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Iodox Process Tests in a Transuranium Element Production Campaign

E. D. Collins
D. E. Benker

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IODOX PROCESS TESTS IN A TRANSURANIUM ELEMENT PRODUCTION CAMPAIGN

E. D. Collins and D. E. Benker

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IODOX PROCESS TESTS IN A TRANSURANIUM ELEMENT PRODUCTION CAMPAIGN

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Chemical Technology Division

ABSTRACT

The Iodox process, an advanced method for removing gaseous radioiodine from airstreams, was tested at high activity levels during transuranium element production operations. Special equipment was used to remove radioiodine from 3-5 M HNO_3 dissolver solutions by volatilization and to absorb the iodine from the dissolver off-gas into hyperazeotropic HNO_3. More than 96% of the ^{131}I in the dissolver solutions was removed by heating to 100°C and air-sparging. Treatments such as boiling, sparging with 5% N_2O_3, and adjustment to 10^{-4} M KI or 1% H_2O_2 effected the additional removal of ^{131}I by factors of 2 to 5. Other than ^{131}I, no fission products were volatilized during the treatments. A six-stage bubble-cap column was used for the absorption. Off-gas decontamination factors were in the range of 1×10^4 to 8×10^4, or 5 to 7 per stage; these values are similar to those obtained during previous low-activity studies.

1. INTRODUCTION

The Iodox process is an advanced method for removing gaseous iodine from air by oxidation of organic iodides and by hydrolysis-oxidation of free iodine to the stable iodate form.[1] The process, which uses hyperazeotropic HNO_3 as the oxidizing agent and a multistage bubble-cap column as the contactor, has been developed at Oak Ridge National Laboratory (ORNL) and has been previously evaluated in experimental engineering studies.[2] Airstreams containing trace amounts of ^{131}I were used in those studies. The objective of the work described in this report was to test the Iodox process at high activity levels. This opportunity was made available at the Transuranium Processing Plant (TRU).

During the production of transuranium elements at TRU, solutions that contain high concentrations of radioactive fission products, including more than 10 Ci per liter of ^{131}I, are generated by the dissolution of irradiated curium targets. The concentrations of many of the fission products are in the same order of magnitude as those calculated for solutions containing 100 g per liter of heavy metal produced by dissolving Fast Flux Test Facility (FFTF) spent fuel that has been irradiated to 45,000 MWd/MT and cooled for 30 days. This is illustrated by the comparison shown in Table 1 and is of interest because the Iodox process was initially developed for breeder reactor fuel reprocessing plants.

As a result of fissions, primarily from the isotope ^{245}Cm, the irradiated targets processed at TRU contain large amounts of ^{131}I (∿200 Ci per target at the time of reactor discharge). The half-lives of most of the transuranium isotopes present in a target are sufficiently long to permit the targets to be cooled until the ^{131}I decays. However, the yield of ^{253}Es, which has only a 20-day half-life, is seriously affected by such cooling. To maximize einsteinium recovery, targets must be processed as soon as possible after they are removed from the reactor. The cooling period usually is 3 weeks, and several hundred curies of ^{131}I is present in a typical group of targets being processed.

The containment of ^{131}I during production campaigns at TRU was accomplished by several treatment methods for process solutions and off-gas streams.[3,4] Often, these methods were experimental and were designed to evaluate promising methods developed in the breeder reactor fuel reprocessing development program at ORNL. These methods did not include silver-based absorbers, which are precluded by the extensive use of HCl at TRU. A treatment system that uses a bed of oxidation catalyst (Hopcalite) to decompose organic vapors and a bed of KI-impregnated charcoal to sorb radioiodine from a 400-cfm (11,300-liters/min) off-gas stream has been used for several years.

Releases of ^{131}I have been kept below a few millicuries, but ∿5 to 25 Ci of ^{131}I has been sorbed on the charcoal during each processing campaign. The sorbed ^{131}I is susceptible to accidental release. Therefore,

Table 1. Potential dissolver solution concentration of gamma-emitting fission products from FFTF spent fuel and irradiated TRU curium targets

	FFTF fuel[a]	TRU targets
	(Ci/liter)	
^{95}Zr	360	33
^{103}Ru	330	95
^{106}Ru	220	68
^{110m}Ag	0.1	1
^{131}I	25	17
^{134}Cs	2	4
^{136}Cs	4	25
^{137}Cs	16	4
^{140}Ba	100	72
^{141}Ce	220	91
^{144}Ce	200	66
^{156}Eu	4	119

[a]Data obtained from an ORIGEN code estimation for FFTF fuel irradiated at 3.17×10^{15} n/sec-cm^2 for 45,000 MWd/MT and cooled for 30 days.

a scrubbing system for the treatment of the 0.25-cfm (7-liters/min) dissolver off-gas (DOG) stream was added and is now used for initial removal of the radioiodine; this allows the Hopcalite--charcoal to serve as a backup system. The location of the two iodine removal systems within the TRU vessel off-gas (VOG) system and the relative airflow rates are shown in Fig. 1.

