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AN EVALUATION OF FOUR PROCESSES FOR
RECOVERING URANIUM FROM ZIRCONIUM FUELS
AT THE IDAHO CHEMICAL PROCESSING PLANT

P. Burn

PHILLIPS
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ATOMIC ENERGY DIVISION

NATIONAL REACTOR TESTING STATION
US ATOMIC ENERGY COMMISSION

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U. S. ATOMIC ENERGY COMMISSION

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A B S T R A C T

Four zirconium fuel processes -- the present STR process, the modified Zirflex process, the barium fluozirconate process, and the sodium formate process -- were evaluated in detail for technical and economic feasibility. The evaluation was based on installation as the second generation Idaho Chemical Processing Plant zirconium process. Two non-aqueous processes, the ARCO and the fused salt fluoride volatility processes, were included in a preliminary evaluation, but were eliminated on the basis that major problems inherent in the processes have not yet been solved. A continuous version of the STR process was concluded to be the leading contender for immediate plant application.

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SUMMARY

An expansion of the zirconium fuel processing capacity of the Idaho Chemical Processing Plant is currently under consideration. Several processes have been or are being developed for processing zirconium fuels, and selection of the particular process to be used in the new installation is of primary importance. Six processes were selected for preliminary evaluation: the present STR process, the barium fluozirconate process, the sodium formate process, the Zirflex process, the ARCO process, and the fused salt fluoride volatility process. The first four processes are aqueous, the last two are non-aqueous.

The two non-aqueous processes were eliminated from further consideration; both processes have inherent process weaknesses that have not been overcome in the development work so far completed. The future potential of these processes was not evaluated in detail, but both of them appear promising.

The feasibility of the aqueous processes has been fairly well established, although additional development work is necessary to complete the process data and to provide solutions to some of the still unresolved operating problems. The amount of such development work required varies among the four processes, but is least for a modification of the present STR process.

Economic evaluations of the four aqueous processes were made for processing capacities of five and ten kilograms of uranium per day from 40 per cent burned-up PWR seed fuel elements. The results of these evaluations are summarized in the following table.

FIVE KILOGRAMS OF URANIUM PER DAY INSTALLATIONS

<u>Process</u>	<u>Investment Required</u>	<u>Processing Cost</u>	
		<u>Per Gram of Uranium *</u>	<u>Investment Recovery Kilograms of Uranium**</u>
STR	\$ 355,000	\$2.79	185
Barium Fluozirconate	1,270,000	2.33	535
Sodium Formate ***	1,270,000	2.33	535
Modified Zirflex	1,510,000	2.04	570

TEN KILOGRAMS OF URANIUM PER DAY INSTALLATIONS

<u>Process</u>	<u>Investment Required</u>	<u>Processing Cost</u>	
		<u>Per Gram of Uranium *</u>	<u>Investment Recovery Kilograms of Uranium**</u>
STR	\$ 450,000	\$1.97	165
Barium Fluozirconate	1,430,000	1.40	435
Sodium Formate ***	1,430,000	1.40	435
Modified Zirflex	2,220,000	1.23	640

* Direct cost plus depreciation for dissolution and first cycle extraction. Does not include final purification of uranium or indirect cost allocations. The comparable cost for the presently installed zirconium fuels process is \$4.70 per gram of uranium.

** Kilograms of uranium that must be processed to recover the investment by savings resulting from the reduction in the comparable cost of \$4.70 per gram of uranium processed through the present system.

*** Sodium formate process investments and processing costs have been tentatively estimated to be comparable to those for the barium fluozirconate process.

The STR process requires the least investment of the four processes, but has the highest operating cost. It is apparent that a selection of the optimum process on an economic basis will require complete knowledge of the schedule of fuel to be processed, information not currently available.

The STR process is definitely preferable on the basis of minimum development time required. The development work done to support the design of the original ICPP installation, and the knowledge gained during operation of this system, put this process at least a year ahead of the other aqueous processes. It is estimated that an expanded STR process could be installed in about eighteen months after project approval.

A compromise installation appears to be attractive if a process selection is necessary in the immediate future. As a compromise, a continuous STR dissolver could be installed that would serve for any of the processes. Furthermore, sufficient cell space could be left to permit the subsequent installation of the process auxiliaries, centrifuges, vessels, etc., required by the more intricate processes, should one of these processes be proved preferable.

I. INTRODUCTION

Zirconium fuel processing at the Idaho Chemical Processing Plant (ICPP) is carried out in a system with a limited capacity and, consequently, incurs high processing costs. ICPP operating schedules indicate that within the next three or four years the operating time that can be allotted to zirconium fuels will not be sufficient to process the scheduled quantities in the present equipment. Furthermore, the limited life expectancy of the present dissolver demands that a decision be made in the immediate future pertaining to its replacement. This decision must be between mere replacement of the original dissolver or extensive equipment changes to permit use of a different and more advanced process.

The existing ICPP zirconium fuels reprocessing system, the "STR" process, was selected on the basis of the best information then available^(1, 13). Since that time, various laboratory and pilot plant programs have been instituted at a number of AEC sites with the objective of developing new and improved zirconium fuel reprocessing methods (27). The selection of the second generation zirconium process for the ICPP is, therefore, at least as complex a decision as was selection of the first process. The STR process has been demonstrated to be operable on a plant scale, the uranium recovery and decontamination have been excellent, and the operating problems have been surmountable. This process must, therefore, be considered still in contention for the second generation installation. The STR process does have serious inherent deficiencies, however, and one or more of the newer processes may possess sufficient process advantages to overshadow the proved performance of the STR process.

This report is intended as a guide to the selection of the second generation ICPP zirconium process. A considerable volume of literature exists on the various zirconium processes under development, but lack of a common basis permits direct comparison of only a tiny fraction of this literature. In this report, each process is measured with the same yardstick, i.e., the suitability of the process as an ICPP installation. The comparisons and conclusions are, therefore, specific, and only by chance would be directly applicable to any other installation.

The economic comparisons of the various processes must be based on a specific zirconium-uranium fuel, since zirconium-uranium fuels vary widely in size, weight and composition, and these factors would affect processing costs for each of the headends to a different degree. The PWR seed core No. 1 fuel was chosen as the basis because its specifications are well known, and there will be a fairly large and steady supply of this fuel to be processed. Each PWR seed subassembly contains 36 kilograms of zirconium, 558 grams of tin, and 431 grams of

total uranium, after 40 per cent burnup (2). The uranium content of a subassembly before burnup is 620 grams of 93 per cent enrichment. The average burnup (defined as the disappearance of the original uranium-235 by combined fission and capture) has been estimated to be 40 per cent.

The selection of the processing rate required for the second generation ICPP zirconium fuel processing system will require more data than are now available. The quantity of zirconium fuel to be reprocessed at the ICPP is scheduled to rise abruptly in the near future, but the future delivery schedules are expressed in terms of "kilograms of uranium, after burnup", not in specific numbers of particular fuel elements. This method of expressing fuel receipts is unfortunate, because two batches of different zirconium fuel element types may have equal uranium contents, after burnup, but have a several-fold difference in their zirconium contents. An ICPP zirconium fuel processing capacity equivalent to between 5 and 10 kilograms of uranium per day from 40 per cent burnup PWR seed elements would appear to be adequate for the next several years. Since the determination of a precise figure would require much more detailed data than are now available, theoretical rates of both 5 and 10 kilograms of uranium per day have been used.

The bases employed in this study, as in any similar study, necessarily contain a certain degree of arbitrariness. Since this report is intended as a preliminary screening, the bases were generally selected so as to preclude the possibility of premature elimination of a valid contender. As the selection process moves on, the field must be narrowed and the development programs adjusted to fill the data gaps in a smaller number of processes.

II. THE PRESENT STR PROCESS

The zirconium fuel process now installed at the ICPP was developed by the Argonne National Laboratory for reprocessing the zirconium Submarine Thermal Reactor fuels (1,13). It has become known as the STR process, and is the only one that has actually been used to reprocess zirconium fuels on a plant scale (14,32).

The present STR process system includes the dissolution, feed adjustment, and first extraction cycle operations. The product from the STR system enters the main ICPP process stream as feed to the second extraction cycle (19). The process flowsheet for the STR system is shown in Appendix I, Figure 1.

The principal distinguishing feature of the STR process is use of 7.42 molar aqueous hydrofluoric acid for dissolution of the fuel elements. The dissolver product is chemically complexed with aluminum nitrate, and additional HF is added to produce the necessary fluoride-to-zirconium ratio in the extraction column feed. The uranium is extracted from the adjusted dissolver solution with 10 per cent tributyl phosphate (TBP) in diluent kerosene (Amsco 125-90W). The dissolver off-gas is primarily hydrogen in rather large quantity (18 standard cubic feet per kilogram of zirconium). Minor quantities of nitrogen oxides may be evolved during the addition of nitric acid at the end of each dissolution cycle. The dissolver is purged with nitrogen to prevent a hydrogen explosion. Immediately downstream from the dissolver, the off-gas is diluted with sufficient air to reduce the hydrogen content to below the lower explosive limit.

The STR dissolver is made of Monel to withstand the aqueous HF. The addition of dilute nitric acid at the end of each batch, used to dissolve the uranium and tin, causes significant, but not intolerable, dissolver corrosion. The coarse feed adjustment tank and the charging water storage tank are made of Carpenter-20 to withstand dilute HF. Since these vessels are exposed to oxidizing agents for much longer periods than the dissolver, the resultant attack on Monel would be intolerable. The remaining process equipment is made of type 304L or type 347 stainless steel. Once the aluminum nitrate complexing agent has been added to the dissolver products, the corrosion rate for stainless steel equipment is negligible.

