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FUEL CYCLES USING ADULTERATED PLUTONIUM

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INTRODUCTION

THIS MORNING, I WOULD LIKE TO ADDRESS THE URANIUM-PLUTONIUM FUEL CYCLE AS IT PRESENTLY EXISTS, AND EXAMINE THE ADJUSTMENTS WHICH ARE NECESSITATED BY A RECENT SERIES OF POLITICAL DECISIONS MADE TO IMPROVE THE NONPROLIFERATION OBJECTIVES OF THE UNITED STATES. INITIALLY, THE MAJOR DECISIONS LEADING TO THE CURRENT CONDITIONS OF THE CYCLE WILL BE REVIEWED AND THE PROGRAMS AIMED AT ADDRESSING THE CONCOMITANT PROBLEMS WILL BE OUTLINED BRIEFLY. SELECTED METHODS TO ALTER THE BACK END OF THE CYCLE WILL THEN BE DESCRIBED BY SELECTING ALTERNATIVE OPERATIONAL MODES THAT ARE UNDER CONSIDERATION TO CONSTRAIN OR "HARDEN" THE CYCLE. ALTHOUGH NO FINAL CHOICE CAN BE MADE AT THIS TIME, SEVERAL TYPICAL REPROCESSING PLANT FLOWSHEETS WILL BE PRESENTED TO GIVE YOU AN APPRECIATION FOR SOME OF THE TECHNICAL ASPECTS OF THESE ALTERNATIVES. THE EFFECTS OF THESE DIVERSION-RESISTANT FLOWSHEETS, WHICH YIELD PRODUCTS OF DIFFERENT CHARACTERISTICS, ON THE OXIDE CONVERSION AND FUEL FABRICATION SYSTEMS WILL BE DISCUSSED IN SOME DETAIL. FINALLY, THE STATUS OF "CLOSING-THE-CYCLE" WILL BE CONSIDERED IN THE LIGHT OF THE PRESENT SITUATION.

POLITICAL DECISIONS AFFECTING THE NUCLEAR FUEL CYCLE

OVER THE PAST FEW YEARS, MAJOR POLITICAL DECISIONS HAVE CAUSED MAJOR PERTURBATIONS TO THE NUCLEAR FUEL CYCLE. WE ARE NOT ATTEMPTING TO SOLVE ANY POLITICAL PROBLEMS IN THIS TALK. OUR TOUCHING ON THESE POLITICAL DECISIONS IS TO ESTABLISH THE CLIMATE IN WHICH THE TECHNICAL DECISIONS WILL HAVE TO BE MADE.

PRESIDENT CARTER'S ANNOUNCEMENT OF APRIL 7, 1977, HAS CERTAINLY HAD A PRONOUNCED EFFECT ON NUCLEAR FUEL CYCLE PLANNING. FIGURE 1 PRESENTS THE POLICY HIERARCHY DIRECTLY AFFECTING THE CYCLE. BASICALLY, HE ANNOUNCED THAT, IN THE NATIONAL INTEREST, THE UNITED STATES SHOULD ACTIVELY DISCOURAGE THE PROLIFERATION OF NUCLEAR WEAPONS. IN ADDITION, HE OFFERED AN IMPLEMENTATION

STRATEGY THAT WOULD (1) ENSURE A TIMELY SUPPLY OF NUCLEAR FUELS FOR FOREIGN AND DOMESTIC NEEDS: AND (2) EXPLORE, ON AN INTERNATIONAL BASIS, AN APPROACH TO REDUCE THE SPREAD OF NUCLEAR EXPLOSIVE CAPABILITY. HE THEN OUTLINED A SERIES OF SHORT-TERM TACTICS TO BE CARRIED OUT WITHIN A TWO-YEAR TIME FRAME. THESE TACTICS INCLUDED THE DEFERRAL OF COMMERCIAL REPROCESSING IN THE UNITED STATES AND ESTABLISHMENT OF MAJOR PROGRAMS TO ADDRESS THE ISSUE. THE INTERNATIONAL FUEL CYCLE EVALUATION (INFCE) AND THE NONPROLIFERATION ALTERNATE SYSTEM ASSESSMENT PROGRAM (NASAP) WERE SPECIFICALLY MENTIONED. BRIEF DISCUSSIONS OF THESE PROGRAMS AND THEIR OBJECTIVES WILL BE INCLUDED IN THE SECTIONS THAT FOLLOW.

THE CONGRESS ALSO EXPRESSED CONCERN ON THE NONPROLIFERATION ISSUE AND RESPONDED WITH LEGISLATION, PASSED IN FINAL FORM IN SEPTEMBER 1977, WHICH SET FORTH THE POLICY OF THE UNITED STATES. THE MOST RECENT LEGISLATION PASSED, HR-8638 AND S-897, SPELLS OUT THE SPECIFIC U.S. POSITION. FIGURE 2 PRESENTS A SUMMARY OF THIS POLICY AS EXTRACTED FROM THE BILL.

IN ADDITION TO THE MORE RECENT DISCUSSIONS RELATING TO NONPROLIFERATION, A SERIES OF POLITICAL DECISIONS MADE OVER THE PAST DECADE REFLECTED THE DESIRES OF THE UNITED STATES. SPECIFICALLY, ON DECEMBER 2, 1967, PRESIDENT JOHNSON STATED IN A SATELLITE TELEVISION COMMUNICATION WITH PRESIDENT SARAGET OF ITALY THAT THE "U.S. WOULD PERMIT THE INTERNATIONAL ATOMIC ENERGY AGENCY TO APPLY ITS SAFEGUARDS TO ALL NUCLEAR FACILITIES IN THE UNITED STATES.... EXCLUDING ONLY THOSE WITH DIRECT NATIONAL SECURITY SIGNIFICANCE." THE OBJECTIVES OF THIS OFFER WAS TO INDICATE THE STRONG SUPPORT THAT THE UNITED STATES HAD FOR THE NONPROLIFERATION TREATY. EACH SUCCEEDING PRESIDENT HAS GONE ON RECORD AS SUPPORTING THE ISSUE. ALTHOUGH THIS OFFER WAS MADE EARLY, IT HAS NOT BEEN ACCEPTED: HOWEVER, THERE IS SOME INDICATION THAT IT WILL SOON BE IMPLEMENTED.

PROGRAMS AIMED AT SOLVING THE PROBLEMS

AS THE FOREGOING DISCUSSION OF THE POLITICAL DECISIONS INDICATES, THE WORLD OF THE NUCLEAR FUEL CYCLE IS ONE OF STUDIES AND PAPER. THE STUDIES INVOLVING THE IMPROVEMENT OF THE DIVERSION-RESISTANT AND NONPROLIFERATION ASPECTS OF THE FUEL CYCLE HAVE NOT PROGRESSED INTO THE LABORATORIES, EQUIPMENT DEVELOPMENT, OR DEMONSTRATION PHASES ON A MAJOR SCALE. SOME OF THE PRINCIPAL STUDY PROGRAMS THAT HAVE BEEN COMPLETED OR ARE UNDER WAY ARE BRIEFLY SUMMARIZED BELOW.

REGIONAL NUCLEAR FUEL CYCLE CENTER STUDY

THE REGIONAL NUCLEAR FUEL CYCLE CENTER STUDY PROJECT WAS UNDERTAKEN BY THE INTERNATIONAL ATOMIC ENERGY AGENCY (IAEA) IN 1975 AND WAS REPORTED IN FINAL FORM IN A SERIES OF TWO VOLUMES IN 1977. THE ADVANTAGES AND LIMITATIONS ESTABLISHED FROM THE STUDY ARE PRESENTED IN FIGURE 3. IT WAS FELT THAT THE ADVANTAGES ACCURING FROM A RFCC WOULD INCLUDE (1) REDUCTION OF INCENTIVES FOR NATIONAL PLANTS, (2) INCREASED CONFIDENCE IN THE SAFEGUARDABILITY OF THE BACK END OF THE CYCLE, (3) RELIEF FROM THE PROBLEM OF SPENT FUEL STORAGE SPACE, (4) REDUCTION OF SAFEGUARDS COSTS, AND (5) ENHANCEMENT OF PUBLIC ACCEPTANCE. LIMITATIONS WOULD INCLUDE (1) POTENTIAL PHYSICAL PROTECTION REQUIREMENTS, (2) THE TRANSFER OF SENSITIVE TECHNOLOGY TO OTHERS, AND (3) TAKEOVER PROBLEMS.