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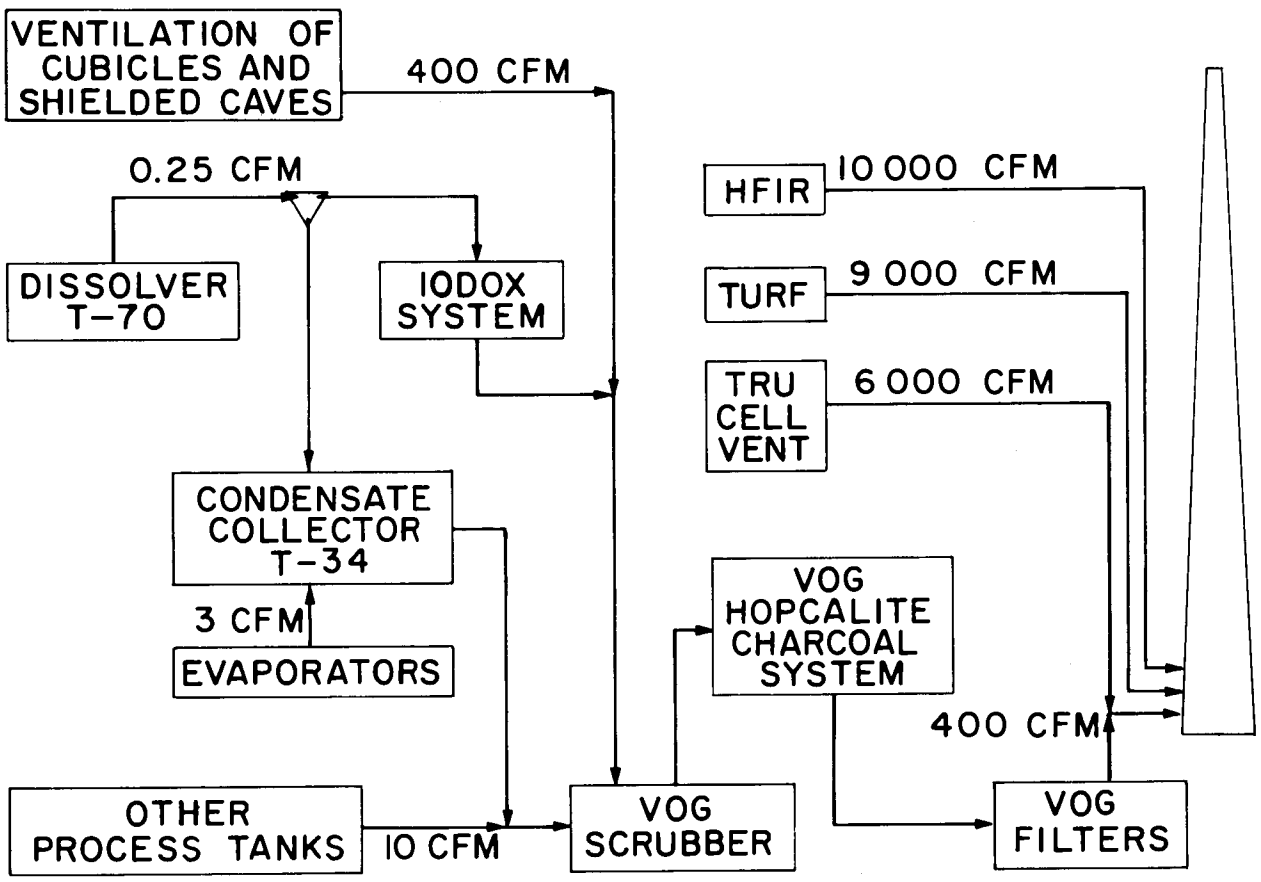

Fig. 1. TRU Vessel Off-Gas System.

2. DESCRIPTION OF EQUIPMENT

A flow diagram of the equipment used to test the Iodox process is shown in Fig. 2. A list of engineering drawings describing this equipment is given in Table A-1 of the Appendix. Photographs of the equipment rack are shown in Figs. 3 and 4. Metallic parts of the equipment that contact HNO_3 solutions are made of zircaloy.

The dissolver, T-70, is an 11-ft-long, 176-liter tank which is designed to handle targets of varying sizes. The tank has a 3-ft-long, 18-liter bottom section in which the curium targets are dissolved. The bottom and middle sections of T-70 are jacketed for heating with a circulating water system. However, the top section (3 ft long) is not jacketed or insulated, and iodine vapors could condense in this section and limit the removal of radioiodine from the solution. Thus, an evolver tank, T-740, which is completely surrounded by a heating water jacket, was included in the Iodox equipment. The dissolver solution is transferred to T-740 for the final iodine removal treatment.

The scrubber column, C-743, has a 3-in. diameter and contains six plates spaced at 8.4-in. intervals. Each plate contains three bubble caps and a liquid downcomer. As indicated in Fig. 2, the gas flow through the column is motivated by the air jet, J-748, which first exhausts into the hot cell (Cubicle 7) and then into the VOG system. The capacity of J-748 is $\sim$1 scfm (28 slpm). Gas feed streams to C-743 come from the T-70, T-740, T-742, and C-743 instrument purges and spargers and from Cubicle 7 via a vacuum-breaker pot, T-747, which contains a liquid (16 $\underline{M}$ HNO_3) seal. This pot allows a variable input of air which serves to maintain a constant total gas flow rate into C-743. The flow path of the off-gas from T-70 can be changed to bypass the Iodox system and go directly to the VOG system.

The function of the analysis pot, T-746, is to provide a measurement of the off-gas decontamination factor (DF) achieved in C-743. This is done by bubbling the column off-gas through 1 liter of fuming HNO_3 in T-746 to absorb most of the remaining iodine and then sampling the acid in T-746.