The waste from the first extraction cycle, containing the zirconium, tin, fission products, fluoride, and aluminum nitrate, is stored in underground tanks. A battery of small (30,000 gallon) type 316L storage tanks was installed as part of the original STR process. Recent corrosion data from in-tank specimens and from laboratory studies indicate that STR wastes can be blended with aluminum fuel wastes and stored in the large (300,000 gallon) type 304L main plant waste tanks (3, 12). Mixing of the wastes would result in more economical storage of the STR wastes, but the available supply of aluminum fuel waste feed material

for the Demonstrational Waste Calcination Facility (DWCF) would be reduced. For every two gallons of STR wastes stored in the large tanks, up to one gallon of aluminum fuel wastes that could otherwise have been calcined might have to be stored indefinitely. The calcination of fluoride-bearing wastes is under study, but has not yet been demonstrated.

The major advantages of the STR process are proved operability on a plant scale, high uranium recovery (about 99.7 per cent), high uranium decontamination factor (about 10^4 in the first cycle); extremely rapid dissolution rates, and relatively low corrosion rates throughout the process equipment (27).

There are several major disadvantages of the STR process. The waste volume is large, i.e., from 4.8 to 5.8 gallons for each kilogram of zirconium metal processed (18). The dissolution and feed adjustment procedures skirt regions of chemical instability, necessitating close process control. The near approach to regions of instability is also a serious hindrance to the adaptation of the process to fuels of higher uranium content. The possibility of precipitate formation limits the batch size to 800 grams of uranium-235 in the dissolver and the feed adjustment system to maintain criticality control. The relatively low solubility of UF_4 limits the process to fuel elements containing not more than 2 weight per cent uranium, unless oxidizing agents are added to the system. Oxidizers, such as nitric acid or hydrogen peroxide which convert the uranium to the more soluble hexavalent state, permit an increase in the allowable uranium content of the fuel, but the dissolver corrosion rates are sharply increased by the oxidizer addition (18). For fuel of more than 3 weight per cent uranium, the amount of oxidizer needed would cause intolerable corrosion rates. It is possible to process fuel containing up to 2.2 weight per cent uranium without the use of oxidizers, by using a dilute flowsheet, but a significant increase in the waste volume would result (18).

The capacity of the STR system is dependent upon several parameters. First, the batch dissolver is limited to three batches per day. The time required for fuel charging, transfer of charging water, addition and heating of reagents and diluents, dissolution of the elements, oxidation of uranium and tin, cooling, transfer, washing, and analysis makes 8 hours a minimum period to complete a batch dissolution. Second, criticality controls limit the amount of uranium-235 in each batch to not more than 800 grams. Since fuel pieces do not normally contain exactly 800 grams of uranium-235, the actual charge per batch will average somewhat less than 800 grams of uranium-235. Third, the extraction system has a throughput limitation of 180 kilograms of zirconium per day. If the fuel being processed contains less than about 1.4 weight per cent uranium, the extraction capacity becomes the limiting factor in the processing of zirconium fuels.

In addition to the capacity limitations of the STR process, there is an additional limit on the number of days the process may be operated each year. A maximum of 60 days per year is currently estimated to be available for processing zirconium fuels. It would be possible to process zirconium and aluminum fuels simultaneously, in the different head-ends, but the present plant staff is not large enough to do so, and it would not be feasible to increase the staff unless a greatly expanded zirconium fuel processing load could be guaranteed. Within the limitations of the present staff, equipment, and fuel processing schedules, the present STR process has an annual capacity of about 2.25 PWR seed cores.

The remaining useful life of the present STR dissolver is estimated to be capable of processing the equivalent of ten PWR seed cores (23). This estimate is based on corrosion specimens that were in the dissolver during the first two runs. If fuel containing over 2 weight per cent uranium is processed by the addition of oxidizing agents, this life expectancy would be shortened considerably. In either case, sometime in the not too distant future, it will be necessary to revamp the STR system at least to the extent of replacing the present dissolver.

III. ECONOMICS OF THE PRESENT STR PROCESS

A. Plant Investment

The STR zirconium fuel processing system was installed at the ICPP during 1954 and 1955. The installation, in and around two existing cells, cost approximately \$2,300,000, including design, overhead, and contractor fees(29). The waste storage system investment is not included in this figure, since it is standard practice at the ICPP to charge for waste tankage as it is filled. The STR waste storage system cost \$4.80 per gallon, compared to \$2.01 for the aluminum fuel waste storage tanks. The differential reflects the cost of using small, heavy-walled, type 316L stainless steel tanks, compared to large, thin-walled, type 304L stainless steel tanks. Because of this cost differential, the fact that the small tanks are over half full, and the knowledge that STR wastes can be stored in the large tanks if they are blended with aluminum fuel wastes, it is planned to store all future STR wastes in the large tanks. In this report, all future STR processing costs have assumed the use of \$2.01 per gallon waste storage facilities.

B. Depreciation Charges

The depreciation charges for the ICPP buildings and process equipment are based on estimated life expectancies of these items. The depreciation charges have been unitized so that any fuel being processed is charged depreciation only for that part of the ICPP actually used in its processing. The depreciation charge for zirconium fuels processed in the present STR system is \$1205 per operating day.

C. Waste Storage Costs

The present STR process produces 5.26 gallons of waste for each kilogram of zirconium dissolved. At a storage cost of \$2.01 per gallon, waste storage would cost \$10.60 per kilogram of zirconium processed.

D. Direct Operating Costs

The direct operating costs at the ICPP include labor, process chemicals, materials and supplies, utilities, and similar miscellaneous items. The direct cost is essentially calculated on a "battery limits" basis, with all administrative personnel, guards, janitors, etc., directly assigned to the ICPP included in the direct operating cost. The direct operating cost of the ICPP is charged against the fuel being processed.

The present operating staff of the ICPP is shown in Appendix III. Salaries, wages, and fringe benefits for the 169 people listed represent a cost of \$4,981 per day. This cost does not vary with the fuel type or quantity (at the present ICPP capacity) being processed.

The process chemicals cost is directly affected by the type and quantity of fuel being processed. For the STR process, this cost is \$2.35 per kilogram of zirconium processed.

The other direct costs are basically those incurred in keeping the ICPP operating, and are relatively independent of the type and quantity of fuel being processed. Past ICPP experience has indicated that these miscellaneous direct costs will average about \$1600 per day.

E. Overall Operating Costs

The overall operating cost of fuel reprocessing at the ICPP is the sum of the fixed costs and the variable costs that are affected by the type and quantity of fuel being processed. If two PWR subassemblies were charged per dissolver batch, two and a half batches per day would yield 180 kilograms of zirconium per day, the capacity of the extraction system. The corresponding uranium throughput would be 2.15 kilograms per day. This capacity is, of course, specific to this particular fuel and the uranium capacity of the STR process for any other zirconium fuel could be greater or less, depending on the fuel composition.

The overall operating cost for reprocessing PWR seed elements at the maximum capacity of the STR process (5 subassemblies per day) would be \$10,119 per day. This cost is \$4.70 per gram of uranium processed (after burnup basis), or \$56.20 per kilogram of zirconium.

F. Indirect Costs

In addition to the overall operating cost, certain indirect costs are charged to the fuel being processed. These costs, incurred in the operation of a multiple-area site, arise from several sources outside the immediate plant area. They include bus transportation, site security, site administration and personnel, area health physics, site maintenance and utilities, and the Idaho Operations Office of the AEC. The indirect costs are prorated to the various operations at the NRTS on the basis of the direct costs that each incurs. The amount allocated to the ICPP varies directly each month with the total site indirect costs and with the relative proportion of the total site direct costs incurred at the ICPP. The allocation is normally from \$0.30 to \$0.35 for each dollar of direct costs. Because of the fluctuations in the indirect cost charges, they have not been included in the processing costs presented in this report. The indirect cost allocations would apply as an essentially equal percentage surcharge on each of the direct operating costs listed.

IV. STR PROCESS EXPANSION

A. Description of the Process

Expansion of the STR process to a capacity of either 5 or 10 kilograms of uranium per day (11.6 or 23.2 PWR subassemblies) would require an increase in both dissolution and first extraction cycle capacities. No changes are required in the second and third extraction cycles, since their processing capacity is presently in excess of 10 kilograms of uranium per day.

A new batch dissolver with its auxiliary equipment would have to be added to attain a capacity of five kilograms of uranium per day. The present STR dissolver cell (E cell) does not have sufficient available space to house an additional dissolver, but there is space available in either of the adjacent cells (D or F). The increased extraction capacity required in the first extraction cycle can be achieved by replacing the existing plate cartridge sections of the columns with larger diameter units; the present column heads are sufficiently large.

To recover 10 kilograms of uranium per day with batch dissolution would require four batch dissolvers (three new, plus the existing one). Both the construction and operating costs for four batch dissolvers would be much higher than for a continuous dissolver of equal capacity. Consequently, continuous dissolution is preferred. The chemistry of hydrofluoric acid dissolution of zirconium is well known; however, a pilot plant-scale development program will be necessary to complete the equipment development and evaluate materials of construction for a continuous dissolution process. Avoidance of zones of high corrosion rates in the equipment and avoidance of areas of chemical instability are expected to be the major design and operational problems encountered. Corrosion rates in a continuous dissolver may be high because it may be necessary to add an oxidizing agent, such as nitric acid or hydrogen peroxide, to the HF dissolvent to prevent the formation and buildup of a UF_4 precipitate in the process. The dissolver would be exposed to the oxidizer-HF mixture continuously during operation rather than during only a small part of the dissolution cycle, as is the case with a batch dissolver. The work on continuous zirconium dissolution now in progress at the ICPP has not yet produced any firm recommendations on materials of construction or on allowable operating conditions (24). In the absence of such data, it is necessary to assume that a continuous dissolver made from Monel or some similar material would have to be replaced frequently because of corrosion damage.

