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BNL 50700

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GUNA S. SELVADURAY, MARK K. GOLDSTEIN, AND ROBERT N. ANDERSON

July 1977

MASTER

PREPARED FOR THE
NATIONAL SCIENCE FOUNDATION
UNDER GRANT NO. OEP-7519422

DEPARTMENT OF APPLIED SCIENCE

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.
UPTON, NEW YORK 11973

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GUNA S. SELVADURAY,¹ MARK K. GOLDSTEIN, AND ROBERT N. ANDERSON²

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RESEARCH SPONSORED
BY THE NATIONAL SCIENCE FOUNDATION
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¹Stanford University, Palo Alto, CA

²San Jose State, San Jose, CA

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Printed in the United States of America

Available from

National Technical Information Service

U.S. Department of Commerce

5285 Port Royal Road

Springfield, VA 22161

Price: Printed Copy \$7.25; Microfiche \$3.00

October 1977

400 copies

ABSTRACT

An analytic methodology has been developed to compare the performance of various nuclear fuel reprocessing techniques for advanced fuel cycle applications including low proliferation risk systems. The need to identify and to compare those processes, which have the versatility to handle the variety of fuel types expected to be in use in the next century, is becoming increasingly imperative. This methodology allows processes in any stage of development to be compared and to assess the effect of changing external conditions on the process.

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1. Introduction

With the advent of President Carter's non-proliferation policy announced on April 1977 there is a need to reevaluate various advanced nuclear reactor concepts, reactor fuels and reprocessing requirements. A number of methods for reprocessing spent nuclear fuels has been proposed. It is important that these processes be evaluated in light of the developing low proliferation risk systems that are currently being scrutinized, so that evaluation methods will be available to identify the most suitable spent fuel reprocessing techniques to facilitate commercial implementation of advanced fuel cycles.

Of the various techniques suggested for the reprocessing of spent nuclear fuel, the one based on solvent extraction is probably the best known, most developed and most widely employed. Other techniques include electrochemical, halide volatility, pyrometallurgical, and photochemical separation among others. Without a formal decision analysis methodology it would be difficult to select a superior technique for a given situation. The comparative evaluation and selection is further complicated by the fact that all of the above processes are at different stages of development. Therefore a clearly superior technique, currently in the conceptual stage, might be rejected in favor of a more developed, but inferior technique. To this complexity can be added such factors as changing fuel types, safety regulations, economics and the world political pressures.

Though the primary aim of any reprocessing technique is the separation of reusable fuel from the poisonous fission products, a comparison of the various techniques should not be based on this one consideration, alone.

Other critical factors, including economics, environmental impact, safeguards of Strategic Nuclear Materials (SNM), acceptability to government and

local regulations, adaptability to changes in fuel type, must be included to provide a valid meaningful comparison. However, it must be noted that the various factors, while important, are not of equal significance. These factors must be weighted according to their importance and contribution. The particular weight assigned to a factor will also depend upon the prevailing conditions at a given time. Also variations in weight will exist as a reflection of the emphasis that a particular individual wishes to place on the analysis. The methodology allows the user the flexibility of analyzing a variety of weighted policy scenarios rapidly and simply.

In order to accommodate all of these variables, an analytical technique employing 11 subjective parameters (listed in Table 1) was developed. These parameters are assigned a 1 to 10 rating depending upon results of an objective 18-item questionnaire 2 (listed in Table 2). By assigning a ranking factor to each parameter, the analysis provides a numerical measure of performance for each process. As an illustration of this methodology of the 32 reviewed¹ fourteen processes selected are listed in Table 3.

Table 1: List of 11 Subjective Descriptors

1. Technical Complexity
2. Safeguards of Strategic Nuclear Materials (SNM)
3. Magnitude of Waste Problems
4. Sensitivity to Changing Safety Regulations
5. Sensitivity to Change in Fuel Type
6. Maintenance Problems
7. Development Factor
8. Reliability
9. Risk to Population
10. Economic Advantage
11. Decontamination Factor

Table 2: 18-Item Questionnaire

1. Unit cost of production for each unit operation at 1 ton/day
2. Estimated capital cost of plant
3. Separation factor for fission products
4. Fission product waste form
5. Waste material produced per kilogram of fuel reprocessed
6. Waste radiation level
7. Fuel type accommodated
8. Fuel cooling requirements
9. Breeder fuel capability
10. Batch or continuous process
11. Handling of cladding material
12. Form of reprocessed material
13. Plutonium handling
14. Handling of radioactive gases
15. Throughput/process inventory
16. Maximum credible accident
17. Advantages
18. Disadvantages

Table 3: List of Processes Selected for This Analysis

Process	Reference Number	Appendix No.
1. Airox	1	A
2. Electrochemical	2	B
3. Halide Volatility	3	C
4. Hydride	4	D
5. Ion-Exchange	5	E
6. Photochemical	6	F
7. Liquid-Liquid	7	G
8. Melt Refining	8,9	H
9. Tin-Nitride	10	I
10. Purex	11	J
11. Redox	12	K
12. Salt Transport	13	L
13. Thorex	14	M
14. Zinca1 (Pyrozinc)	15	N

2. The Requirement to Evaluate Reprocessing Techniques

The aqueous solvent extraction reprocessing methods all have a common principle of separation. The other reprocessing methods, selected for this sample analysis, are based upon different principles of separation which we feel illustrates the methodology adequately without having to consider all available techniques. The halide volatility process is based upon the difference in vapor pressure of the halides of uranium, plutonium and the fission products, at a given temperature. Electrochemical separation is based upon the difference in activity in solution, and hence the difference in electromotive force required to selectively drive the fission product to one of the electrodes. Pyrometallurgical and other techniques are based on various other principles of separation. In all cases, the starting point and the end point do not differ; what differs is the route taken. The various factors having effects on this route are constantly changing, and the sensitivity of each route to changing conditions needs to be established.

However, before the fuel reprocessing technique itself can be considered, the constraints that apply to the input material must be examined. For example, the spent fuel will be in claddings and will have a finite radioactivity level. Processes which cannot simultaneously process the fuel and the cladding material will require that the cladding be separated from the fuel before reprocessing. Processes which utilize media susceptible to radiation damage will require the fuel be cooled to an acceptable activity prior to reprocessing. The former constraint means head-end treatment facilities will be required. The latter constraint will determine the necessity for and the length of storage for pre-cooling.

A further constraint on the input material is its chemical form. Nuclear fuels could come in many forms - metallic, oxides, carbides, nitrides, and alloys. A process designed to handle all materials as oxides might or might not be converted easily to process a chemically different form of fuel. The ease of conversion will depend upon the chemistry and thermodynamics of the process. If the process is limited to handling the spent fuel in only one form, for example, in the oxide form, then, non-oxide fuels would either have to be converted to oxides before being reprocessed, or an alternative process would be required.

The physical form of the fuel adds a further complication. Techniques which require dissolution of the input before separation will be able to handle metallic fuels with greater ease than carbon-coated pellets. The carbon coating would have to be removed by some means, prior to separation. The dissolution of fuels with a carbon coating could result in the formation of the carbides, thus rendering it unsuitable to separation by liquid metal techniques; or, the solubility of carbon in the solvent might have adverse effects on the solubility and subsequent reaction of the fuel.

A significant aspect of reprocessing spent nuclear fuels is associated with waste disposal. The nature and quantity of the wastes produced has to be considered. A waste disposal method which merely transforms the waste to another form of waste would be self-defeating; such a method would not solve the problem of separating the wastes in a disposable form.

Factors affecting the economics are multifarious. A highly efficient process requiring less plant equipment will probably require less capital and lower operating expenses compared to another process having a lower efficiency and requiring more plant equipment. Two factors which have a great influence on process economics are:

1. the fuel pre-cooling requirements; and
2. the location of the reprocessing plant, i.e., on-site or off-site.

A reprocessing method requiring fuel pre-cooling immediately incurs two expense items: capital expenditure for spent fuel storage and higher fuel inventory costs. Reprocessing plant location is basically a trade-off between transportation costs and processing costs. To minimize processing costs, any processing plant should operate at, or close to, 100% of capacity. As the facility utilization decreases, the cost of reprocessing per unit increases.

One possibility is to have one reprocessing plant service a single reactor thereby eliminating the cost and hazards of transportation. Such an operation would probably be on a relatively smaller scale and the reprocessing plant might not run at 100% of design capacity.

On the other hand, it would also be possible to build larger centrally located, reprocessing plants which would have lower per kilogram of throughput processing costs. The penalty of transportation costs and hazards would have to be considered. Such a choice would naturally be influenced by the number, capacity and location of the nuclear reactors to be serviced as well as the proliferation risks.

In essence, what is needed is a method of analysis which will not just indicate which process is most technically suited for the reprocessing of spent fuel from advanced nuclear reactors, but more importantly, the method should enable us to make integrated decisions via properly formulated guidelines.

In order to execute such a comprehensive analysis, the pertinent factors have to be identified, and the effect these factors will have on the system as a whole determined. With that objective in mind, the methodology described

in the following section has been developed. It should be emphasized that in the analysis presented the weighted policy parameters have been chosen to il-lustrate the methodology, not to set policy for reprocessing decision makers. Quantifying these policy parameters will have to be determined by more a detailed study, which is currently in preparation.²

3. The Evaluation Technique

In comparing any two processes due consideration has to be given to all related factors. An economic analysis will be meaningful for the specific purpose of studying economic considerations; but to attempt to establish superiority of one process over another based purely on an economic analysis will be meaningless. The same can be said for any such comparative attempt based on just one or two criteria.

To make a meaningful comparison, not only must the relevant factors be identified, but the impact of these factors in the comparison must be established. The "impact" consideration is called "ranking" in this report. The different factors need to be ranked according to their degree of importance in the analysis. The ranks assigned will invariably depend on the analyst; however, by virtue of having established a ranking, the direction of emphasis (or the bias) of the analyst will be evident. The ranking chosen herein is for illustrative purposes only, and is not meant to be absolute.

The superiority of the technique developed here lies in the fact that while permitting emphasis in any chosen direction, it simultaneously compels the analyst to take into account, though to a lesser degree, other pertinent factors. In essence, a one-criterion comparison is avoided.

The purpose of this analysis is to establish a method by which various spent fuel reprocessing techniques can be evaluated for their application to low proliferation risk fuel cycles or other advanced fuel cycles.