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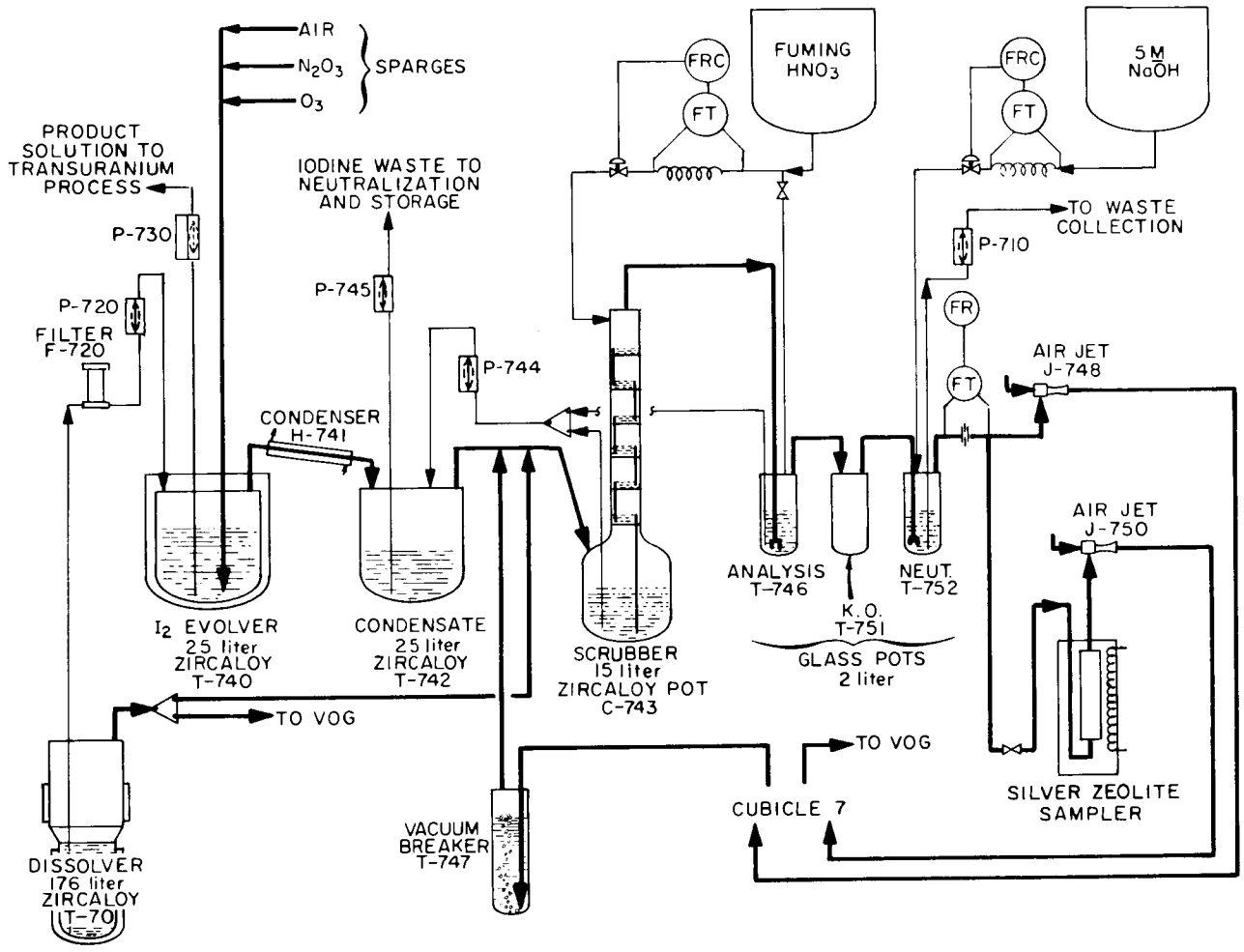

Fig. 2. TRU Dissolver Off-Gas System Iodine Removal System.

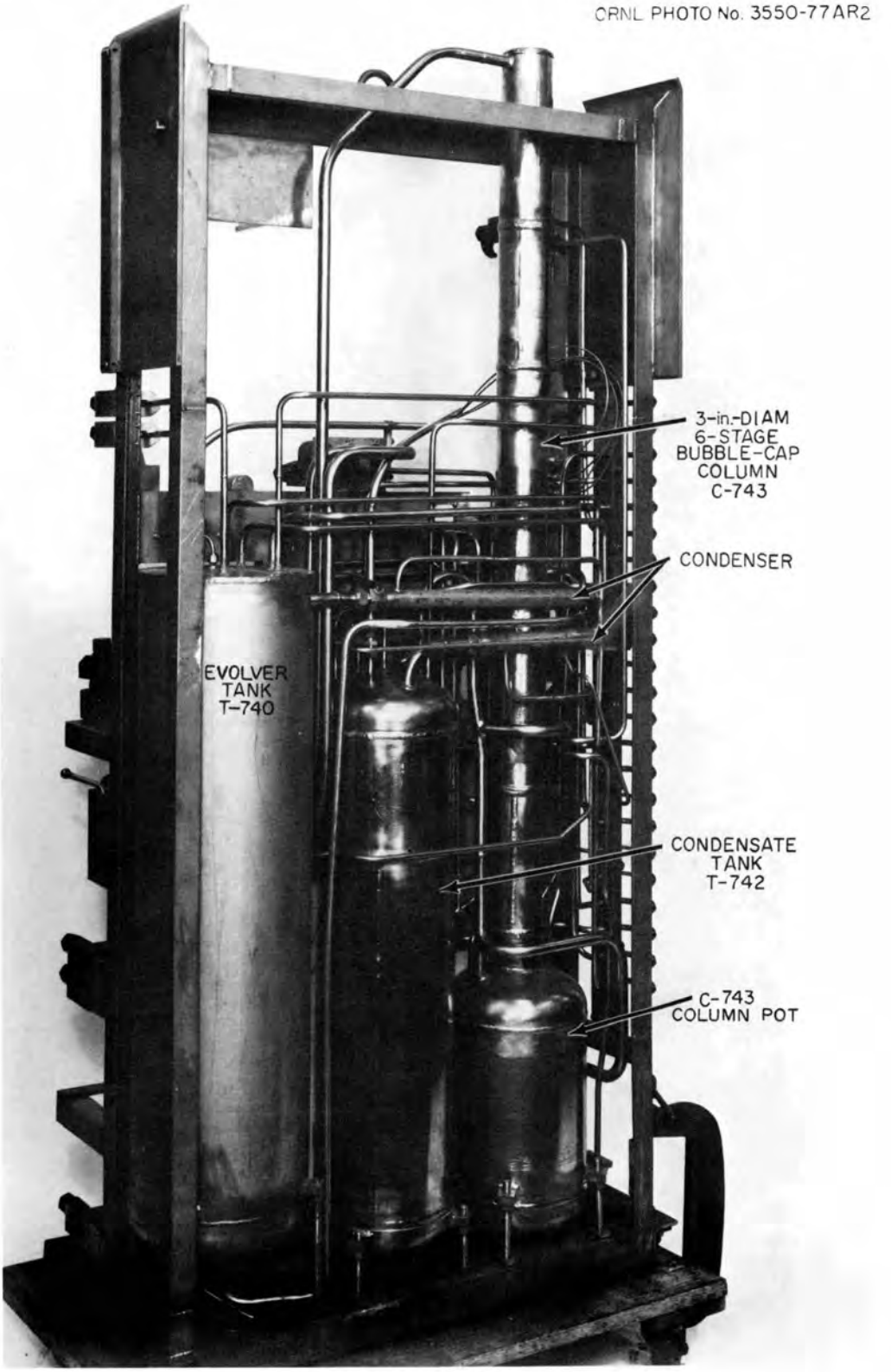

Fig. 3. Back of Iodox equipment rack.