The required increase of first extraction cycle capacity for a 10 kilogram per day process could be obtained either by replacing the existing STR columns or by minor modifications of the large columns in the aluminum fuel first cycle TBP extraction system. The necessity for new intercell transfer lines in the second case makes the two alternatives a standoff economically. The selection between these alternatives has not been made.

B. New Plant Investment

Installation of the new dissolver system and the revisions to the extraction system necessary to achieve a processing capacity of 5 kilograms of uranium per day are estimated to cost \$344,000. Details of the new investment estimate are shown in Appendix II, Table 1. The process flowsheet for the 5 kilograms of uranium per day process is shown in Appendix 1, Figure 2.

Installation of a continuous dissolver and modification of the extraction system that are necessary for a processing capacity of 10 kilograms of uranium per day are estimated to cost \$449,000. Details of the investment estimate are shown in Appendix II, Table 1, and the process flowsheet is shown in Appendix I, Figure 3. The estimated investment is based on the use of Monel or Carpenter-20 for the dissolver, and does not include the costs incurred in development of the system.

C. Depreciation Charges

The expanded STR facilities would be depreciated at standard rates, except for the dissolvers. The life expectancy of the batch dissolvers is estimated to be five years (1825 operating days). The life expectancy of the continuous dissolvers is estimated to be only six months (180 operating days or three calendar years). The estimated daily depreciation charges are as follows:

5 kg U per day plant (batch dissolvers)	\$1287
10 kg U per day plant (continuous dissolver)	\$1726

D. Waste Storage Costs

The waste storage cost would be \$10.60 per kilogram of zirconium, regardless of processing rate or dissolver type. The daily waste storage costs would be:

5 kg U per day plant	\$4410
10 kg U per day plant	\$8820

E. Direct Operating Costs

Additional personnel would be required over and above the present staff, shown in Appendix III, for either of the STR expansion systems. These additional personnel would be as follows:

	<u>Operations</u>	<u>Analytical</u>	<u>Maintenance</u>
5 kg U per day plant	9	4	0
10 kg U per day plant	0	9	1

The daily cost of the enlarged staff would be:

5 kg U per day plant	\$5616
10 kg U per day plant	\$5541

Process chemicals costs would remain at \$2.35 per kilogram of zirconium. The daily process chemicals cost would be:

5 kg U per day plant	\$ 981
10 kg U per day plant	\$1962

Other direct costs are estimated to increase slightly with the increased capacity. The estimated daily costs are:

5 kg U per day plant	\$1650
10 kg U per day plant	\$1700

F. Overall Operating Costs

The overall operating costs for the two cases would be the sum of the preceding figures:

	<u>Overall Operating Cost per</u>		
	<u>Day</u>	<u>Kg Zr</u>	<u>g U (After burnup)</u>
5 kg U per day	\$13,944	\$33.70	\$2.79
10 kg U per day	\$19,749	\$23.70	\$1.97

G. Potential Process Improvements

The expansions in the STR process discussed in the preceding sections represent simple extrapolations of the current STR process. Recent development work has indicated that improvements might be made in the basic process that would (1) reduce chemical costs, (2) reduce extraction solution volume, (3) reduce waste volume, and (4) permit processing zirconium fuel containing up to 3 weight per cent uranium.

The first three of these potential benefits are interrelated and stem from a more concentrated adjusted dissolver product. With a fluoride-to-zirconium ratio of 5.2:1 and an aluminum nitrate concentration of 0.5M, a solution 0.8M in zirconium (current flowsheet is 0.55M Zr) has been found stable for at least four days (3). Four days is long enough to process the solution through the first extraction cycle and transfer it into the waste tank. If this waste is stored directly, a precipitate will form, and the solution will eventually come to equilibrium at 0.67 molar zirconium. If aluminum wastes are mixed with the STR waste (for corrosion control to permit storage in the large waste tanks, see Section II), this precipitation can be prevented (3).

The limitations on the uranium content of the fuel, imposed by the limited solubility of UF_4 , and the potential improvement resulting from the addition of oxidizers were discussed in Section II. The addition of dilute hydrogen peroxide (0.06M for batch dissolution or 0.01M for continuous dissolution) or dilute nitric acid (1.5 or 0.3M) to the dissolver reagent permits the homogeneous dissolution of zirconium fuels containing up to 3 weight per cent uranium (18).

Adoption of these flowsheet modifications would reduce the process chemicals cost by \$0.70 per kilogram of zirconium and the waste storage cost by \$2.10 (1.04 gallons of waste) per kilogram of zirconium. Process flowsheets incorporating the modifications are included in Appendix I, Figures 1, 2, and 3.

V. THE BARIUM FLUOZIRCONATE PROCESS

A. Description of the Process

The barium fluozirconate process now being developed is basically a modification of the STR process that presents a means of reducing the waste volume (15, 17, 25, 26). Since the cost of storing the STR process waste represents about 40 per cent of the overall operating cost of a 10 kilogram per day continuous dissolution system (see Section IV), the potential economic benefit is obvious.

Dissolution for the barium fluozirconate process is identical with the STR process, and may be either batch or continuous. Chemical treatment of the dissolver product is the distinguishing feature of the barium fluozirconate process. A mixture of barium nitrate and barium fluoride is added to the dissolver effluent solution. After digestion for one hour at 90°C, over 90 per cent of the zirconium and fluoride precipitates as BaZrF_6 and BaZrF_5 (17). Essentially no uranium is precipitated. The precipitate is washed, to remove the uranium-bearing mother liquor, and sent to storage as a dried powder or as a slurry. The supernate and wash solutions are concentrated by evaporation to form the first extraction cycle feed.

Development of the barium fluozirconate process has not yet progressed beyond the laboratory stage. There are several engineering problems yet to be solved (primarily solids handling), and the process chemistry and corrosion data are still incomplete. The laboratory results are encouraging, and the economic incentives are very attractive. Aqueous waste storage costs for the barium fluozirconate process would be about \$1.50 per kilogram of zirconium, compared to \$10.60 for the STR process. However, an additional cost of about \$1.70 per kilogram of zirconium would be incurred for solid waste storage, resulting in a net saving over the STR process waste storage cost of \$7.40 for each kilogram of zirconium processed. The process chemicals cost would be only slightly increased; \$2.44 per kilogram of zirconium for the barium fluozirconate process, and \$2.35 for the STR process.

Barium fluozirconate process flowsheets for 5 and 10 kilograms of uranium per day are shown in Appendix I, Figures 4 and 5. The dissolution systems are the same as for the corresponding STR systems, i.e., batch dissolvers and a continuous dissolver, respectively.

The dissolver product is transferred to the fluozirconate precipitator in batches containing not more than 800 grams of uranium-235, to insure nuclear safety. Barium nitrate and barium fluoride are added as solids to prevent needless dilution of the solution; since the supernate is saturated with zirconium, the smaller the solution volume, the lower the zirconium loss. Barium fluozirconate precipitation is completed after one hour of stirring at 90°C. The solids are centrifuged, washed to recover the uranium-bearing supernate, and then transported to permanent waste storage. A slurry system has been tentatively selected to

transport the solids to storage, but a development program would be necessary to permit final selection of the conveying method.

The solid wastes from the barium fluozirconate process would not contain gross fission products other than zirconium, strontium, and cerium (5, 15). No provisions for cooling the solids appear to be necessary, and stainless steel (type 304L) tanks would be satisfactory. It would be best to store the solids separately from the aluminum fuel aqueous wastes; the aluminum waste solutions would dissolve significant quantities of the solids. The problems resulting from contamination of aluminum wastes with fluoride were discussed in Section II.

The supernate and wash solutions from the fluozirconate precipitation contain essentially all of the uranium in the dissolver product, along with about 5 per cent of the zirconium and 7 per cent of the fluoride. The supernate is concentrated by evaporation to reduce the extraction feed volume and to provide solvent extraction salting strength. The additional barium fluozirconate precipitated during this concentration is filtered out and returned to the centrifuge.

The materials of construction for the precipitator vessel and the supernate evaporator have not yet been selected. Corrosion rates for stainless steels and Carpenter-20 are 0.2 mil per month at 35°C and increase to 7 to 14 mils per month at 95°C (4, 6). Except for the dissolver system (see Section II), type 304L stainless steel would be adequate for the remaining process equipment.

The major fields requiring engineering development are the centrifuging, solids washing, solids sampling, and solids handling. It may be very difficult to obtain representative samples of radioactive slurries and solids, but if a representative sample is not obtained, a significant uranium loss could occur undetected. A satisfactory solution to this problem could require an extensive development effort.

B. New Plant Investment

Barium fluozirconate systems for 5 and 10 kilograms of uranium per day would require the same dissolution equipment as that for STR process systems of the same capacity. The existing STR process first extraction cycle equipment would be adequate, with perhaps some very minor modifications, for either a 5 or 10 kilograms of uranium per day barium fluozirconate installation. Additional process equipment necessary would include precipitators, centrifuges or filters, supernate evaporator, solids transport system, and the associated piping and instrumentation. Detailed investment estimates for barium fluozirconate units with capacities of 5 and 10 kilograms of uranium per day are presented in Appendix II, Table II. The total investments are estimated at \$1,268,000 and \$1,431,000, respectively.

