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THE APPLICATION OF PRESSURIZED ION EXCHANGE TO SEPARATIONS OF TRANSPLUTONIUM ELEMENTS*

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INTRODUCTION

One of the first triumphs of ion exchange chromatography was the separation and identification of fission product rare earths in the Manhattan Project in the early 1940s. Initial publication of this work was withheld for several years, and in 1947 nine papers from the Oak Ridge National Laboratory and the Ames Laboratory at Iowa State University appeared in the Journal of the American Chemical Society.¹⁻⁹ The science of rare earth separations was indeed revolutionized. Whereas it had taken years to separate and purify these elements, and lifetimes had been devoted to the problem, now it could be done in one or a few days.

There weren't any transplutonium elements, or plutonium for that matter, before the early 1940s, and this symposium is about transplutonium element separations. However, the heavier actinides and the rare earths, or lanthanides, are so similar chemically, that what is true for one group is generally true for the other. In practice, process development work is usually carried out with lanthanides, and a lot of data are collected. Frequently, all the solutions end up as analytical samples; and with luck, beautiful elution curves result.

With transplutonium elements, the situation is quite different. We want the maximum yield of pure products. They are simply too valuable and rare to play around with. Accordingly, the methods and equipment developed with rare earth separations are applied to heavy actinides directly, starting immediately with production separations. These may be quite small in scale, but this is "production" for some of these elements. Since one wants products and not analytical samples, the result is that there is relatively little data giving detailed elution curves for actinides. Most of the development data that is suitable for theoretical

interpretation, for example, is for rare earth separations; so I will be talking quite a bit about rare earths. Fortunately, such data can be transferred to actinide separations with great confidence, as long as certain precautions are taken into account.

Two basic approaches are used to separate these elements, namely elution development and displacement development chromatography. Both were defined in the original work; and in both, the separations are based primarily on differences in complexing of the trivalent ions by an organic complexing solution during elution through a column of strong sulfonic acid ion exchange resin. Displacement development is appropriate to larger-scale separations because higher column loading can be used and product concentrations are greater. Elution development is particularly suited to smaller scale (even tracer) separations because the product bands can be completely separated from each other. The division between the two methods is not sharp, but it is usually within the range of a few tenths of a gram to a few grams.

Since the World War II days there have been significant advances in three general areas. One is the acquisition of data for the interaction of these elements with a large number of diverse complexing agents. The appropriate data include distribution coefficients and separation factors for the different elements, and complex stability constants. It is important to remember that complex stability constants do not correlate exactly with distribution coefficients because other interactions in addition to complexation are involved in the separations. The result is that alpha-hydroxyisobutyrate has been generally used for elution development separations, following the work of Choppin and Silva in

1956,¹⁰ and a buffer of one of the polyaminopolycarboxylic acids, such as EDTA, DTPA, or NTA, is used for displacement development. Citrate, which was used in the original work for both approaches, is now only of historical interest.

The second advance occurred at about the same time for displacement development chromatography. This involved the use of a metal "barrier" ion such as Cu, Fe, or Ni, and was demonstrated by Spedding, Powell, and Wheelwright.^{11,12} The metal ion forms a stronger complex with the eluent, than do the trivalent ions of interest; and thereby it holds back or "retains" these ions. This alleviated several problems, and contributed substantially to the usefulness of the process.

The third advance, and the primary subject of this talk, occurred in a completely different discipline, biochemistry. This was the development of dependable systems for high pressure liquid chromatography during the 1960s. The motivation for this development was the need to separate a number of very similar materials in biological and medical research, such as nuclide acids. The usual ion exchange chromatographic methods were partially successful, yet inadequate. It was recognized that greater resolution was required to gain information about several key problems. Note that the goal was improved resolution.

Reviews of the biochemical work generally start with Martin and Synge in 1941¹³ and then jump to the work of Cohn in 1949.¹⁴ There is an interesting story here. Cohn's work in 1941 on nucleic acid separations by ion exchange chromatography, is generally considered to be the germinal factor that provided the incentive for improved separation methods and led, eventually, to the pressurized ion exchange systems that are common today. It so happens that Waldo Cohn was coauthor of one of those original publications on rare earth

separations in 1947. It was a logical and well-conceived approach to try this new chromatographic method in his original field of interest, biochemistry, once the wartime priorities were suspended.

Heftman¹⁵ has written, for example, that the application of ion exchange chromatography to the nucleic acid field followed directly from the development of the technique for rare earth separations by Tompkins, Khym, and Cohn.¹ The high performance pressurized ion exchange systems were developed later to satisfy the need for greater resolution. The fascinating point is that the technology that grew out of this work has come full circle after some twenty years, with the application of the pressurized system to separations of the trivalent actinides, the homologues of the rare earths. This technology was reviewed in 1976,¹⁶ and it contributes importantly to several papers at this symposium, since it is the method used for separation and purification of nearly all the transcurium elements produced today.

The road to better resolution was really quite obvious. It was to use ever smaller and more uniform ion exchange particles. The problem is that the small particles cause the flow rate to practically disappear unless the columns are very short. The way around that problem is to apply a high pressure to the column inlet. In the case of this development, at least, it wasn't the idea that was the breakthrough; there was no brilliant new insight. What made a success of pressurized ion exchange was the development and commercial availability of dependable hardware like pumps, valves, fittings, and such, which occurred generally in the 1960s.