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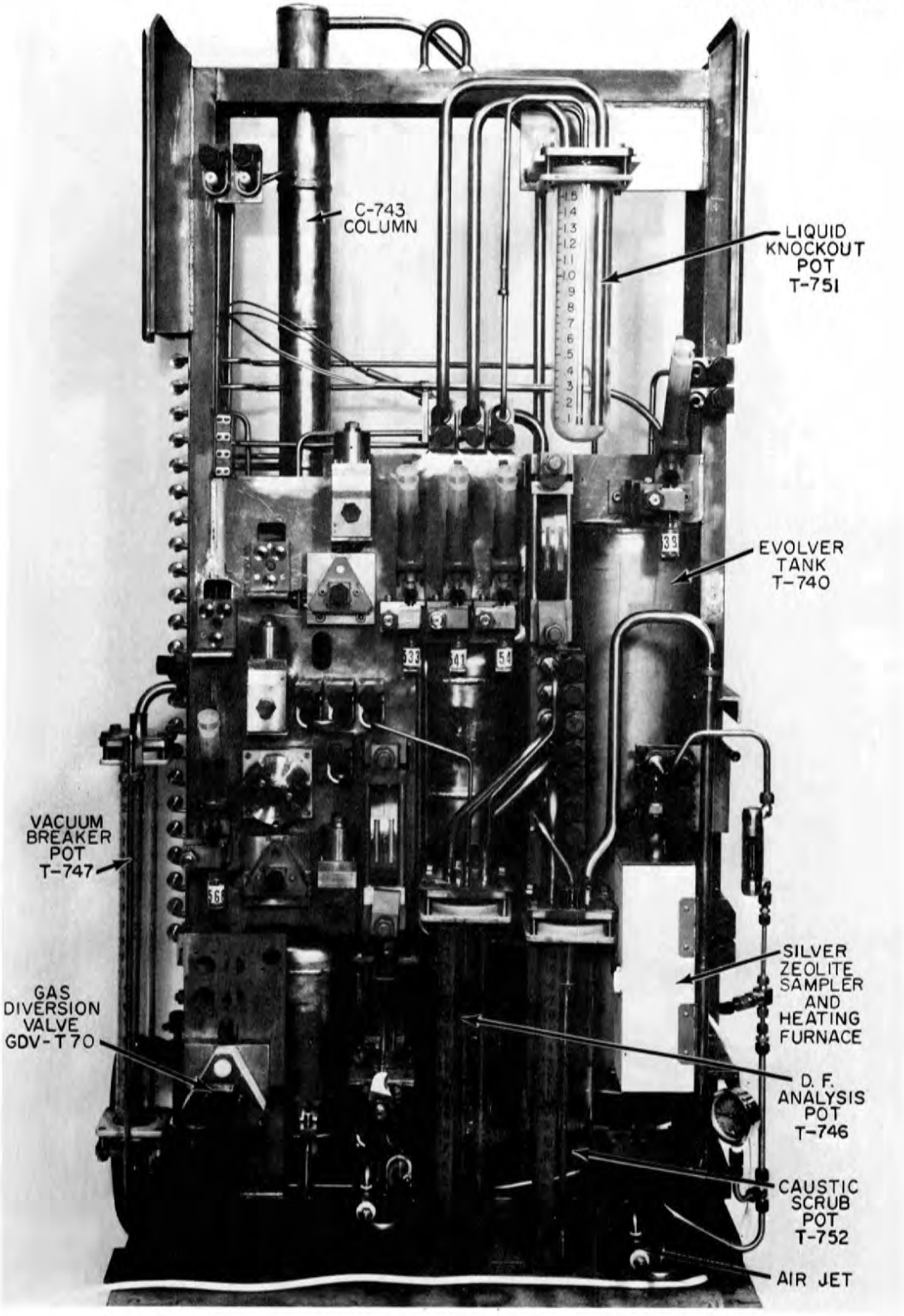

Fig. 4. Front of Iodox equipment rack.

T-752 is a single-stage contactor used to treat the off-gas from T-746 by adding ∿1 liter of 5 M NaOH each hour to remove acidic vapors. The silver zeolite trap is operated at 150°C to sample a fraction of the air exhausted to Cubicle 7.

3. TEST PROCEDURE

Four dissolver runs were made to test various methods of evolving residual radioiodine from acidic (HNO_3) dissolver solutions and to measure the effectiveness of the Iodox process for absorbing the radioiodine from the DOG stream (∿7 liters/min). The number of targets dissolved (4 to 13) and the cooling time (7 to 23 days) were chosen so that the ^{131}I content in each run could be maintained within the range of 200 to 300 Ci. Each run included the following steps:

1. The aluminum cladding and pellet matrix material were dissolved in T-70 in caustic nitrate solution. During this step, the off-gas from T-70 was diverted around the Iodox column and routed directly to the VOG system. This was done because previous experience had shown that very little radioiodine was evolved during the aluminum dissolution and 5 to 20 moles of NH_3 was evolved. If the NH_3 had been allowed to enter the Iodox column, C-743, insoluble amounts of NH_4NO_3 could have been formed. The small amount of radioiodine evolved was deemed low enough to be suitable for trapping in the VOG Hopcalite--charcoal system.

2. When the aluminum dissolution was completed, the aluminum-bearing solution contained from 35 to 55% of the ^{131}I in the targets. This solution was transferred through a porous stainless steel filter to a tank where the solution was stored until the ^{131}I decayed to an acceptable level for retransfer to the Intermediate-Level Waste System. Sodium thiosulfate was added (to a concentration of 0.05 M) to the stored solution in order to reduce any free iodine to the nonvolatile iodide form.

3. The T-70 off-gas was rerouted to the Iodox system which had been brought to steady-state operation under the conditions shown in Table 2. A new silver zeolite trap was installed and put on-stream under conditions that also are shown in Table 2.

4. The remaining actinide and fission product oxides in T-70 were dissolved by:

   1. adding ∿9 liters of 3.5 M HNO_3;
   2. heating the acid solution to 103°C (just below the boiling temperature) while sparging with air at 0.2 to 1.3 liters/min;
   3. holding the temperature at 103 ± 2°C for 2 hr and continuing the air sparge;
   4. cooling the solution to ∿30°C.

   A summary of the measured conditions for each run is given in Table 3.

5. The dissolver solution was filtered through a polypropylene-fiber cartridge (with 50 μm openings) to remove silicon-based insolubles. The filtered solution was transferred and flushed into the evolver tank, T-740. When this operation was completed, T-740 contained ∿18 liters of 4 M HNO_3.