C. Depreciation Charges

The dissolvers in these systems are identical to those in the expanded STR process systems discussed in Section IV, and would have equal life expectancies and depreciation rates. Other barium fluo-zirconate process equipment with lower than normal life expectancies are the precipitators and supernate evaporators. The life expectancy of these units is estimated to be twelve months (360 operating days). The total daily depreciation charges for the barium fluozirconate systems are estimated to be:

5 kg U per day (batch dissolution)	\$1800
10 kg U per day (continuous dissolution)	\$1850

D. Waste Storage Costs

The liquid waste would be compatible with the existing large waste tanks and would be charged for at \$2.01 per gallon. A new storage tank will be required to store the solid wastes. This tank is estimated to cost \$25 per cubic foot (\$3.35 per gallon) of capacity. The daily waste storage costs would be:

	<u>Liquid</u>	<u>Solid</u>	<u>Total</u>
5 kg U per day	\$ 624	\$ 708	\$ 1332
10 kg U per day	\$1248	\$1416	\$ 2664

E. Direct Operating Costs

The operating and maintenance manpower required for the barium fluozirconate systems is estimated to be the same as for the expanded STR processes of the same capacity. The increase in the number of analyses required would increase the analytical manpower by one man per shift for the 10 kilograms of uranium per day plant. The total daily labor costs are estimated to be:

5 kg U per day plant	\$5844
10 kg U per day plant	\$5770

The process chemicals shown in the barium fluozirconate flowsheet are estimated to cost \$2.44 per kilogram of zirconium processed. The daily cost would be:

5 kg U per day plant	\$1020
10 kg U per day plant	\$2040

The other daily direct costs would be the same as for the corresponding size expanded STR process:

5 kg U per day plant	\$1650
10 kg U per day plant	\$1700

F. Overall Operating Costs

The overall operating costs for the barium fluozirconate systems would be the sum of the preceding costs:

	<u>Overall Operating Cost per</u>		
	<u>day</u>	<u>Kg Zr</u>	<u>gU (after burn-up)</u>
5 kg U per day plant	\$11,646	\$ 28.00	\$2.33
10 kg U per day plant	\$14,024	\$ 16.90	\$1.40

G. Potential Process Improvements

Recent work on the barium fluozirconate process indicates that further reductions in processing costs are highly probable (6, 17). A saturated barium nitrate-barium hydroxide solution has been successfully used to carry out the precipitation at room temperature. The increase in supernate solution volume that results from substitution of a barium solution for the solid barium salts can be overcome by a slight additional concentration in the supernate evaporator. Several benefits result from the substitution. Lowering the precipitation temperature from 95°C to 25°C reduces the precipitator corrosion rate by a factor of 100, and thereby makes a significant reduction in the precipitator depreciation charge. The barium hydroxide neutralizes most of the excess acid in the dissolver product, markedly reducing corrosion rates in the supernate evaporator. The time required to complete the barium fluozirconate precipitation is reduced from one hour to only a few minutes. The cost of process chemicals would be reduced from \$2.44 to \$1.40 per kilogram of zirconium. The separation of uranium from zirconium would be at least as good as with the solid precipitant. Solid and liquid waste volumes would not be affected. Laboratory work on these modifications is continuing.

VI. THE SODIUM FORMATE PRECIPITATION PROCESS

A. Description of the Process

The sodium formate process is similar to the barium fluozirconate process described in Section V, and is an outgrowth of the work on that process (16). The development of the sodium formate process has not yet advanced beyond the preliminary laboratory stage, but it appears to have significant advantages when compared to the barium fluozirconate process (5, 6). These advantages are (1) virtually complete separation of uranium from zirconium, (2) reduced corrosion rates, (3) more rapid reaction rates, and (4) reduced solid waste mass (although the relative solid waste volume is still uncertain).

The feature of the sodium formate process that distinguishes it from the barium fluozirconate process is the substitution of a sodium formate solution for the barium salts. A standard STR dissolution is used, followed by chromic acid addition to the dissolver product to oxidize the uranium to the hexavalent state. A 26 weight per cent sodium formate solution is mixed with the chromic acid dissolver product mixture in a ratio of 4 moles of sodium per mole of zirconium. The precipitation is almost instantaneous at 60°C. The solid reaction product is apparently a sodium fluozirconate, but no specific compound has been identified. The precipitate does not settle out rapidly, and a flocculating agent is required for satisfactory filtration rates.

The precipitate is washed with dilute sodium nitrate or nitric acid to recover the mother liquor from the solids. An appreciable fraction of the solids dissolves in the wash solution, but it is recovered and recycled when the supernate and wash solution are concentrated, by evaporation, to form the first extraction cycle feed. About 99.7 per cent of the zirconium goes to the solid waste, and about 99.9 per cent of the uranium is recovered in the supernate and wash solution.

The combined supernate and wash solution is boiled down to 2 molar sodium nitrate. After the residual sodium formate and formic acid are destroyed with chromic acid, the concentrated solution is satisfactory for TBP extraction. No aluminum nitrate is necessary for either fluoride complexing or solvent extraction salting. The sodium nitrate first extraction cycle waste can be stored in the large stainless steel waste tanks, either separately or mixed with aluminum wastes. Fluid bed calcination of the wastes will cause problems, since sodium nitrate fuses before it decomposes. Aluminum wastes containing sodium nitrate are pre-disposed to forming alpha alumina in fluidized bed calciners, resulting in high attrition rates and the generation of excessive fines (5).

The nature and properties of the solid wastes have not been completely defined. It is known that about 2 1/2 kilograms of solids are formed for each kilogram of zirconium processed, but the bulk density of the solids has not been determined. The solids storage volume requirements are, therefore, not yet established. Stainless steel type 304L should be a satisfactory material of construction.

A preliminary chemical flowsheet for the sodium formate process is shown in Appendix I, Figure 8. It is probable that the equipment flowsheet would be similar to that for the barium fluozirconate process, Appendix I, Figures 4 and 5. The two processes could probably even be operated in the same equipment, but the present state of development of the sodium formate process is not sufficiently advanced to prepare a process flowsheet.

B. Economics of the Process

There is a possibility that new plant investment for the sodium formate process would differ from that for the barium fluozirconate process, but no significant differences can be detected at the present development level of the sodium formate process. Investment estimates of \$1,200,000 and \$1,400,000, respectively, appear to be valid for 5 and 10 kilogram per day sodium formate systems. Operating costs for the sodium formate process would be about the same as for the barium fluozirconate process, except that process chemicals would be about \$0.30 less and liquid waste storage about \$0.50 less per kilogram of zirconium with the sodium formate process. The sodium formate process would produce less weight of solid waste, but a bulk density difference could make the relative solid volume higher.

It is almost certain that the economics of the sodium formate and barium fluozirconate processes will be too close to select either process on that basis. The choice must be based on process considerations, such as operability or uranium recovery.

VII. THE ZIRFLEX PROCESS

A. Description of the Process

The name "Zirflex" is applied to a series of processes; the common feature is the use of an aqueous ammonium fluoride solution to dissolve zirconium (8, 9, 10, 19, 22). The Zirflex process was originally developed to remove the zirconium cladding from low-enriched fuels (8). Subsequent modifications have been made to adapt the process to highly enriched zirconium-uranium alloy fuels. One process variation is the addition of nitric acid and aluminum nitrate to the dissolver product to form a stable extraction system feed (9). A second variation is the addition of ammonium hydroxide to the dissolver product, precipitating the uranium and zirconium and regenerating the ammonium fluoride for recycle (19, 10). The uranium-zirconium precipitate is dissolved in nitric acid to prepare the solvent extraction feed.

The first process variation has no significant advantage over the STR process except for lower dissolver corrosion rates; the extraction system feed composition is essentially identical. The second variation does have some advantages over the STR process, such as reduced waste volume, a more stable waste, very low uranium losses, and low corrosion rates at all points in the process. This second process variation was selected as the Zirflex modification to be included in this study.

The fuel elements are homogeneously dissolved in boiling 6 molar NH_4F , 1 molar NH_4NO_3 . The ratio of dissolvent feed to zirconium feed is set so that the final fluoride-to-zirconium ratio is at least 7:1. The dissolution rate is slow but adequate, about 10 to 20 mils/hour penetration until the ratio drops below 7:1; the reaction stops at about 6:1. The NH_4NO_3 is added principally to keep the tin and uranium in solution; it also reduces the hydrogen-to-ammonia mole ratio in the off-gas from 1:2 for a straight NH_4F dissolution to 1:30 for a NH_4F - NH_4NO_3 dissolution. The dissolver is not refluxed because of the necessity for removing the ammonia generated by the dissolution reaction, and an appreciable concentration of the dissolver solution results.

The dissolver product is transferred to a precipitation vessel in critically safe batches containing not more than 800 grams of uranium-235. Ammonium hydroxide solution is added, and additional ammonia is introduced as a gas sparge.

The metathesis operation, conducted at room temperature, precipitates the uranium and zirconium as hydrous oxides, leaving most of the fluoride in solution as NH_4F . A 350 per cent excess of NH_3 plus NH_4OH will produce a precipitate with a fluoride-to-zirconium ratio of 1:1, leaving about 85 per cent of the fluoride in the supernate.

The supernate and wash solutions (containing about 85 per cent of the fluoride, 5 per cent of the uranium, and less than 1 per cent of the zirconium) are concentrated by evaporation to 6M HN_4F , adjusted to 1M NH_4NO_3 , and recycled to the dissolver. The overhead NH_4OH product from this evaporation is reused as wash solution. This dilute ammonia solution could be discarded, but it would have to be routed through the low-level waste evaporator and the volume would overload the evaporator.

