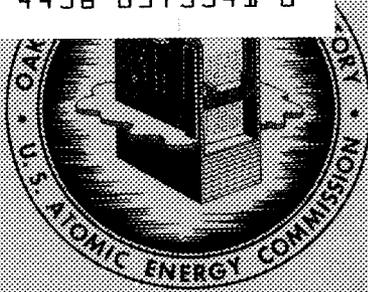




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PROPOSED AQUEOUS PROCESSES FOR RECOVERING POWER REACTOR FUELS

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ABSTRACT

Aqueous fuel reprocessing methods that have been proposed for the principal power reactor fuels are described. The volume and composition of decladding waste, of solvent extraction feed, and of high level waste are summarized for each fuel reprocessing method. The status of the process development work for each fuel reprocessing method is summarized.

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INTRODUCTION

In this paper, development of processing methods for a variety of power reactor fuels is summarized. Fuel processing is only one of the steps in the fuel cycle, but must be considered in the overall economic evaluation of each reactor type. Development of processing methods, of course, lags behind evolution of new reactor types and often requires simultaneous evaluation of several potential methods for chemically processing one type of reactor fuel. Ultimate choice of the processing method, as with selection of optimum reactor designs, must await full-scale engineering tests. To illustrate the applicability of the relatively versatile aqueous processes which have been developed, or which are being developed, reactors were classified into several groups and typical examples were chosen. For each example, the aqueous processes which apply are briefly summarized with respect to mechanical pre-treatment, dissolution reagents for cladding and core, solvent extraction method, and volumes of radioactive waste which would be generated in the processing plant. The state of development for each method is indicated. A bibliography is given.

Table I gives the approximate flowsheet conditions for one fuel element of each of the selected representative reactor types. The processes for (1) cladding dissolution or removal, (2) core dissolution, and (3) solvent extraction are described generally in the numbered notes. Table II lists other reactor fuels similar to the representative reactors in Table I.

The processes in the following tabulation (Table I) are based on flowsheets that have been developed in the laboratory to the point where they can be used with a reasonable assurance of success in existing plants, taking into account such factors as fuel dissolution equipment, corrosion, criticality control, solvent extraction, and waste storage practices that are used at various sites at present. Where reasonably firm flowsheets were not available, (and this is the case for most of the proposed processes in the accompanying tabulation), approximately standard Purex or Thorex solvent extraction flowsheets were assumed to follow fuel dissolution without restricting the fissionable material concentration to achieve criticality control by dilution as is proposed for existing plants. Instead,



soluble nuclear poisons (Reference 37) were assumed to be present in process solutions for criticality control, thus permitting high concentrations of fissionable material in geometrically unsafe vessels.

There are many properties of fuel elements that significantly complicate reprocessing. Table II presents a short summary of a few of these. If fuel elements incorporate features in this table, additional development will be required and revisions to flowsheets will have to be made.

PROPOSED DECLADDING PROCESSES

1. Sulfex Process (References 1-5)

Stainless steel cladding is dissolved in three times the stoichiometric amount of boiling 4 M H_2SO_4 yielding a solution containing about 67 g of stainless steel per liter. Off-gas is hydrogen, 1.1 moles for each 55 g of stainless steel dissolved. After decladding, UO_2 and ThO_2-UO_2 cores are washed with a volume of water equal to 25% of decladding solution. Decladding solution is centrifuged to remove fuel particles and neutralized, evaporated, and stored as a sludge containing >50 g of stainless steel per liter. Swaged UO_2 fuels may present major handling problems due to release of gross amounts of powdered UO_2 in the dissolver when cladding is removed. Low carbon Nionel or HW-BMI-20 dissolver.

2. Chopping (References 6-9, 43)

Stainless steel- and zirconium-clad oxide, carbide, or uranium alloy fuels are chopped into short 1/2-1 in. sections using a shear. Sodium or NaK bonding agents possibly can be hydrolyzed with steam prior to core dissolution in acid (not yet tried). The off-gas would be hydrogen. Steaming of chopped Hallam 2 fuel would hydrolyze the sodium bond and the UC core and produce water, hydrogen, and methane as off-gas (proposed; not yet tried). Volume of cladding scrap may be decreased 50% or more by crushing the rings. Stainless steel dissolver.