6. The solution was treated in T-740 to reduce the ^{131}I concentration to a minimum. The treatment procedures used in the runs were different and are described below in the Experimental Results (Sect. 4.2).

7. Following the ^{131}I removal treatment, the solution was transferred and flushed from T-740 to the feed tank (T-72) for the next transuranium element processing step.

8. Operation of the bubble-cap absorption column was continued for 8 hr before either the start of a new run or shutdown of the system.

Samples were taken from T-70, T-742, C-743 pot, T-746, and T-752 at varying times during the dissolution steps, the dissolver solution transfer steps, and the iodine evolution treatment steps.

Table 2. Operating conditions for the bubble-cap column and silver zeolite off-gas sampler

Run No.	1	2	3	4
HNO_3 concentration, M (top plate)	23	23	21	21
HNO_3 concentration, M (bottom plate)	21.7	21.6	19.4	19.5
Liquid flow rate to column, ml/hr	420	270	250	390
Gas flow rate, slpm	6.5	6.8	7.1	7.1
Cubicle temperature, °C	40	40	40	40
Silver zeolite sampler gas flow, slpm	0.03	0.03	0.03	0.03
Silver zeolite sampler temperature, °C	138-160	155-163	157-161	153-160

Table 3. Operating conditions for the acid dissolution of actinide and fission product oxides

Run No.	1	2	3	4
Volume, liters	8.9	8.8	8.7	9.6
HNO_3 concentration, M	4.9	3.9	5.2	2.8
Temperature, °C	99-105	99-103	97-103	95-104
Dissolution time, hr	3.0	2.5	2.0	3.4
Air purge rate, liters/min	0.2	0.8	0.8	1.3

4. EXPERIMENTAL RESULTS

4.1 Evolution of ^{131}I from the Dissolver Solution in T-70

For the four runs, the amounts of ^{131}I remaining with the undissolved oxides (actinides and fission product elements) in the dissolver tank (T-70), after removal of the aluminum-bearing caustic-nitrate solution, ranged from 120 to 147 Ci. During the dissolutions of the oxides in HNO_3 (step 4 of the test procedure described above in Sect. 3), most of this ^{131}I was evolved. This is illustrated in Fig. 5 in which data obtained during two of the runs are presented. In this graph, the time scales for the two runs were adjusted to show the heatup period (B) beginning at the same time (4 hr). This was done to enable a comparison of the iodine evolution from the two runs. Iodine evolution was not only a function of time but also of the temperature and sparging conditions in the dissolver. At the beginning of step B, the HNO_3 addition had been completed, the heating and sparging period was beginning, and >50% of the actinide elements (represented by curium) had been dissolved. However, the dissolver solution contained <15% of the ^{131}I, and <1% had reached the Iodox column pot. Thus, >84% of the ^{131}I was located in the vapor space of the dissolver or in the absorption stages of the column. At the 6-hour time, the digestion period (C) was in progress, and the curium had been completely dissolved; the ^{131}I concentration in the dissolver solution was decreasing, while the concentration in the Iodox column pot was increasing rapidly. At the end of the digestion times, the ^{131}I collection rates in the column pot had ceased to increase rapidly; however, in Run 2, only 40% of the ^{131}I had been collected. At some later time, between 10 and 30 hr (no samples were taken during that period), the remaining ^{131}I was collected. This behavior indicates that some refluxing of the ^{131}I occurred during Run 2; a further indication is the increase of ^{131}I in the dissolver solution during the cooling period (D). Refluxing during Run 4 was lessened by a more rapid sparge rate (1.3 liters/min versus 0.8 liter/min in Run 2) and a slightly longer digestion time.

The fractions of ^{131}I evolved during the dissolution steps in T-70 were 89%, 96.5%, 98.3%, and 98%, respectively, for the four runs. The lesser amount evolved during the first run is attributed to a slower sparging rate (0.2 liter/min).

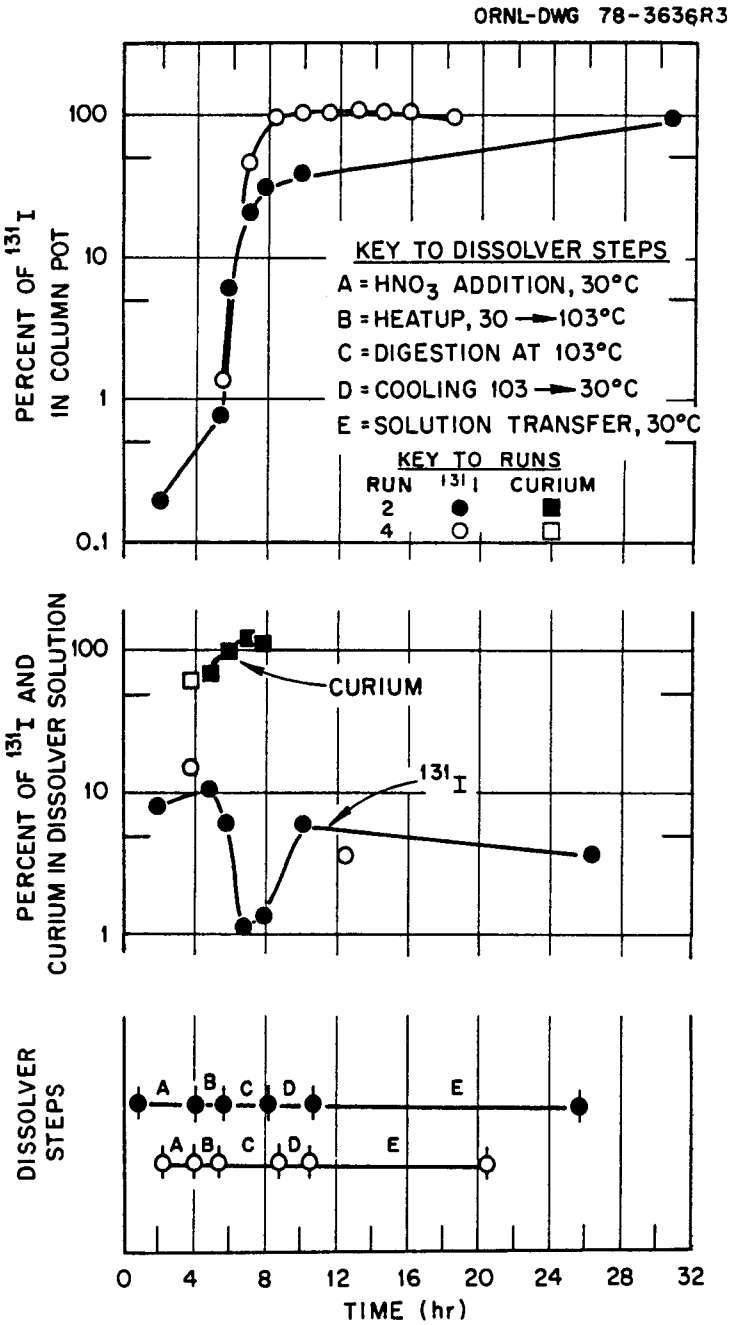

Fig. 5. Iodine evolution during dissolution of oxides.