The uranium-zirconium precipitate is separated from the supernate and washed with dilute ammonium hydroxide in either a centrifuge or a filter. A batch centrifuge has been tentatively selected for this step, but the final choice will require further pilot plant tests. The washed solids are dissolved in 8M nitric acid. The resulting first extraction cycle feed is about 1.0M zirconium and 3M HNO_3 , at a uranium concentration of about 1.1 grams per liter. Since uranium can leave the process only through the extraction system, there is an excellent opportunity to attain very high uranium recoveries.

The waste from the first extraction cycle can be concentrated to about 3 molar zirconium and still be a stable solution because of the low fluoride-to-zirconium ratio. The permanent waste volume is therefore only about 20 per cent of the volume produced by the STR process. The low fluoride-to-zirconium ratio also makes the waste less corrosive. The potential for further concentration, by a simple evaporation to separate crystalline zirconium nitrate or by a calcination process, is very good (7).

Process flowsheets for 5 and 10 kilograms of uranium per day Zirflex systems are shown in Appendix I, Figures 6 and 7, respectively. Stainless steel type 309SCb is satisfactory for the dissolver construction material (10, 22). Type 304L stainless steel would be adequate for the remainder of the process equipment. Elimination of the need for more expensive alloys, such as Monel or Carpenter-20, is a major advantage of the Zirflex process. Equipment design would generally be either standard or a minor extrapolation of proved designs. A continuous dissolver is preferred for both processing rates. The Zirflex dissolution rate is too slow to achieve a capacity of 5 kilograms of uranium per day in less than four batch dissolvers.

A continuous Zirflex dissolver has not been demonstrated, but the existing laboratory data show no reason why continuous dissolution would not be feasible. The centrifuge, or filter, would be a special piece of equipment and might require a considerable development effort, plus probably a year to design, manufacture, and install.

The laboratory development of the chemical flowsheet for the Zirflex process is virtually complete. Some gaps in the data need to be filled in, particularly in the field of solubility and solution stability, and some minor flowsheet changes might result in process improvements. Additional solvent extraction and corrosion rate data are needed. A considerable pilot plant development program is required,

particularly on continuous dissolution and on solids separation, washing, and handling. If the Zirflex process is selected for plant installation, a long-term program on ultimate disposal of Zirflex waste would be beneficial.

B. New Plant Investment

Two existing plant cells, D and E, could be used for installation of an ICPP Zirflex dissolver and metathesis system. The equipment now in D cell is obsolete, and the STR dissolver and feed adjustment equipment in E cell would be superseded by the Zirflex equipment. The existing STR first extraction cycle system, with a few minor modifications, would be adequate to process 10 kilograms of uranium per day with a Zirflex process. Other existing ICPP equipment would be adequate without modification.

The new plant investments for 5 and 10 kilograms of uranium per day Zirflex systems are estimated to be \$1,508,000 and \$2,230,000, respectively. Details of the estimates are presented in Appendix II, Table III. The use of a continuous dissolver was assumed for both rates. It is estimated that construction could be completed in about one year, if the centrifuge were ordered well in advance of the start of construction. Allowing for design time and test runs, about two years would be required from project approval to the start of routine fuel processing.

C. Depreciation Charges

Standard depreciation rates would be used for all the new Zirflex equipment except the dissolver. The dissolver life expectancy is estimated to be three years (1080 operating days). The daily depreciation charge would be:

5 kg U per day Zirflex plant	\$1180
10 kg U per day Zirflex plant	\$1273

D. Waste Storage Costs

The Zirflex process waste would be compatible with the large waste tanks, charged for at \$2.01 per gallon. The daily waste storage cost would be:

5 kg U per day plant	\$ 907
10 kg U per day plant	\$1814

E. Direct Operating Costs

A 5 kilograms of uranium per day Zirflex process would require three extra operators and one extra analyst per shift (17 additional men added to the payroll) over and above the present plant staff shown in Appendix III. These extra men would be required for the metathesis, centrifugation, cake dissolution, and supernate evaporation steps, operations that have no counterpart in the STR process. A 10 kilogram per day process would require one more analyst per shift, for a total of 22 new men added to the payroll. The total daily cost of the expanded plant staff would be:

5 kg U per day plant	\$5730
10 kg U per day plant	\$6015

Only four process chemicals are used in the Zirflex system: ammonium fluoride, ammonium nitrate, ammonia, and nitric acid. Although these chemicals are used in large quantities, they are relatively cheap and recycling is used extensively. As a result, the process chemicals cost for the Zirflex process is relatively low. The daily process chemicals costs are estimated to be:

5 kg U per day plant	\$ 630
10 kg U per day plant	\$1260

The other direct costs for the Zirflex systems would be slightly higher than for comparable STR systems because of the significant increase in process steam consumption. The daily other direct costs are estimated to be:

5 kg U per day plant	\$1750
10 kg U per day plant	\$1900

F. Overall Operating Costs

The overall operating costs would be the sum of the preceding figures:

	<u>Overall Operating Cost per</u>		
	<u>Day</u>	<u>Kg Zr</u>	<u>g U (After burnup)</u>
5 kg U per day plant	\$10,197	\$24.50	\$2.04
10 kg U per day plant	\$12,262	\$14.75	\$1.23

G. Potential Process Improvements

The major disadvantages of the Zirflex process are the large volumes of many of the process streams, the large physical size of the equipment, and the complex concentration and recycle system. The volume of solution involved in the recycle of NH_4F is a particular problem. Some of the vessels required would be too large to fit in the process cells, and it would be necessary to locate them underground adjacent to the main process building.

It is probable that an intensive pilot plant development program would result in substantial process improvements. The recycle procedures and equipment are suggested as a field particularly in need of a major engineering development effort.

The Zirflex process waste volume (just under one gallon per kilogram of zirconium processed) is not particularly large for a zirconium fuel process, but any reduction would be beneficial. So far as is known, no work is now in progress specific to ultimate disposal of Zirflex wastes.

VIII. OTHER ZIRCONIUM PROCESSES

A. ARCO Process

The ARCO process is based on the dissolution of zirconium fuels in molten lead chloride at 510 to 575°C (11, 28). The zirconium sublimes as ZrCl_4 , and the uranium and tin remain as chloride in the molten salt. The reduced lead forms a molten pool under the salt layer. The volatilized zirconium tetrachloride is condensed and stored as a solid. The lead can either be cast in ingots and stored, or be chlorinated to PbCl_2 and recycled to the dissolver. The uranium chloride-lead chloride molten salt is cooled and then treated with concentrated nitric acid. This treatment removes the bulk of the chloride and converts the salt to a nitric acid system. Lead nitrate crystallizes and is stored as a waste solid. The resultant solution is highly concentrated in uranium.

This process is still in the preliminary laboratory stage and will not be ready for plant installation during the next few years. The present very preliminary designs require the extensive use of titanium equipment, particularly in the chloride removal and lead recycle steps (20, 21, 25, 26), and titanium construction would result in plant investments considerably greater than the competitive processes. The multiplicity of process steps would result in a large plant staff and high operating costs. Although waste volumes would be low, the production of four different wastes is an undesirable feature.

The ARCO process development work could lead to a feasible zirconium processing system with favorable economics, but the present state of development is probably considerably removed from the final evolution of the process. There are several features of the present ARCO process that may be drastically changed, and it is considered unwise to proceed to the design of plant installations based on the present state of development.

B. Fused Salt Fluoride Volatility Process

The fused salt fluoride volatility process is being developed at the Argonne and Oak Ridge National Laboratories (27). The ORNL program is directed especially toward enriched zirconium-uranium fuels. This program, now in the hot pilot plant stage, has demonstrated good uranium recovery and decontamination and low waste volume (30, 31).

This process is completely anhydrous; the uranium is produced as purified UF_6 . The fuel elements are dissolved in a molten NaF-LiF or NaF-ZrF_4 salt batch and sparged with anhydrous HF at 550 to 650°C. As the fuel dissolves, the zirconium content of the salt batch increases and the melting point of the salt mixture rises. The amount of zirconium that can be dissolved in each batch of salt is set by the maximum melting point that can be tolerated. Uranium, as UF_4 , also dissolves in the salt, but the relatively small quantity does not significantly affect the properties of the salt. The loaded salt melt is transferred to a second vessel and sparged with elemental fluorine at 500 to 550°C

for one to four hours. Up to 99.8 per cent of the uranium is vaporized as the volatile UF_6 , and the waste salt, only 0.16 gallon per kilogram of zirconium processed, is cast in cans for storage. The UF_6 from the fluorinator is decontaminated and purified by adsorption and desorption on a series of sodium fluoride beds.

Materials of construction for the hydrofluorinator (dissolver) and fluorinator are a major problem. The ORNL pilot plant hydrofluorinator, made of Inor-8, has shown corrosion rates of about 25 to 30 mils per month while sparging. The fluorinator is made from pure L-nickel, the best material found so far. Corrosion rates are fantastically high by normal standards, being about one mil per hour while sparging. The feature of the process that keeps such corrosion rates within the realm of process operability is the large batch size that may be processed. The limit of 800 grams of uranium-235 per batch imposed on an aqueous system for criticality safety does not apply to the anhydrous fused salt fluoride volatility process; single batches containing 20 kilograms of fully enriched uranium have been processed in the ORNL pilot plant (30).