3. Zirflex (References 10-13)

Zirconium or Zircaloy cladding is dissolved in boiling 5.5 M NH_4F -0.5 M NH_4NO_3 (F/Zr mole ratio of 7). The off-gas contains ~5 moles of ammonia and 0.1 mole of H_2 per mole of zirconium dissolved. Ammonia is removed from

the off-gas by water scrubbing. Hot decladding solution is diluted with 0.3 volume of water (used to wash the oxide core) to prevent precipitation of ammonium fluorozirconates on cooling, and is centrifuged to recover UF_4 and UO_2 fines. At F/Zr mole ratio of 7, maximum attainable stable zirconium concentration in waste solution is 0.6 molar. Decladding waste may be neutralized with 0.07 liter of 50% NaOH per liter of waste and stored in carbon steel-lined tanks. Stainless steel, HW-BMI-20, or low-carbon Nionel dissolver.

4. Combustion (Reference 14)

Burning graphite-matrix fuels in oxygen at 750-900°C produces residues of U_3O_8 or $ThO_2-U_3O_8$ which are dissolved by conventional methods in a stainless steel or low-carbon Nionel dissolver. Nickel or stainless steel furnace. (Proposed only)

5. Grinding (References 14-15)

Graphite-matrix fuels containing 100- to 400-micron fuel particles coated with pyrolytic carbon or sintered Al_2O_3 must be ground fine enough (about 200 mesh) to ensure rupture of fuel particles. Uranium and thorium are recovered from the resulting powder by leaching with HNO_3 or HNO_3-HF , respectively. An appreciable fraction of the fission product activity may remain in the graphite sludge. Substantial engineering problems are anticipated with all graphite fuels. Stainless steel or low-carbon Nionel dissolver. (Proposed only)

6. Darex (References 1, 4, 16, 23, 25)

Stainless steel cladding is dissolved in dilute aqua regia. ThO_2-UO_2 cores are largely insoluble but losses prohibit clad solution discard; UO_2 is soluble (see below). Chloride is removed from the decladding solution by distillation-stripping, and recycled. Uranium and thorium contained in the declad solution are recovered by simultaneous extraction with the core solution (see below). A chloride-bearing waste may be generated if <90% HNO_3 (90-95% HNO_3 recommended) is used to batch strip the chloride from decladding or fuel plus clad solutions, or if chloride is scrubbed from process off-gases prior to disposal. Direct disposal of chloride-bearing off-gases, after filtration, to the plant stack may be feasible if excessive radioiodine escape is prevented by long decay of

the fuel. Titanium dissolver and chloride stripping system.

7. Electrolytic Disintegration (References 17, 27)

Zirconium and Zircaloy claddings are anodically disintegrated to zirconium oxide sludges in nitric acid. Uranium oxide cores are simultaneously dissolved. ZrO_2 sludge handling may be a problem in the head end system. With washing, $\sim 0.1\%$ uranium is lost to the sludge. Niobium cathode and platinum clad niobium anode (liquid contact electrode system) in a stainless steel dissolver vessel.

8. Carbonaceous Film Removal (Reference 34)

OMRE fuel is coated with a carbon film that is removed by alkaline permanganate ("Turco") to permit dissolution of the fuel.

PROPOSED CORE DISSOLUTION PROCESSES

1. Nitric Acid (References 1-13, 18-21)

Uranium oxide cores dissolve in boiling nitric acid solutions with evolution of nitrogen oxides and require 3-5 moles of HNO_3 per mole of uranium, depending on nitric acid recovery in the condenser and off-gas equipment. The nitric acid concentration used depends on the fuel concentration and acidity desired in the solvent extraction step. Solutions from leaching chopped fuel elements may be dilute due to washing of the cladding but may be evaporated to desired feed concentration. Hydrated uranium (IV) oxide, from hydrolysis of uranium monocarbide, dissolves in nitric acid. Concentrated (11-13 M) HNO_3 is used for dissolution of U--10% Mo alloys if virtually complete precipitation of MoO_3 is desired. Terminal acidity must be 8 molar for maximum precipitation of MoO_3 . MoO_3 is collected by centrifugation and then dissolved in hot 5 M NaOH leaving occluded uranium and plutonium as a HNO_3 -soluble precipitate. Dissolution of U--3% Mo in boiling 6 M HNO_3 produces stable solutions containing 0.6 M U and ~ 3 M HNO_3 . Maximum molybdenum solubility at ~ 3 M HNO_3 . Aluminum nitrate may be required in the acid for dissolving Zirflex-declad UO_2 cores to minimize corrosion from traces of fluoride carried over from decladding step. Stainless steel dissolver.