INTERNATIONAL NUCLEAR FUEL CYCLE EVALUATION (INFCE)

IN ACCORD WITH PRESIDENT CARTER'S DIRECTION, THE INFCE PROGRAM WAS INITIATED OFFICIALLY ON OCTOBER 19, 1977. THE BASIC GOAL OF THIS PROGRAM IS TO CONDUCT, ON AN INTERNATIONAL BASIS, TECHNICAL AND ANALYTICAL STUDIES OF MEASURES WHICH CAN BE TAKEN AT THE NATIONAL LEVEL AND THROUGH INTERNATIONAL AGREEMENTS TO MINIMIZE THE PROLIFERATION OF NUCLEAR WEAPONS WITHOUT JEOPARDIZING

ENERGY SUPPLIERS OR THE DEVELOPMENT OF NUCLEAR ENERGY FOR PEACEFUL PURPOSES. THE EVALUATIONS WERE DIVIDED INTO A SERIES OF EIGHT MAJOR TASKS, AS PRESENTED IN FIGURE 4. THIS SLIDE ALSO INCLUDES THE NATIONS RESPONSIBLE FOR EACH OF THE TASKS TO BE EVALUATED. THE TARGET COMPLETION DATE FOR THE STUDY WAS ESTABLISHED AS NOVEMBER 1979.

NASAP

THE MAJOR NONPROLIFERATION STUDY UNDER WAY IN THE UNITED STATES IS NASAP, WHICH IS BEING CONDUCTED UNDER THE DIRECTION OF THE DEPARTMENT OF ENERGY (DOE). THIS PROGRAM HAS THREE MAJOR OBJECTIVES (SEE FIG. 5): (1) TO IDENTIFY PREFERRED NUCLEAR SYSTEMS ALTERNATIVES AND RECOMMEND PROGRAMS FOR IMPLEMENTING THESE ALTERNATIVES: (2) TO IDENTIFY OPTIONS FOR INSTUTIONAL ARRANGEMENTS TO ENHANCE THE PROLIFERATION RESISTANCE OF PREFERRED NUCLEAR SYSTEM ALTERNATIVES, AND (3) TO PROVIDE TECHNICAL ASSISTANCE TO THE DEPARTMENT OF STATE IN SUPPORT OF THE INFCE PROGRAM.

ACTIVITIES CONCERNING THE BARNWELL NUCLEAR FUELS REPROCESSING PLANT (BNFP)

THE ROLE AND OUTCOME OF THE STUDIES CURRENTLY IN PROGRESS TO DECIDE THE FATE OF THE $250 MILLION BNFP LOCATED IN SOUTH CAROLINA WILL BE HIGHLY SIGNIFICANT TO U.S. NONPROLIFERATION POLICY AND THE NUCLEAR FUEL CYCLE. TWO MAJOR STUDIES PRESENTLY UNDER WAY ARE SCHEDULED FOR COMPLETION IN 1978. AUTHORIZED BY CONGRESSIONAL LEGISLATION AND DIRECTED BY THE DOE, THEY ARE FUNDED IN TWO PACKAGES TOTALING $14 MILLION. THE FIRST OF THE STUDIES, THE BARNWELL APPLICABILITY STUDY (BAS), IS AUTHORIZED AT THE $1 MILLION LEVEL AND IS BEING CARRIED OUT BY DOE CONTRACTORS, PRIVATE FIRMS, AND SEVERAL DIVISIONS OF DOE, INCLUDING NPD, DSS, IA, AND THEIR RESPECTIVE CONTRACTORS. IT IS EXPECTED TO INTERFACE CLOSELY WITH THE OBJECTIVES OF THE INFCE PROGRAM, THE IAEA, AND THE UNITED NATIONS. FIGURE 6 PRESENTS A SUMMARY OF THE BAS AS IT RELATES TO THE OBJECTIVES

OF THESE OTHER PROGRAMS. THE SECOND PROGRAM, AUTHORIZED AT THE $13 MILLION LEVEL, WILL BE CARRIED OUT BY THE BNFP STAFF IN SUPPORT OF THE BAS. BASICALLY, THE LATTER STUDY (FIGURE 7) WILL INVOLVE R&D AND WILL BE DIRECTED TOWARD (1) ASSESSING SPENT FUEL MANAGEMENT FUNCTIONS, (2) TESTING THE PERFORMANCE OF ADVANCED SAFEGUARDS SYSTEMS WHEN INTEGRATED WITH PROCESS CONTROL SYSTEMS, (3) EVALUATING THE ALTERNATIVE REPROCESSING MODES FOR URANIUM-BASED LWR FUELS, (4) EVALUATING THE FEASIBILITY OF THE REPROCESSING OF THORIUM-BASED FUELS, AND (5) STUDYING THE MAINTENANCE, TECHNICAL TRAINING, AND DEVELOPMENT OF A PROGRAM TO FACILITATE MOTHBALLING OR DECOMMISSIONING OF A REPROCESSING PLANT.

"HARDENING" THE NUCLEAR FUEL CYCLE

THE FOREGOING DISCUSSIONS ARE INTENDED TO FAMILIARIZE YOU WITH THE BACKGROUND OF THE SIGNIFICANT EVENTS THAT LEAD UP TO THE MORE TECHNICAL DISCUSSION RELATIVE TO THE SCHEMES PROPOSED FOR "HARDENING," OR CONSTRAINING, THE FUEL CYCLE. THE COMPLEX PROBLEMS INVOLVED WITH NONPROLIFERATION HAVE NO PERFECT TECHNICAL SOLUTION BUT WILL DEPEND BOTH ON AN APPLICATION OF TECHNOLOGICAL IMPROVEMENT AND ON POLITICAL SOLUTIONS AMONG NATIONS. WITH THIS IN MIND, I WOULD LIKE TO TALK ABOUT SOME OF THE TYPICAL SCHEMES BEING CONSIDERED FOR ALTERING THE FUEL CYCLE TO PROVIDE FOR A SYSTEM THAT IS MORE RESISTANT TO DIVERSION AND PROLIFERATION. IN THIS RESPECT, I HAVE DRAWN HEAVILY ON TECHNICAL INFORMATION GENERATED AT ORNL AND AT HEDL IN SUPPORT OF THE BARNWELL APPLICABILITY STUDY.

A HANDY "MAP" OF THE PROCESSING STEPS REQUIRED IN THE BACK END OF THE FUEL CYCLE AND SOME OF THE POSSIBLE ALTERNATIVES IS GIVEN IN FIGURE 8. IN THIS DIAGRAM, SEVERAL OF THE BACK-END STEPS ARE SHOWN IN THE 5 COLUMNS TO THE RIGHT: REPROCESSING, STORAGE, CONVERSION, SHIPPING, AND FUEL FABRICATION. THE FOUR RUNS ILLUSTRATE ALTERNATIVE FUEL CYCLE WITH DIFFERING DEGREES OF PROTECTION AGAINST DIVERSION. INCIDENTALLY, THERE ARE TWO DIFFERENT KINDS OF DIVERSIONS WHICH IS THE MAJOR CONCERN OF THIS SYMPOSIUM, BUT IT GOES

WITHOUT SAYING THAT PROTECTION AGAINST SUBNATIONAL DIVERSION, FOR EXAMPLE, BY A TERRORIST GROUP IS ALSO NEEDED. SINCE THE RESOURCES AND OBJECTIVES OF THESE TWO TYPES OF DIVERSION DIFFER, SO ALSO WILL THE EFFECTIVENESS OF DIFFERENT COUNTERMEASURES. UNLESS WE STATE OTHERWISE, IN THIS PAPER, WE WILL BE TALKING ABOUT PROLIFERATION.