Actinide Production Considerations

The need for greatly increased production of the heavier actinides became apparent in the late 1960s. There had been several separations of multi-gram quantities of americium and curium, but only much smaller amounts of heavier actinides. Two programs were initiated, one at Oak Ridge, and one at Savannah River. The High Flux Isotope Reactor (HFIR) and the Transuranium Processing Plant (TRU) were built at Oak Ridge National Laboratory,¹⁷ and they have continued to supply elements up to Fermium, as discussed in other papers here. The Californium Production Program¹⁸ was established at the Savannah River Laboratory to produce more californium in a shorter time, but it was subsequently scaled down.

Both these programs were designed originally to utilize solvent extraction predominantly (although at ORNL anion exchange was also scheduled for the partial separation of heavy actinides from the rare earths and much of the americium and curium), and cation exchange was used for the purification of the individual transcurium elements. At both sites various operational problems developed with solvent extraction, and ion exchange performance was unexpectedly good. In addition, pressurized ion exchange came along at just the right time, and it permitted ion exchange to be applied to the highest radiation levels anticipated in these programs. Presently ion exchange is used almost exclusively for transplutonium element separation, and solvent extraction is relegated to feed preparation and adjustment.

It was recognized when the programs were first considered that a very high radiation intensity would be encountered, well beyond that in reactor fuel reprocessing, for example. At the same time, the separations are among the most difficult to accomplish. To put the problem in perspective, the separation factors

for successive pairs of transplutonium elements vary upwards from about 1.3 and both the yield and the extent of separation from adjacent elements are desired to be about 99.9%. These requirements translate into a separation system capable of achieving about 500 equivalent theoretical plates. This is not really outstanding performance in terms of small-scale, modern, high resolution chromatography; but it is exceptional performance when the radiation damage problems are taken into account.

The scale of work ranges from hundred gram (and even kg) quantities of fission products, rare earths, americium, and curium, down to 100 mg quantities of californium, <1 mg of einsteinium and <1 pg of fermium. The radiation power density encountered in some separations is uniquely large for a chemical operation. When the programs were started there was at least a little doubt about how the separations would be accomplished and how successful they would be.

The highest concentration of each element usually occurs in its final separation and purification. This is also when the greatest radiation intensity occurs, and when the chemical operations are most critical. There are several radiation damage effects, occurring in both the aqueous phase (where radiolysis causes gas generation) and the organic phase or resin (where resin properties are changed). In some cases Wheelwright reported that gas generation was so great with conventional ion exchange that the resin bed sometimes separated into segments.¹⁹ Clearly, it would be difficult to obtain hundreds of theoretical plates in a column under such conditions.

The requirements for this work, then, may be generally summarized as reasonably good (but not extreme) resolution, small to moderate capacity (up to perhaps a few moles), suppression of the effects of radiation damage (particularly gassing), and a very high speed of separation to minimize the radiation exposure. These goals are uniquely met by pressurized ion exchange chromatography.

The short diffusion paths of the small resin particles permit very high flow velocities while still attaining good resolution, and the high pressure allows the high flow rate actually to be achieved. As a result, the elutions are fast, thereby diminishing the exposure time and, proportionately, the radiation damage. The high pressure, itself, which is something of a necessary evil in conventional work, is a distinct benefit here because it alleviates the gassing problem. Gas solubilities are proportional to their pressure, so gases dissolve and, if bubbles do form (near the bottom of the column), they are immediately swept out.

Experimental Studies - Elution Development

The first application of pressurized ion exchange to lanthanide and actinide separations was carried out in a program initiated in 1967 to examine this technique for the final separation of trivalent actinides in the TRU facility. As usual, initial work was done with rare earths, and it was demonstrated that 200 mg quantities of Nd and Pr could be adequately separated in times under an hour.²⁰ This pair is as difficult to separate as any actinide pair, and the time and scale of separation easily met the requirements projected for actinide production at TRU. Subsequently, separations of multi-mg quantities of all the rare earths were demonstrated in times as short as about 1.5 h.^{21,22}

Mixtures of transplutonium elements were also studied, once operating conditions and procedures were defined²³ (Fig. 1). This work used elution development with buffers of alpha-hydroxyisobutyric acid partially neutralized with NH_4OH and Dowex 50-X12 resin with a particle size range of 20-40 μm . The elution bands showed good separation of Es, Cf, Bk (the band labelled "B" is a combination of Bk and Eu, which are not adequately separated in this

system) and Cm. The very small amount of Fm present in this early production material is in the extreme leading edge of the Es band.

The initial pressurized ion exchange equipment was patterned after systems being studied at the time for biochemical separations, but it was operated somewhat differently. For actinide separations the speed of separation is critical because of radiation effects, but for biochemical problems the goal is maximum resolution. Since system resolution is so great it is possible to trade off some resolution for a faster separation. In practice, much higher flow rates and somewhat larger resin particles were usually used. Flow velocities are typically in the range of 5 to 20 ml cm⁻² min⁻¹ (cm min⁻¹) for elution and up to 50 cm min⁻¹ for loading. In contrast, conventional ion exchange separations of trivalent actinides commonly used 0.1 to 0.2 cm min⁻¹. Thus, the time required for the separation was reduced by factors of 10 to 100, with comparable reduction in radiation damage.

Advantageous ranges of operating conditions were determined. Performance was excellent with 20-40 μm resin particles in columns of to 1.5 m long, but frequently larger resin particles were used to permit higher flow rates with available pressures, up to 10 MPa. The resin particle size range should be narrow, certainly within a factor of 2. Column loadings of 5 to 10% of the resin capacity gave good results, and problems with band overlap were significantly greater at higher loadings. The resin must be uniformly packed into the column, and this can be achieved by loading the resin from a slurry with forced flow so that the flow velocity is substantially greater than the resin settling velocity. It is important that the column be free of acid before the elution

(sometimes appreciable amounts of acid are present in the feed, and this loads on the column) because H^+ ion will interact with the eluent, reducing the pH to an undesirably low value during the early part of the elution.