4.2 Minimization of ^{131}I Concentration in the Dissolver Solution

Although the procedure used during the dissolution in T-70 was essentially the same in all four runs, the treatments conducted in T-740 to minimize the ^{131}I concentrations in the dissolver solutions were different in each run. In Run 1, the treatment was as follows:

1. Approximately 5% of the solution was evaporated while being sparged with air at 3 liters/min.
2. The solution was cooled to ∿95°C, which is a few degrees below the boiling point. Then sufficient KI was added to adjust the solution concentration to 10^{-4} M I^-.
3. The solution was digested at 95-100°C for 3 hr while being sparged with air at a rate of 3 liters/min.

Treatment during the second run was identical to that of the first run except that the sparge gas composition was 95% air--5% N_2O_3. Conditions during the third run were similar to those of the second, except that after the KI addition, the solution was sparged with 2% O_3--98% O_2 at 3 liters/min. Somewhat different conditions were used during Run 4; these were as follows:

1. Approximately 5% of the solution was evaporated; during the evaporation, the solution was sparged with 95% air--5% N_2O_3 at a rate of 3 liters/min.
2. The solution was cooled to 95°C. Hydrogen peroxide was added until the solution contained 1 vol%.
3. The solution temperature was held at 95-100°C for 90 min. Sparging with 5% N_2O_3 at 3 liters/min was continued during this time.
4. A second addition of H_2O_2 (as in step 2) was made.
5. The 90-min sparging period (as in step 3) was repeated.

The results of the various treatments are summarized by the graph in Fig. 6.

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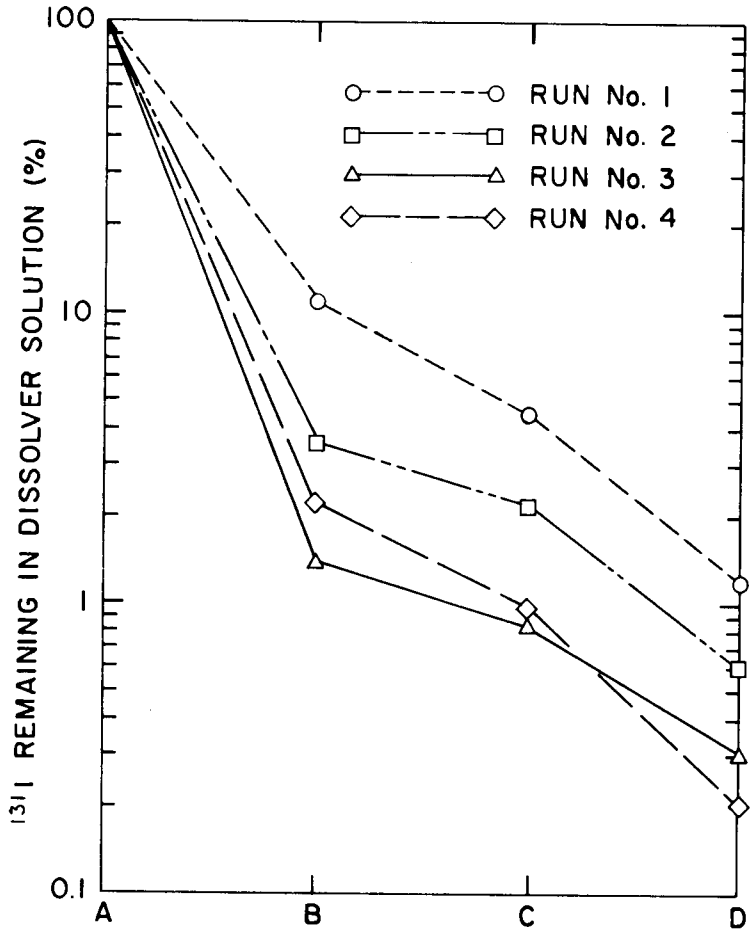

A. BEFORE HNO_3 ADDITION

B. AFTER DISSOLUTION IN HNO_3

C. AFTER BOILING OFF 1 LITER (5% VOLUME REDUCTION)

D. AFTER TREATMENT WITH KI (RUN 1, 2, 3) OR WITH H_2O_2 (RUN 4)

Fig. 6. Removal of ^{131}I from dissolver solutions.

The first step, evaporation and sparging with either air or 5% N_2O_3, reduced the ^{131}I concentrations in the solutions by a factor of ∿2 for each run. The second step of the first three runs, adding KI (with or without ozone sparging), reduced the ^{131}I concentrations by factors of 3 to 4. In Run 4, the addition of H_2O_2 reduced the ^{131}I concentration by a factor of 5. For each run, the final concentration was in the range of 20 to 90 mCi/liter and represented from a few tenths to ∿1% of the total ^{131}I measured during the acid dissolution steps.

4.3 Absorption of Radioiodine from the Dissolver Off-Gas

The operating conditions of the bubble-cap column and the silver zeolite sampler are shown in Table 2. During the first two runs, the column was fed with specially prepared 23 M HNO_3; commercially obtained 21 M HNO_3 was used during Runs 3 and 4. The operating temperature of the column was estimated to be the same as the ambient temperature of the hot cell. Flow through the silver zeolite sampler was ∿0.5% of the total gas flow, and the intended operating temperature of the trap was 150°C.