RETURNING TO THE FIGURE: WE WILL FIRST DISCUSS THE ALTERNATIVE SCHEMES FOR CARRYING OUT THE FUEL CYCLE, AND THEN GO BACK AND DISCUSS IN MORE DETAIL SEVERAL OF THE STEPS AND HOW THE ALTERNATIVES INTERACT WITH EACH OTHER. IT SHOULD BE OBSERVED THAT THERE IS ONE MAJOR STEP IN THE FUEL CYCLE THAT WE HAVE LEFT OUT: HIGH LEVEL RADIOACTIVE WASTE DISPOSAL. NONE OF THE SCHEMES DISCUSSED HERE WILL HAVE ANY SIGNIFICANT EFFECT ON THE WASTE PROBLEM, SO THAT IT IS A CONSTANT WE WILL DROP OUT OF TODAY'S DISCUSSION.

PUREX

THE FIRST ROW, LABELED PUREX, ILLUSTRATES WHAT MIGHT BE CALLED THE CONVENTIONAL URANIUM-PLUTONIUM FUEL CYCLE. IN THIS SCHEME, THE PLUTONIUM IS SEPARATED FROM URANIUM, HIGHLY PURIFIED, AND HELD IN A STORAGE TANK AS PURIFIED PLUTONIUM NITRATE. LATER, IN A CONVERSION FACILITY, THE PLUTONIUM IS CONVERTED TO A CERAMIC-GRADE OXIDE AND AGAIN PLACED IN STORAGE. STILL LATER, THE OXIDE IS SHIPPED TO A FUEL FABRICATION PLANT WHERE IT IS BLENDED WITH URANIUM OXIDE (UO_2) AND FABRICATED INTO REACTOR FUEL ELEMENTS. ALTHOUGH THE COMPOSITION IS DIFFERENT, SUCH RECYCLE FUEL ELEMENTS COULD BE UTILIZED EITHER IN A CONVENTIONAL LIGHT WATER REACTOR OR AN LMFBR. INDEED, THAT'S EXACTLY HOW A NUMBER OF TEST ELEMENTS HAVE BEEN PREPARED FOR IRRADIATION IN LWR'S AND THE INITIAL LOADINGS FOR THE FFTF REACTOR. THIS, INDEED, IS DEMONSTRATED TECHNOLOGY, ALTHOUGH IT HAS NOT YET BEEN FULLY COMMERCIALIZED. IT WAS ON THE VERGE OF BECOMING COMMERCIALIZED WHEN PRESIDENT CARTER ANNOUNCED THE NEW U.S. POLICY.

A QUICK LOOK SHOWS THE REASONS FOR THE POLICY CHANGE. THE PRESENCE OF SIGNIFICANT QUANTITIES OF PURIFIED PLUTONIUM IN PROCESS INVENTORY AND IN STORAGE COULD SUPPLY A READY SOURCE OF FEED TO MAKE BOMBS, IN THE EVENT OF A NATIONAL TAKEOVER OF A REPROCESSING PLANT. EVEN A SMALL SUBNATIONAL GROUP MIGHT BE ABLE TO HIJACK A SHIPMENT, OR SECURE SOME PRODUCT BY AN ARMED ATTACH ON A STORAGE VAULT. IN THE ABSENCE OF CONSTRAINTS, THE ENGINEERS HAS CHOSEN THESE STEPS AS THE EASIEST, AND HENCE CHEAPEST AND MOST RELIABLE PROCEDURE FOR MAKING RECYCLE FUEL. IN THE CONTEXT OF POTENTIAL PROLIFERATION, THIS IS CLEARLY NOT A DESIRABLE FUEL CYCLE. ONE APPROACH IS TO DRAW BACK FROM USING PLUTONIUM. ANOTHER APPROACH IS TO ADULTERATE THE PLUTONIUM IN SOME WAY SO THAT IT IS NOT IMMEDIATELY USABLE FOR EXPLOSIVE DEVICES, AND THEREBY DISCOURAGE ITS DIVERSION.

BLEND NITRATES

THE FIRST ALTERNATIVE IS TO BLEND THE PURIFIED URANIUM AND PLUTONIUM NITRATES TOGETHER IMMEDIATELY AFTER PURIFICATION, THEN CARRY THE TWO MATERIALS TOGETHER THROUGH THE SUBSEQUENT STEPS TO MAKE MIXED OXIDE (MOX) AND RECYCLE FUEL. THE RATIONALE FOR THIS IS THAT SUCH PLUTONIUM CANNOT BE MADE INTO AN EXPLOSIVE DEVICE WITHOUT FIRST SEPARATING IT FROM THE URANIUM. THIS IS SOME DEGREE OF PROTECTION FROM A TERRORIST GROUP, SYMBOLIZED BY THE DOTTED LINES, AS IT INCREASES THE TIME AND EFFORT INVOLVED IN MAKING A BOMB, AND HENCE, THE LIKELIHOOD OF DISCOVERY BEFORE SUCCESS. IT HAS RELATIVELY LITTLE IMPACT ON PROLIFERATION, HOWEVER, AS A NATION OWNING A REPROCESSING PLANT COULD EASILY NOT BLEND THE URANIUM AND PLUTONIUM WHEN THEY WERE READY TO DIVERT, AND MIGHT EVEN RECYCLE THE INVENTORY OF MIXED OXIDE BACK THROUGH THE PURIFICATION PLANT. TO ACCOMPLISH THIS DEGREE OF PROTECTION REQUIRES DEVELOPING A NEW PROCESS FOR MAKING MIXED OXIDE, AND MAKING PROVISIONS FOR HANDLING ABOUT

5 TIMES AS MUCH MATERIAL IN THE STORAGE, CONVERSION, AND SHIPPING OPERATIONS. THERE WOULD BE NO CHANGE IN THE REPROCESSING PLANT, AND NO CHANGE IN THE FUEL FABRICATION PROCEDURES, PROVIDED A SUITABLE QUALITY OF MIXED OXIDE COULD BE PREPARED.

COPROCESSING

THE NEXT ALTERNATIVE SHOWN INVOLVES COPROCESSING THE URANIUM AND PLUTONIUM THROUGH THE REPROCESSING PLANT SO THAT THEY ARE NEVER SEPARATED FROM EACH OTHER, BUT TOGETHER ARE HIGHLY PURIFIED FROM FISSION PRODUCTS AND OTHER CONTAMINANTS. FROM THE OUTPUT OF THE REPROCESSING PLANT ON, THERE WOULD BE NO CHANGE FROM THE PREVEIOUS VARIATION. HOWEVER, THE RATIO OF URANIUM AND PLUTONIUM IN SUCH A PRODUCT IS FIXED BY THE RATIO IN THE FEED. IN ORDER TO BRING THE RATIO BACK TO THE PROPER OR FOR RECYCLE TO THE REACTOR, SOME URANIUM MUST BE WITHDRAWN FROM THE MIXTURE, THEREBY INCREASING THE RATIO OF PLUTONIUM TO THE URANIUM REMAINING.

WHILE IT IS GENERALLY FELT THAT SUCH A PROCESS CAN BE MADE TO OPERATE, IT IS ALSO CONCEEDED THAT A PLANT WITH THOSE CAPABILITIES COULD BE READJUSTED TO PRODUCE PURE PLUTONIUM AGAIN. THEREFORE, THE PROCESS IS DIVERSION RESISTANT ONLY IF THERE IS FULL CONTROL OVER THE PHYSICAL FACILITIES.