3.1 Performance Factor

The 18-point questionnaire shown in Table 2 was formulated to record the performance and ability of each process in an efficient and easily compared manner. Based on this data, the 11 subjective descriptors listed in Table 1

were assigned a 1 to 10 rating. The rating for each descriptor is multiplied by a ranking factor which assigns the desired importance to be given to this descriptor. The product of the rating, "r", and the ranking "R", gives the total value for the item. The sum of the product, rR, for all descriptors, divided by the maximum potential value which is equal to $10 \sum R$, gives the numerical Performance Factor, "e", for the process as shown by the equation:

$$e = \frac{\sum rR}{10\sum R} \quad (1)$$

The questionnaire in Table 2 outlines the factors to be considered about the various processes, but does not answer the critical questions involved in decision making. The critical questions are the subjective descriptors listed in Table 1. Though these descriptors are not directly quantifiable, the knowledge gained from Table 2 provides the necessary information to assess the ratings. Needless to say, these ratings will also be on a comparative basis, depending on the nature of the descriptor.

3.1.1. Technical Complexity

In general, the overall complexity of a process can be equated to the complexity of the principle employed to achieve the goal. This appears in terms of increased number of unit operations, more stages in each operation, a greater need of safeguards to assure the degree of achievement, more precise control equipment, sophisticated labor requirements, and greater capital investment. One criterion used to assess the technical complexity of the processes being evaluated in this report is the principle of separation employed. The various methods have been divided into absolute and relative separation techniques. An absolute separation technique, (for example, a sink-float separation based on

differences of densities) will separate two materials of differing densities in one stage. Another technique, based on differences in relative solubilities, might achieve 90% separation in the first stage, 99% in the second stage, and so on, with 100% separation being theoretically achieved by an infinite number of stages.

Therefore, if a relative principle of separation is used, a cut-off point will have to be established; then, the number of stages to achieve this degree of separation will have to be determined. As the number of stages increase, the contents of the valuable material will decrease, and the control equipment required will have to be of greater precision. An increase in the quantity and quality of equipment invariably links with increased capital expenditure.

Absolute separation techniques may have some inherent contamination. If this level of contamination is above the permissible level, then further refining equipment will be required.

In addition to the above process complexities, all processes which require remote refabrication of the fuel rods have been penalized, as this additional requirement increases the technical complexity of the tail-end of the Fuel Cycle. Details of quantization are given by Selvaduray.²

3.1.2 Safeguards of Strategic Nuclear Materials

Strategic nuclear materials (SNM) consist of some fissile materials from which weapons can be made, namely ^{233}U , ^{235}U , and Pu, and have been defined as follows by the Nuclear Regulatory Commission:

- i. 2 kg. of Pu or ^{233}U ;
- ii. 5 kg. of uranium enriched to more than 20% in ^{235}U ;
- iii. a combination of these materials.

These quantities are established at a level substantially below that required for the manufacture of nuclear explosives.

Other actinides can be used to construct weapons, e.g., neptunium, and should be considered as SNM. Once reprocessing has become common world wide, tons of neptunium and other actinides could be diverted for weapon construction if overlooked by international safeguards.

Safeguards of strategic nuclear materials can be thought of on two levels:

- i. International Nuclear Proliferation or horizontal proliferation; and
- ii. Diversion of weapons grade material by subnational groups.

International nuclear proliferation is the increase in the number of countries that are capable of manufacturing a nuclear explosive. Implicit in this concept is the fact that the weapons grade material can be clandestinely or openly produced.

Of the strategic nuclear materials, ^{235}U can be obtained only by the arduous task of isotope enrichment via either gaseous diffusion or centrifuging. (The advent of laser isotope enrichment could possibly simplify this task greatly.) The technology is extremely sophisticated, the capital expenditure very high, and as a result is not within the reach of most nations at this time.

The other weapons materials, ^{233}U and Pu are bred (or converted) in nuclear power reactors. The fertile ^{232}Th is chemically different from the fissile ^{233}U ; likewise with ^{238}U and Pu. ^{233}U and Pu can be separated chemically from ^{232}Th and ^{238}U respectively, by processing (or reprocessing) the spent nuclear fuel. However, spent nuclear fuel also contains fission products, several of which are neutron poisons (absorbs neutrons without fissioning).

Materials containing ^{233}U , ^{235}U , and Pu can be used for making fission explosives only if these isotopes are sufficiently concentrated. For each iso-

tope, a minimum concentration in ^{238}U can be specified below which the mixture is not usable in a practical nuclear explosive. For ^{235}U this concentration is 20%. This will be a bare sphere critical mass of metal containing 20% ^{235}U and 80% ^{238}U , and weighing about 850 kg. The critical mass can be reduced by a factor of two to three by the use of a neutron reflector. The ratios of ^{233}U , ^{235}U , ^{239}U , ^{239}Pu and reactor-grade Pu to ^{238}U , corresponding to a critical mass of about 850 kg. are 1:8, 1:5, 1:8, and 1:7 respectively.

In fitting the spent nuclear fuel reprocessing industry into the international proliferation scenario, it is evident that reprocessing techniques that do not separate the fissile from the fertile materials, and at the same time having low decontamination factors, run a lower risk of making available weapons grade SNM.

Safeguarding of strategic nuclear materials from subnational groups basically involves the guarding of the sources of these materials. The basic elements of this aspect of safeguards are surveillance, containment or physical protection, and material balance accounting. Containment can involve the use of fences, substantial walls and enclosures, locks, tags, seals and similar measures. Surveillance includes direct observation and monitoring, and verification of plant operation and plant data. Material balance accounting is concerned with records, reports, and source data from the facility being inspected, and independent measurement as needed to form independent conclusions on materials accountability. While surveillance and physical measures provide direct and timely information on safeguarded material, accounting procedures provide indirect or circumstantial evidence.

The unauthorized movement of SNM from protected areas can take place by two means: it can either be stolen by force, or diverted by people having ac-

cess to it. However, for the material to be stolen or diverted, it would have to be in a form that is desirable from the point of view of the potential saboteur. In terms of "desirability," isolated plutonium without any diluents and in a form readily convertible to metal will probably be the most desirable. With increasing contamination the desirability decreases, since the thief will have need of sophisticated refining know-how and special equipment. Moreover, the fission-product contaminants make it easier to trace the plutonium.

The easiest point of diversion of SNM is probably during transportation. Transportation can be one of four modes: ship, train, airplane, or truck. Past hijacking incidents have shown that airplanes and trucks are predominantly the subjects of potential hijackers. This can be attributed to the fact that both airplanes and trucks can be relatively easily diverted to the hijackers desired destination once he/she has gained control over the vehicle. Trains on the other hand, can travel only on rails. Though the opportunities to hijack a train may be more abundant, the difficulty of transporting the required materials to the desired destination does seem to be a deterrent. Ships travel so slowly that even if hijacked, can be quite easily blocked. Furthermore, if they can be sufficiently separated from areas of population, any threatened damage will be of little, if any, consequence. Hence, it is felt that it can be concluded that the likelihood of a hijacker hijacking a ship or train are small, while airplanes and trucks run a much larger likelihood of being hijacked.

Reprocessing methods suitable for operation on a small scale, i.e., those which are suitable for the reprocessing of spent fuel from just one reactor, will have no long-distance transportation requirements. Both reactor and fuel reprocessing plant can be contained within one security system, and any material leaving the premises can more easily be identified. On the other hand, methods

which are suitable for large scale operation, or those that benefit greatly from economy of scale will probably be centrally located so that a number of nuclear reactors can be serviced. Short of the establishment of nuclear parks, such a system will, of course, have transportation needs, and will increase the potential for theft.

The factors affecting the safeguards issue can be redivided into two categories:

- i. Those which are a function of the process; and
- ii. Those which are a function of implementation and policy.

It is the first of these two categories that is of most concern in this analysis. The following factors can be identified as being either a function of the process, or being closely related to it:

- i. Separation of fissile material from fertile materials - i.e., is plutonium produced as an independent stream, or is the process aimed at plutonium separation only?;

- ii. Decontamination Factor;

- iii. Suitable for on-site operation or off-site operation servicing two or more reactors;

- iv. Labor intensity of the process;

- v. Materials accountability - this is related to the process in the sense that processes with fewer effluent streams will afford better materials accountability as opposed to processes with several effluent streams.

If plutonium does exist, then it has to be available for diversion; off-site transportation greatly facilitates this - especially in the case of international proliferation. Once the material comes off-site and is available for diversion, its "desirability" can be directly correlated to its purity.

Labor intensity and materials accountability (interpreted in terms of number of effluent streams) are also factors that could facilitate diversion. The larger the working force, the larger the number of people having access to restricted areas, or "legal" entrance into the area in which the facility is situated. This increases the risk of an "inside job" being planned.

Materials accountability should be good in a reprocessing plant, since this can be a crucial factor in the discovery of the occurrence of a diversion. If there exists several streams carrying plutonium, then a group could enter a plant, drain off one of these lines, and leave undetected with a significant quantity of SNM. They could alternately accumulate the material over a span of time, operating within the limits of error of these several streams. On the other hand, if there is just one stream, the lack of any material can be detected in the next process step, thus leading to early detection of the loss.

However, these latter two factors have been considered on lower level of concern because the role they play is one of facilitating the diversion, rather than actual participation in the act of diverting.

3.1.3 Waste Volume

Waste from a reprocessing plant can be evaluated in terms of volume, form (gas, liquid or solid), activity levels, and toxicity. Three of the important radioactive waste gases are iodine, krypton, and xenon. These are liberated when the fuel element is dissolved or heated. It can be safely assumed that all the reprocessing methods considered here produce approximately the same amount of waste gases.

For processes utilizing aqueous solutions, liquid wastes constitute the major aspect of the disposal problem. From the standpoint of disposal, liquid wastes can be divided into two broad categories: (a) "high-level" wastes with

activities in the range of curies per liter, and (b) "low-level" wastes with activities in the microcurie per liter range. High-level radioactive wastes from fuel reprocessing plants in the past have been stored in underground tanks. Low level wastes are in the best situation concentrated or stored in barrels.

Processes employing liquid metals will produce solid wastes. In addition, filters, absorption materials, and discarded process equipment from any reprocessing method constitute solid wastes.