Although the ORNL pilot plant work is well along, the magnitude of the unsolved problems, such as corrosion and operating difficulties, is sufficient to preclude the design of a plant installation. It is believed that the unique nature of this process will require pilot plant demonstration with fuels up to and including full-level irradiation before the design of a full-scale installation can be undertaken successfully.

The initial investment for a fused salt fluoride volatility system could be extremely high and could be compounded by very frequent replacement of major equipment items. It can not yet be determined if the potentially low waste storage, operating labor, and process chemicals costs will compensate for the high investment in a reasonable period of time at the fuel processing rates currently foreseen.

IX. CONCLUSIONS

The technical feasibility of three of the aqueous zirconium fuel processes--STR, barium fluozirconate and modified Zirflex--has been fairly well demonstrated. An STR process using batch dissolution represents little more than duplication of existing facilities and technology. A continuous STR dissolution process has not been demonstrated on a pilot plant scale, but the information needed for such a demonstration is available, and construction of the necessary equipment is well advanced. The laboratory investigation of the barium fluozirconate process is not yet complete, but the basic features of the process have been outlined and preparation for pilot plant tests could be started at any time. Laboratory development of the Zirflex process is well advanced, and some batch dissolution studies have been carried out in pilot plant equipment, but no pilot plant work has been done on continuous Zirflex dissolution or the metathesis modification.

The technical feasibility of the fourth aqueous process--sodium formate--and the two anhydrous processes--ARCO and fused salt fluoride volatility--has not been fully demonstrated. The sodium formate and ARCO processes have not progressed beyond the exploratory investigation stage of the laboratory development program. The pilot plant tests of the fused salt fluoride volatility process have encountered serious corrosion and operating problems. None of these processes is ready for consideration as a plant installation.

The economic factors involved in the selection of a process for ICPP installation are summarized in Appendix IV. The proper evaluation of these economic factors requires that due allowance be made for the time factors involved. Of prime importance are the time available to design and install a new zirconium fuel system and the time that this system may be in operation before it is in turn superseded by a third generation operation. (This later time might be better expressed in terms of the quantity of fuel that will be processed through the new system during its life expectancy.) If only a short period is available to have a new ICPP zirconium process in operation, a disproportionate weight must be given to the STR process; if the period is long, the time required to complete the development of the competitive processes is of little consequence. If the new process is to be used for only a short period (or a limited quantity of fuel), the low investment for the STR process would make it very attractive; if a long operating period can be assumed, the lower operating cost of a competing process could more than recover a higher initial investment. No particular process can be selected now as the most economical second generation ICPP zirconium installation; the time factors required to make the choice cannot be determined from the available information.

The information developed in this study is not sufficient to permit the final selection of the second generation ICPP zirconium fuel process. It does appear that one of three or four aqueous processes is the most likely choice, and that some modification of the present STR process would be preferred for a shortest-possible-time installation.

X. RECOMMENDATIONS

Identical dissolver systems would be required for 10 kilograms of uranium per day for STR, barium fluozirconate, or sodium formate processes. The same dissolver system would very probably also be satisfactory for the Zirflex process, even though the material of construction might be more corrosion resistant than necessary. Any immediate plant design work should be based on such a dissolver system, and pilot plant investigation of continuous zirconium dissolution should have the highest priority.

Laboratory work should continue on flowsheet development of the barium fluozirconate, sodium formate, and Zirflex processes. Pilot plant tests should be started as soon as possible to investigate the precipitation, solids separation, and solids handling steps of these processes. The equipment so developed could then be installed to operate in conjunction with the continuous dissolver, if one of these processes were selected in preference to the basic STR process.

The development of anhydrous zirconium fuel processes would appear justifiable as "third generation" candidates. It does not seem possible to complete the development and installation of these processes in time to meet the anticipated zirconium fuel load. During this development, continual consideration should be given to new zirconium fuel types, types that may not be compatible with the aqueous processes under development. At the present time, it appears that a period of at least five years is available to complete the development of anhydrous processes for zirconium fuels.

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APPENDICES

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	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
	FUEL	HF	REAGENT	PRODUCT	RINSE WATER	AGENT	SEED FUEL	COARSE														
BASED ON PRESENT ICPP STR FLOWSHEET FOR PWR SEED FUEL (2 SUBASSEMBLIES PER BATCH, 5.85 BATCHES PER DAY)																						
LITERS/BATCH	480	15	479	75	791	1367	1438	1830	8380	1830	910	360	910	2190	545	2190	545	55	55	545	213	
LITERS/DAY	862g			1.80		0.63	0.60	<0.006	2.75	9.10	3.60	9.10	2.25	545	<0.002	9.18				9.18	235	
U g/l	72kg			1.65		0.58	0.55		0.55													
Zr M		7.42	1.0	0.84		1.60	1.22	1.16		0.20			0.39	0.005	0.01		0.03			0.03	0.77	
H+ N			1.0	0.016		4.08	2.37	2.25		2.21	0.20	2.1	2.49	0.005	0.01		0.03			0.03	0.77	
NO ₃ M						1.60	3.53	3.35		3.35												
F- M		7.42		7.43		0.03	0.017	0.016		0.016												
CrO ₃ M						0.007	0.007	0.007		0.007												
Sn M	1.08kg			0.019		1.36	0.79	0.75		0.75												
Al M																						
TBP %									10		10	0.70	10	0.70	10	10						
DILUENT									AMSCO		AMSCO	AMSCO	AMSCO	AMSCO	AMSCO	AMSCO		AMSCO	AMSCO			
BASED ON MODIFIED ICPP STR FLOWSHEET FOR PWR SEED FUEL (2 SUBASSEMBLIES PER BATCH, 5.85 BATCHES PER DAY)																						
LITERS/BATCH	197	197	394	75	512	987	1038	1335	6140	1335	666	265	666	1600	492	1600	492	50	50	492	21.3	
LITERS/DAY																						
U g/l	862g			2.19		0.87	0.82	<0.008	3.82	1.26	0.20		0.39	0.005	0.01		0.03			0.03	0.69	
Zr M	72kg			2.00		0.80	0.76		0.76													
H+ N		10.0	10.0	1.94		1.14	1.37	1.30		1.26	0.20	2.1	2.49	0.005	0.01		0.03			0.03	0.69	
NO ₃ M						3.95	2.05	1.95		1.91	0.20											
F- M		10.0	10.0	100		0.53	4.51	4.21		4.21												
H ₂ O ₂ M			0.12	<0.005																		
Sn M	1.08kg			0.023		0.009	0.009		0.009													
Al M					1.12	0.58	0.55		0.55		0.70	0.70										
TBP %																						
DILUENT									12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5		AMSCO	AMSCO			

5kg/DAY STR HEAD END

Appendix I Figure 2

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STREAM	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	
	FUEL	DISSOLVER ACID	DISSOLVER REAGENT	DISSOLVER PRODUCT	COMPLEXING REAGENT	COARSE FEED	IAF	IAx	IAW	IAp-IBF	IBS	IBX	IBW	IBP-ICF	ICX	ICW	ICP-IDF	IDS	IDW	IDP	2AF	
BASED ON PRESENT ICPP STR FLOWSHEET FOR PWR SEED FUEL (11.6 SUBASSEMBLIES PER DAY)																						
LITERS/DAY		5550	174	5560	10,000	15,800	16,670	3620	16,670	3620	1815	720	1815	4440	1075	4440	1075	100	100	1075	42.1	
U g/l	10kg/day			1.80		0.63	0.60		<0.006	2.75			<0.003	2.25		<0.002	9.18			9.18	235	
Zr M	835kg/day			1.65		0.58	0.55		0.55													
H ⁺ N		7.42		0.83	1.46	1.22	1.16		1.12	0.20			0.39	0.005	0.01		0.03			0.03	0.77	
NO ₃ M					3.75	2.37	2.25		2.21	0.20	2.1		2.49	0.005	0.01		0.03			0.03	0.77	
F ⁻ M		7.42		7.43	1.46	3.53	3.35		3.35													
H ₂ O ₂ M			0.32	0.01	<0.005																	
Sn M	12.5kg/day			0.019	0.007	0.007			0.007													
Al M					1.25	0.79	0.75		0.75		0.70		0.70									
TBP %								10		10		10		10		10						
DILUENT								AMSCO		AMSCO		AMSCO		AMSCO		AMSCO		AMSCO	AMSCO			
BASED ON MODIFIED ICPP STR FLOWSHEET FOR PWR SEED FUEL (11.6 SUBASSEMBLIES PER DAY)																						
LITERS/DAY		4580		4580	6870	11,450	12,000	2610	12,000	2610	1300	520	1300	3130	960	3130	960	100	100	960	42.1	
U g/l	10kg/day			2.18		0.87	0.83		<0.008	3.82			<0.003	3.15		<0.003	10.3			10.3	235	
Zr M	835kg/day			2.00		0.80	0.76		0.76													
H ⁺ N		10.0		1.94	0.87	1.30	1.24		1.20	0.20			0.39	0.005	0.01					0.03	0.69	
NO ₃ M					3.25	1.95	1.86		1.82	0.20	2.1		2.49	0.005	0.01					0.03	0.69	
F ⁻ M		10.0		10.0	0.38	4.23	4.02		4.02													
H ₂ O ₂ M			0.01	0.005																		
Sn M	12.5kg/day			0.023		0.009	0.009		0.009													
Al M					0.97	0.58	0.55		0.55		0.70		0.70									
TBP %								10		10		10		10		10						
DILUENT								AMSCO		AMSCO		AMSCO		AMSCO		AMSCO		AMSCO	AMSCO			