CIVEX

CIVEX, WHICH IS A PROPOSAL RECENTLY MADE BY LEVENSON AND MARSHALL, IS A VARIANT OF THE COPROCESSING SCHEME ABOVE. IN CIVEX, CERTAIN FISSION PRODUCTS PRESENT IN THE SPENT FUEL ARE ENCOURAGED TO FOLLOW THROUGH THE PROCESS AND CONTAMINATE THE PLUTONIUM-URANIUM PRODUCT. THIS ADDED INGREDIENT OFFERS CONSIDERABLE ADDITIONAL PROTECTION FROM DIVERSION (HENCE THE SOLID LINE AROUND THE PROCESSING STEPS) BOTH BY SUBNATIONAL AND BY NATIONAL GROUPS. TO SUCCESSFULLY COUNTER NATIONAL DIVERSION, IT IS IMPORTANT THAT THE REPROCESSING PLANT BE INCAPABLE OF PRODUCING HIGHLY PURIFIED PLUTONIUM. IN THIS CASE, THE RADIATION ALSO PROTECTS THE PLANT, DELAYING ANY ATTEMPTS TO MODIFY THE INCELL

EQUIPMENT. IT REMAINS TO BE DEMONSTRATED WHETHER THESE FEATURES CAN ACTUALLY BE ENGINEERED INTO THE PLANT.

NOTE THAT ALL THE SUBSEQUENT FUEL CYCLE STEPS MUST BE RE-ENGINEERED TO HANDLE THE RADIOACTIVITY PASSED ON FROM THE REPROCESSING PLANT. AFTER A DISCUSSION OF RADIATION DETERRENCE (SOMETIMES CALLED SPIKING), I WILL RETURN FOR A MORE DETAILED DISCUSSION OF SOME OF THESE FUEL CYCLE STEPS. FORTUNATELY, ONCE THE RECYCLE FUEL IS BACK IN A REACTOR, THE RADIOACTIVITY WILL BE SWAMPED BY NEW FISSION PRODUCTS. THUS, THESE FUEL CYCLE ALTERNATIVES WILL NOT PERTURB THE REACTOR OPERATIONS AND MAXIMUM USE IN THE NONPROLIFERATION MODE CAN BE MADE OF EXISTING REACTOR FACILITIES AND TECHNOLOGY.

RADIATION DETERRENCE OR "SPIKING"

"SPIKING" IS THE ADDITION OF ONE OR MORE RADIOISOTOPES TO FISSILE MATERIAL FOR THE PURPOSE OF INCREASING THE DIFFICULTY OF DIVERSION OF THAT MATERIAL FROM THE NUCLEAR FUEL CYCLE AND INTO THE PREPARATION OF A NUCLEAR EXPLOSIVE. IN THE CASE OF FISSILE MATERIAL RECOVERED FROM IRRADIATED FUEL (AS IN FUEL REPROCESSING), IT MAY BE ADEQUATE TO ALLOW SOME OF THE LARGE AMOUNTS OF RADIOACTIVE FISSION PRODUCTS ALREADY PRESENT TO REMAIN WITH THE FISSILE MATERIAL, RATHER THAN TO ADD RADIOACTIVITY. THIS SITUATION CAN ALSO BE TERMED "SPIKING", AS THE END RESULT WILL BE THE SAME.

THE SAFEST PLACE FOR FISSILE MATERIAL IS IN A REACTOR, AND THE NEXT SAFEST PLACE IS IN THE HIGHLY RADIOACTIVE FUEL ELEMENTS (SPENT FUEL) REMOVED FROM THE REACTOR. THE RADIATION PROTECTS THE FUEL FROM UNAUTHORIZED USE. IN RECOGNITION OF THIS, SPENT FUEL IS EXEMPT FROM SOME SAFEGUARDS REGULATIONS.

A REASONABLE EXTENSION OF THIS CONCEPT TO OTHER PARTS OF THE NUCLEAR FUEL CYCLE IS TO MAINTAIN OR REINTRODUCE SIMILARLY HIGH LEVELS OF RADIOACTIVITY IN THE FISSILE MATERIAL. EVEN AT LOWER RADIATION LEVELS, THERE ARE ADVANTAGES WITH RESPECT TO PREVENTING ILLICIT USE.

THE CONCEPT OF SPIKING INCLUDES A VERY WIDE RANGE OF SITUATIONS. THE DEGREE OF SPIKING, WHICH DETERMINES THE RADIATION LEVEL, CAN VARY OVER A FACTOR OF ABOUT A BILLION: IT RANGES FROM THE INHERENT RADIATION OF THE FISSILE MATERIAL (WHICH CAN PERHAPS BE HELD IN THE HAND) TO A LEVEL THAT WOULD IMMOBILIZE A PERSON IN A MATTER OF MINUTES. IN PRINCIPLE, A LARGE NUMBER OF ISOTOPES COULD BE USED TO SPIKE FISSILE MATERIAL, WITH A VERY WIDE RANGE OF PROPERTIES. IN PRACTICE, ONLY A FEW ISOTOPES NEED BE CONSIDERED IN DETAIL. THE CHEMICAL PROPERTIES OF THE ISOTOPES MUST BE COMPATIBLE WITH ALL FUEL CYCLE OPERATIONS PLUS THE REQUIREMENTS FOR REFABRICATED FUEL, WHICH IS THE END PRODUCT OF THE OPERATIONS.

THE RADIOISOTOPE USED FOR SPIKING SHOULD BE ONE WHICH EMITS PENETRATING RADIATION, EITHER GAMMA OR NEUTRONS. AS SHOWN IN FIGURE 9, SUCH RADIATION AT LOW LEVELS CAN IMPROVE DETECTION OF THE REMOVAL OF FISSILE MATERIAL FROM ITS PROPER PLACE -- THIS IS CALLED SPIKING FOR DETECTION. AT INTERMEDIATE LEVELS, TERMED "SPIKING FOR DELAY," IT CAN AID IN THE LOCATION OF STOLEN FISSILE MATERIAL (E.G., BY AERIAL MONITORING) AND IT CAN INTERFERE SERIOUSLY WITH ATTEMPTS TO PROCESS SUCH MATERIAL INTO WEAPONS. AT VERY HIGH LEVELS, SPIKING WOULD BE EXTREMELY HAZARDOUS TO THOSE ATTEMPTING DIVERSION (I.E., IT COULD IMMOBILIZE ANYONE COMING NEAR THE MATERIAL IN A MATTER OF MINUTES). THIS IS CALLED "SPIKING FOR DETERRENCE", WHICH IS AN EUPHEMISM FOR KILLING PEOPLE.

ALL THESE LEVELS OF SPIKING ARE TECHNOLOGICALLY FEASIBLE. THE POSITIVE IMPACTS FROM IMPROVED RESISTANCE TO DIVERSION AND PROLIFERATION MAY BE OFFSET BY NEGATIVE IMPACTS, ESPECIALLY AT THE HIGHER LEVELS OF SPIKING. MANY NEGATIVE IMPACTS CAN BE TRANSFORMED INTO COSTS: BUT SOME GO BEYOND THAT, TO SOCIAL AND POLITICAL PROBLEMS, AS IS PROLIFERATION, ITSELF. BOTH BENEFITS AND COSTS ARE SMALL AT LOW LEVELS OF SPIKING. AT MODERATE LEVELS (AROUND 0.1 TO 1 Ci/KG HEAVY METAL) THE COST RISES ABRUPTLY BECAUSE ALL FUEL CYCLE OPERATIONS MUST BE

CARRIED OUT AND MAINTAINED REMOTELY. COSTS RISE VERY LITTLE AT STILL HIGHER LEVELS. THE INCREASE IN TOTAL ELECTRICAL GENERATING COSTS IS EXPECTED TO BE NO MORE THAN 2% IN THE LWR FUEL CYCLE. HOWEVER, THIS SEEMINGLY SMALL NUMBER TRANSLATES TO ABOUT $400 MILLION PER YEAR IN THE MID-EIGHTIES.