For processing batches containing higher radiation levels there is benefit to using a separate "loading" column, a short column usually of larger diameter, that is used to load actinides from the feed. After loading, which can be carried out at a very high flow rate to reduce radiation damage, the column is washed with dilute NH_4NO_3 solution to remove H^+ ion, and then valved to the top of the long elution column. This way, most of the resin (which is in the elution column) is not exposed to impurities in the feed.

Band tailing is a problem in some of these separations because of the extreme variation in the amounts of different elements present. This is indicated by the elution curves for Es and Cm in Fig. 1. It is possible to follow these elements over concentration ranges of about 10^6 , and it is characteristic that each band tails to the right (that is, into the volume following the elution peak) at a concentration gradually decreasing from about 10^3 to 10^5 times smaller than the peak. The band tails contribute some degree of impurity to all succeeding bands; thus, in this system, lighter elements are contaminated to some extent by any heavier element present, since the elution order is heavy actinide to light. In fact, there is a curium tail across the entire elution because a large amount of curium had been eluted in the run with this column previous to the run shown.

The practical significance of this is that bands following each element will be decontaminated with respect to that element by a factor like 10^4 or 10^5 , whereas bands preceding can be very highly decontaminated, at least if a new column

is used. Of course, further decontamination can be achieved by repeated cycles. Since the amount of each element usually increases as the atomic number decreases, the problem is limited somewhat. There are exceptions to this, however, such as the recovery of ^{248}Cm daughter from ^{252}Cf . When extreme purity is required, in such cases, the best solution is to utilize a different chemical system in which the elution order is reversed. This can be accomplished with extraction chromatographic systems as discussed below.

Production Separations

Because of its promise, the pressurized ion exchange approach was applied immediately to transcurium element production at TRU, and Fig. 2 indicates the sort of separation that was obtained. This shows the relative alpha count rate given by an in-line detector, and it demonstrates good separation of Fm, Es, Cf, and Cm. Berkelium is also well separated, appearing between Cf and Cm, but it is not shown because it is not an alpha-emitter.

Typical "plant" equipment is shown in Fig. 3. The equipment racks are assembled and tested before being installed in hot cells. This rack, which served for some five years, has one high pressure pump, a short "loading" column, two long elution columns, and appropriate associated valves, feed vessels, product collection apparatus, and plumbing. Resin was periodically replaced by hydraulic transfer.

These columns were 120 cm long and were made from 3/8- and 1/2-in.-OD stainless steel tubing, although diameters up to 1.5 cm have been used. These columns contain 50 and 105 ml of resin, respectively. The resin is graded into size ranges such as 25-50 or 70-100 μm diameter, the size selected depending on the application. Flow velocities are typically 15 cm min^{-1} for loading (they can

be much higher if necessary) and 12 cm min^{-1} for elution. Full-scale separations of transcurium elements normally take less than 2 h; and second cycle purification of individual elements and separations of two elements require less than one hour. These methods are entirely adequate for all present and planned production requirements.

Elution development is used at TRU because the preliminary partial separation (LiCl anion exchange) yields a fraction containing all the transcurium elements along with only a small fraction of the Am, Cm, and rare earths. The total amount of trivalent elements to be processed in one run is generally not more than a few tenths of a gram. For large-scale separations (100 g or more) displacement development is the method of choice, and this has been pursued at Savannah River Laboratory. In the range in between, the choice is less clear.

Burney and Harbour²⁴ demonstrated elution development separations with 35 g of Am plus Cm along with 1 mg of Cf. This work used a column 5.1 cm in diameter by 122 cm long and a flow rate of 8 cm min^{-1} ; the maximum loading was about 10% of the resin capacity, but better band separation was obtained with lower loadings. It is significant that elution development can be used for this scale of work, and it is doubtful that separations of such quantities would even be attempted without pressurized ion exchange.

The time average throughput for elution development with a pressurized ion exchange system is high, probably comparable to that with displacement development; and it should be practical to use this method for larger scale separations. In particular, for separating larger quantities of short-lived alpha-emitters (such as ²⁴²Cm or Cf) elution development is superior, in principal, because the

relatively high velocity of the elution bands and the low concentration of the elements in the bands (compared to displacement development) diminishes the radiation damage effects.

Displacement Development

Larger-scale separations of americium and curium are based on the pioneering work of Wheelwright and coworkers¹⁹ and the very large scale use of displacement development for commercial rare earth separations. Application of pressurized ion exchange to displacement development for transplutonium element separations has been pursued at Savannah River Laboratory by Hale, Lowe, and co-workers,^{25,26} and the work was reviewed in 1972.²⁷ In general, the same benefits are applicable for processing highly radioactive materials as was the case for elution development.

The shapes of elution curves are quite different than for elution development (Fig. 4). With displacement development the metal complexes are eluted at essentially a constant concentration (determined by the concentration of complexing agent and the pH), and the different elements are eluted sequentially one after the other. There are overlap regions between the bands, analogous to the edges of the peaks in elution development; but the concentrations in the overlap regions (and the amount of metal contained in them) are much larger. Thus, there is strong incentive to diminish the relative length of these regions. If only a small amount of an element is present there may be no reasonably pure product; rather, it will all occur in association with neighboring elements. Band overlap is an inherent characteristic of this method, in contrast to elution development.

