Plutonium impurity added as the oxide.

Results of these extractions have shown that the solvent extraction method can reasonably be applied to the decontamination facility. Its major disadvantage is related to safety. The combination of radioactive materials and potentially flammable solvents requires special design and operation considerations.

Precipitation

The separation of impurities from solution by precipitation is a time-related process depending on such factors as impurity concentration, temperature, hydrogen ion activity, nature of the solvent or mixed solvents and other ions in solution. Several different methods of precipitation were considered in this study: alcohol precipitation, dilution, neutralization, sulfide precipitation, and barium or potassium salt precipitation.

Alcohol precipitation combines the action of a completely miscible solvent in an acid feed with the addition of alkali metals or ammonia. The separation of iron, chromium, and nickel impurities was assessed from small-scale tests using a 75% phosphoric acid containing 2 wt% metal ions (the iron, chromium, and nickel electrolytically dissolved from 304 stainless steel). The spent electrolyte was first ammoniated, then either methanol or isopropanol was added to precipitate complex ammonium-impurity phosphates. Table 6 summarizes the purified acid recoveries and the impurity concentration from these precipitation tests.

Results of the alcohol precipitation tests showed that a decrease in the impurity load in the spent electrolyte can be obtained with reasonably high recovery of the phosphoric acid. The disadvantage of the alcohol precipitation method is the chemistry control needed to precipitate impurities while not forming an excessive filter cake.

Dilution, partial neutralization and specific precipitation reactions with hydrogen sulfide, ammonia, barium salts, or potassium salts were evaluated as a way to remove metal impurities (iron, chromium, and nickel) from 75 wt% phosphoric acid for subsequent recycle of the "purified" acid as decontamination electrolyte. The volume of water needed for adequate dilution of the acid to cause precipitation of a part of the impurities as hydroxides does not make dilution a practical separations method. In partial neutralization tests, the

TABLE 6. Summary of the Alcohol Precipitation Results on the Separation of Impurities from 75 wt% Phosphoric Acid

<u>Vol</u>	<u>Solution Component</u>	<u>Alcohol/P₂O₅ (wt)</u>	<u>NH₃/P₂O₅ (mole)</u>	<u>Est. Acid Recovery</u>	<u>Feed Acid Impurity (g/l)</u>		<u>Product Acid Impurity (g/l)(a)</u>	
100	75% acid	0.5	0.13	78	Fe	25.3	Fe	19.7
6.3	NH ₄ OH				Cr	7.2	Cr	5.6
50	isopropanol				Ni	3.8	Ni	3.0
100	75% acid	3.4	0.38	90	Fe	25.3	Fe	14.5
16	NH ₄ OH				Cr	7.2	Cr	4.7
370	methanol				Ni	3.8	Ni	3.4
100	75% acid	1.9	0.40	79	Fe	25.3	Fe	3.1
17	NH ₄ OH				Cr	7.2	Cr	0.9
200	isopropanol				Ni	3.8	Ni	1.7
100	75% acid	3.0	0.28	80	Fe	25.3	Fe	15.4
12	NH ₄ OH				Cr	7.2	Cr	4.7
225	methanol				Ni	3.8	Ni	2.8

(a) The analysis of the purified acid has been corrected to the corresponding feed acid volumes.

precipitates that formed in the concentrated acid/base or acid/ammonia mixtures were difficult to separate and to characterize. The liquid separated from these mixtures generally contained too much residual impurity for partial neutralization to be an effective method for reprocessing a spent phosphoric acid electrolyte.

The removal of impurities from the synthetic spent electrolyte was attempted by the addition of potassium salts with subsequent precipitation of a complex potassium-iron-phosphate. Analysis of the filtrate showed an approximate 30% decrease in the iron content, but no decrease in either chromium or nickel. The precipitation of barium sulfate with coprecipitation of the impurities was also tested. X-ray fluorescence analysis of the recovered filtrate showed only 2.7% decrease in the iron content and no change in either the nickel or chromium content.

Other Techniques

Concentration of a synthetic spent electrolyte by distillation was attempted. The acid was concentrated to about 100 wt% phosphoric acid and was a mixture of pyrophosphoric acids and high molecular weight acid polymers. The volume reduction of the spent acid electrolyte by distillation amounted to about 12%. The extreme pressure and temperature conditions required to effect separation make distillation a poor choice for the electrolytic decontamination program.

Metallic impurities can be removed from phosphoric acid solutions by the cathode of an electrochemical cell, provided the reduction of the metallic ion is favored over the reduction of the hydrogen ion. When applied to large-scale processes, the high ratio of cathode surface to electrolyte volume needed for effective metal ion reduction and removal becomes a problem. Also, any mercury in contact with a plutonium-contaminated solution would be considered radioactively contaminated. Special handling would be required in the secondary processing of the iron-, chromium-, and nickel-loaded mercury.