LOW LEVELS OF SPIKING MAY BE ADVANTAGEOUS, BUT PRESENT DETECTION METHODS CAN PROBABLY BE MADE ADEQUATE TO COUNTER COVERT THEFT. MODERATE AND HIGH LEVELS OF SPIKING APPEAR TO BE REASONABLY EFFECTIVE DETERRENTS FOR TERRORIST ACTIONS, BUT COSTS ARE SO LARGE THAT ALTERNATIVE METHODS OF PROTECTION NEED EVALUATION. FOR PREVENTION OF NATIONAL DIVERSION, HIGH LEVELS OF SPIKING BY THEMSELVES ARE OF LIMITED VALUE, AND ADDITIONAL ACTIONS WHICH GO BEYOND THIS ARE ESSENTIAL. IN ALL CASES, THERE IS SUBSTANTIAL BENEFIT TO CONCEPTS THAT REQUIRE CHEMICAL PROCESSING OF THE DIVERTED MATERIAL (INCLUDING COPROCESSING AND SPIKING AT HIGH ENOUGH LEVELS) BECAUSE THIS WILL INVOLVE ADDITIONAL MANIPULATIONS AND DELAYS. SPIKING FURTHER COMPLICATES SUCH PROCESSING.

MUCH MORE INFORMATION IS REQUIRED, ESPECIALLY EXPERIMENTAL DATA UNDER REALISTIC CONDITIONS, TO PERMIT A MEANINGFUL AND ADEQUATE EVALUATION OF SPIKING, COMPARED TO THE ALTERNATIVES. INFORMATION TO DATE CONSISTS LARGELY OF THEORETICAL STUDIES BASED ON HYPOTHETICAL SITUATIONS. AN OPERATING PLANT PROCESSING POWER REACTOR FUELS WOULD OFFER AN EXCELLENT TESTING GROUND FOR SOME OF THESE CONCEPTS.

WHILE MODERATE TO HIGH LEVELS OF SPIKING APPEAR TO BE REASONABLY EFFECTIVE DETERRENTS FOR TERRORIST ACTIONS, THERE IS SUBSTANTIAL DISAGREEMENT ABOUT RADIATION LEVELS REQUIRED FOR DETERRENT SPIKING, RANGING FROM 1000 R/HR at 1 FOOT TO 20,000 R/HR AT 1 METER (OR EVEN MORE), FOR 5 KG OF FISSILE MATERIAL. THIS IS CERTAINLY ONE PARAMETER WHICH NEEDS EARLY RESOLUTION. THE LOWER PART OF THIS RANGE WAS SELECTED FOR THE BARNWELL APPLICABILITY STUDY AND CAN BE REACHED BY COPROCESSING A SIGNIFICANT PORTION OF THE FISSION PRODUCTS WITH THE FISSILE MATERIAL, OR BY RECYCLING SOME OF THE MATERIALS RECOVERED FROM

THE WASTE, SO LONG AS THE TIME FOLLOWING REACTOR DISCHARGE DOES NOT EXCEED A FEW YEARS (SEE FIGURE 10). THE HIGHER VALUES (OR THE RECYCLE OF LONGER COOLED FUEL) REQUIRE SPIKING BY OTHER ISOTOPES MANUFACTURED FOR THE PURPOSE, OF WHICH ^{60}CO IS PROBABLY THE BEST. THE ^{60}CO WOULD PREFERABLY BE UTILIZED AS DETEROGENEOUS, ATTACHED SOURCES.

THE MOST SUITABLE ISOTOPES FOR SPIKING DEPEND SOMEWHAT ON THE GOAL AND THE FUEL CYCLE. FOR URANIUM-FUELED LWRs UTILIZING COPROCESSED FISSION PRODUCTS, ^{106}RU-RH PROVIDES MOST OF THE RADIATION AFTER THE FIRST YEAR BECAUSE THE ZIRCONIUM DECAYS AND CS WILL NOT FOLLOW PU THROUGH REPROCESSING. FOR ADDITION TO ANY FISSILE MATERIAL TO PROVIDE A GAMMA RADIATION FIELD UP TO THE HIGHEST LEVELS SUGGESTED, ^{60}CO IS SUPERIOR TO ANY OTHER ISOTOPE.

COBALT-60 IS A RADIOACTIVE MATERIAL WHICH IS ALREADY AVAILABLE IN MEGACURIE QUANTITIES. THE TECHNOLOGY FOR PRODUCTION, HANDLING, AND DISTRIBUTION IS WELL WORKED OUT. THE NUCLEAR PROPERTIES OF COBALT ARE JUST ABOUT RIGHT TO PRODUCE THE GREATEST AMOUNT OF RADIATION AT LOWEST COST. THE RELATIVELY LONG HALF-LIFE (5.27 YR) MEANS LITTLE DECAY ALLOWANCE WOULD BE REQUIRED, EVEN FOR LONG MISSIONS. OTHER CONSIDERATIONS MAY ARISE, SUCH AS THE CHEMICAL SOLUBILITY OF COBALT IN THE PLUTONIUM PRECIPITATION STEP WHICH WOULD REQUIRE THE USE OF ANOTHER ISOTOPE.

REFERRING AGAIN TO FIGURE 10, WE WILL GO OVER SOME OF THE POINTS TO BE CONSIDERED CONCERNING THE USE OF FISSION PRODUCTS.

ZIRCONIUM WOULD BE SUITABLE FROM A PROCESSING STANDPOINT BUT PROBABLY HAS TOO SHORT A HALF-LIFE TO PROVIDE SAFEGUARDS LEVELS OF RADIATION FOR PERIODS OF SEVERAL YEARS.

RUTHENIUM ISOTOPES PRODUCE A VERY HIGH LEVEL OF RADIATION, AND BY VIRTUE OF THE RELATIVELY LONG HALF-LIFE OF ^{106}RU, MAINTAIN A HIGH LEVEL FOR A NUMBER OF YEARS. RUTHENIUM (ALONG WITH ZIRCONIUM) WAS THE RECOMMENDED SPIKE OF AN

EARLIER STUDY BY EPRI WHICH SUGGESTED THAT ABOUT 1/3 OF BOTH THE RUTHENIUM AND THE ZIRCONIUM COULD BE SENT THROUGH THE PUREX PROCESS WITH THE PLUTONIUM PRODUCT. THIS FRACTION OF THE RUTHENIUM WOULD BE ENOUGH TO ACHIEVE THE SAFEGUARDS CRITERIA FOR NEARLY 5 YEARS. RUTHENIUM, LIKE ZIRCONIUM, WILL NOT PRECIPITATE IN THE PLANNED PLUTONIUM OXIDE CONVERSION PROCESS. HOWEVER, THESE 2 ISOTOPES WILL COME DOWN IN A HYDROXIDE PRECIPITATION, WHICH IS THE REFERENCE PROCESS FOR MIXED OXIDE PREPARATION. FURTHER POTENTIAL DIFFICULTIES WITH RUTHENIUM ARE THE POSSIBLE EVOLUTION OF VOLATILE RuO_4 DURING SINTERING OF THE FUEL PELLETS (ALTHOUGH IT IS BELIEVED THIS CAN BE CONTROLLED) AND THE PRODUCTION OF ADDITIONAL INSOLUBLE RESIDUES DURING DISSOLUTION OF THE FUEL AFTER THE NEXT IRRADIATION PERIOD. THESE, AND ANY OTHER POSSIBLE DIFFICULTIES WITH FUEL INCOMPATIBILITY, NEED TO BE CAREFULLY CONSIDERED BEFORE ADOPTING ^{106}RU AS A SPIKE.