2. Darex (References 1, 22-24)

Stainless steel--clad UO_2 and stainless steel-- UO_2 cermet fuels dissolve completely in boiling 5 M HNO_3 --2 M HCl ; concentrations up to 100 g/liter of both uranium and stainless steel are attainable. The off-gas is a mixture of nitrogen oxides, $NOCl$, and chlorine. Prior to solvent extraction, chloride is removed by distillation-stripping from concentrated nitric acid solutions. Chloride is recycled to dissolution equipment. (See Darex decladding above.) Titanium dissolver and chloride stripping system.

3. HNO_3 -cat. HF (References 1, 25, 26, 35)

Sintered ThO_2 - UO_2 dissolves in boiling 13 M HNO_3 containing 0.04 M HF as catalyst to produce concentrations of 1 M Th and 8 M HNO_3 when using 3 times the stoichiometric amount of acid. Without the fluoride catalyst, both uranium and thorium recoveries are low from ground graphite-matrix-fuels. Little off-gas is produced from thoria. Low-carbon Nionel or stainless steel dissolver (Darex requires titanium).

4. Electrolytic (References 17, 27-30, 36)

Stainless steel--clad UO_2 , stainless steel-- UO_2 cermet, and Zr-clad U-Mo alloy plus stainless steel structural parts are dissolved electrolytically using nitric acid as the electrolyte. If Zr is present, a ZrO_2 sludge will result. Generally, the fuel rests in a niobium basket anode submerged in the acid. However, in a series dissolver, the fuel does not contact either electrode but becomes an induced electrolytic cell in the solution between the electrodes. Niobium dissolver and electrodes or niobium cathode and platinum clad niobium anode in a stainless steel dissolver.

5. HNO_3 - $Fe(NO_3)_3$ (References 19-21)

Uranium-molybdenum alloys dissolve in nitric acid--ferric nitrate solutions. Iron solubilizes molybdenum by complexing as a heteropolymolybdate. A 1 M uranium solution can be produced by dissolution of U--10% Mo in 4 M HNO_3 --1 M $Fe(NO_3)_3$ and U--3% Mo in boiling 8 M HNO_3 --0.5 M $Fe(NO_3)_3$. HW-BMI-20 or low-carbon Nionel dissolver.

6. HF- HNO_3 (Reference 31)

Zircaloy-2--clad U-Zr alloy containing less than 2% uranium dissolves in 4.8 M HF without exceeding the solubility limit of UF_4 .

Two moles of hydrogen are produced per mole of zirconium dissolved. After dissolution, nitric acid and chromic acid are added to oxidize U(IV) to U(VI) and dissolve tin. Aluminum nitrate is added to complex fluoride and reduce corrosion and to increase salting strength for solvent extraction. Monel dissolver.

7. Modified Zirflex (References 32, 33)

Zircaloy-2--clad U-Zr alloys containing up to 10% uranium dissolve in boiling 6 M NH_4F --1 M NH_4NO_3 to which hydrogen peroxide is added continuously. The off-gas is mainly ammonia, 5 moles NH_3 per mole of zirconium dissolved and also contains about 1% H_2 and 0.3% O_2 . After dissolution, nitric acid and aluminum nitrate are added to produce an extraction feed solution similar to that for the HF- HNO_3 process. Stainless steel or low-carbon Monel dissolver.

8. Dilute Niflex (Reference 17)

The zirconium-clad U-Mo and Zircaloy-2--clad U-Zr alloy fuels are dissolved in 1 M HNO_3 to which HF is added continuously. Alternatively, zirconium cladding on U--10% Mo alloy is dissolved in 0.075 M HF and then 3 M HNO_3 --0.075 M $\text{Al}(\text{NO}_3)_3$ is added to dissolve the core. At 12 g U/liter or less, molybdenum does not precipitate and criticality control is adequate. Stainless steel dissolver.