Based upon the assumption that all wastes produced will be stored it is evident that reliability of storage facilities are best for solid wastes. Liquid and gaseous wastes contain within them the inherent ability to disperse when released from containers. The potential danger from escaped wastes is directly proportional to radioactivity levels and the chemical form of the material as well as its surroundings. Hence, in terms of ease of handling, convenient storage and over-all safety, low volume low activity, solid wastes are quite manageable. Large volume-high activity liquid and gaseous wastes are less manageable. These parameters have been quantified based on the above criteria.²

3.1.4. Sensitivity to Changing Regulations

Development in the nuclear industry has been so fast that, generally, regulations are lagging behind. Federal and local regulatory bodies are constantly developing more stringent safety requirements. Many of the more recent regulations have been enacted long after plants have been built, resulting in increased capital equipment costs.

It is extremely difficult to foresee the types of regulations that might be enacted in the future. However, it is believed that regulations regarding

safety, waste disposal, and extraction and isolation of the fission products are the areas that will have a large impact on fuel reprocessing facilities. Sensitivity of reprocessing methods to changing regulations has been judged on the above criteria.²

3.1.5 Sensitivity to Change in Fuel Type

Fuel specifications for nuclear reactors are continually changing. In addition to metallic uranium, the oxides, carbides, nitrides, as well as alloyed fuels are being used. Further, some of these fuels are in the form of coated particles.

Uranium metals are being used in low exposure natural uranium systems. For water-cooled reactors, the presently favoured and most thoroughly proven fuel material is uranium oxide. Carbide fuels appear promising for non-water reactors. Studies of other fuel compounds such as nitrides, sulfides, and silicides are also progressing. For future applications, ceramic fuel particles coated with carbon (or other material) offer an interesting fuel for high-temperature gas cooled reactors. A number of fluid concepts, utilizing molten salt, gaseous core, molten plutonium and aqueous slurries, have been studied. Fast breeder reactors using the plutonium and U-238 or thorium and U-233 fuel cycle, or a combination of these such as the denature thorium cycle, and thermal breeders fueled on thorium and U-233 are very attractive as they promise to extend, by an order of magnitude or more, the fuel utilization of our uranium and thorium resources.

The ideal reprocessing technique should be able to reprocess any fuel type that is fed into it. Such adaptability will naturally depend upon the chemistry and thermodynamics of the process. Some of the processes have been developed

for one specific fuel type and the risk of adopting such a process for further development needs no emphasis.

Processes believed to be able to handle any conceivable fuel type (i.e., 8 or more) were given a rating of 10. Processes capable of handling only one type of fuel receive a rating of 3; the intermediate levels are prorated.²

3.1.6 Maintenance

An important factor for a successful process is trouble-free operation. Likely operational troubles and maintenance requirements will depend on the materials used in the process and the materials used in the equipment. Equipment that is remotely controlled might have a breakdown once a year; however, if the corrective maintenance required that the whole plant to be shut down, and, in addition, required highly skilled labor to effect the repair, the economic significance might make that system unattractive. For comparison, stainless steel tanks require regular maintenance; however, that work can be done relatively easily and without plant shut-down. An attempt has been made to assess the dollar-value of the maintenance work required and quantify the parameter associated with the maintenance.²

3.1.7 Development Factor

The commercial availability of a process is directly dependent on the level to which it has been developed. Therefore, processes that have been operated on a commercial scale have been rated 10; processes that have been developed to the pilot plant stage have been rated 8 or 9; techniques that have been studied on a laboratory scale from 3 to 7, depending upon the quantity and quality of the study; and reprocessing methods that are in the conceptual stage, a rating of 1.²

The inclusion of the development factor is important in this analysis as it focuses attention on the processes which might otherwise be dismissed as not feasible for the simple reason that insufficient effort has gone into proving their worth.

3.1.8 Reliability

Reliability has been assessed in terms of the ease with which the process attains the final objective, and in addition, the vulnerability to changing and/or fluctuating conditions. Therefore, methods requiring multistage separation will be less reliable than a single stage separation. The uncertainties in each stage are multiplicative.²

Techniques utilizing reagents, solvents, and/or equipment sensitive to radiation will not tolerate large fluctuation in activity levels. Any error in quality control on the input could easily have adverse effects on the process, enlarging the quality of the end product as well as safeguards, e.g., the limit of error of material unaccounted for (LEMUF).

3.1.9 Risk to Population

Each process has been evaluated for the potential danger it might pose to the nearby population in the event of a natural calamity (such as an earthquake), or man-inspired damage (i.e., sabotage). A main objective is to prevent the ease of dispersion of the nuclear products. Aqueous liquids when spilled, will flow to lower levels. If they come into contact with ground water or streams, they will then be carried further. Even in stagnant pools, liquid diffusion is quite fast. On the other hand, liquid metals, and salts, when spilled, will cool and solidify, naturally preventing dispersion. Winds will only enhance the cooling of these high temperature liquids. Therefore, processes employing large volumes of aqueous liquids pose the greatest poten-

tial danger; whereas, processes which will automatically contain themselves, in the event of a calamity are least hazardous.² The probability of design failure and process effluents are other parameters that need to be accounted for in a more detailed analysis.²

3.1.10 Economic Advantage

In assessing the economic advantage of the various processes, the cost of processing 1 kilogram of fuel per day, was estimated. These cost estimates were based on flow sheets which indicate only blocks of equipment, and not on detailed engineering designs. In cases where more detailed information was available, the information was incorporated into the estimates, and the costs updated to 1975 dollars using the Marshall and Stevens Equipment Cost Index and Chemical Engineering Plant Cost Index. It must be reiterated that processing costs only have been estimated; other costs, such as head-end treatment, fuel transportation, inventory, safeguards and safety requirements, as well as R & D have not been included. The inclusion of such factors would, of course, affect the over-all costs. However, from the standpoint of illustrating the methodology presented in this paper these costs estimates are adequate.

The process with the lowest cost of reprocessing was given a rating of 10, that with the highest a rating of 1.² The processes in between, have been assigned ratings by linear interpolation.²

3.1.11 Decontamination Factor

Decontamination of the recycled fuel is necessary for a preservation of neutron economy in the reactor. Higher decontamination factors are desirable. To meet neutron economy requirements, a decontamination factor of at least 10^2 should be achieved. This has been assigned a rating of 1. Decontamination

factors of 10^6 and above have been rated 10; the interval being prorated on a logarithmic scale.²

There is another concept called co-processing which could reverse these ratings, i.e., the co-processing concept assumes the least decontamination required the better since diversion of sum would be less likely. This concept would have advantages from a safeguards view point but would suffer economically because of remote fuel fabrication requirements.¹

4. Results of Analysis

The results of this sample analysis are shown summarized in Table 4. The Performance Factor shown in this Table is that calculated according to Equation (1) multiplied by 100 for convenience.

The ranking of these 11 parameters represent the subjective decision of the authors made primarily to illustrate the utility of the methodology. A survey has been made to determine the general ranking importance assigned to these parameters by the technical community, government agencies, utilities and the public.²

The Tin-Nitride high temperature Process has the highest performance factor and the Ion Exchange Process has the lowest performance factor based on the authors ranking (a complete analysis using this new methodology is in preparation²).

It is unfortunate that more than half of the processes investigated have not been developed to the pilot plant stage. Hence, the data available is from limited laboratory experiments. The development of pilot plants will establish both the advantages and limitations more vividly. This type of analysis could prove useful in identifying those separation processes most promising for further development.

A summary of the cost of reprocessing spent fuel by the 14 processes is given in Table 5. The last column shows the cost factor compared to Purex which was taken as the base. A summary of the fuel type accommodated by each reprocessing method is compiled in Table 6. While the decontamination factors of the various processes are depicted in Figure 1.

Table 4: Summary of Ratings & Performance Factors for the 14 Processes

		Process													
Descriptor	Rank	Airox	Electrochemical	Halide Volatility	Hydride	Ion Exchange	Photochemical	Liquid-Liquid	Melt Refining	Tin-Nitride	Purex	Redox	Salt Transport	Thorex	Zincal (Pyrozinc)
1. Technical Complexity	7	8	5	4	3	4	4	7	9	8	3	3	4	3	6
2. Safeguards of Plutonium	10	9	8	5	7	3	3	8	8	8	5	5	5	5	8
3. Magnitude of Waste Problem	8	9	8	4	9	3	4	8	9	9	3	3	6	3	9
4. Sensitivity to Changing Safety Regulations	5	3	7	6	3	4	4	5	5	5	4	4	7	4	5
5. Sensitivity to Change in Fuel Type	5	3	3	8	3	4	10	7	3	7	4	4	8	4	3
6. Maintenance Problems	8	8	4	6	5	5	3	5	5	5	8	8	6	8	5
7. Development Factor	4	4	3	9	3	9	1	3	9	4	10	9	8	10	3
8. Reliability	10	4	7	8	2	8	6	5	7	8	9	9	7	9	6
9. Risk to Population	10	7	8	3	7	4	5	9	9	9	4	4	6	4	9
10. Economic Advantage	5	6	10	8	9	5	9	10	8	10	3	1	9	4	10
11. Decontamination Factor	5	1	2	10	2	3	10	4	1	4	10	10	10	10	2
TOTAL	770	473	483	464	390	366	393	515	536	564	434	420	506	439	506
PERFORMANCE FACTOR		61	63	60	51	48	51	67	70	73	56	55	66	57	66

Table 5: Summary of Cost Estimates (All Costs in 1975 U.S. \$)

Process	Equipment	Total Capital	Operating Cost per annum	Process Cost per kg fuel	Process Cost Purex Cost
1. Airox	3,354,000	17,590,300	14,190,667	47.30	0.74
2. Electrochemical	3,000,000	12,480,000	4,065,140	13.55	0.21
3. Halide Volatility	4,672,510	20,811,389	8,292,238	27.64	0.43
4. Hydride	4,425,000	16,558,750	5,660,272	18.87	0.29
5. Ion-Exchange	6,830,000	26,318,500	14,558,132	48.53	0.76
6. Photochemical	5,324,000	19,904,300	6,327,688	21.09	0.33
7. Liquid-Liquid	3,400,000	11,460,000	4,145,622	13.82	0.22
8. Melt Refining	13,538,460	39,154,932	9,262,387	30.87	0.48
9. Tin-Nitride	2,850,000	12,382,500	4,641,342	15.47	0.24
10. Purex	6,909,883	32,974,174	19,236,227	64.12	1.00
11. Redox	9,303,366	43,869,227	24,874,654	82.92	1.29
12. Salt Transport	4,280,000	12,438,400	6,348,854	21.16	0.33
13. Thorex	3,341,540	20,898,496	18,145,751	60.49	0.94
14. Zinca (Pyrozinc)	4,625,000	15,648,750	5,045,184	16.82	0.26

Table 6: Fuel Types Accommodated by the Reprocessing Techniques

Process	Fuel Type							Remarks
	U	UO ₂	UC	Alloy	Pu	Th	ThO ₂	
1. Airox		X						
2. Electrochemical	X				X	X		
3. Halide Volatility	X	X		X	X	X	X	Possibly UC
4. Hydride	X							
5. Ion-Exchange	X	X			X	X	X	Soluble in HNO ₃
6. Photochemical	X	X	X	X	X	X	X	
7. Liquid-Liquid	X				X	X		
8. Melt Refining	X							
9. Tin-Nitride	X	X	X	X				
10. Purex	X	X			X			Soluble in HNO ₃
12. Salt Transport	X	X	X	X	X	X		
13. Thorex					X	X		Soluble in HNO ₃
14. Zincal	X	X						Possibly UC

Figure 1. Log₁₀ decontamination factor.