10kg/DAY STR HEAD END

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STREAM	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
	FUEL	Dissolver Reagent 1	Dissolver Reagent 2	Dissolver Product	Dissolver Off Gas	Precipitate Reagent	Supernate	Precipitate	Wash	Wash	Solid Waste	Complexing Reagent	Evaporator Feed	Evaporator Product (AF)	Evaporator Solids	1AX	1BS	1BX	1BP	1CX	1CP	1DS	1DP	2AF	1AR	1BR
FLOW liters/batch		2785	60	480			384	96	2x240	2x240		144	1008	210		300	100	50	350	175	175	17.5	175	14.1	210	100
FLOW liters/day		2785	60	2785			2230	555	2785	2785		1670	5846	1220						175	175	17.5	175	14.1	1220	100
U g/l	5kg/day			1.79			2.04	78g/batch		8 x 10 ⁻²	15g/batch		0.85	4.1					14.3				28.6	353	1x10 ⁻³	
Zr M	416			1.65			0.1	753mols/batch		0.11	700mols	BaZrFx	0.1	0.233	100mols	BaZrFx									0.233	
Ba M							0.2	1592mols BaF ₂ /batch		0.06			0.058	0.28											0.28	
H ⁺ M		7.42		0.82	0.10scfm H ₂		1.03		0.01	0.01		-0.2	0.37	1.77			-0.20		0.005	0.01	0.01		0.01	0.12	1.77	0.39
NO ₃ M							1.03		0.01	0.01		6.6	0.91	4.4			2.1		0.12	0.01	0.25		0.25	3.1	4.4	2.39
F ⁻ M		7.42		7.42			0.8			0.6			0.59	2.74											2.74	
H ₂ O ₂ M			0.5	<0.005									0.006	0.04											0.04	
Sn M	6.25 kg			0.019			0.024					2.2	0.312	1.50			0.70								1.50	0.70
Al M																10		10								
TBP %																Amsco		Amsco								
DILUENT																										

5 kg U / DAY
BARIUM FLUOROZIRCONATE
HEAD END

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STREAM	1	2	2A	3	4	5	6	7	8	8A	9	10	11	12	12A	13	14	15	16	17	18	19	20	21	25	26
	FUEL	Dissolver Reagent 1	Dissolver Reagent 2	Dissolver Product	Dissolver Off Gas	Precipitate Reagent	Supernate	Precipitate	Wash	Wash	Solid Waste	Complexing Reagent	Evaporator Feed	Evaporator Product (AF)	Evaporator Solids	1AX	1BS	1BX	1BP	1CX	1CU	1DS	1DU	2AF	1AR	1BR
FLOW liters/batch				480			384	96	2x240	2x240		144	1008	210											210	
FLOW liters/day		5570	120	5570			4460	1110	5570	5570		1670	11,692	2440		600	200	100	700	350	350	35	350	28.3	2440	200
U g/l	10 kg			1.79			2.04	78g/batch		8×10^{-2}	15g/batch		0.85	4.1					14.3					28.6	353	1×10^{-3}
Zr M	832 kg			1.65			0.11	753 mols/batch		0.11	700mols	BaZrFx	0.1	0.233	100mols	BaZrFx									0.233	
Ba M						197 mols Ba(NO ₃) ₂ 1592 mols BaF ₂ /batch	0.2			0.06			0.058	0.28											0.28	
H ⁺ N		7.42		0.82	10cfm H ₂		1.03		0.01	0.01		-0.2	0.37	1.77			-0.07		0.005	0.01	0.01			0.12	1.77	0.51
NO ₃ M							1.03		0.01	0.01		6.6	0.91	4.4			2.1		0.12	0.01	0.25			3.1	4.4	2.61
F ⁻ M		7.42		7.42			0.8			0.6			0.59	2.74											2.74	
H ₂ O ₂ M			0.5	<0.005																						
Sn M	12.5 kg			0.019			0.024						0.006	0.04											0.04	
Al M												2.2	0.312	1.50			0.7		10	10	10				1.50	0.70
TBP %																10		10	10							
DILUENT																AMSCO		AMSCO	AMSCO							

10 kg U/DAY
BARIUM FLUOROZIRCONATE
HEAD END

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Appendix I Figure 5

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STREAM	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
	Fuel	Dissolver Reagent	Dissolver Off-Gas	Dissolver Product	Precipitation Reagent	Precipitation Reagent	Centrifuge Feed	Centrifuge Wash	Centrifuge Supernate	Centrifuge Solids	Solid Dissolution Reagent	Extraction Feed	Concentrate Waste	Supernate Concentrate	Supernate Overhead	Dissolver Reagent Make Up	IAF	IAX	IAR	IBS	IBX	IBP	ICX	ICP	IDP	2AF
FLOW liters/batch				790		636	1426	6700	8000	158 kg/batch	790	790														
liters/day		5350		4590		3680	8260	38800	46400	915 kg/day	4580	4580	1525	4530	41800	817	4580	900	4580	300	150	1050	350	350	350	141
U g/l	5 kg/day	0.026		1.12			0.621		3 x10 ⁻³	5 kg/day		1.1	0.002	0.03			1.1		<10 ⁻³			4.8		14.3	14.3	353
Zr M	416 kg/day			1.0			0.553		0.001	4580 mols		1.0	3.0	0.01				1.0		1.0						
NH ₄ ⁺ M		7.0		1.83		1.28	7.66	1.0	1.75	4930 mols		1.07	3.2	6.0	1.28	11.4	1.07		1.07							
F ⁻ N		6.0		7.0			3.88		0.586	4930 mols		1.07	3.2	6.0		6.0	1.07		1.07							
NO ₃ M		1.0		0.2			0.11		0.02		8.0	3.2	9.6	0.2			3.2		3.2	2.1			0.01	0.25	0.25	3.1
NH ₃ MOLS			12 cfm		8600																					
H ⁺ N			0.4 cfm H ₂								8.0	3.2	9.6				3.2		3.2	-0.20			0.01	0.01	0.01	0.12
OH ⁻ N						1.28	6.65		1.15	18400 mols					1.28	5.4										
Sn M	625 kg/day			0.011			0.006			9 mols		0.01	0.03				0.01		0.01							
Al M																				0.70						
TBP %																		10			10					
DILUENT																		Amsco			Amsco					

5 kg U/DAY
MODIFIED ZIRFLEX
HEAD END

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STREAM	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
	Fuel	Dissolver Reagent	Dissolver Off-Gas	Dissolver Product	Precipitator Reagent	Precipitator Reagent	Centrifuge Feed	Centrifuge Wash	Centrifuge Supernate	Centrifuge Solids	Solids Dissolution Reagent	Extraction Feed	Concentrate Waste	Supernate Concentrate	Supernate Overhead	Dissolver Reagent Make Up	IAF	IAX	IAR	IBS	IBX	IBP	ICX	ICP	IDP	2AF
FLOW liters/batch				790		636	1426	6700	8000	158 kg/batch	790	790	3050	9060	83600	1634	9160	1800	9160	600	300	2100	700	700	700	28.3
FLOW liters/day		10700		9160		7360	16520	77600	92800	1830 kg/day	9160	9160	3050	9060	83600	1634	9160	1800	9160	600	300	2100	700	700	700	28.3
U g/l	10 kg/day	0.026		1.12			0.621		3 x 10 ⁻³	10 kg/day		1.1	0.002	0.03			1.1		10 ⁻³			4.8		14.3	14.3	35.3
Zr M	832 kg/day			1.0			0.553		0.001	9160 mols		1.0	3.0	0.01			1.0		1.0							
NH ₄ ⁺ M		7.0		1.83		1.28	7.66	1.0	1.75	9860 mols		1.07	3.2	6.0	1.28	11.4	1.07		1.07							
F ⁻ N		6.0		70			388		0.586	9860 mols		1.07	3.2	6.0		6.0	1.07		1.07							
NO ₃ M		1.0		0.2			0.11		0.02		8.0	3.2	9.6	0.2			3.2		3.2	2.1	0.01		0.01	0.25	0.25	3.1
NH ₃ mols			24 cfm		17200						8.0	3.2	9.6				3.2		3.2	-0.2			0.01	0.01	0.01	0.12
H ⁺ N			0.8 cfm H ₂																							
OH ⁻ N					1.28		6.65		1.15	36800 mols		0.01	0.03		1.28	5.4	0.01		0.01							
SN M	12.5 kg/day			0.011			0.006			18 mols										0.7						
AL M																										
TBP %																		10 Amso			10 Amso					
DILUENT																										

10kg U/DAY
MODIFIED ZIRFLEX
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APPENDIX I, Figure 8

PRELIMINARY 5 kg U/Day SODIUM FORMATE HEADEND

	<u>Fuel 2 PWR Subassembly</u>	<u>Dissolver Reagent (1)</u>	<u>Dissolver Reagent (2)</u>	<u>Dissolver Solution</u>	<u>Precipitation Reagent</u>	<u>Supernate</u>	<u>Precipitate</u>	<u>Wash</u>	<u>Solid Waste</u>	<u>Evaporator Feed</u>	<u>Evaporator Concentrate</u>
Flow, Liters/Batch		533	25	535	1070	1500	100	1070	100	2570	100
U, g/l	862 g			1.61		0.55	37 g		0.9 g	0.335	8.6
Zr, <u>M</u>	72 kg			1.48		0.0015	788 mols		788 mols	.001	0.02
H ⁺ , <u>N</u>		7.42	1.0	1.50		0.535				0.312	8.0
NO ₃ , <u>M</u>			1.0	0.01		0.003		0.1		0.044	1.13
CrO ₃ , <u>M</u>			1.0	0.047		0.016				0.01	0.25
F ⁻ , <u>M</u>		7.42		7.40		0.008	3940 mols		3940 mols	0.005	0.10
Sn, <u>M</u>	1.08 kg					0.0006				0.0003	0.008
Na, <u>M</u>					3.0	1.09	1576 mols	0.1	1576 mols	0.042	1.08
COOH ⁻ , <u>M</u>					3.0	2.15*					

* The Disposition of the COOH⁻ ion has not been quantitatively determined.