9. HNO_3 - H_2SO_4 (Reference 34)

In processing OMRE fuel, stainless steel-- UC_2 cermets are dissolved in the presence of steel wool as an activator in 6.5 M H_2SO_4 . An equal volume of 6 M HNO_3 is added to dissolve the UC_2 . Carpenter 20 dissolver.

PROPOSED SOLVENT EXTRACTION PROCESSES

1. Purex Process (Reference 38)

Uranium and plutonium are extracted from nitric acid solutions using 30 vol % tributyl phosphate in a hydrocarbon diluent (dodecane). Scrub solution is 2 M HNO_3 . Typical flow ratios are, feed: scrub: extractant; 1: 0.7: 3.5. Flowsheet is applicable where the bulk of the cladding and/or alloying constituents are separated from the uranium in the head end process. Some hot laboratory tests were performed at 100 g

U/liter rather than 320 g/l (Ref. 13). Subject to high-level waste storage cooling limitations, the extraction waste may be concentrated by a factor of ≤ 80 prior to storage.

2. Modified Purex Process (References 38, 17)

When the feed contains stainless steel, iron, aluminum, zirconium, or molybdenum salts, and possibly fission products in such concentrations that stable solutions are not obtained at normal Purex feed uranium concentrations, the feed concentration is reduced until a stable solution is achieved. Feed and scrub acidities and flow ratios are adjusted as required for extraction. The solvent may be $<30\%$ TBP in dodecane. Feed solutions are also diluted for criticality control purposes. Evaporation of high-level extraction waste is usually limited by salt solubility rather than fission product heat generation. Storage of wastes after neutralization may be complicated by precipitation of metallic salts.

3. Zirconium Alloy Fuel Process (References 31, 39, 40)

The flowsheet was developed for zirconium-uranium alloy fuels containing $\sim 1\%$ U and has been modified for the higher uranium content in the PWR-1 seed. Extractant is 12.5 vol % TBP in Amsco 125-90W (or dodecane) hydrocarbon diluent. Flow ratios are, feed: extractant; 1 : 0.625. The scrub column is separate from extraction column to avoid dilution of the high-level waste. An alternate flowsheet uses a compound extraction-scrub column with 1 M HNO_3 as scrub and 5% TBP in dodecane as solvent. Flow ratios are, feed : scrub : extractant; 1 : 0.2 : 1 (Reference 41).

4. Fermi Core Flowsheet (References 17, 42)

Developed for use in existing equipment using dilution for criticality control. Scrub is 3 M HNO_3 and the extractant is 10% TBP in dodecane. Flow ratios are, feed : scrub : extractant; 1 : 0.5 : 4.

5. OMRE (References 34, 44)

Extractant is 10% TBP in Amsco 125-90W (or dodecane). Flow ratios are, feed : extractant; 1 : 0.55. The scrub column is separate from extraction column to avoid dilution of high level waste. The high-level waste could be, but is not, evaporated prior to storage as acidic waste.

6. Acid Thorex (References 45, 46)

Flowsheet developed to give the maximum decontamination factor when recovery of both uranium and thorium is desired. Nitric acid is substituted for the aluminum nitrate previously used in the Thorex process to achieve a lower waste volume. Scrub #1 is 0.5 M HNO_3 , Scrub #2 is 0.01 M Na_3PO_4 , 0.01 M $\text{Fe}(\text{NH}_2\text{SO}_3)_2$, the salting agent (introduced several stages below the feed plate) is 13 M HNO_3 , the extractant is 30% TBP in dodecane.

Flow ratios are, feed : Scrub #1 : Scrub #2 : salting agent : extractant; 1 : 0.2 : 0.8 : 0.3 : 7.

For Darex-Thorex, the 13 M HNO_3 salting agent stream is replaced by the chloride-free stainless steel decladding solution to simultaneously recover U and Th contained in the Darex declad solution.

7. Interim-23 Type Thorium Flowsheet (Reference 46)

This flowsheet is used when thorium is not recovered. The scrub is 5 M HNO_3 , and the extractant is 5% TBP. Flowratios are, feed : scrub : extractant; 1 : 0.4 : 2.