Another method for separation of impurities from an aqueous media takes advantage of semipermeable ion selective membranes. This method may be applicable to the purification of the waste decontamination electrolyte, although it has not been fully assessed either through literature or experimental evaluation.

Other progress in solution treatment studies has included the ordering of a reverse osmosis water processing unit to provide makeup water

for the solution processing and demonstration decontamination systems. This purification unit removes greater than 90% of the dissolved organic and inorganic impurities in the incoming water. It can produce up to 500 gal (1900 ℓ) of distilled-quality water per day.

The rinse solutions and water from the pretreatment facility will be purified using a commercial-type evaporator which is now on order. This will be a dual-effect stainless steel evaporator with 50 gal/hr (190 ℓ /hr) capacity. It can process nitric acid rinse solutions in addition to the rinse water. It can also be used to concentrate phosphoric acid from the acid processing unit. This dual-effect system can be operated in a double-distillation mode to increase product purity or, alternatively, used to process two different solutions simultaneously.

Entrained Contamination Studies

Some of the contamination on metal surfaces will be incorporated in the recast layer that is formed on cut edges by fusion-type metal cutting operations. We hope to minimize this entrained contamination problem by: 1) developing pre-cleaning treatments to remove most of the surface contamination before sectioning, 2) identifying cutting techniques and operating procedures that will minimize the thickness and contamination content of the recast layer, and 3) developing pretreatment and electropolishing techniques for the sectioned material that will preferentially remove all or part of the recast layer.

Discussions were held this quarter with members of the engineering staff of the Product Engineering Department, Union Carbide Corporation, to identify optimum plasma arc cutting equipment and operating procedures for our sectioning applications. Their studies show that the thickness of the recast layer for plasma arc cut metal can be minimized by using a small torch (small nozzle orifice and low heat input) and operating at the maximum cutting speed for each metal thickness. Based on this information, we plan to initiate our plasma arc sectioning studies using a heavy duty machine carriage capable of moving the torch at controlled speeds in a straight line up to 200 in./min (508 cm/min). We also will add a water muffle to the torch to help contain dross and contamination and reduce noise and ultraviolet radiation from the cutting operation.

An added benefit of the use of a small torch and low heat input will be minimization of metal loss (secondary waste) from the sectioning process through a reduction in cut width. Calculations show that the metal loss for the 100-A torch should be less than 2 wt% for sectioned planes 2 ft x 2 ft (61 cm x 61 cm) or larger.

Pretreatment tests are in progress using a 4 ft³ (0.11 m³) vibratory finisher to remove rust, paint and gross contamination from metal surfaces in preparation for final decontamination using electropolishing. This equipment also was used as part of the entrained contamination studies to determine if vibratory finishing would preferentially remove the recast layer from cut edges. Rectangular stainless steel samples of varying length-to-width ratios were processed for up to 31 hr using a conical-type plastic abrasive media and a chemical cleaning compound. The results of these tests showed that the sharp corners and edges were rounded by the abrasion process, but the actual amount of metal removed was small (less than 0.5 wt% for 31 hr of processing). There was no preferential removal of material from the planar part of the cut surface. It is concluded that vibratory finishing using plastic-type media would not be an effective method for removal of a contaminated recast layer.

PLANS FOR NEXT QUARTER

Technology transfer activities will continue with visits to designers and manufacturers of electropolishing systems, solution processing components, and sectioning equipment. Additional tests will be conducted to confirm the encouraging results of the titanium basket studies. The suitability of tantalum for this application also will be investigated. Design and procurement activities will continue for the acid purification system, the evaporator for the rinse solutions, and the associated solution handling and secondary waste disposal systems. The plasma arc sectioning studies will be initiated and edge-effect studies will continue using the vibratory finisher with other types of abrasive media.*

*Additional information on electropolishing as a decontamination technique is available in the PNL Nuclear Waste Management Quarterly. The latest issue is PNL-2377-3.

ENVIRONMENTAL EFFECTS

PROJECT TITLE: U.S. Scale Transport, Dispersal,
and Removal Model Comparisons

PROJECT MANAGER: C. L. Simpson, Manager
Atmospheric Sciences Department

PRINCIPAL INVESTIGATORS: W. E. Davis, R. L. Drake,
Atmospheric Chemistry and Dynamics Section,
Atmospheric Sciences Department

OBJECTIVE

The primary objective of this study is to provide air concentration assessments from a simulated release of tracer, using the PNL U.S. scale model for sources in four regions of the U.S. for the year 1975. This model simulates the processes of atmospheric transport, diffusion, dry deposition and precipitation scavenging. Model simulations are used to assess the effects of no deposition or combinations of dry and wet deposition.