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APPENDIX II

ESTIMATED INVESTMENT FOR PROPOSED ZIRCONIUM FUEL HEADENDS AT THE IDAHO CHEMICAL PROCESSING PLANT

TABLE I

ESTIMATED INVESTMENT FOR INCREASED CAPACITY FOR STR PROCESS HEADENDS

	<u>5 kg U/Day</u>	<u>10 kg U/Day</u>
Dissolver	\$20,000 (Batch)	\$15,000 (Continuous)
Coarse Feed Tank	10,000 (1)*	20,000 (2)*
DOG Condenser	5,000	-----
DOG Scrubber	3,000	-----
HF Feed Tank	5,000 (1)	12,000 (2)
Column Changes	10,000	20,000
Slide Valve	10,000 (1)	30,000 (1)
HF Pump	2,000 (1)	3,000 (1)
DOG Blower	5,000 (1)	8,000 (1)
BX Pump	-----	5,000
Instruments	10,000	15,000
Piping	90,000	110,000
Electrical	10,000	15,000
Remove Existing Equipment	<u>10,000</u>	<u>10,000</u>
TOTAL DIRECT COSTS	\$190,000	\$248,000
Indirect Costs 26%	<u>49,000</u>	<u>64,000</u>
	\$239,000	\$312,000
Design 15%	<u>36,000</u>	<u>47,000</u>
	\$275,000	\$359,000
Contingency 25%	<u>69,000</u>	<u>90,000</u>
TOTAL	\$344,000	\$449,000

* Number of items required.

TABLE II

ESTIMATED INVESTMENT FOR BARIUM FLUOZIRCONATE HEADENDS

	<u>5 kg U/Day</u>	<u>10 kg U/Day</u>
Dissolver	\$ 20,000 (Batch)	\$ 15,000 (Continuous)
Coarse Feed Tank	10,000 (1)*	20,000 (2)*
Precipitator	20,000 (1)	40,000 (2)
Supernate Evaporator	30,000	30,000
Supernate Collection Tank	20,000 (2)	20,000 (2)
Barium Nitrate Feed Tank	2,500	2,500
Barium Fluoride Feed Tank	2,500	2,500
HF Feed Tank	10,000 (1)	20,000 (2)
DOG Scrubber	5,000	-----
DOG Condenser	5,000	-----
Centrifuge	100,000	100,000
Solids Transport System	200,000	200,000
Filter	10,000	10,000
DOG Blower	5,000	8,000
Piping	205,000	252,000
Instruments	30,000	40,000
Electrical	15,000	20,000
Removal of Existing Equipment	<u>10,000</u>	<u>10,000</u>
TOTAL DIRECT CONSTRUCTION COST	\$700,000	\$ 790,000
Indirect Costs (26%)	<u>\$182,000</u>	<u>\$ 206,000</u>
	\$882,000	\$ 996,000
Design (15%)	<u>\$132,000</u>	<u>\$ 149,000</u>
	\$1,014,000	\$1,145,000
Contingency (25%)	<u>254,000</u>	<u>286,000</u>
TOTAL	\$1,268,000	\$1,431,000

* Number of items required.

TABLE III

ESTIMATED INVESTMENT FOR MODIFIED ZIRFLEX HEADENDS

	<u>5 kg U/Day</u>	<u>10 kg U/Day</u>
Dissolver - 309SCb	\$ 15,000 (1)*	\$ 15,000 (1)*
Dissolver Solution Holdup Tanks	20,000 (2)	30,000 (3)
Precipitator	20,000 (1)	40,000 (2)
Centrifuge	100,000 (1)	180,000 (2)
Supernate Collection Tanks	60,000 (2)	80,000 (2)
Coarse Feed Tank	5,000 (1)	10,000 (2)
Fine Feed Tank	5,000 (1)	8,000 (1)
Waste Evaporator	12,000 (1)	
Column Modifications	10,000	20,000
Dissolver Condenser	3,000 (1)	5,000 (1)
Evaporator Condenser	3,000 (1)	-----
Supernate Evaporator	40,000 (1)	60,000 (1)
Supernate Evaporator Condenser	12,000 (1)	18,000 (1)
Dilute Ammonia Hold Tanks	20,000 (2)	30,000 (2)
Ammonia Storage Tank	20,000 (1)	20,000 (1)
DOG Blower	3,000 (1)	5,000 (1)
Piping	400,000	600,000
Instruments	40,000	50,000
Electrical	15,000	30,000
Remove Existing Equipment	<u>30,000</u>	<u>30,000</u>
TOTAL DIRECT COST	\$ 833,000	\$1,231,000
Indirect Costs 26%	<u>\$ 216,000</u>	<u>320,000</u>
	\$1,049,000	\$1,551,000
Design 15%	<u>157,000</u>	<u>233,000</u>
	\$1,206,000	\$1,784,000
Contingency 25%	<u>302,000</u>	<u>446,000</u>
TOTAL	\$1,508,000	\$2,230,000

* Number of items required.

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APPENDIX III

PRESENT PERSONNEL REQUIREMENTS FOR OPERATION OF ICPP STR HEADEND AND
FIRST CYCLE SOLVENT EXTRACTION

<u>Plant Operations</u>	<u>Number of Personnel</u>
Staff	8
Operation Supervisors	11
Operators	<u>46</u>
SUBTOTAL	65
 <u>Maintenance</u>	
Staff	5
Supervisors	4
Craft Personnel	<u>32</u>
SUBTOTAL	41
 <u>Analytical</u> (Charged 75 per cent to Operations, 25 per cent to other projects)	
Staff	3
Supervisors	11
Chemists	21
Analysts	<u>8</u>
SUBTOTAL	43
 <u>Health and Safety</u>	
Staff	5
Supervisors	1
Technicians	<u>14</u>
SUBTOTAL	20
 TOTAL	 169

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APPENDIX IV

SUMMARY OF ZIRCONIUM FUEL PROCESS ECONOMIC FACTORS

ITEM	PROCESS									
	Present STR	Expanded STR		Revised STR Flowsheet (8)	Barium Fluozirconate	Revised Barium Fluozirconate (8)	Sodium Formate (8)	Modified Zirflex		
Processing Rate (1)		5 (9)	10 (10)	10	5	10	10	5	10	
Kg U per day	2.15			10	5	10	10	5	10	
Kg Zr per day	180	416	832	832	416	832	832	416	832	
Subassemblies per day	5	11.6	23.2	23.2	11.6	23.2	23.2	11.6	23.2	
Development Time, Years (2)	0	0	0.5	1	1	1	1.5	1.5	1	
Construction Time, Years (2)	0	1	1	1	1	1	1	1	1	
New Plant Investment (3)	0	\$344,000	\$449,000	\$449,000	\$1,268,000	\$1,431,000	\$1,400,000	\$1,400,000	\$1,508,000	\$2,218,000
Direct Operating Cost per Operating Day										
Labor	\$4981	\$5616	\$5541	\$5541	\$5844	\$5770	\$5770	\$5770	\$5730	\$6015
Process Chemicals	423	981	1962	1380	1020	2040	1180	930	630	1260
Other Direct Costs (4)	1600	1650	1700	1700	1650	1700	1700	1700	1750	1900
Total Direct Cost	\$7004	\$8247	\$9203	\$8621	\$8514	\$9510	\$8650	\$8400	\$8110	\$9175
Depreciation, per Operating Day (5)	\$1205	\$1287	\$1726	\$1726	\$1800	\$1850	\$1400	\$1400	\$1180	\$1273
Waste Storage, per Operating Day (6)	\$1910	\$4410	\$8820	\$6355	\$1332	\$2664	\$2664	\$2200	\$ 907	\$1814
Overall Operating Cost, per Operating Day	\$10,119	\$13,944	\$19,749	\$16,702	\$11,646	\$14,024	\$12,714	\$12,000	\$10,197	\$12,262
Unit Processing Cost (7)										
per gram U	\$4.70	\$2.79	\$1.97	\$1.67	\$2.33	\$1.40	\$1.27	\$1.20	\$2.04	\$1.23
per Kg Zr	\$56.20	\$33.70	\$23.70	\$20.05	\$28.00	\$16.90	\$15.30	\$14.40	\$24.50	\$14.70

- (1) Based on FWR Seed Core No. 1 subassembly. After burn-up composition: 36.0 kg Zr, 0.56 kg Sn, 431 g total U.
- (2) Some overlapping of development and construction would occur. Sum of two figures presented equals estimated total time to finished installation.
- (3) Includes all design, overheads and fees. Does not include any presently installed equipment that might be used.
- (4) Includes supplies, utilities, guard force, miscellaneous chemicals, etc.
- (5) Includes new equipment plus any existing equipment used. Does not include buildings or waste storage system.
- (6) Charged at \$2.01 per gallon for liquid storage and \$25 per cubic foot for solid storage.
- (7) Does not include cost of final purification and recovery of uranium, about \$0.30 per gram.
- (8) Based on present estimate of final process flowsheet. Subject to extensive revision as development program progresses.
- (9) Batch dissolution.
- (10) Continuous dissolution.

**PHILLIPS
PETROLEUM
COMPANY**

ATOMIC ENERGY DIVISION