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TABLE I. PROPOSED AQUEOUS PROCESSES FOR POWER REACTORS

Reactor	Fresh Element Active Section			Spent Element			Process ⁽¹⁾			Head End Off-Gases ⁽²⁾	Cladding Waste		Solvent Extraction Feed Solution		Solvent Extraction Waste		Process Development Status	
	Composition	Geometry	Construction	Avg. Burnup per mt U	Composition	Heat Generation at 180 d. Cooling, Watts	Declabbing	Core Dissolution	Solvent Extraction		Composition	Volume, liters	Composition	Volume, liters	Composition	Volume, liters	Head End	Solvent Extraction
e	319 kg UO ₂ 77 kg SS 3.4% U-235 enriched	94" long 7.61" square	Tubes connected by brazed ferules	7800 Mwd per mt U	2.6% U-235 en. 0.47% Pu	~2400	2	1	1	Nitrogen Oxides	1" x 0.34" Ø SS Rings	~ 77	1.5 M U, 1.0 M HNO ₃ 1.7 gm Pu/l, ~0.1 M NO ₂	790	1.4 M HNO ₃ , 0.06 M Na	1340	Cold engineering chopper tests Integrated cold engineering chopper - continuous leacher tests in progress Cold engineering and hot cell tests; Eurochemic pilot plant under construction for Sulfex process Cold engineering and hot cell tests	Hot cell tests Hot cell tests
							1	1	1	Hydrogen/Nitrogen Oxides	53.3 gm SS/l, 2.1 M H ₂ SO ₄	1455	1.5 M U, 1.0 M HNO ₃ 1.7 gm Pu/l, ~0.1 M NO ₂ (trace H ₂ SO ₄ in Sulfex Deacid fuel)	790	1.4 M HNO ₃ , 0.06 M Na	1340		
							-	2	2	Nitrogen Oxides, Nitrosyl Chloride, Chlorine	Off Gas Scrubber Waste Containing Chloride Salts	Unknown	~0.85 M U, >0.5 M HNO ₃ ~1 gm Pu/l 55 gm SS/l ~0.05 M NO ₂	1400	1.1 M HNO ₃ , .03 M Na, 32.4 gm SS/l	2380		
							-	4	2	Nitrogen Oxides	0.9 M U, 2.75 M HNO ₃ 0.7 gm Pu/l 39 gm SS/l, 0.1 M NO ₂	1970	2.8 M HNO ₃ , 23 gm SS/l, 0.06 M Na	3290	Cold engineering and hot cell tests in progress	Hot cell tests		
outer region)	13.8 kg UO ₂ 143 kg ThO ₂ 50 kg SS 93% U-235 en.	102" long 5.7" square	Tubes connected by brazed ferules	20,500 Mwd per mt Th + U	7.9% UO ₂ 9% U-235 en. 76% U-235 en.	~2600	2	3	7 (or 6)	Nitrogen Oxides	1" x 0.3" Ø SS Rings	~ 50	1.5 M Th, 0.14 M U, <0.3 M HNO ₃ 0.06 M F, 0.15 M Al	360	0.93 M Th, 2.1 M HNO ₃ , 0.04 M NaF, 0.1 M Al	580	Cold engineering tests scheduled Cold engineering and hot cell tests Cold engineering and hot cell tests Tracer level laboratory tests	Similar flowsheet tests in Thorex Hot Pilot plant at lower activity levels Similar flowsheet tests in Thorex Hot Pilot plant at lower activity levels Tracer level laboratory tests
							1	3	7 (or 6)	Nitrogen/Nitrogen Oxides	53.3 gm SS/l, 2.1 M H ₂ SO ₄	940	1.5 M Th, 0.14 M U, <0.5 M HNO ₃ 0.06 M F, 0.15 M Al	360	0.93 M Th, 2.1 M HNO ₃ , 0.04 M NaF, 0.1 M Al	580		
							6	3	6 (or 7)	Nitrogen Oxides, Nitrosyl Chloride, Chlorine	Cladding Scrap: 0.83 M Na ₂ MoO ₄ , 3.3 M NaOH Stainless Steel Rings and Misc. Scrap	Unknown	Feeds: 1.15 M Th, 0.14 M U 0.15 M Acid Def., 0.04 M F 0.1 M Al Salting Agent: 122 gm SS/l, 1.0 M HNO ₃ (~3% of Th + U)	470	37 gm SS/l, 0.3 M HNO ₃ , 0.014 M NaF, 0.035 M Al, 0.003 M Na ₂ PO ₄ , .003 M Fe (NH ₂ SO ₃) ₂	1350		
							-	5	5	Hydrogen/Nitrogen Oxides	1" x 0.66" Ø SS Rings and Misc. Scrap	~50	1.0 M U, 0.27 M Mo, 0.5 M HNO ₃ 1.0 M Fe, 0.1 M Na, 0.1 M NO ₂ 0.7 gm Pu/l	850	1.1 M HNO ₃ , 0.16 M Mo, 0.6 M Fe, 0.12 M Na	1450		