5. Application of this Analysis to Low Proliferation Risk and Advanced Fuel Cycles

A continuing review of the advantages and disadvantages of various re-processing methods for advanced fuel cycles is required because the relative position of these techniques will change as new technical developments occur in materials and processing and as new perception of risks become factored into policy decision analysis. This methodology is capable of characterizing and quantifying the advantages and disadvantages of alternative fuel cycles. This analysis can be performed as a function of a chosen mix of reactor fuel types employed to meet a variety of future energy demands.

An example of its application is shown in the following scenario presented in Table 7. This is based on an assumed fuel mix in 2020. The results show the required processing for the constraints given in Notes 1 and 2. This scenario is not intended to be a forecast, but was chosen strictly to illustrate the usefulness of this methodology in planning and analysis exercises.

Table 7: Scenarios of Reprocessing Requirements for
Advanced Fuel Cycle in 2020

Reactor Type	Number in Operation	Fuel Type	Spent Fuel Tons/Year	Applicable Processes	Performance Factor	Number of Processes Refined
LWR	130	UO ₂ (low burn-up)	390,000	Airox	61.4	Tin-Nitride 230,400 Tons/Year
				Halide Volatility	60.3	Salt Transport 76,800 Tons/Year
				Ion Exchange	47.5	Zincal 76,800 Tons/Year
				Photochemical	51.0	
				Tin-Nitride	73.2	
				Purex	56.4	
				Redox	54.5	
HTGR	20	UC	60,000	Salt Transport	65.7	
				Zincal	65.7	
LMFBR	1	UO ₂ (high burn-up)	30,000	Photochemical	51.0	Tin-Nitride 36,000 Tons/Year
				Tin-Nitride	73.2	Salt Transport 24,000 Tons/Year
				Salt Transport	65.7	

Table 7 (Cont'd)

Reactor Type	Number in Operation	Fuel Type	Spent Fuel Tons/Year	Applicable Processes	Performance Factor	Number of Processes Refined
Mis	10	Metal Alloys	30,000	Halide Volatility	60.3	Tin-Nitride 18,000 Tons/Year
				Photochemical	51.0	Salt Transport 12,000 Tons/Year
				Tin-Nitride	73.2	
				Salt Transport	65.7	

Notes: 1. The Performance Factor (PF) is based on ranking presented in this report in Table 4. To avoid reliance on just a single process the highest PF will share the field with the second highest PF value in 60--40 ratio if a second is available.

2. It is assumed that there is 3000 tons spent fuel per year per reactor.

6. Conclusions

An analytic methodology has been developed to compare the performance of various nuclear fuel reprocessing techniques for advanced low proliferation risk fuel cycle applications. The analysis employs 11 subjective descriptors which are given a 1 - 10 rating after an 18 item questionnaire is completed for the process in question. The rating for each descriptor is multiplied by a ranking factor which assigns the desired importance to be given to these descriptors. The sum of the rating and ranking product for all descriptors divided by the maximum potential value gives the numerical figure of performance for the process.

Through this analytical method, different importance can be assigned to a given item by changing the ranking values. For example, the comparison between the processes could be on cost alone or on environmental safety, regulatory and safeguard considerations alone or any combination of the mix by adjusting the appropriate ranking coefficient from 0 to 10.

This technique offers an easily applied yet formal approach to gain insight into the effect that a change in external conditions can produce on a given reprocessing technique. The subjective components can be refined to improve confidence in the analysis when better data becomes available.

This methodology has been applied to 14 different reprocessing concepts as a sample illustration.

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APPENDIX A: AIROX PROCESS⁽³⁾

AIROX Process

1. Cost of Production of 1 Kg (300 MT/year) \$ 47.30
2. Estimated Capital Cost \$ 17,590,300
3. Separation Factor for fission products
Decontamination Factor: $\approx 10^2$
Kr,Xe,Cs,I : 99% removed
Ru : 90% removed
Tc,Cd,In : 50% removed
Mo,Nb : 2% removed
4. Fission Product Waste Form: Gaseous
5. Waste Material produced / Kg fuel reprocessed
No liquids or solids from process
6. Waste radiation level: No data
7. Fuel Type Accommodated: UO_2 only
8. Fuel Cooling Requirements: None
9. Breeder Fuel Capability : None
10. Batch or Continuous: Could be either
11. Handling of cladding Material :
No Head-End treatment required. After the "oxidation and reduction decladding" step, the cladding material is separated from the U_3O_8 .
12. Form of reprocessed Material : Sintered pellets
13. Plutonium handling : Plutonium not separated
14. Handling of radioactive gases : Collect & Store
15. Throughput/process inventory : No Data
16. Maximum credible accident :
Accidental release of radioactive gases into the atmosphere

AIROX Process (Continued)

- 17. Advantages : (1) Rapid reprocessing
(2) No separate head-end treatment required
- 18. Disadvantages : (1) Low decontamination; recycle of poisonous f.p. (2) flexibility (adaptability) good only for UO_2 .
(3) Remote refabrication required

Operating Costs

1. Annual Plant Costs	2,089,735
2. Chemicals	3,933,000
3. Labor	4,000,000
4. Fringe Benefits (25% of 4)	1,000,000
5. Maintenance (1% of Total Capital Costs)	175,000
6. Utilities (25% of 1)	522,434
7. Insurance (5% of 1)	104,487
	<hr/>
	11,825,556

8. Contingencies	2,365,111
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Total Operating Costs	<hr/> 14,190,667
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Cost of Reprocessing per Kg fuel	<hr/> \$ 47.30
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Total Capital Costs

1. Total Process Equipment	3,354,000
2. Installation (40%)	1,341,600
3. Instrumentation (10%)	335,400
4. Buildings	4,000,000
5. Waste Disposal Facility	2,000,000
6. Services, Stores and Yards	1,000,000
7. Laboratory and Administrative Facilities	1,500,000
	<hr/>
	13,531,000
8. Engineering 10%)	1,353,100
9. Contingencies (20%)	2,706,200
	<hr/>
Total Capital Cost	<u>17,590,300</u>
Annual Plant Cost	2,089,735

Process Equipment

1. Furnaces	1,032,000
2. Classifiers and Blenders	206,400
3. Granulators	206,400
4. Drying Oven	103,200
5. Sintering Furnace	1,032,000
6. Pellet Press	103,200
7. Pellet Inspection Equipment	607,800
Total Process Equipment	<u>3,354,000</u>

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APPENDIX B: ELECTROCHEMICAL SALT REPROCESSING⁽⁴⁾

Figure 3. Proposed fused salt electrolysis system of reprocessing involving a dripping manganese cathode.

Electrochemical Process

1. Cost of Production of 1 kg (300 MT/Year): \$ 13.55
2. Estimated Capital Cost: : \$ 12,480,000
3. Separation Factor for Fission products
Decontamination Factor: $10^2 \approx 10^3$ f.p.
close to U, cannot be separated electrolytically.
4. Fission Product Waste Form: Salt; active f.p. in salt, noble f.p. metallic anode muds.
5. Waste material produced/kg fuel reprocessed: 1/25 kg, Anode residue and residual salt.
6. Waste radiation level: 3.5 watts/cc
7. Fuel-Type Accommodated: Metallic
8. Fuel cooling requirements: None
9. Breeder Fuel Capability: Yes, if metallic
10. Batch or continuous: Probably batch
11. Handling of cladding material: Head-End Treatment required
12. Form of reprocessed material: Metal alloy which can be converted to oxide or hexafluoride if desired
13. Plutonium handling: Pu can be separated or can go with the uranium; separate extraction step required
14. Handling of radioactive gases: Very effective for gases, since non-obscuring of tritium, etc.
15. Throughput/process inventory: 1 kg fuel day/ 1 kg molten salt
16. Maximum credible accident: Salt loses heat and batch is dumped as solid
17. Advantages:
 - (1) Can handle 1 in short cooled fuel.
 - (2) Can work with thorium
18. Disadvantages:
 - (1) Corrosion problems
 - (2) Applicable to limited (metallic) fuel types.
 - (3) Contamination of U resulting in further refining being required.
 - (4) Remote refabrication required.