It is common practice to use several columns in series, with the diameter decreasing sequentially, for example, 122 cm long columns successively 10, 7.5, 5, and 2.5 cm in diameter. Since the bands are longer in the smaller diameter column the overlap region becomes relatively smaller, and a larger fraction of the product is obtained in pure form. An elution curve for such a system is shown in Fig. 4. Usually 30 to 40% of the resin in the largest column is loaded with the mixture to be separated (or about 20% of the total resin); this is at least twice the loading that gives good results with elution development.

One problem with this system is that Cf and heavier actinides are not retained by Zn^{2+} , which is the usual barrier ion; these heavy actinides run ahead into the large volume of Zn-DTPA solution that precedes the products. This result is an excellent separation from Cm, but a rather messy recovery operation because of the large volume of solution from which the actinides must be recovered. This problem can be overcome by using different barrier ions, such as Ni^{2+} , but then the heavy actinides are found in the leading part of the Cm band. Elution development chromatography can be used in a subsequent cycle to separate the heavier actinides from each other and from Cm since the bulk of the Cm, Am, and rare earths are removed at that point.

For separations involving large amounts of Am, Cm, or rare earths, displacement development provides a satisfactory first cycle separation and yields a feed suitable for final separation by elution development. However, alternative methods for the first cycle (removal of the bulk of the lighter actinides and rare earths) are available; besides displacement development chromatography, these include solvent extraction and the LiCl-anion exchange system. The

latter system is used at TRU, while the SRL development program demonstrated the suitability of displacement chromatography. Both methods appear to be satisfactory, and the choice will depend on the particular constraints for each problem. As mentioned before, solvent extraction led to substantial operational problems at both ORNL and SRL.

Until now, and for the foreseeable future, the quantity of transcurium elements has been too small to justify any separation process other than elution development. Thus, elution development, probably with alpha-hydroxisobutyrate, will continue to be used for purification and concentration of those elements, following their enrichment in the first cycle fractionation. For americium and curium, the choice will depend on the amount to be processed, with displacement chromatography favored for larger-scale operations.

With displacement development there is an intermixing of the heavy rare earth fission products (above gadolinium) and the transplutonium elements. Wheelwright demonstrated that Am and Cm can be separated from the rare earths by using different complexing agents in successive cycles, namely DTPA and NTA.¹⁹ The elution order is shifted somewhat for the two complexing agents, so that elements that interfere with Am or Cm when one complexing agent is used do not interfere when the other is used. In this way, quite pure products were obtained.

Kelly investigated a modification of the process to separate 1.7 kg of Am and 0.7 kg of Cm (a mixture containing 20 g of ²⁴²Cm) from 167 moles of fission product lanthanides.²⁸ This material probably had the highest decay energy of any material to be processed on that large a scale. To prevent boiling because of heat generation from radioactive decay in the curium band, it was necessary

to operate with unusually high flow rates. The last column in the series, with the smallest diameter, has the greatest problem from heat generation because the curium band is longest there; it was necessary to elute this column with a flow velocity of 32 cm min^{-1} . Full-scale separations were demonstrated using heavy rare earth standins for Am and Cm, but the system was not operated with the actinides. However, this points the direction for separations of larger amounts of actinides more radioactive than those processed so far.

One possible application in which large amounts of rare earths and actinides would be processed occurs in some schemes for nuclear waste management. If it should prove to be advantageous to remove transplutonium elements from nuclear waste, for example, the recovery of Am and Cm from the much larger amounts of rare earths would be required. This problem has been investigated by the author in tracer tests with rare earth mixtures typical of fission products, using a heavy rare earth such as holmium as a standin for Am and Cm (Fig. 5). It is clear that the bulk of the holmium can be recovered in reasonable purity but that a substantial recycle fraction containing Gd, Eu, and some Sm would be produced. However, the major bulk of the lighter rare earths is effectively separated from the very small amount of heavy rare earths, Am, and Cm. This figure again shows the low level band tailing that is typical of all such processes.

Extraction Chromatography

There are some applications for which different chemical systems are advantageous, and the choice with ion exchange resins is rather limited. Extraction chromatography offers a wide range of possible systems, and as mentioned before, the elution order can be changed and even reversed. Baybarz

and Knauer applied the pressurized ion exchange method to this technique for separating ^{248}Cm from ^{252}Cf parent.²⁹ With the alpha-hydroxyisobutyrate ion exchange system the Cm is contaminated by the tail from Cf, which elutes earlier; and extremely high purity ^{248}Cm is desired. Extraction chromatography using di(2-ethylhexyl)orthophosphoric acid on a porous glass support as the fixed phase and nitric acid as the mobile phase gave excellent purity of the ^{248}Cm product; DFs greater than 10^{10} were obtained after two purification cycles. The high DF is directly attributable to the reversal of elution order.

Horwitz and co-workers investigated very rapid separations of tracer actinides using small extraction chromatographic columns, with the goal being separation of very short-lived products of nuclear reactions.³⁰ They demonstrated separations of Am and Cm or Bk and Cf into pure fractions in one or a few minutes. However, it is not clear that extraction chromatography is inherently superior to ion exchange in this respect, since small column ion exchange experiments with rare earths also suggest that separations can be obtained in about one minute.³¹ Experimental studies have not yet really established the limit of the tradeoff between resolution and speed of separation, or the time (rather than the height) of an equivalent theoretical plate.