-1	202 kg U 22 kg Mo 18 kg SS 2 kg Na 3.6% U-235 en.	185" long 4.2" dia cluster	Tubes connected to spacers	8800 mwd per mt U	2.8% U-235 en. 0.3% Pu	~ 200	2	5	2	Hydrogen/Nitrogen Oxides	Cladding Scrap: Molybdate Waste: 0.83 M Na ₂ MoO ₄ , 3.3 M NaOH Stainless Steel Rings and Misc. Scrap	~50 275	0.63 M U, 0.013 M Mo, 4.0 M HNO ₃ 0.44 gm Pu/l, 0.06 M Na, 0.05 M NO ₂	1350	3.2 M HNO ₃ , 0.008 M Mo, .07 M Na	2300	Cold engineering chopper tests scheduled for Na banded fuel Cold laboratory tests of U-Mo dissolution Cold laboratory tests of U-Mo dissolution	Cold laboratory tests Cold laboratory tests
							2	1	1	Hydrogen, Methane/Nitrogen Oxides	~50	1.5 M U, 1.0 M HNO ₃ , ~2 gm Pu/l 0.1 M NO ₂ , 0.15 M Na	~570	1.4 M HNO ₃ , 0.15 M Na	970			
-2	125 kg UO ₂ 32 kg Zr 1.5% U-235 en.	117" long 4.4" square	Tubes connected by spacers	9000 Mwd per mt U	0.9% U-235 en. 0.35% Pu	~ 960	2	1	1	Nitrogen Oxides	1" x 0.6" Ø Zr-2 Rings	~40	1.5 M U, 1.0 M HNO ₃ , ~1.6 gm Pu/l 0.1 M NO ₂ , Trace F	310	1.4 M HNO ₃ , 0.06 M Na, 0.03 M Al, Trace F	530	Limited cold engineering chopper tests; integrated cold engineering chopper - continuous leacher tests scheduled Cold engineering and hot cell tests; Eurochemic Pilot plant under construction for Zrflex process Cold engineering tests in progress; Hot cell test Hot Pilot plant tests completed on Zr-U fuel Cold engineering tests Cold engineering and hot cell tests on Zr-U fuel	Hot cell tests Hot cell tests None Cold engineering and tracer level lab tests Hot cell tests on Zr-U fuel
							3	1	1	H ₂ , NH ₃ ; Nitrogen Oxides	2 M NH ₄ OH Scrubber Waste 0.6 M Zr, 0.6 M F, 0.06 M NO ₂	880 580	1.5 M U, 1.0 M HNO ₃ , 0.5 M Al ~1.6 gm Pu/l, trace F, 0.1 M NO ₂	310	1.4 M HNO ₃ , 0.06 M Na, 0.3 M Al, Trace F	530		
							7	1	1	Nitrogen Oxides	ZrO ₂ Sludge at 50 gm ZrO ₂ /liter	~870	1.5 M U, 1.0 M HNO ₃ , ~1.6 gm Pu/l 0.1 M NO ₂ , ~0.1 M Zr, 0.03 M F 1.44 g U/l, 0.8 M Zr, 0.55 M Al, 0.009 M Sn	310 1740	1.4 M HNO ₃ , 0.06 M Na, ~0.06 M Zr, 0.02 M NaF Same as feed except without U	530 1740		
							8	3	3	H ₂ , NH ₃ ; Traces of Nitrogen Oxides	2 M NH ₄ OH Scrubber Waste	3480	1.3 M U, 4.23 M F, 1.95 M NO ₃ Comparable to Dilute HF Process	1740	Comparable to dilute HF process	1740		
Seed	2.5 kg U 127 kg Zr 93% U-235 en.	72" long 5.5" square	Welded flat plate assembly	40% U-235	82% U-235 en.	~1050	6	3	3	Hydrogen/Traces of Nitrogen Oxides	—	—	—	—	—	Cold engineering tests Cold engineering and hot cell tests on Zr-U fuel	Cold engineering and tracer level lab tests Hot cell tests on Zr-U fuel	
							7	3	3	H ₂ , NH ₃ ; Traces of Nitrogen Oxides	2 M NH ₄ OH Scrubber Waste	3480	0.7 gm U/l, 0.4 M Zr, 2 M F 0.5 M Al, 0.025 M CrO ₄ NO ₂ , Sn, HNO ₃	3480	0.27 M Zr, >1.3 M F			5320
Seed	UO ₂ -ZrO ₂ (pyrolytic C coated) 21-4 clad 93% & 75% U-235 en.	98" long 7.5" square	Welded flat plate assembly	50% U-235	—	—	NCNE			No applicable process								
							No applicable process											