SILVER-110m IS NOT A DIRECT FISSION PRODUCT, BUT IS AN ACTIVATION PRODUCT OF A STABLE FISSION PRODUCT (^{109}AG). THUS, IT COULD EITHER BE RECOVERED FROM FISSION PRODUCT WASTE, OR IT CAN BE PRODUCED BY SPECIAL IRRADIATIONS OF NATURAL SILVER. SILVER DOES NOT SEEM TO HAVE ANY CHEMICAL ADVANTAGES OVER ^{60}CO IN THE PLUTONIUM CONVERSION PROCESS, AND SINCE ^{60}CO HAS THE ADVANTAGE OF A LONGER HALF-LIFE, SILVER WOULD PROBABLY NOT BE CHOSEN AS A SPIKE.

CESIUM VOLATILIZES DURING THE PELLET SINTERING OPERATION. UNLESS A STABLE HIGH-TEMPERATURE COMPOUND CAN BE FOUND WHICH IS COMPATIBLE WITH THE OXIDE FUEL SYSTEM, WE MUST RULE OUT CESIUM ISOTOPES. OTHERWISE, CESIUM WOULD BE THE PRIME SOURCE OF PENETRATING RADIATIONS IN MIXED FISSION PRODUCTS.

CERIUM-144 IS THE SPIKING MATERIAL MOST NEARLY COMPATIBLE, CHEMICALLY, WITH OXIDE PREPARATION AND FUEL FABRICATION. HOWEVER, ^{144}CE GENERATE A SIGNIFICANT AMOUNT OF HEAT AND WOULD NECESSITATE A REDESIGN AND REOPTIMIZATION OF THE PuO_2 HANDLING AND STORAGE FACILITIES FOR DISSIPATION OF THIS ADDITIONAL HEAT. IT IS DIFFICULT TO ADJUST PUREX PROCESS CHEMISTRY TO RECOVER CERIUM

ALONG WITH THE PLUTONIUM PRODUCT, BUT PROCESSES FOR RECOVERY OF CERIUM FROM PUREX WASTE ON A COMMERCIAL SCALE ARE KNOWN.

EUROPIUM-154 IS ANOTHER OF THE RARE-EARTH ELEMENTS WHOSE CHEMISTRY IS COMPATIBLE WITH THE PLUTONIUM OXIDE FUEL. IT IS ALSO, LIKE ^{110m} , AN ACTIVATION PRODUCT OF A FISSION PRODUCT, WHICH WOULD BE AN ADVANTAGE IN REPEATED RECYCLE, AND IT HAS A FAVORABLY LONG HALF-LIFE. UNFORTUNATELY, ^{153}EU HAS A RELATIVELY HIGH NEUTRON ABSORPTION CROSS-SECTION. EUROPIUM-154 COULD ALSO BE PRODUCED BY ACTIVATING NATURAL EUROPIUM, BUT THE NEUTRON CROSS SECTION WOULD BE EVEN HIGHER THAN FOR FISSION PRODUCT EUROPIUM. THE HIGH NEUTRON ABSORPTION CROSS-SECTION WOULD BE RELATIVELY UNIMPORTANT IN PROTECTING PLUTONIUM WHICH IS INTENDED FOR FAST REACTOR FUEL.

FUEL CYCLE STEPS

REFERRING BACK TO OUR MAP (FIG. 8) WE WILL NOW LOOK AT SOME OF THE DETAILS OF THE FUEL CYCLE STEPS AND SEE SOME OF THE WAYS THAT CHANGES IN THESE STEPS INTERACT WITH EACH OTHER.

A CURSORY UNDERSTANDING OF THE BASIC PUREX PROCESS CAN SERVE AS A LOGICAL POINT OF COMPARISON WITH SOME OF THE ALTERNATIVE SCHEMES PROPOSED IN THE STUDIES UNDER WAY. IN THIS FIGURE 11, THE PATH OF EACH MAJOR COMPONENT IN THE PROCESS MAY BE FOLLOWED BY A COLOR SCHEME. FISSION PRODUCTS ARE COLORED _____, URANIUM _____, AND PLUTONIUM _____.

REFERRING AGAIN TO FIGURE 11, FUEL IS DISSOLVED AND THE RESULTING URANIUM-PLUTONIUM MIXTURE IS EXTRACTED USING A 30% TBP NORMAL PARAFFIN MIXTURE TO REMOVE THE FISSION PRODUCT AND IONIC CONTAMINANTS FROM THE FEED. THE PLUTONIUM IS SEPARATED INTO AN AQUEOUS STREAM BY MAKING A CHEMICAL VALENCE ADJUSTMENT IN THE PARTITIONING OPERATION. THE PLUTONIUM IS THEN OXIDIZED AND FURTHER PURIFIED IN TWO ADDITIONAL CYCLES OF SOLVENT EXTRACTION TO YIELD A PURIFIED PLUTONIUM NITRATE SOLUTION. THE DECONTAMINATION FACTOR, BASED ON

33,000 MWD/TON IRRADIATED MATERIAL, IS APPROXIMATELY 10^6 TO 10^7. THE URANIUM IN THE FIRST CYCLE IS STRIPPED FROM THE ORGANIC STREAM INTO AN AQUEOUS MEDIUM AND PASSED THROUGH TWO SUBSEQUENT SOLVENT EXTRACTION CYCLES FOR FURTHER PURIFICATION. THE PLUTONIUM PRODUCT FROM THIS PROCESS IS IN A HIGHLY PURIFIED FORM.

COPROCESSING

ONE OF THE MAJOR CONTENDERS FOR A MORE DIVERSION-RESISTANT PROCESS IS THE COPROCESSING MODE OF OPERATION. THE UNIQUE FEATURE OF THIS SCHEME, PRESENTED IN FIGURE 12, IS THAT SOME OF THE URANIUM IS ALLOWED TO FOLLOW THE PLUTONIUM PRODUCT STREAM, THEREBY MAKING A CHEMICAL SEPARATION MANDATORY BEFORE THE FISSILE PLUTONIUM COULD BE USED IN A NUCLEAR WEAPON. THE COLORING METHOD UTILIZED IN THIS FLOWSHEET IS THE SAME AS THAT APPLIED IN THE BASIC PUREX SCHEME. THE TECHNOLOGY INVOLVED IN COPROCESSING IS READILY AVAILABLE, AND SOME EXISTING PUREX PLANTS HAVE UTILIZED "CODECONTAMINATION" FIRST CYCLES AS THE PRIMARY STEP IN NORMAL OPERATION. THIS LATTER SCHEME DOES PRESENT THE SAME BASIC DISADVANTAGE TO DIVERSION AS THE PUREX PROCESS BECAUSE OF THE "WINDOW" CREATED BY HAVING A PURE FISSILE PLUTONIUM STREAM IN THE PLANT.

THIS FLOWSHEET PRESENTS THREE BASIC CODECONTAMINATION CYCLES WHICH PROVIDE COMPLETE DECONTAMINATION FROM FISSION PRODUCTS AND IONIC IMPURITIES: HOWEVER, EQUIPMENT AND FLOWSHEET MODIFICATIONS CAN BE USED TO RESTRICT THE NUMBER OF CYCLES TO YIELD LOWER DECONTAMINATION FROM FISSION PRODUCTS. THIS SCHEME THEN CREATES AN "INTERNAL SPIKE" IN THE COMBINED URANIUM-PLUTONIUM PRODUCT. OF THE FISSION PRODUCTS CONTAINED IN THE PROCESS, ONLY RUTHENIUM AND ZIRCONIUM CAN BE MANIPULATED BY REASONABLE METHODS TO CARRY A SIGNIFICANT FRACTION THROUGH WITH THE PRODUCT PLUTONIUM STREAM. BOTH RUTHENIUM AND ZIRCONIUM HAVE APPRECIABLE DISTRIBUTION COEFFICIENTS AND ARE THE LIMITING FACTORS IN HIGH-DECONTAMINATION PROCESSING. THEY WILL EXTRACT BY ELIMINATING STEPS NORMALLY TAKEN TO ACHIEVE HIGH-DECONTAMINATION PROCESSING. SUCH MODIFICATIONS INCLUDE

OPERATING WITH LOW URANIUM SATURATION IN THE SOLVENT, HIGH ORGANIC FLOWS, AND LITTLE SCRUBBING OF THE ORGANIC STREAMS. RESULTS OF LABORATORY STUDIES INDICATE THAT 55% OF THE ^{106}RU PRESENT IN THE FEED COULD BE MADE TO FOLLOW THE PLUTONIUM IN THIS SCHEME OR IN THE STANDARD PUREX FLOWSHEET. BECAUSE OF THE COOLING PERIODS NECESSARY PRIOR TO REPROCESSING AND THE SHOFT HALF-LIFE OF ZIRCONIUM, LITTLE OF THE ZIRCONIUM ACTIVITY WOULD REMAIN: HOWEVER, THE ^{106}RU WOULD HAVE SUFFICIENT ACTIVITY TO PROVIDE A RADIATION DETERRENT TO RECONSTITUTED FUEL (1000 R/HR at 1 FT FROM 5 KG OF PU) FOR APPROXIMATELY 5 YEARS.