The final distribution of ^{131}I during each run is listed in Table 4. As intended, most of the ^{131}I was absorbed in the column acid liquor. Only 0.0012 to 0.008% of the ^{131}I was measured in the effluent gas and downstream traps. Thus, the column DFs ranged from 1×10^4 to 8×10^4, or 5 to 7 per stage. These values are similar to measurements made during the tracer-level, engineering-scale studies.[2]

No effect of acid concentration on DF could be determined from the results. The precision of measurements made from the remotely obtained samples was not sufficient to differentiate between values within the same order of magnitude. In the tracer-level studies that were previously conducted, the DF was increased exponentially by increasing acid concentration.

The evolution of radioiodine from the dissolver, and thus the absorption from the off-gas, was a function of time, temperature, and sparging conditions within the dissolver, as shown in Fig. 7. This

Table 4. Distribution of ^{131}I

Run No.	1	2	3	4
Sum of curies (≡ 100%) in all streams	140	147	131	120
Final dissolver solution, %[a]	1.1	0.63	0.36	≤0.33
Evaporator condensate, %	1.0	0.68	0.41	0.24
Iodox column liquid effluent (C-743), %	97.9	98.6	99.2	99.4
DF analysis (T-746), %	7.9×10^{-3}	4.3×10^{-3}	7.8×10^{-4}	7.1×10^{-4}
Caustic scrubber effluent, %	b	b	b	6.3×10^{-4}
Silver zeolite sampler, %	6×10^{-5}	4×10^{-4}	4.6×10^{-4}	2.1×10^{-3}
Column DF	1.2×10^{4}	2.1×10^{4}	8.0×10^{4}	2.9×10^{4}

[a]After evolution of radioiodine.

[b]Not measured.

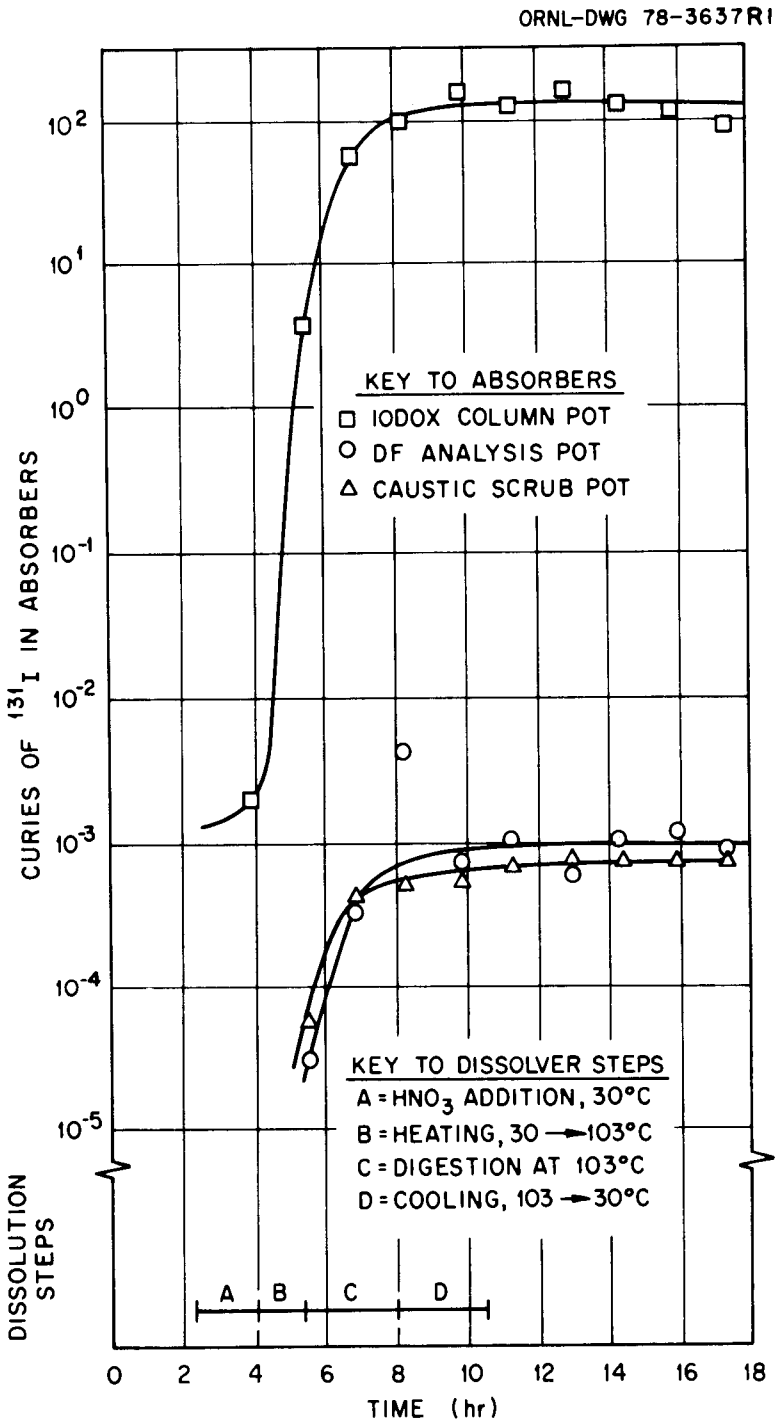

Fig. 7. Absorption of ^{131}I during dissolution of oxides (Run 4).

diagram also shows some of the variations of the data points and the relative collection rates in the various absorbers.

4.4 Fission Product Distribution

The behavior of potentially volatile elements, especially ruthenium, were of interest in this study. The distributions of measured amounts of ^{103}Ru are compared with those of ^{131}I in Table 5 and indicate that only a fraction of the ruthenium was evolved from the dissolver solution. The measured distribution of all fission products and alpha emitters within the system, for Runs 1, 2, and 3, are shown in Tables A-2, A-3, and A-4, respectively, in the Appendix. Very little evolution of any of the fission products, except ^{131}I, occurred.

Table 5. Comparison of volatilization of iodine and ruthenium[a]

	^{131}I	^{103}Ru
Total amount in HNO_3 dissolution, Ci	139	824
Percent found in:		
Dissolver solution	0.7	99.9
Condensate	0.7	1.0×10^{-3}
Absorption column liquid	98.6	$<6 \times 10^{-3}$
Downstream pots and traps	4.7×10^{-3}	3.4×10^{-4}

[a]The data shown are averages of values measured during Runs 1, 2, and 3.