Operating Costs

1. Annual Plant Costs	1,482,629
2. Mn Consumption	35,400
3. Salt Consumption	300,000
4. Utilities	370,657
5. Personnel 40 at \$ 20,000 p.a.	800,000
6. Fringe Benefits (25% of 5)	200,000
7. Maintenance (1% of Total Capital Costs)	124,800
8. Insurance (5% of 1)	74,131
	<hr/>
	3,387,617
9. Contingencies	677,523
	<hr/>
Total Operating Costs	4,065,140
	<hr/>
Cost of Reprocessing per kg fuel	\$ 13.55

Total Capital Cost

1. Process Equipment	3,000,000
2. Installation	1,200,000
3. Instrumentation (10%)	300,000
4. Buildings 20,000 ft ² @ \$30/ft ²	600,000
5. Waste Disposal Facilities	2,000,000
6. Services, Stores and Yards	1,000,000
7. Laboratory and Administrative Facilities	1,500,000
	<hr/>
	9,600,000
8. Engineering	960,000
9. Contingencies	1,920,000
	<hr/>
Total Capital Costs	12,480,000
	<hr/>
Annual Plant Costs	1,482,629

Process Equipment

1. Electrolytic Cell with supporting equipment and shielding	1,500,000
2. Mn distillation and U casting	500,000
3. Salt Recycle and Pu recovery by Chlorination	1,000,000
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Total Process Equipment	3,000,000

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APPENDIX C: HALIDE VOLATILITY⁽⁵⁾

Halide Volatility

1. Cost of Production of 1 Kg fuel (300 MT/year)	\$ 27.64
2. Estimated Capital Cost	\$ 20,811,389
3. Separation factor for fission products	
Decontamination factor: 10^8	
4. Fission Product Waste Form:	Fluorides--Volatile and non volatile and gases
5. Waste Material produced per Kg fuel reprocessed $\approx$ 0.5 gal/Kg high level wastes	
6. Waste radiation level:	
7. Fuel Type accommodated:	Metallic, oxide U, Pu, Th Molten salt possible
8. Fuel cooling requirements:	None
9. Breeder Fuel Capability:	Yes
10. Handling of cladding materials, possible to declad while fluorinating, preferable to have separate head-end treatment	
11. Continuous	
12. Form of reprocessed material:	UF ₆
13. Pu handling :	Can be separated as the fluoride
14. Handling of radioactive gases:	Collect and Store
15. Throughput/process inventory :	
16. Maximum credible Accident :	In addition to ordinarily gaseous f.p. the volatile f.p. could be released into the atmosphere. Liquid f.p. could spill.

Halide Volatility (Continued)

17. Advantages

(1) UF_6 can be sent directly to enrichment plant

(2) High decontamination

18. Disadvantages:

(1) Accident risk very high-volatile f.p.

(2) Corrosion problems.

Operating Costs

1. Annual Plant Cost	2,472,401
2. Chemicals	987,983
3. Labor 100 @ \$ 20,000 p.a.	2,000,000
4. Fringe Benefits (at 25% of 4)	500,000
5. Maintenance (1% of Total Capital Costs)	208,114
6. Utilities (25% of 1)	618,100
7. Insurance (5% of 1)	123,600
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	6,910,198
8. Contingencies (20%)	1,382,040
Total Operating Costs	<hr/>
	8,292,238
Cost of Reprocessing per kg fuel	\$ 27.64

Total Capital Costs

1. Process Equipment	4,672,510
2. Installation and Overheads (40%)	1,869,000
3. Instrumentation (10%)	467,251
4. Buildings	3,500,000
5. Waste Disposal Facility	2,500,000
6. Services, Stores, and Yards	1,000,000
7. Laboratory and Administrative Facilities	1,500,000
8. Chemical Make-up and Storage	500,000
	<hr/>
	16,008,761
9. Engineering (10%)	1,600,876
10. Contingencies (20%)	3,201,752
	<hr/>
Total Capital Costs	20,811,389
	<hr/>
Annual Plant Cost	2,472,401

Process Equipment

1. Uranium dissolution, solvent Regeneration and UF ₆ purification	1,592,916
2. Pu recovery and purification	150,148
3. Scrubber	63,772
4. Fluorine Plant	2,865,674
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Total Process Equipment	4,672,510

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APPENDIX D: HYDRIDE PROCESS⁽⁶⁾

Figure 5. Hydride reprocessing schemes as visualized by the authors.

Hydride Process

1. Cost of Production of Kg (300 MT/Year)	\$ 18.87
2. Estimated Capital Cost	\$ 16,558,750
3. Separation factor for fission products	Poor (probably $10^2 \approx 10^3$)
4. Fission product waste form:	Intermetallic solid containing f.p.
5. Waste material produced per kg fuel reprocessed:	$\approx 0.2 \approx 0.3$ Kg, pre-dominantly uranium. Also gases
6. Waste radiation level:	No Data
7. Fuel type accommodated:	Metallic; uranium only
8. Fuel cooling requirements:	None
9. Breeder Fuel Capability:	None
10. Batch or continuous process:	Batch
11. Handling of cladding material:	Head-end Treatment necessary
12. Form of reprocessed material:	Uranium Hydride
13. Plutonium handling:	No specific separation
14. Handling of radioactive gases:	Should be collected during initial melting
15. Throughout/process inventory:	Sn_2Cl_2
16. Maximum credible accident:	Release of radioactive gases into atmosphere
17. Advantages:	(1) Rapid reprocessing
(2) No liquid waste
18. Disadvantages:	(1) Suitable only for metallic uranium
(2) Low decontamination
(3) Hydriding in solid state-slow reaction kinetics
(4) Possible use of silver could be very expensive
(5) High loss of U, Pu
(6) Very primitive

Operating Costs

1. Annual Plant Costs	1,967,186
2. Sn Consumption	113,960
3. HCl and H ₂ consumption	280,000
4. Crucibles	350,000
5. Utilities (25% of 1)	491,800
6. Personnel 50 at \$ 20,000 p.a	1,000,000
7. Fringe Benefits (25% of 6)	250,000
8. Maintenance (1% of Total Capital costs)	165,588
9. Insurance (5% of 1)	98,359
	<hr/>
	4,716,893
10. Contingencies	943,379
Total Operating Costs	<hr/>
	5,660,272
Cost of Reprocessing per Kg fuel	\$ 18.87

Process Equipment

1. 200 kg Induction Furnace with support equipment and shielding	750,000
2. Crucible removal Remote controlled	1,000,000
3. Hydriding Chamber	1,500,000
4. HCl leach tank	325,000
5. Dissociation Chamber	500,000
6. HCl Recycle	350,000
Total Process Equipment	<u>4,425,000</u>

Consumable Items

1. Crucibles (300 + 500) ZrO_2 @ \$100 each 10 cm x 10 cm x 50 cm	350,000
2. Sn consumption 14,800 kg @ \$ 7.70/kg	113,960
3. HCl	250,000
4. Hydrogen	30,000
Total Consumable Items	<u>1,033,960</u>

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APPENDIX E: ION EXCHANGE⁽⁷⁾

Figure 6. Excer process of reprocessing in which uranium in fuels is converted to uranyl nitrate solution and is separated from alloying element and fission products by cation exchange and electrolytic reduction and precipitation.

Ion Exchange

1. Cost of production of 1 kg (300 MT/year)	\$ 48,53
2. Estimated Capital Cost	\$ 26,318,500
3. Separation Factor for fission products
Decontamination Factor:	$10^5 - 10^6$
4. Fission Product Waste form:	Aqueous soln, and gases from dissolution
5. Waste Material produced per kg fuel reprocessed	
6. Waste radiation level:	No Data
7. Fuel type accommodated:	Metallic, oxide; basically any fuel that will dissolve in HNO_3 to form $\text{UO}_2(\text{NO}_3)_2$
8. Fuel cooling requirements:	Depends upon resins and membranes. Generally radiation should not exceed 1 ~ 4.5 watt-hr per gram of dry resin ($0.38 \times 10^9 \sim 1.7 \times 10^9$ r)
9. Breeder Fuel Capacity:	Aqueous homogenous reactor-- maybe LMFBR and MSBR-NO
10. Continuous	
11. Form of reprocessed material:	Anhydrous UF_4
12. Handling of cladding material:	Head-End treatment required
13. Plutonium handling:	Though the Excer process does not include Pu separation this is possible by adding another Ion Exchange stage using silica-gel, pretreated with an aqueous reducing agent and 30 v/v TBP
14. Handling of radioactive gases:	Collect and Store
15. Throughput/process inventory:	

Ion Exchange (Continued)

16. Maximum credible Accident: Spill of liquids and subsequent seepage to water-table could result in large scale contamination
17. Advantages:
- (1) Can be applied to specific purposes; e.g., tail-end Pu separation
 - (2) Good selectivity, and thus higher over-all product concentration
 - (3) Smaller reagent requirement compared to other aqueous processes.
18. Disadvantages:
- (1) Resin susceptible to radiation damage - therefore precooling required
 - (2) Liquid Wastes
 - (3) Loss of $\approx 5\%$ of uranium

Operating Costs

1. Annual Plant Cost	3,126,648
2. Chemicals and Reagents	2,803,950
3. Utilities (25% of 1)	781,662
4. Personnel 200 at \$ 20,000 p.a.	4,000,000
5. Fringe Benefits (at 25% of 4)	1,000,000
6. Maintenance (1% of Total Capital Cost)	263,185
7. Insurance (5% of 1)	156,332
	<hr/>
	12,131,777
8. Contingencies (20%)	2,426,355
Total Operating Cost	<hr/>
	14,558,132
Cost of Reprocessing per kg fuel	\$ 48.53

Total Capital Costs

1. Chemical Make-up and Storage	500,000
2. Process Equipment	6,830,000
3. Installation and Overheads (40% of 2)	2,732,000
4. Instrumentation (10% of 2)	683,000
5. Buildings	3,000,000
6. Liquid and Waste Disposal Tanks	4,000,000
7. Services, Stores, and Yards	1,000,000
8. Laboratory and Administrative	1,500,000
	<hr/>
	20,245,000
9. Engineering (10%)	2,024,500
10. Contingencies (20%)	4,049,000
	<hr/>
	26,318,500
Annual Plant Cost	3,126,648

Process Equipment

1. Dissolution Tank	325,000
2. Ion Exchange Columns	2,500,000
3. Electrolysis Cell	1,500,000
4. Precipitator	300,000
5. Evaporator	400,000
6. Filter	70,000
7. HCl & HNO ₃ Recycle	100,000
8. Pipes, Valves and Fittings (50% of 2,4,5 and 6)	1,635,000
Total Process Equipment	<hr/>
	6,830,000

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APPENDIX F: PHOTOCHEMICAL (8)

Figure 7. Flow chart of photochemically modified purex process for treatment of low enriched uranium fuel (9).