A SCHEME FOR GENERATING A PRODUCT CONTAINING 20 TO 30% PLUTONIUM IS PRESENTED IN FIGURE 13. THIS SCHEME PRODUCES THE MASTER MIX OF PLUTONIUM-URANIUM WHICH CAN BE FINALLY BLENDED WITH URANIUM TO YIELD A PRODUCT MORE AMENABLE TO FAST REACTOR APPLICATION. AGAIN, THE FLOWSHEET AND EQUIPMENT CAN BE DESIGNED TO PROVIDE A MORE RADIOACTIVE PRODUCT WITH THE ADDED PROTECTION AFFORDED BY HAVING A MIXED ISOTOPE COMPOSITION. THIS FIGURE ALSO SHOWS THE ADDITION OF AN EXTERNAL SPIKE, IN THE EVENT THAT THIS SHOULD BE CONSIDERED A FEASIBLE APPROACH TO PROTECTION.

THE NATURE OF THE PRODUCT FROM THE REPROCESSING PLANT HAS A MAJOR IMPACT ON THE "DOWNSTREAM OPERATION" SUCH AS OXIDE CONVERSION AND FUEL FABRICATION.

OXIDE CONVERSION

THE NEXT MAJOR STEP IN THE PROCESS IS THE CONVERSION OF THE PRODUCT PLUTONIUM NITRATE (OR MIXED PLUTONIUM-URANIUM NITRATE) TO AN OXIDE SUITABLE FOR FUEL FABRICATION. FIGURE 14 SHOWS THE STEPS IN THE CONVENTIONAL PuO_2 CONVERSION PROCESS. THIS PROCESS STARTS WITH A HIGHLY PURIFIED PLUTONIUM NITRATE AND PRODUCES A HIGH QUALITY CERAMIC GRADE OXIDE POWDER. THE OXALATE PRECIPITATION STEP PROVIDES CONSIDERABLE ADDITIONAL PURIFICATION, AND INDEED IF RADIOACTIVELY CONTAMINATED PLUTONIUM WERE PUT THROUGH SUCH A PROCESS, A SIGNIFICANT DEGREE OF DECONTAMINATION WOULD RESULT. THUS, SOME OTHER PROCESS

MUST BE USED IF THE PLUTONIUM IS TO BE CONVERTED TO THE OXIDE IN THE PRESENCE OF OTHER SUBSTANCES AND THIS INCLUDES URANIUM.

THE "COPRECAL" PROCESS (FIG. 15) IS ONE SUCH PROCESS PRESENTLY UNDER DEVELOPMENT BY GENERAL ELECTRIC COMPANY. IN THIS PROCESS, THE FEED IS PRECIPITATED WITH AMMONIA AND THE ENTIRE VOLUME OF SLURRY PLUS SUPERNATE IS FED TO THE FLUID-BED CALCINER. THERE IS NO FILTRATE STREAM TO CARRY AWAY THE ADDED RADIOACTIVE SPIKE, WHICH THEREFORE WILL APPEAR IN THE PRODUCT. HOWEVER, ANY OTHER NON-VOLATILE IMPURITIES PRESENT IN THE FEED WILL ALSO REPORT TO THE PRODUCT, SO THAT IT REMAINS TO BE DEMONSTRATED WHETHER THE MIXED OXIDE PRODUCT WILL MEET ALL SPECIFICATIONS FOR FUEL FABRICATION FEED. THE STEPS SHOWN HERE ARE TECHNICALLY MUCH MORE DIFFICULT TO PERFORM THAN IN THE CASE OF THE OXALATE PROCESS ABOVE, AND WILL BE MADE EVEN MORE DIFFICULT IF THEY MUST BE OPERATED REMOTELY IN THICK CONCRETE CELLS. MOST AUTHORITIES AGREE THAT WHATEVER COST INCREASES ARE INCURRED IN HANDLING HIGHLY RADIOACTIVE PLUTONIUM THROUGH THIS CONVERSION STEP, THEY WILL BE MILD COMPARED TO THE INCREASE THAT WILL BE SEEN IN THE FUEL FABRICATION STEP.

FUEL FABRICATION

THE CONVENTIONAL FUEL FABRICATION PROCESS IS OUTLINED IN FIGURE 16. A BETTER ESTIMATE OF THE TRUE COMPLEXITY OF THE PROCESS IS THAT THERE ARE ABOUT 10 MANIPULATIONS OF THE MATERIAL OR HARDWARE ASSOCIATED WITH EACH BLOCK SHOWN. THIS IS BASICALLY THE PROCESS (PELLETS - PINS - BUNDLES) WHICH IS USED TO FABRICATE VIRTUALLY ALL THE UO_2 POWER REACTOR FUEL IN THE U.S. TODAY. THE ADDITION OF PLUTONIUM DOESN'T CHANGE THE PROCESS SIGNIFICANTLY, BUT IT DOES ADD COMPLEXITY AS THE EQUIPMENT MUST BE BUILT IN ENCLOSURES WHICH WILL ADEQUATELY CONTAIN THE TOXIC PLUTONIUM AND SHIELD THE OPERATORS FROM THE DIRECT RADIATIONS. HOWEVER, THE RADIATION FROM PURE PLUTONIUM ARE NOT SO STRONG AS TO PREVENT HANDS ON MAINTENANCE OF THE EQUIPMENT THROUGH GLOVED

PORTS IF MOST OF THE FUEL MATERIALS CAN BE MOVED AWAY FROM THE FAILED EQUIPMENT.

FABRICATION OF MIXED OXIDE FUEL IN THIS MANNER WAS APPROACHING COMMERCIAL REALITY, AS WITNESS WESTINGHOUSE'S APPLICATION IN 1974 FOR A CONSTRUCTION PERMIT TO BUILD SUCH A FACILITY IN SOUTH CAROLINA. IF WE ARE TO CONSIDER FABRICATING "HOT" FUEL THEN A GREAT DEAL OF FURTHER DEVELOPMENT WORK WILL BE REQUIRED IN TWO DIRECTIONS. ONE IS TO STREAMLINE THE PROCESS, SO THAT THERE WILL BE A MINIMUM NUMBER OF MANIPULATIONS AND INSPECTIONS. THE OTHER IS TO DEVELOP TECHNIQUES TO PERFORM REMOTELY THOSE INSPECTIONS WHICH CANNOT BE AVOIDED. FURTHERMORE, ALL OF THE EQUIPMENT MUST BE DEVELOPED TO THE POINT WHERE IT CAN BE REMOTELY MAINTAINED AS WELL AS OPERATED.