re A	18.6 kg U 2.1 kg Mo 1.4 kg Zr 5 kg SS 23.6% U-235	33" long 2.65" square	Pins held by spacer grids	5% U-235	24% U-235 en. 0.3% Pu	~ 700	8	4	4	Hydrogen/Nitrogen Oxides	5 kg SS Scrap to be Retrieved from dissolver	—	7.5 gm U/l, 0.02 gm Pu/l, 0.009 M Mo, 0.006 M Zr, 2.5 M HNO ₃ , 0.05 M Al, 0.05 M F	2480	2.6 M HNO ₃ , 0.006 M Mo, 0.004 M Zr, 0.03 M Al, 0.03 M F	3720	Cold laboratory and hot cell tests Scouting cold tests Cold engineering tests of chipping U-Mo-SS; additional tests on U-Mo-Na-SS scheduled; Cold lab tests of dissolution Cold laboratory tests of U-Mo dissolution Hot Pilot plant tests completed Cold engineering and hot cell tests Cold laboratory tests Laboratory tests in progress Laboratory tests in progress	Cold laboratory tests Untraced Cold laboratory tests Cold laboratory tests Hot Pilot plant tests completed Hot cell tests on similar fuel Hot cell tests on similar feed Cold laboratory tests scheduled Cold laboratory tests scheduled
							4	1	1	Hydrogen/Nitrogen Oxides	—	—	7.5 gm U/l, 0.02 gm Pu/l, 0.009 M Mo, ~0.001 M Zr, 2.5 M HNO ₃ , ~2 gm SS/l	2480	2.6 M HNO ₃ , 0.006 M Mo, ~1.3 gm SS/l	3720		
							2	1	1	H ₂ /Nitrogen Oxides	1" x 0.44"	~20	0.6 M U, 0.57 gm Pu/l, 0.04 M Mo, .03 M Na, 0.05 M NO ₂ , 3 M HNO ₃	440	2.6 M HNO ₃ , 0.03 M Mo, 0.05 M Na	750		
							2	5	2	H ₂ /Nitrogen Oxides	1" x 0.44"	~20	1 M U, 0.95 gm Pu/l, 0.07 M Mo, .05 M Na, 0.05 M NO ₂ , 0.5 M Fe, 1 M HNO ₃	265	1.4 M HNO ₃ , 0.04 M Mo, 0.06 M Na, 0.29 M Fe	450		
	1 kg UO ₂ 8.3 kg SS 93% U-235 en.	37" long 2.8" x 2.9"	Mechanical assembly of flat plates	~10% U-235	~90% U-235 en.	~ 100	8	9	5	H ₂ /Nitrogen Oxides	Detergent Solution from Carbonaceous Film Removal	50	2.1 gm U/l, 20 gm SS/l, 4.5 M H, 1.2 M SO ₄ , 3 M NO ₃	420	20 gm SS/l, 4.4 M H, 1.2 M SO ₄ , 2.9 M NO ₃	426	Hot Pilot plant tests completed Cold engineering and hot cell tests Cold laboratory tests Laboratory tests in progress	Hot Pilot plant tests completed Hot cell tests on similar fuel Hot cell tests on similar feed Cold laboratory tests scheduled
							8	2	2	Nitrogen Oxides, Nitrosyl Chloride Chlorine	Detergent Solution from Carbonaceous Film Removal	50	5.9 gm U/l, 55 gm SS/l, 2.5 M HNO ₃ , <150 ppm Cl	150	55 gm SS/l (~1 M), 2.4 M HNO ₃	150		
							8	4	2	Nitrogen Oxides	Detergent Solution from Carbonaceous Film Removal	50	5.9 gm U/l, 55 gm SS/l, 2.5 M HNO ₃	150	55 gm SS/l (~1 M), 2.4 M HNO ₃	150		
							4	3	6 (or 7)	CO ₂ /Nitrogen Oxides	—	—	1.15 M Th, 0.19 M U, 0.15 M acid deficient, 0.1 M Al, 0.04 M F	5.5	1.7 M HNO ₃ , 0.04 M Al, 0.02 M NaF, 0.004 M PO ₄ , 0.004 M Fe(NH ₄ SO ₃) ₂	12.6		
	0.267 kg UC ₂ 1.65 kg ThC ₂ (pyrolytic C coated particles) 23 kg C 93% U-235 en.	90" long 3.5" dia	Integral reflector and moderator	75,000 Mwd per mt Th + U	0.18 kg U 1.37 kg Th 28% U-235 en. 46% U-235 en.	~ 80	4	3	6 (or 7)	CO ₂ /Nitrogen Oxides	Carbon Powder Sludge	~25	1.5 M Th, 0.25 M U, <0.5 M HNO ₃ 0.04 M F, 0.1 M Al	4.2	1.0 M Th, 2.0 M HNO ₃ , 0.03 M NaF, 0.07 M Al	6.3	Laboratory tests in progress Laboratory tests in progress	Cold laboratory tests scheduled Cold laboratory tests scheduled
							5	3	7 (or 6)	CO ₂ /Nitrogen Oxides	Carbon Powder Sludge	~25	1.5 M Th, 0.25 M U, <0.5 M HNO ₃ 0.04 M F, 0.1 M Al	4.2	1.0 M Th, 2.0 M HNO ₃ , 0.03 M NaF, 0.07 M Al	6.3		