Photochemical Separation

1.	Cost of Production of 1 kg (300 MT/year)	\$ 57.73
2.	Estimated Capital Cost	\$ 30,904,300
3.	Separation factor for fission products:	
	Decontamination Factor: $\approx 10^8$	
4.	Fission product waste form:	Basically liquid, and rare gases from dissolution - ref. Purex
5.	Waste Material produced per kg fuel reprocessed:	Half the volume of Purex waste
6.	Waste radiation level:	No data
7.	Fuel Type accommodated:	Any type, so long as oxidation-reduction can be photochemically induced
8.	Fuel cooling requirements	None
9.	Breeder Fuel Capability:	Yes
10.	Continuous	
11.	Handling of cladding material:	Head-End treatment required
12.	Form of reprocessed material:	Liquid. If HNO_3 dissolution is employed then probably uranyl nitrate
13.	Plutonium handling:	Pu can be isolated in a relatively pure form. Solution can be treated to obtain desired chemical form
14.	Handling of radioactive:	Collect and store
15.	Throughput/process inventory:	No data
16.	Maximum credible accident:	Spill of liquid solution could result in seepage down to water table
17.	Advantages:	(1) High decontamination
(2) Good separation of f.p. depending upon their lives
18.	Disadvantages:	(1) Low energy efficiency
(2) Liquid wastes

Operating Costs

1. Annual Plant Costs	3,364,638
2. Reagents for Dissolution (estimate)	5,000,000
3. Utilities (25% of 1)	841,159
4. Personnel 190 at \$ 20,000 p.a.	3,800,000
5. Fringe Benefits (at 25% of 4)	950,000
6. Maintenance (1% of Total Capital cost)	309,043
7. Insurance (5% of 1)	<u>168,232</u>
	14,432,722
8. Contingencies (20%)	<u>2,886,554</u>
Total Operating Costs	<u>17,319,326</u>
Cost of Reprocessing per kg fuel	\$57.73

Total Capital Costs

1. Dissolution Tank	504,609
2. Process Equipment (stage 1)	4,133,140
3. Process Equipment (3 more stages each costing 40% stage 1)	4,959,768
4. Installation (40% of 2 and 3)	3,306,510
5. Buildings 50,000 ft ² @ \$ 30/ft ²	2,328,967
6. Waste Disposal Facilities	4,657,934
7. Services, Stores and Yards	1,552,645
8. Laboratory and Administrative Facility	<u>2,328,967</u>
	23,772,540
9. Engineering (10%)	2,377,200
10. Contingencies (20%)	<u>4,754,510</u>
Total Capital Costs	<u>30,904,300</u>
Annual Plant Cost	3,364,638

Processing Equipment

Stage 1.

1. Photoexcitation Equipment	1,027,851
2. Solvent Separation	2,328,967
3. Photochemical reactors	<u>776,322</u>
Total Processing Equipment	<u>4,133,140</u>

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APPENDIX G: LIQUID-LIQUID PARTITIONING⁽⁹⁾

Liquid-Liquid Partitioning (Mg.)

1. Cost of production of 1 kg (300 MT/year) \$ 13.82
2. Estimated Capital Cost: \$ 11,460,000
3. Separation Factor for fission products
Decontamination Factor: $\approx 10^3$
4. Fission Product Waste Form: Solid and Gases
5. Waste Material produced per kg fuel reprocessed: ≈ 0.4 kg Mg assuming the Uranium and Magnesium are recovered and recycled respectively
6. Waste radiation level
7. Fuel type accommodated: Metallic U and Pu and Th
8. Fuel Cooling requirements: None
9. Breeder Fuel Capability: No
10. Batch
11. Handling of cladding material: Head-End Treatment necessary
12. Form of reprocessed material: Pu -- slightly contaminated with Mg
U -- slightly contaminated with Mg
(assuming f.p. is separated from U)
13. Plutonium Handling: Pu is selectively separated
14. Handling of radioactive gases: Collect and store
15. Throughput/process inventory
16. Maximum credible accident: Release of radioactive gases into the atmosphere
17. Advantages:
 - (1) Rapid reprocessing
 - (2) Economic advantage
 - (3) No liquid wastes
18. Disadvantages:
 - (1) Dependent upon Mg supply
 - (2) Low decontamination
 - (3) Corrosion of equipment by liquid metals.

Figure 8. Schematic flowsheet for magnesium extraction of plutonium from molten uranium.

Operating Costs

1. Annual Plant Cost 2 year deferment followed by 20 year straight line depreciation at 8% interest p.a.	1,361,453
2. Magnesium Consumption (at 8% loss per cycle) 275,725 kg @ \$ 2.07 per kg	570,197
3. Utilities (25% of 1)	340,363
4. Personnel 40 at \$ 20,000 p.a.	800,000
5. Fringe Benefits (at 25% of 4)	200,000
6. Maintenance (1% of Total Capital cost)	114,600
7. Insurance (5% of 1)	68,072
	<hr/> 3,454,685
8. Contingencies (at 20%)	690,937
Total Annual Operating Cost	<hr/> 4,145,622
Cost of Reprocessing per kg fuel	\$ 13.82

Total Capital Costs

1. Processing Equipment	3,400,000
2. Installation & Overheads (at 40% of 1)	1,360,000
3. Instrumentation (at 10% of 1)	340,000
4. Buildings (1500 ft ² @ \$ 30/ft ²)	450,000
5. Services, Stores and Yards	1,000,000
6. Laboratory and Administrative Facilities	1,500,000
7. Waste Disposal Facilities	1,500,000
	<hr/> 9,550,000
8. Contingencies (at 20%)	1,910,000
Total Capital Costs	<hr/> 11,460,000
Annual Plant Costs	1,316,453

Process Equipment

1. 7 ton Furnace including support equipment and shielding	1,500,000
2. Mg distillation equipment	500,000
3. Mg Recycle equipment	1,200,000
4. Pu and U receivers	200,000
Total Process Equipment	<hr/> 3,400,000

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APPENDIX H: MELT REFINING^(10,11)

Figure 9. Melt refining cycle.

Melt Refining

1. Cost of production of 1 kg (330 MT/yr plant) \$ 30.87
2. Estimated Capital Cost \$ 39,154,932
3. Separation factor for Fission Product

Decontamination Factor: $\approx 10^2$

On heating, Xe, Kr, Cs, Cd & Ru removed 100%. More than 75% I removed.

Product composition: U: 90 $\approx$ 95% of original content
Pu: 90 $\approx$ 95%
Noble metals: 90 $\approx$ 95%
4. Fission Product Waste Form: Gaseous and Solid
5. Waste material produced /kg fuel reprocessed: Xe, Kr, Fume trap, skull (5 $\approx$ 10% of charged material), ingot mould and crucible
6. Waste radiation level

Input Radioactivity 7×10^4 R/hr

Products:

Ingot	4.5×10^3 R/hr (8%)
Crucible skull	5.0×10^4 R/hr (84%)
Fumes	4.0×10^3 R/hr (8%)
7. Fuel type accommodated:

Metallic Uranium Process operated at 1400° C.

Material	Melting Point	Material	Melting Point
Uranium	1132° C	UO ₂	2700° C
Plutonium	640° C	Zr ²	1852° C
Thorium	1750° C		
UC	< 2200° C		
UN	< 2600° C		

8. Fuel Cooling requirements	None in particular; however, as burn-up increases, pouring yield decrease. Therefore, probably beneficial to have precooling period.
9. Breeder Fuel Capability:	If metallic, yes, if oxides, or mixed oxides, no.
10. Batch or continuous:	Batch
11. Handling of cladding materials:	Head-End Treatment required.
Simultaneous Metal Refining
Zr highly improbable
12. Form of reprocessed material:	Basically ingot
13. Plutonium handling	Pu not isolated
14 Handling of radioactive gases	Collected, then released to atmosphere through 200 ft stack
15. Throughput/process inventory:	
16. Maximum credible Accident:	Solidification of molten mass
17. Advantages:	(1) Rapid Reprocessing
(2) No additional Fabrication required
(3) No liquid wastes
18. Disadvantages:	(1) Separation factor very bad
(2) Remote control required for refabrication of fuel elements
(3) High fuel loss

Operating Costs

1. Annual Plant Cost	4,651,621
2. Chemicals	1,000,000
3. Utilities (25% of 1)	1,162,905
4. Personnel 40 at \$ 20,000 p.a.	800,000
5. Fringe Benefits (at 25% of 4)	200,000
6. Maintenance (1% of Total Capital Costs)	391,549
7. Insurance (5% of 1)	232,581
	<hr/> 7,718,656
8. Contingencies	1,543,731
Total Operating Costs	<hr/> 9,262,387
Costs of Reprocessing per kg fuel	\$ 30.87

Total Capital Costs

1. Process Equipment	13,538,460
2. Installation (40%)	5,415,384
3. Instrumentation (10%)	1,353,846
4. Buildings	2,416,128
5. Process Cell Construction	2,895,360
6. Waste Disposal Facilities	2,000,000
7. Services, Stores and Yards	1,000,000
8. Laboratory and Administrative Facilities	1,500,000
	<u>30,119,178</u>
9. Engineering (10%)	3,011,918
10. Contingencies (20%)	6,023,836
Total Capital Cost	<u>39,154,932</u>
Annual Plant Cost	4,651,621

Process Equipment

1. Process Cell Service Equipment	3,525,600
2. Process Cell Equipment	2,246,400
3. Process Equipment	5,800,860
4. Supporting Equipment	1,965,600
Total Process Equipment	<u>13,538,460</u>

APPENDIX I: TIN-NITRIDE (12)

Figure 10. Tin-nitride process for spent fuel reprocessing.