Schadel, Trautmann, and Hermann compared the HDEHP extraction chromatography system to ion exchange elution development for rare earth separations,³² and found the two methods to be about equally effective under optimum conditions. From their data for separating seven rare earths plus yttrium, they projected that all the rare earths could be separated in about 20 minutes. However, they did not include in their study those pairs most difficult to separate.

This problem, the simultaneous separation of all the rare earths, is of recurring interest. Campbell accomplished the separation with multi-mg quantities of each element (except tracer Pm) in about 1.5 hours using ion exchange chromatography.²² Subsequently, Qaim and co-workers carried out similar studies at greater column loadings.³³ They showed that the height of an equivalent theoretical plate decreased sharply with larger column loadings in the case of the light rare earths, but there was little effect with the heavy members. It appears that such separations can generally be carried out in times of the order of an hour using either extraction chromatography or elution development ion exchange.

It must be recognized that extraction chromatography is clearly superior to ion exchange in terms of the choice of exchange properties, because of the wide range of organic extractants that can be used, compared to the limited types of ion exchange resins. The radiation damage problem may be somewhat less severe for extraction chromatography. However, the incentive for maximum speed of separation in these problems requires the same pressurized chromatography approach, using very small support particles. It has been adequately shown that performance in pressurized systems with very high flow rates is satisfactory with several useful extractants; in particular, with properly prepared columns, there has been no problem from sweeping the extractant off its support.

Future Developments

Both production of and demand for transplutonium elements are relatively stable, and pressurized ion exchange processes that have been used for several years are entirely satisfactory for these requirements. Three general areas can be visualized which could require extension of these methods. These are: (1) tracer-scale separations in the shortest possible time for very short-lived isotopes in nuclear research; (2) separations similar to those utilized now, but on a much larger scale, perhaps because of radioactive waste processing or

production of heat sources; and (3) separations on a larger scale of such moderately short-lived isotopes as ^{242}Cm or ^{252}Cf .

For all three areas the direction is already well established. Techniques that have been studied would be refined and optimized for the particular problem. Pressurized ion exchange in its present state of development permits successful processing of materials 10 to 100 times more radioactive than does conventional ion exchange chromatography. It is not clear what the ultimate limits may be, but a significant extension of present technology is clearly available if the need arises.

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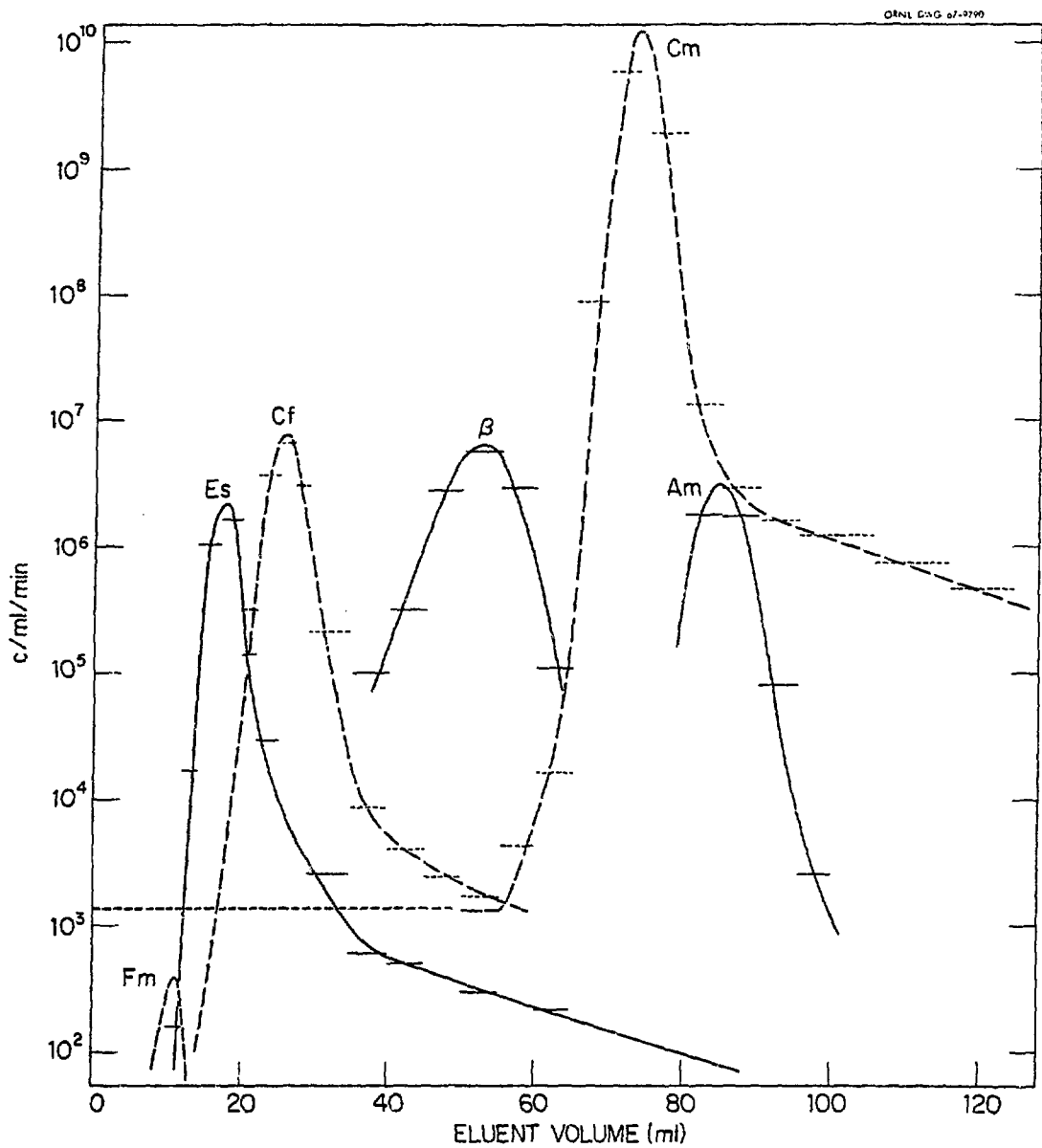