volatile fission product gases (I₂, Xe, Kr) which remain for process description.

Table II. Features Which Can Complicate Aqueous Processing

1. Very long fuel elements.
2. Very large cross-section elements.
3. Bundle sheaths not removed at reactor.
4. Use of stainless steel and Zircaloy in same element.
5. Presence of spring materials of different metal than clad.
6. Central solid stainless steel rods, and/or boron impregnated metal or ceramic poison rods inside fuel tubes.
7. Presence of refractory insulators, thermocouples, or burnable poisons that are insoluble.
8. Components with appreciable silicon, niobium, or ceramic content resulting in solids in process solutions.
9. Sodium or sodium-potassium liquid metal bonds.
10. Clad or core dissolutions procedures that evolve potentially hazardous gases (i.e., H_2 , CH_4 , etc.)
11. Coated fuel particles.
12. Use of $U^{235}O_2$ - ThO_2 and slightly enriched UO_2 in the same element.
13. Fuels requiring combustion as a precursor to aqueous processing.
14. Fuels with core alloying components that require addition of complexing agents to insure solubility (i.e., $Fe(NO_3)_3$ in dissolvent for U-Mo cores).
15. Swaged or vibratory compacted oxide powder fuels that may disintegrate into powder during a chemical decladding step.
16. Low theoretical density ceramic fuels or irradiation induced solubility effects that may require recovery of fuel values from decladding waste solutions.

Table III. Reactor Fuel Elements Similar to Examples

<u>Reactor Element</u>	<u>Similar to</u>
N. S. Savannah	Yankee
EGCR	↓
BR-3	
SELNI	
SENA	
BONUS Superheater	
Saxton	
Borax-5 Boiler	
Big Rock Point	
Humboldt #3	
Bodega Bay	
So. Calif. Edison	
BONUS Boiler	
<hr/>	
RWE	Dresden
PRTR Blanket	↓
SENN	
PWR Blanket	
Pathfinder Boiler	
Carolinas-Virginia	
JAERI	
<hr/>	
Elk River	Con. Ed.
<hr/>	
APPR	OMRE
Fermi Core B	↓
Pathfinder Superheater	
Borax-5 Superheater	
<hr/>	
Fermi Axial Blanket	Fermi Rad. Blkt.
City of Piqua	Fermi Rad. Blkt.*
<hr/>	
HWCTR Driver	PWR-1 Seed

*After decladding

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