Tin-Nitride Process

1. Cost of production of 1 kg (300 MT/year) \$ 15.47
2. Estimated Capital Cost \$ 12,382,500
3. Separation factor for fission products
Decontamination Factor: $\approx 10^3$
4. Fission product waste form: Gaseous and solidified tin ingot containing the f.p.
5. Waste material produced per kg fuel reprocessed: ≈ 0.2 kg solidified in containing f.p.
6. Waste radiation level:
7. Fuel type accommodated: Metallic, oxide, carbide, uranium thorium, plutonium
8. Fuel Cooling requirements: None
9. Breeder Fuel Capability: Yes for liquid metal reactor, if the liquid metal used is suitable for the process
10. Batch or continuous: Batch
11. Handling of cladding material: Head-End treatment thought to be necessary. However, it might be possible to dissolve both fuel & cladding & separate them by sink float means.
12. Form of reprocessed material: UN
13. Plutonium handling: Not selectively separated
14. Handling of Radioactive gases: Can be collected during melting
15. Throughput/process inventory:
16. Maximum credible accident: Release of radioactive gases into atmosphere. Liquidation will solidify, containing within it all radioactive material

Tin-Nitride Process (Continued)

17. Advantages:

- (1) No cooling requirements,
Sn resistant to radiation
damage
- (2) Rapid reprocessing
- (3) Economical, compact equip-
ment
- (4) No liquid wastes
- (5) Possibility of eliminating
Head-end treatment

18. Disadvantages:

- (1) Low decontamination factor
- (2) Remote refabrication required

Operating Costs

1. Annual Plant Cost	1,471,046
2. Sn consumption (4% loss per cycle) 108,000 kg at \$ 7.70/kg	831,600
3. Utilities (25% of 1)	367,762
4. Personnel 40 at \$ 20,000 p.a.	800,000
5. Fringe Benefits (25% of 4)	200,000
6. Maintenance (1% of Total Capital Costs)	123,825
7. Insurance (5% of 1)	73,552
	<u>3,867,785</u>
8. Contingencies (20%)	773,557
Total Operating Costs	<u>4,641,342</u>
Cost of Reprocessing per kg fuel	\$ 15.47

Total Capital Costs

1. Process Equipment	2,850,000
2. Installation (40%)	1,140,000
3. Instrumentation (10%)	285,000
4. Buildings 25,000 ft ² @ \$ 30/ft ²	750,000
5. Waste Disposal Facilities	2,000,000
6. Services, Stores, and Yards	1,000,000
7. Laboratory and Administrative Facilities	1,500,000
	<hr/> 9,525,000
8. Engineering (10%)	952,500
9. Contingencies (20%)	1,905,000
Total Capital Costs	<hr/> 12,382,500
Annual Plant Cost	1,471,046

Process Equipment

1. 7 Ton Furnace including support equipment and shielding	1,500,000
2. 4 Ton Furnace for Sn recycle (at 75% of 1)	1,125,000
3. Sn distillation and condensation equipment (15% of 1)	225,000
	<hr/> 2,850,000

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APPENDIX J: PUREX PROCESS⁽¹³⁾

Figure 11. Flow chart of purex process for treatment of low enriched uranium fuel.

Purex Process

1. Cost of production of 1 kg (300 MT/year) \$ 64.12
2. Estimated Capital Cost \$ 32,974,174
3. Separation Factor for fission products
Decontamination Factor: $10^6 \approx 10^8$
4. Fission Product Waste Form: Large Volume of liquid
5. Waste material produced/kg fuel reprocessed:
Warm and cold Waste $\approx 1 \text{ m}^3$ (264 gal)
(Data from Eurochemic Plant):
Hot Waste: $0.8 \approx 1.6$ gal
Raffinate Column: 0.12 gal
6. Waste Radiation level
Warm and Cold Waste: $< 10^2 \text{ Ci/m}^3$
Hot Waste: $50 \approx 100 \text{ Ci/m}^3$
Raffinate Column: $7 \times 10^5 \text{ Ci/m}^3$
7. Fuel type accommodated: U, Pu, Th. Metallic and oxides; should be dissolvable in HNO_3
8. Fuel Cooling Requirements: Required Minimum 100 days, otherwise reagents suffer radiation damage
9. Breeder fuel capability: Possibly for Aqueous Homogenous Reactors. Necessary to pre-treat fuel to make it suitable for solvent extraction. Not suitable for Molten Salt or Liquid metal Reactors.
10. Batch or continuous: Continuous
11. Handling of cladding material: Head-end treatment required
12. Form of reprocessed material: UNH

13. Plutonium Handling:

Pu separated in 2nd Plutonium cycle, End-product is Pu O₂

14. Handling of Radioactive gases:

Depends on Head-end Treatment

In case of HNO₃ dissolution the reaction gases are:

NO	4.05 ft ³ /kg
NO ₂ N ₂ O ₄	2.95 ft ³ /kg
N ₂	0.12
N ₂ O	0.12
CO H ₂	0.12

15. Throughput/process inventory:

See Reagent consumption list

16. Maximum credible accident:

Spill of radioactive solutions which could seep down to subterranean water tables resulting larger scale contamination.

17. Advantages:

- (1) Good decontamination
- (2) Suitable for centralized servicing of several reactors

18. Disadvantages:

- (1) Fuel precooling required
- (2) Large volumes of liquid wastes
- (3) Large facilities, and therefore high capital costs.

Operating Costs

1. Annual Plant Cost	3,917,345
2. Reagent Cost	5,607,900
3. Utilities (25% of 1)	979,336
4. Personnel 200 at \$ 20,000 p.a.	4,000,000
5. Fringe Benefits (at 25% of 4)	1,000,000
6. Maintenance (1% of Total Capital Costs)	329,741
7. Insurance (5% of 1)	195,867
	<hr/>
	16,030,189
8. Contingencies	3,206,038
	<hr/>
Total Operating Costs	19,236,227
Cost of Reprocessing per kg fuel	\$ 64.12

Total Capital Costs

1. Chemical Make-up and Storage	500,000
2. Process Equipment	6,909,883
3. Installation and Overhead (40%)	2,763,933
4. Instrumentation (10%)	690,983
5. Buildings	8,000,000
6. Liquid and Waste Disposal Facilities	4,000,000
7. Services, Stores and Yards	1,000,000
8. Laboratory and Administrative Facilities	1,500,000
	<hr/>
	25,364,749
9. Engineering (10%)	2,536,475
10. Contingencies (20%)	5,072,950
	<hr/>
Total Capital Costs	32,974,174
	<hr/>
Annual Plant Costs	3,917,345

Process Equipment

1. Dissolution	325,000
2. Solvent Extraction Equipment	3,490,490
3. Evaporators	651,000
4. Pipes, valves and fittings (50% of 2)	1,745,245
5. Electrical and special equipment (20% of 2)	698,098
	<hr/>
Total Process Equipment	6,909,833

Reagent Consumption Per Day

1. HNO_3	137 kg @ \$ 67.28/kg	9,215
2. TBP	360 kg @ \$ 12.85/kg	4,632
3. Kerosene	228 gal @ \$ 13.10/gal	2,993
4. Other reagents		<u>1,853</u>
Total Reagent Costs		<u>18,693</u>

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APPENDIX K: REDOX PROCESS⁽¹⁴⁾

Figure 12. Redox flow diagram.

Redox Process

1. Cost of production of 1 kg (300 MT/year) \$ 82,92
2. Estimated Capital Costs \$ 43,869,227
3. Separation Factor for Fission products
Decontamination Factor: $10^6 \approx 10^8$
4. Fission Product Waste Form; Liquid
5. Waste material produced /kg fuel reprocessed: More than Purex
6. Waste radiation level:
Warm and Cold Waste ~ < Purex
Hot Waste ~ < Purex
Raffinate Column ~ < Purex
7. Fuel type accommodated
U, Pu, Th, metallic and oxides should be dissolved in HNO_3
8. Fuel cooling requirements: Approximately 100 days (sufficient for radioactive decay U-237)
9. Breeder Fuel Capability: Possibly for Aqueous Homogenous Reactors necessary to pre-treat fuel to make it suitable for solvent extraction.
10. Batch or continuous: Continuous
11. Handling of cladding material: Head-end Treatment required
12. Form of reprocessed material: Solution $\text{UO}_2(\text{NO}_3)_2$ Pu (IV) in aqueous solution
13. Plutonium handling: About 99% of the Pu is recovered in the 3rd Pu cycle, in the form of Pu (IV) in aqueous solution. This can then be further processed to desired chemical form.
14. Handling of radioactive gases: Depends on Head-end Treatment. If HNO_3 dissolution is done ref purex. In addition, RuO_4 is volatilized during boiling prior to centrifugation.

Redox Process (Continued)

15. Throughput/process inventory: See chemicals and Reagents Consumption list.
16. Maximum credible accident: Spill of radioactive solutions which could seep down to subterranean water tables, resulting in large scale contamination.
17. Advantages:
- (1) Good decontamination
 - (2) Suitable for large scale operation; benefits from economy of scale
18. Disadvantages:
- (1) Fuel precooling required
 - (2) Large volumes of liquid wastes
 - (3) Large plant facilities, and therefore high capital costs
 - (4) Hexone - HnO_3 dangerous mixture, possible explosion.

Operating Costs

1. Annual Plant Cost 2 year deferment followed by 20 year straight line depreciation at 8% interest per annum	5,211,682
2. Chemicals and Reagents	8,256,000
3. Utilities (25% of 1)	1,561,920
4. Personnel 200 at \$ 20,000 p.a.	4,000,000
5. Fringe Benefits (at 25% of 4)	1,000,000
6. Maintenance (1% of Total Capital Cost)	438,692
7. Insurance (5% of 1)	260,584
	<hr/> 20,728,878
8. Contingencies (at 20%)	4,145,776
Total Operating Cost	<hr/> 24,874,654
Cost of Reprocessing per kg fuel	\$ 82.92

Total Capital Costs

1. Chemical Make-up and Storage	500,000
2. Processing Equipment	9,303,366
3. Installation and Overheads (at 40%)	3,721,346
4. Instrumentation (at 10% of 2)	930,336
5. Buildings	11,190,511
6. Liquid and Waste Disposal Tanks	5,600,000
7. Services, Stores, and Yards	1,000,000
8. Laboratory and Administrative Facilities	1,500,000
	<u>33,745,559</u>
9. Engineering (10%)	3,374,556
10. Contingencies (20%)	6,749,112
Total Capital Costs	<u>43,869,227</u>
Annual Plant Cost	5,211,682

Process Equipment

1. Dissolution	325,000
2. Processing Equipment (Purex x 1.4)	4,886,686
3. Evaporators	651,000
4. Pipes, Valves and Fittings (50% of 2)	2,443,343
5. Electrical and Special Equipment (20% of 2)	997,337
Total Process Equipment	<u>9,303,366</u>

Chemicals and Reagent Consumption

		Total Cost per day	Cost per day after recovery
1.	HNO_3 90% recovery	30,296	3,030
2.	Hexone 90% recovery	88,884	8,888
3.	$\text{Na}_2 \text{Cr}_2 \text{O}_7$ No recovery	305	305
4.	NaNO_3 No recovery	475	475
5.	$\text{Al} (\text{NO}_3)_3$ No recovery	14,694	14,694
6.	$\text{Fe} (\text{NH}_4)_2 \text{SO}_4$ No recovery	63	63
7.	$\text{NH}_4 \text{SO}_3$ No recovery	65	65
Total Reagent and Chemical Cost per day			<u>27,520</u>

APPENDIX L: SALT TRANSPORT PROCESS⁽¹⁵⁾

Figure 13. Salt transport process.