Fig. 1. Separation of transplutonium elements with alpha-hydroxyisobutyrate vs 20-40 μm Dowex 50-X12 resin; 2 ml min^{-1} ; $0.32 \times 66 \text{ cm}$ column.

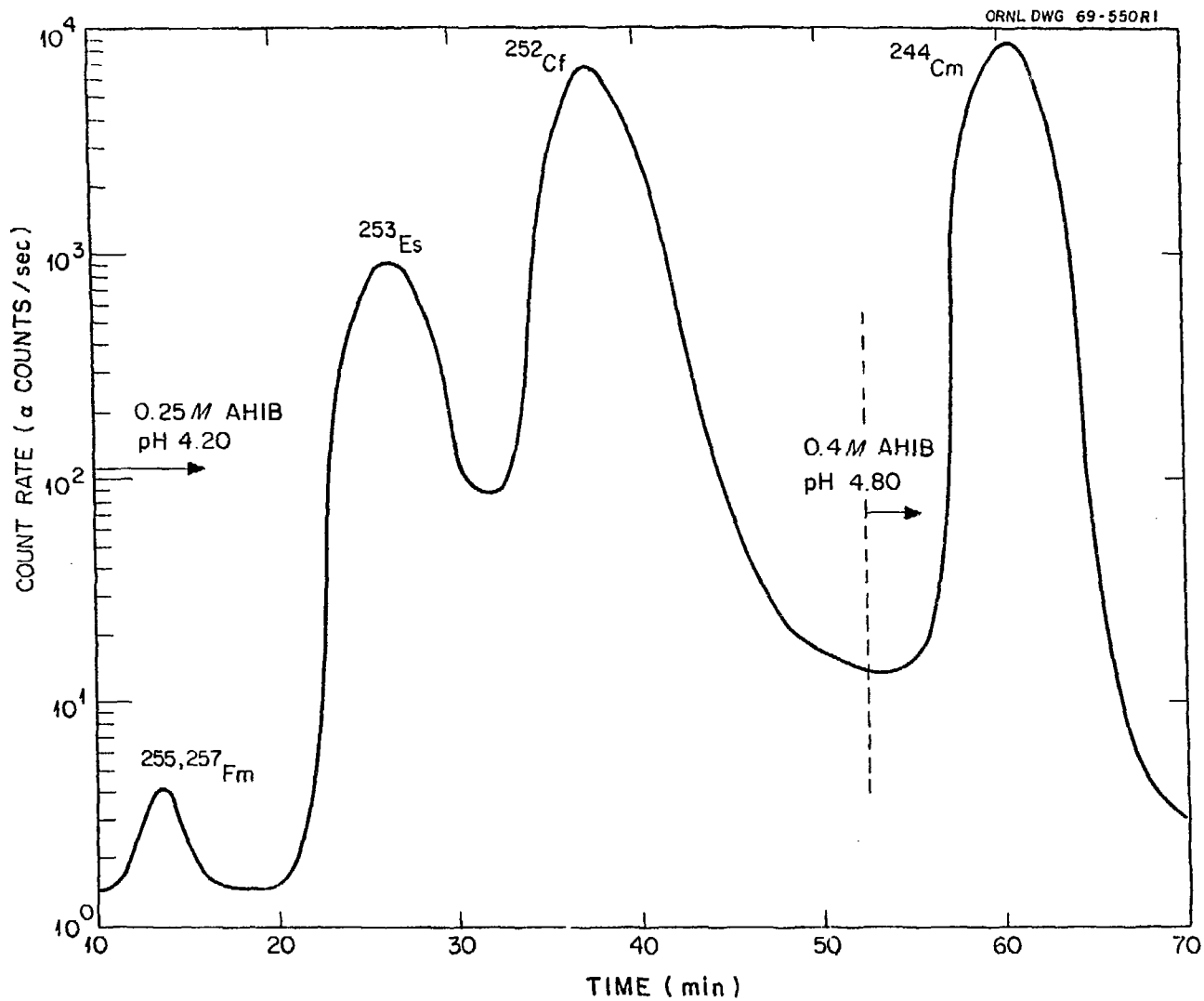
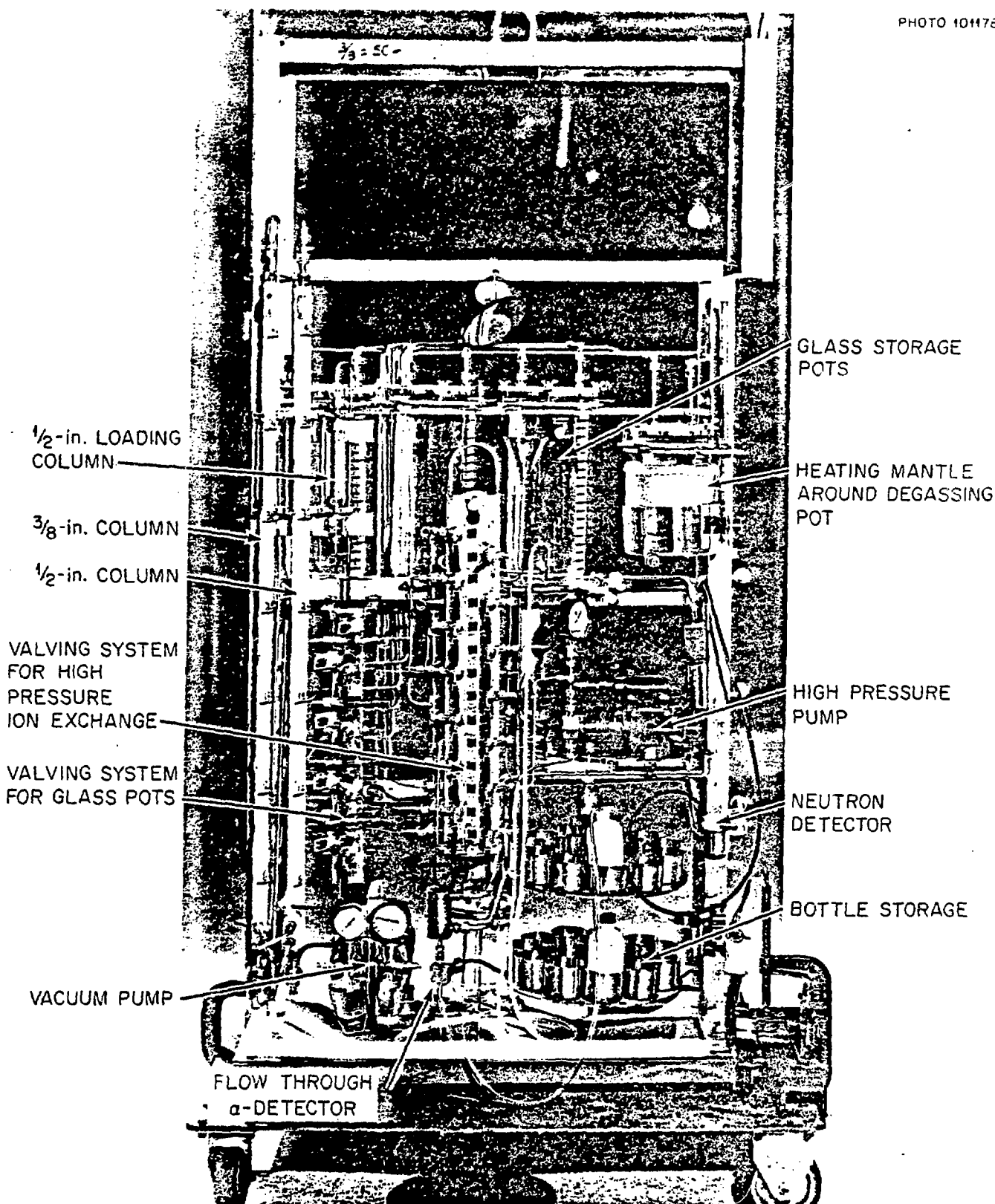