The secondary objective of this work is to provide estimates of the confidence limits for radionuclide surface air concentrations and deposition amounts computed by U.S. scale assessment models. The approach used to meet this objective involves state-of-the art modifications of the basic parameters in short-term comparison tests.

SUMMARY

- An annual assessment was made for the SE using SRL as a source site.
- Gridding of winds and precipitation was completed for the SW.
- An annual assessment was made for the SW using Roswell, NM, as the source site.
- An advanced model was developed to compute the three options of the model at the same time.
- Comparisons were made of varying horizontal dispersion.

TRIPS AND VISITORS

Dr. Jim Schubert from SRL reviewed PNL progress in making assessments November 9, 1977.

Discussions with Jerome Heffter on AFCT program were held in Salt Lake City, December 1, 1977.

TECHNICAL PROGRESS

Annual assessments for the SE and the SW were prepared and sent to SRL this quarter. The computer model for the U.S. scale assessment was improved.

Annual Assessment for SW and SE

Through the use of gridded winds and gridded precipitation prepared last quarter, a U.S. scale assessment was run for the SE. A data tape was prepared and sent to SRL. During this quarter, fields of gridded winds and precipitation were prepared for the SW assessment. With these winds and precipitation an assessment was made for the SW. Work is underway to prepare a tape of the results for transmittal to SRL.

Data Transmittal

The tape sent to SRL for the SE assessment was prepared using three different formats: BCD, EBCDIC, and ASCII. Making a tape in EBCDIC format was delayed due to internal computer problems. Two other formats were tried before the difficulties were corrected and an EBCDIC tape sent. All of these tapes were successfully read at SRL. Graphics were produced from the data of this assessment for monthly, seasonal and annual deposition, and air concentrations. These graphics were also set to SRL. The results are shown in Figures 4-8, which indicate annual model results for air concentrations and total deposition using a dry deposition rate of 1 cm/sec and, in the case of wet deposition, a washout ratio of 5×10^5 . (A simulated release rate of 1 Ci/sec was used in the U.S. scale assessment with a release height of 62 m.) A dramatic drop-off in air concentrations between the depositing and non-depositing cases can be observed.

Advanced U.S. Scale Assessment Model

A standardized computer model for U.S. scale assessments was developed to produce annual assessments. The basic model was the same as that used for

U.S. scale assessments in previous studies;⁽¹⁾ however, instead of making separate assessments for the three modes of operation (nondepositing, dry depositing, and wet and dry depositing), all three were run simultaneously. This assured that the transport and diffusion were identical among the modes. Also, computing cost was lowered.

FIGURE 4. Surface Air Concentrations Ci/M^3 , No Deposition

FIGURE 5. Surface Air Concentrations Ci/M^3 , Dry Deposition 1 cm/sec

FIGURE 6. Surface Air Concentrations Ci/M^3 , Wet Depositions 10^5 ,
Dry Deposition 1 cm/sec

FIGURE 7. Total Ground Deposition Ci/M^2 , Dry Deposition 1 cm/sec

FIGURE 8. Total Ground Deposition Ci/M^2 , Wet Depositions 10^5 , Dry Depositions 1 cm/sec

Comparisons of Horizontal Dispersion

Two cases were considered in U.S. scale assessments: 1) horizontal diffusion by synoptic scale variations alone, an assumption past authors have used,⁽²⁾ and 2) horizontal dispersion along with synoptic scale variations.

The first case is simulated by distributing the pollutant mass over one grid box, σ_{y1} at the end of each time interval. The second case allows horizontal diffusion over a maximum of nine grid boxes, σ_{y3} . Identical wind fields were used in this study. Table 7 indicates the maximum range of results given by the σ_{y1} values as a fraction of σ_{y3} values in percentages for all twelve months. Maximum ranges in percentages are also given for the annual values.

TABLE 7. Fractional Change in % of Model Results Using σy_1 Rather than σy_3

	<u>Monthly Range</u>	<u>Annual Range</u>
Air Concentrations No Deposition	71-125	82-108
Air Concentrations Vd=1cm/sec	51-126	80-119
Total ground Deposi- tion Vd=1cm/sec	52-132	80-125

A check was made of the sum of air concentration values for 225 grid areas centered on the release point for the σy_1 and σy_3 cases. The resulting totals for both the monthly and annual values showed differences between the two methods of 4% or less. The main effect in using σy_3 was to redistribute or smooth the mass used in calculating air concentrations and ground depositions. These results indicate that using σy_3 is equivalent to smoothing σy_1 results. As can be seen in Table 7, the short term (monthly) assessments showed differences of as much as a factor of two. In the longer term (annual) assessment only 20 to 25% variations occur. This demonstrates that the influence of horizontal diffusion is lessened in longer assessments. If these variations are acceptable, costs can be reduced by using the σy_1 case of assuming horizontal diffusion estimated by synoptic scale variations.