Salt Transport Process

1. Cost of production of 1 kg (300 MT/year) \$ 21.16
2. Estimated Capital Cost \$ 12,438,400
3. Separation Factor for fission products
Decontamination Factor: $< 10^6$
4. Fission Product Waste Forms: Contained in waste salt or metal:
solids at room temperature.
Gaseous wastes too - Ar, Kr, Xe, I
5. Waste material produced per kg fuel
reprocessed:
6. Waste radiation level: No data
7. Fuel Type Accommodated: Metallic, oxide, carbide fuels
8. Fuel Cooling Requirements: 30 days
9. Breeder fuel capacity: Yes, LMFBR and Molten salt B.R.
10. Batch or continuous Decladding oxidation, reduction:
Batch; extraction, U-Accumulation:
Continuous
11. Handling of cladding material: Zinc dissolution
12. Form of Reprocessed Material: UO_2 , PuO_2
13. Plutonium Handling: Pu is separated, and converted
to PuO_2 in Fluid Bed Converter
14. Handling of radioactive gases: Collect in inert gas and store
15. Throughput/process inventory: 910 kg Zn/day; 277 kg Ca/day
376 kg Cn/day; 181 kg Mg/day
16. Maximum credible accident: Release of radioactive gases into
the atmosphere. High temperature
molten salt and liquid metal con-
taining fission produced will
solidify on cooling.

17. Advantages

- (1) Versatility
- (2) Short Cooling period
- (3) Zinc Decladding - no separate Head-End treatment required.
- (4) Solid Wastes.

18. Disadvantages

- (1) Possible contamination by Cu, Mg or Cd.
- (2) Several different reagents used; 6 salts and 4 metals.

Operating Costs

1. Annual Plant Cost	1,477,687
2 year deferment followed by 20 year straight line depreciation at 8% interest p.a.	
2. Zinc Consumption (at 8% loss per cycle)	210,395
273,240 kg at \$0.77 per kg	
3. Ca consumption (277 kg/day x \$ 2.92/kg x 300 days)	243,000
4. Cu consumption (376 kg/day x \$ 1.63/kg x 300 days)	55,080
5. Mg consumption (181 kg/day x \$ 2.06/kg x 300 days)	33,660
6. Salt consumption	703,200
CaCl ₂ (111 kg/day x \$ 2.31/kg x 300 days)	
CaCl ₂ (19.5kg/day x \$ 6.86/kg x 300 days)	
7. Utilities (25% of 1)	369,422
8. Personnel 80 at \$ 20,000 p.a.	1,600,000
9. Fringe Benefits (at 25% of 8)	400,000
10. Maintenance (1% of Total Capital Cost)	124,384
11. Insurance (5% of 1)	73,884
	<hr/> 55,290,712
12. Contingencies (at 20%)	<hr/> 1,058,142
Total Operating Cost	<hr/> 6,348,854
Cost of reprocessing per kg fuel	\$ 21.16

Total Capital Costs

1. Processing Equipment	4,280,000
2. Installation and Overheads (at 40%)	1,712,000
3. Instrumentation (at 10% of 1)	428,000
4. Buildings 50,000 ft ² @ \$ 30/ft ²	1,500,000
5. Services, Stores and Yards	1,000,000
6. Laboratory and Administrative Facilities	1,500,000
7. Waste Disposal Facilities	3,000,000
	<u>9,568,000</u>
8. Engineering (at 10%)	956,800
9. Contingencies (at 20%)	1,913,600
Total Capital Costs	<u>12,438,400</u>
Annual Plant Cost	1,477,687

Process Equipment

1. 7 Ton Furnace including support equipment and shielding	1,500,000
2. Hold Tank	10,000
3. 7-stage mixer settler	1,000,000
4. Pu Retort	70,000
5. U Extraction Unit	500,000
6. Fluid Bed Convertor	500,000
7. U accumulation and Vacuum Melting	700,000
Total Process Equipment	<u>4,280,000</u>

APPENDIX M: THOREX PROCESS⁽¹⁶⁾

Figure 14. Thorex process flowsheet.

Thorex Process

1. Cost of production of 1 kg (300 MT/year) \$ 60.49
2. Estimated Capital Cost \$ 20,898,496
3. Separation Factor for fission products:
Decontamination Factor: $10^6 \approx 10^8$
4. Fission product waste form:
Liquid Wastes
Hot Wastes: $\approx 10^{12}$ c/min/ml (8)
Warm Wastes: $\approx 10^3$ c/min/ml (8)
Cold Wastes: $\approx 10^2$ c/min/ml (8)
Gaseous waste from HNO_3 dissolution: Ref Purex
5. Waste material produced per kg fuel reprocessed:
 ≈ 25 litres total/kg
 ≈ 17.4 litres warm
 ≈ 3.8 litres cold
6. Waste radiation level: See 4 above
7. Fuel type accommodated: Thorium; Thorex is Purex equivalent for Thorium
8. Fuel cooling requirements: Minimum 40 days
9. Breeder Fuel Capability: Not Molten Salt or liquid metal reactor fuels
10. Batch or continuous: Continuous
11. Handling of cladding materials: Head-End Treatment required
12. Form of reprocessed material: Liquid; Thorium in aqueous nitrate solution
13. Plutonium handling: None
14. Handling of radioactive gases: Collected and Stored
15. Throughput/process inventory: See Reagents List
16. Maximum credible accidents: As in Purex
17. Advantages: (1) Good separation factor
18. Disadvantages: (1) Precooling required
(2) Liquid wastes
(3) Economic Disadvantages

Operating Costs

1. Annual Plant Costs 2 year deferment followed by 20 year straight line depreciation at 8% interest p.a.	2,482,750
2. Chemicals and Reagents	6,684,900
3. Utilities	620,687
4. Personnel 200 @ \$ 20,000 p.a.	4,000,000
5. Fringe Benefits (at 25% of 4)	1,000,000
6. Maintenance (1% of Total Capital Cost)	208,985
7. Insurance (5% of 1)	124,137
	<u>15,121,459</u>
8. Contingencies (at 20%)	3,024,292
Total Annual Operating Cost	<u>18,145,751</u>
Cost of Reprocessing per kg fuel	\$ 60.49

Total Capital Costs

1. Chemical Make-up and Storage	500,000
2. Processing Equipment	3,341,540
3. Installation and Overheads (40% of 2)	1,336,616
4. Instrumentation (at 10% of 2)	334,154
5. Buildings (2.29 x Processing Equipment)	4,063,456
6. Services, Yards and Stores	1,000,000
7. Laboratory and Administrative Facilities	1,500,000
8. Liquid and Waste Disposal Tanks	4,000,000
	<u>16,075,766</u>
9. Engineering (at 10%)	1,607,577
10. Contingencies (at 20%)	3,215,153
Total Plant Cost	<u>20,898,496</u>
Annual Plant Cost	2,482,750

Process Equipment

1. Dissolution	325,000
2. Processing Equipment Purex x $(\frac{34}{105})^{0.6}$	1,774,435
3. Pipes, Valves and Fittings (50% of 2)	887,218
4. Electrical and Special Equipment (20% of 3)	354,887
Total Process Equipment	<u>3,341,540</u>

Reagent Cost (Per Day)

		Total Cost per day	Cost per day at 90% recovery
1.	HNO ₃ 90% Recovery	73,384	7,338
2.	Al No Recovery	216	216
3.	HF No Recovery	16	16
4.	TBP 90% Recovery	100,931	10,093
5.	Odourless Kerosene 90% Recovery	37,824	3,782
	Total Reagent Cost		<u>22,283</u>

APPENDIX N: ZINCAL PROCESS⁽¹⁷⁾

Figure 15. Zincal (pyrozinc) reprocessing flow diagram.

Zincal Process

1. Cost of production of 1 kg (300 MT/year) \$ 16.82
2. Estimated Cost \$ 15,648,750
3. Separation Factor for Fission Products:
Decontamination Factor: 10^3
4. Fission Product Waste For: Concentrated in solid Zinc; gas.
5. Waste material produced per kg:
fuel reprocessed ≈ 0.4 kg Zn
6. Waste radiation level:
7. Fuel type accommodated: Metallic and Oxide U
UC possible after conversion
to UO_2
8. Fuel Cooling Requirements: None
9. Breeder Fuel Capability: Liquid metal, if it is metallic
uranium
10. Batch
11. Handling of cladding material: Head-End treatment least com-
plicated; however, possible to
dissolve Zr cladding material
simultaneously
12. Form of reprocessed material: Metallic uranium ingot
13. Plutonium handling: No selective separation; Pu
probably comes out with the
 $U_2 Zn_{17}$
14. Handling of radioactive gases: Collect and store
15. Throughput/process inventory:
16. Maximum credible accident: Release of radioactive gases to
the atmosphere
17. Advantages:
 - (1) Rapid reprocessing - no
precooling requirements
 - (2) Economical; compact equip-
ment
 - (3) No liquid wastes

Zincal Process (Continued)

18. Disadvantages:

- (1) U_2Zn_{17} alloy very large molecules-easy to be contaminated
- (2) Low decontamination

Operating Costs

1. Annual Plant Cost	1,859,077
2. Zn consumption (at 8% loss per cycle) 775,224 kg at \$ 0.81/kg	631,032
3. Utilities (25% of 1)	464,769
4. Personnel 40 at \$ 20,000 p.a	800,000
5. Fringe Benefits (25% of 4)	200,000
6. Maintenance (1% of Total Capital costs)	156,488
7. Insurance (5% of 1)	92,954
	<hr/> 4,204,320
8. Contingencies (20%)	840,864
Total Operating Costs	<hr/> 5,045,184
Cost of Reprocessing per kg fuel	<hr/> \$ 16.82

Total Capital Costs

1. Process Equipment	4,625,000
2. Installation and Overheads (40% of 1)	1,850,000
3. Instrumentation (10% of 1)	462,500
4. Buildings 20,000 ft ² @ \$ 30/ft ²	600,000
5. Waste Disposal Facilities	2,000,000
6. Services, Stores and Yards	1,000,000
7. Laboratory and Administrative Facilities	1,500,000
	<u>12,037,500</u>
8. Engineering (10%)	1,203,750
9. Contingencies (20%)	2,407,500
Total Capital Costs	<u>15,648,750</u>
Annual Plant Cost	1,859,750

Process Equipment

1. 2 x 7 Ton Furnaces including support equipment and shielding	2,500,000
2. Filtration Equipment	500,000
3. EP concentration and Zn Recycle	1,125,000
4. U Recovery and Zn Retort Distillation	500,000
Total Process Equipment	<u>4,625,000</u>