Fig. 2. Production separation of transplutonium elements in TRU facility; 25-50 μ m Dowex 50-X8 resin, 5 ml min⁻¹, 0.77 x 122 cm column.

PHOTO 10M73A



1/2-in. LOADING COLUMN
3/8-in. COLUMN
1/2-in. COLUMN

VALVING SYSTEM FOR HIGH PRESSURE ION EXCHANGE
VALVING SYSTEM FOR GLASS POTS

VACUUM PUMP

FLOW THROUGH α-DETECTOR

GLASS STORAGE POTS
HEATING MANTLE AROUND DEGASSING POT

HIGH PRESSURE PUMP

NEUTRON DETECTOR

BOTTLE STORAGE

Fig. 3. Pressurized ion exchange equipment rack used for transplutonium element separations in TRU facility.

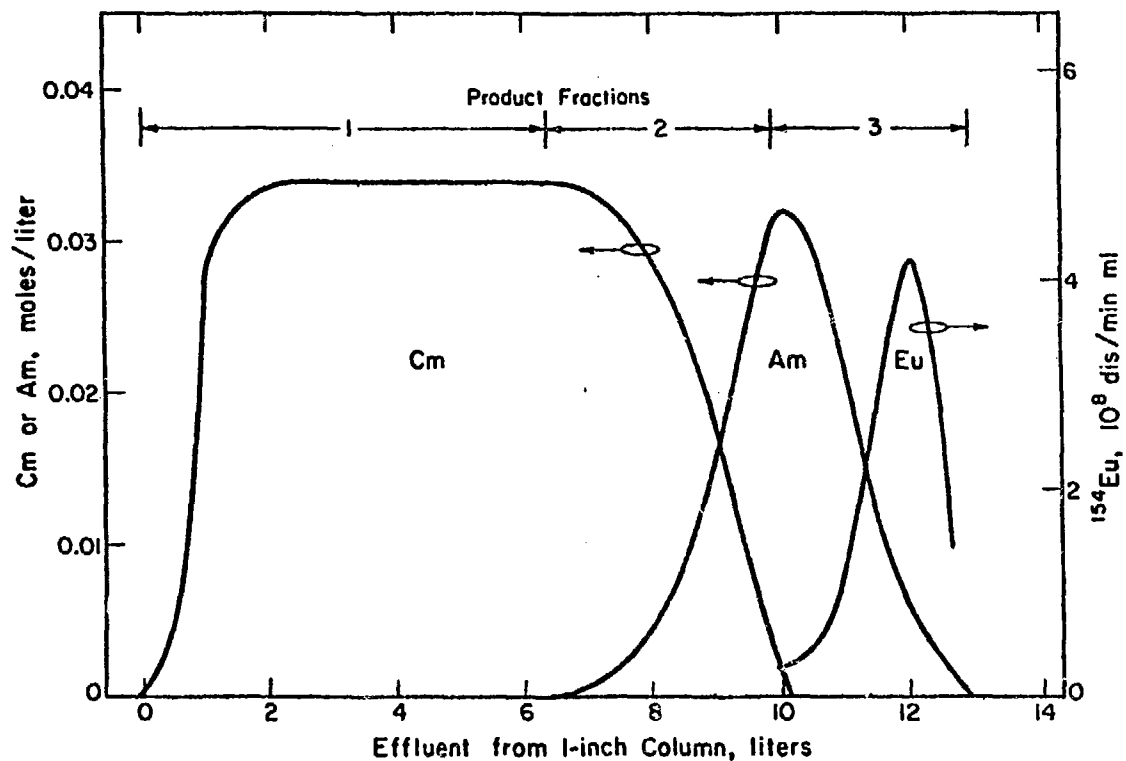


Fig. 4. Typical elution curves for displacement development separation of transplutonium elements using DTPA and four columns in series, 122 cm long x 10, 7.5, 5, and 2.5 cm diameter.

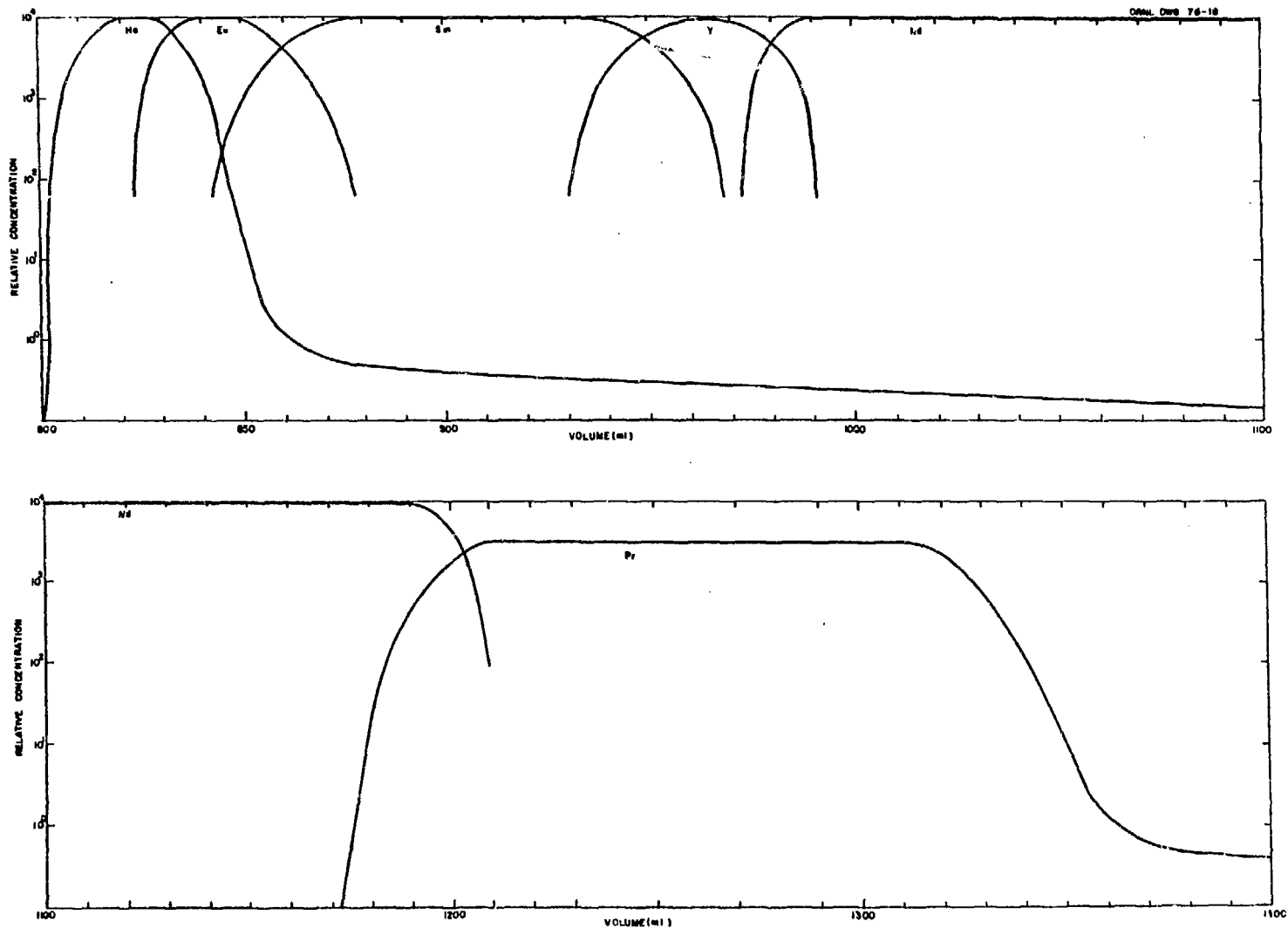


Fig. 5. Laboratory separation of holmium (stand-in for Am and Cm) from rare earths representative of irradiated light water reactor fuel using displacement development with DTPA.