PLANS FOR NEXT QUARTER

- Mail SW assessment tape to SRL.
- Produce graphics on SW assessment.
- Start gridding winds and precipitation for central U.S. assessment.
- Run assessment for central U.S.
- Grid winds and precipitation for NE U.S. scale assessment.
- Run assessment for NE U.S.

GENERAL SUPPORT

PROJECT TITLE: Safety Criticality Experiments

PROJECT MANAGER: E. D. Clayton, Nuclear Criticality Section,
Energy Systems Department

PRINCIPAL INVESTIGATOR: R. C. Lloyd, Nuclear Criticality Section,
Energy Systems Department

OBJECTIVES

The objectives of the criticality safety support task are to:

- utilize the PNL Critical Mass Laboratory to confirm criticality data required to support alternative fuel cycle R&D;
- establish benchmark data for code validation and safety assessment; and
- provide criticality safety parameters to support design concept and equipment specifications.

SUMMARY

Criticality experiments were completed on two different lattice assemblies of 4.3 wt% ^{235}U -enriched UO_2 fuel rods in water containing soluble neutron absorbers (gadolinium, boron and cadmium) at different concentrations.

TRIPS AND VISITORS

None.

TECHNICAL PROGRESS

Criticality experiments were conducted to obtain benchmark data for validating criticality control calculations on the use of soluble neutron absorbers.

The experiments on lattices of fuel rods immersed in water include measurements at each of three different lattice spacings with soluble neutron absorbers. The center-to-center fuel rod spacings are 22.9 mm,

27.9 mm and 33.0 mm. The fuel rods house UO_2 pellets of 4.3 wt% ^{235}U enrichment in stainless steel tubes with a clad OD of 14.4 mm (clad thickness of 0.183 mm). A detailed drawing is shown in Figure 9. Measurements have been completed on the first two of these lattices. The critical number of fuel rods was determined for three soluble neutron absorbers, gadolinium, cadmium and boron, at various concentrations in the water moderator with the 22.9 mm lattice, and with gadolinium and boron in the 27.9 mm lattice. The measurements completed on the second lattice include critical experimental data with two different concentrations of gadolinium and two concentrations of boron in the water.

Preliminary analysis of these data show that for the 22.9 mm lattice spacing, the critical number of fuel pins increases from about 223 in water without neutron poison to about 422 in water containing 0.21 g Gd/l, 392 in water containing 1.1 g Cd/l, and 433 in water containing ~ 0.6 g B/l. Figure 10 shows a graph of the critical number of rods plotted against the neutron absorber concentration for the 22.9 mm lattice.

Preliminary analysis of the data for the 27.9 mm lattice shows that the critical number of fuel pins varies from about 167 in water without neutron poison to about 324 in water containing 0.12 Gd/l and 350 in water containing 0.38 g B/l. Figure 11 shows the graph of the critical number of rods plotted against neutron absorber concentration for the 27.9 mm lattice.

PLANS FOR NEXT QUARTER

- Complete experiments with the UO_2 fuel rods in water and in water containing soluble neutron absorbers.
- Prepare the system for experimentation with fuel rods in uranyl nitrate solution and in the solution with neutron absorbers.
- Plan and develop study for the experimental series with mixed oxide rods in water and in water containing neutron absorbers.

FUEL TUBE CANNED LENGTH*	(34.421 in.)	874.29 mm
FUEL ROD CORE LENGTH	(32.394 in.)	822.81 mm
FUEL PELLET LENGTH	(0.625 in.)	15.88 mm
CLAD - OD	(0.567 in.)	14.40 mm
CLAD THICKNESS (304L SS)	(0.032 in.)	0.813 mm
FUEL COLUMN DIAMETER	(0.498 in.)	12.649 mm
UO ₂ DENSITY (% THEORETICAL)	94 - 98	
ENRICHMENT	4.3 w/o ²³⁵ U	

* MEASURED FROM BOTTOM OF END SPADE TO BOTTOM OF TOP SPADE

FIGURE 9. Description of 4.3 wt% ²³⁵U Enriched Fuel Rods

FIGURE 10. Effect of Neutron Adsorber on 0.9 in. (22.9 mm) Lattice

FIGURE 11. Effect of Neutron Absorber on 1.1 in. (27.9 mm) Lattice

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