5. SUMMARY AND CONCLUSIONS

The Iodox process was tested at high activity levels during transuranium element production operations at TRU. Special equipment was installed to remove radioiodine from dissolver solutions by volatilization and to absorb the iodine from the dissolver off-gas into fuming HNO_3; a six-stage bubble-cap column was used for the absorption. Several methods for reducing the iodine concentration in the dissolver solution were tested.

From the results of the tests, the following conclusions were made:

1. More than 96% of the radioiodine in 3-5 M HNO_3 dissolver solutions can be removed by volatilization when the solution is heated to ∿100°C and sparged with air.

2. Treatments such as boiling, sparging with 5% N_2O_3, and adding KI or H_2O_2 are effective for additional removal of iodine by factors ranging from 2 to 5. Combinations of these treatments can reduce the radioiodine remaining in solution to concentrations of <100 mCi/liter. This activity is estimated to represent $<5 \times 10^{-7}$ g-atoms of radioiodine (^{131}I and ^{129}I) per liter.

3. The treatments used in this study did not appear to cause volatilization of fission products other than radioiodine.

4. The dissolver off-gas decontamination factors (DFs) obtained in the absorption column were in the range of 1×10^4 to 8×10^4, or 5 to 7 per stage. These DFs were similar to those obtained during previous tracer-level studies.

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7. APPENDIX

Table A-1. Engineering drawings of the equipment used to test the Iodox process

Equipment	ORNL drawing number
Engineering flow sheet	M-12175-CP-256E
Dissolver T-70 assembly	M-12175-CP-440E
T-740 assembly	M-12175-CP-288E
T-742 assembly	M-12175-CP-287E
C-743 column assembly and details	M-12175-CP-517E
T-746 assembly	M-12175-CP-518E
T-751 assembly	M-12175-CP-557E
T-752 assembly	M-12175-CP-558E
T-747 assembly	M-12175-CP-519E
Silver zeolite sampler and furnace	M-12175-CP-538E
Rack equipment layout	M-12175-CP-522E
Rack front elevation piping	M-12175-CP-524E

Table A-2. Run 1 — distribution of fission products

Isotope	Total number of curies	Percent of total					
		$NaAlO_2$ solution	Transuranium element solution[a]	Condensate	Absorption column liquid	DF pot liquid	Silver zeolite sampler
^{95}Zr	247	1.6	98.4	3×10^{-3}	<0.007	9×10^{-5}	
^{103}Ru	741	0.4	99.6	5×10^{-4}	<0.01	1×10^{-4}	
^{131}I	295	52.5	0.58	0.47	46.4	4×10^{-3}	3×10^{-5}
^{137}Cs	67	39.1	60.9	$<7 \times 10^{-4}$	<0.03	2×10^{-4}	
^{140}Ba	585	--	∿100	$<4 \times 10^{-4}$	<0.03	1×10^{-4}	
^{144}Ce	558	--	∿100	$<2 \times 10^{-3}$	<0.2	2×10^{-4}	
^{156}Eu	1230	<0.2	99.8	$<1 \times 10^{-3}$	<0.007	2×10^{-4}	
Gross gamma	2.31×10^{15}[b]	10.4	87.4	0.03	2.1	5×10^{-4}	
Gross alpha	6.1×10^{14}[b]	2×10^{-3}	∿100	4×10^{-4}	0.007	3×10^{-4}	

[a]After treatment to evolve radioiodine.

[b]Counts per minute.

Table A-3. Run 2 — distribution of fission products

Isotope	Total number of curies	Percent of total					
		$NaAlO_2$ solution	Transuranium element solution[a]	Condensate	Absorption column liquid	DF pot liquid	Silver zeolite sampler
^{95}Zr	270	--	∿100	3×10^{-3}	<0.03	$<7 \times 10^{-6}$	3×10^{-4}
^{103}Ru	773	1.2	98.8	2×10^{-3}	<0.006	$<6 \times 10^{-6}$	4×10^{-4}
^{131}I	263	43.9	0.35	0.37	55.4	2.4×10^{-3}	2×10^{-4}
^{137}Cs	53.8	29.9	70.1	3×10^{-3}	<0.02	$<2 \times 10^{-6}$	6×10^{-5}
^{140}Ba	680	<0.3	99.7	$<2 \times 10^{-3}$	<0.02	$<4 \times 10^{-6}$	7×10^{-5}
^{144}Ce	601	<3.7	96.3	3.8×10^{-3}	<0.04	7×10^{-4}	1×10^{-4}
^{156}Eu	865	0.2	99.8	$<3 \times 10^{-3}$	<0.005	$<4 \times 10^{-6}$	5×10^{-4}
Gross gamma	1.83×10^{15}[b]	6.1	88.3	0.02	5.6	2×10^{-4}	--
Gross alpha	6.68×10^{14}[b]	0.05	∿100	--	2×10^{-3}	--	--

[a]After treatment to evolve radioiodine.

[b]Counts per minute.

Table A-4. Run 3 — distribution of fission products

Isotope	Total number of curies	Percent of total					
		$NaAlO_2$ solution	Transuranium element solution[a]	Condensate	Absorption column liquid	DF pot liquid	Silver zeolite sampler
^{95}Zr	364	<0.2	99.8	8×10^{-4}	<0.06	$<9 \times 10^{-6}$	2×10^{-4}
^{103}Ru	980	0.98	99.0	6×10^{-4}	<0.004	3×10^{-5}	4×10^{-4}
^{131}I	202	35.2	0.23	0.27	64.5	5×10^{-3}	2×10^{-4}
^{137}Cs	55.3	46.1	53.9	$<3 \times 10^{-4}$	<0.03	$<9 \times 10^{-6}$	3×10^{-5}
^{140}Ba	679	<0.5	99.5	$<5 \times 10^{-4}$	<0.02	$<5 \times 10^{-6}$	9×10^{-5}
^{144}Ce	631	<1.3	98.7	$<2 \times 10^{-3}$	<0.09	3×10^{-5}	5×10^{-4}
^{156}Eu	1120	<0.3	99.7	$<4 \times 10^{-4}$	<0.01	$<4 \times 10^{-6}$	1×10^{-4}
Gross gamma	2.51×10^{15}[b]	3.8	94.4	0.01	1.8	3×10^{-5}	--
Gross alpha	1.68×10^{15}	--	∿100	4×10^{-4}		--	--

[a]After treatment to evolve radioiodine.

[b]Counts per minute.

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