WHAT WILL IT COST TO FABRICATE RADIOACTIVE FUEL? EARLIER STUDIES HAVE ESTABLISHED THAT THE INCREMENTAL FUEL FABRICATION COST RISES SLOWLY WITH LOWER LEVELS OF SPIKING UNTIL A VERY SHARP INCREASE OCCURS AT A LEVEL CORRESPONDING TO APPROXIMATELY 0.1 Ci OF ^{60}CO PER KILOGRAM OF PLUTONIUM. THE LEVEL PROPOSED TO MEET SAFEGUARDS CRITERIA (25 Ci OF ^{60}CO PER KILOGRAM OF PLUTONIUM WHICH WILL PROVIDE A RADIATION DOSE RATE OF 1000 R/HR AT 1 FT FROM AN UNSHIELDED STORAGE CONTAINER HOLDING 8 KG OF PLUTONIUM) IS WELL ABOVE THE POINT WHERE SUCH A BREAK OCCURS. THE REASON FOR THE BREAK IS THAT A MARKED CHANGE OF TECHNOLOGY IS REQUIRED TO PROVIDE THE NECESSARY RADIATION PROTECTION TO THE FABRICATION PLANT STAFF.

AS THE RADIATION LEVEL INCREASES, VARIOUS OPERATIONS MUST BE DONE REMOTELY, OR WITH SOME SHIELDING: THIS CAUSES A STEADY INCREASE IN COST. DIRECT MAINTENANCE OF THE EQUIPMENT IS PRACTICAL UNTIL THE LEVEL REACHES THE EQUIVALENT OF 0.1 TO 1 CI OF ^{60}CO PER KILOGRAM: ABOVE THAT, HOWEVER, REMOTE MAINTENANCE BECOMES NECESSARY. FIGURE 17 WHICH WAS REDRAWN FROM A SAFEGUARDS STUDY MADE AT BNL ILLUSTRATES THIS POINT.

THIS FUNDAMENTAL CHANGE (FROM DIRECT MAINTENANCE OF THE EQUIPMENT TO REMOTE MAINTENANCE) NECESSITATES A COMPLETE REARRANGEMENT OF THE FACILITY, ESPECIALLY INCREASED SPACING OF THE EQUIPMENT, CRANE AND MANIPULATOR DECONTAMINATION AND REPAIR FACILITIES, AND OTHER ANCILLARY FACILITIES. PROCESSES TAKE LONGER: HENCE THE FACILITY MUST EXPAND IN SIZE AGAIN IN ORDER TO MAINTAIN ITS THROUGHPUT. THE COSTS INCREASE IN SEVERAL WAYS: HIGHER CAPITAL CHARGES, LARGER OPERATING STAFF, AND ADDITIONAL COSTS ASSOCIATED WITH ANALYTICAL, WASTE PROCESSING, AND BUILDING MAINTENANCE. HOWEVER, ONCE THE RADIATION LEVEL BECOMES HIGH ENOUGH TO FORCE THE DESIGN TOWARD FULLY REMOTE OPERATION AND MAINTENANCE, THE COSTS LEVEL OFF AND RISE ONLY SLIGHTLY AS SPIKING IS FURTHER INCREASED.

INTERFERENCE WITH NONDESTRUCTIVE ASSAY AND INSPECTION

THE BNL STUDY ALSO CONSIDERED THE IMPACT OF GAMMA OR NEUTRON SPIKING ON THE NUMEROUS NONDESTRUCTIVE ASSAY SYSTEMS THAT HAVE BEEN DEVELOPED IN THE NUCLEAR FUEL INDUSTRY. THESE SYSTEMS ARE GENERALLY CONSIDERED TO HAVE MARKEDLY ENHANCED THE CAPABILITY FOR SAFEGUARDING SPECIAL NUCLEAR MATERIAL. EXPERIENCE HAS SHOWN THAT INTRODUCTION OF EVEN A SMALL AMOUNT OF EXTRANEOUS RADIOACTIVITY WILL DEGRADE THE SENSITIVITY AND THE PRECISION OF THESE SYSTEMS FOR DETECTING PLUTONIUM AND MEASURING ISOTOPIC ASSAY. SMALL AMOUNTS OF ACTIVITY MAY POSSIBLY PROVE ADVANTAGEOUS WITH REGARD TO IMPROVING THE DETECTION SENSITIVITY OF PORTAL MONITORS AND WASTE DRUM MONITORS, PROVIDED THE RATIO BETWEEN THE SPIKANT AND THE SPECIAL NUCLEAR MATERIAL CAN BE DEPENDED UPON. HOWEVER, SPIKING TO THE LEVELS ASSUMED FOR DETERRENCE WILL COMPLETELY INVALIDATE ASSAY SYSTEMS, INCLUDING PRESENT IAEA INSPECTION METHODS.

THIS IMPACT NOT ONLY HAS SAFEGUARDS IMPLICATIONS, BUT ALSO AFFECTS THE QUALITY-CONTROL MEASUREMENTS WHICH RELATE TO THE UNIFORMITY OF THE FISSILE LOADING OF THE FUEL RODS AND, HENCE, THE ALLOWABLE OPERATING POWER. ANOTHER IMPORTANT ASPECT IS THE FINANCIAL VALUE OF THE PLUTONIUM. A GREAT DEAL OF

MONEY IS CONTIGENT ON THE RESULTS OF THE VERY DIFFICULT ANALYTICAL DETERMINATION. SOME ALTERNATIVE ANALYTICAL TECHNIQUES MUST BE DEVELOPED TO HANDLE THESE PROBLEMS IN THE CASE OF SPIKED FUEL.

A RELATED ASPECT IS THE GREATLY ENHANCED DIFFICULTY OF INSPECTING THE COMPONENTS AND THE COMPLETED FUEL ASSEMBLIES UNDER CONDITIONS OF HIGH RADIATION LEVEL. A MAJOR DEVELOPMENT PROGRAM WILL HAVE TO BE ACCOMPLISHED BEFORE WE WILL KNOW THAT IT IS FEASIBLE TO PRODUCE AND INSPECT REACTOR-READY RECYCLE FUEL WHICH IS HIGHLY RADIOACTIVE.

PUTTING THIS TOGETHER (FIG. 18), WE SEE THAT "HOT" FUEL FABRICATION INVOLVES REMOTE MAINTENANCE AS WELL AS REMOTE OPERATION. INTERFERENCE WITH THE FISSILE ASSAY SYSTEM AND MECHANICAL INSPECTIONS AND ALMOST CERTAINLY HIGH COST.

SUMMARY

FIGURE 19 SUMMARIZES THE TECHNICAL CONSIDERATIONS WE HAVE DISCUSSED THIS MORNING. THE URANIUM-BASED FUEL CYCLE, USING BRED PLUTONIUM TO PROVIDE THE FISSILE ENRICHMENT, IS THE FUEL SYSTEM WITH THE HIGHEST DEGREE OF COMMERCIAL DEVELOPMENT AT THE PRESENT TIME. HOWEVER, BECAUSE PURIFIED PLUTONIUM CAN BE USED IN WEAPONS, THIS FUEL CYCLE IS POTENTIALLY VULNERABLE TO DIVERSION OF THAT PLUTONIUM. IT DOES APPEAR THAT THERE ARE TECHNOLOGICALLY SOUND WAY IN WHICH THE PLUTONIUM MIGHT BE ADULTERATED BY ADMIXTURE WITH ^{238}U AND/OR RADIO-ISOTOPES, AND MAINTAINED IN THAT STATE THROUGHOUT THE FUEL CYCLE, SO THAT THE LIKELIHOOD OF A SUCCESSFUL DIVERSION IS QUITE SMALL. ADULTERATION OF THE PLUTONIUM IN THIS MANNER WOULD HAVE RELATIVELY LITTLE EFFECT ON THE OPERATIONS OF EXISTING OR PLANNED REACTORS. STUDIES NOW IN PROGRESS SHOULD SHOW WITHIN A YEAR OR TWO WHETHER THE LESS EXPENSIVE COPROCESSING SCHEME WOULD PROVIDE ADEQUATE PROTECTION (COUPLED PERHAPS WITH ELABORATE CONVENTIONAL SAFEGUARDS PROCEDURES) OR IF THE MORE EXPENSIVE SPIKED FUEL CYCLE IS NEEDED AS IN THE PROPOSED CIVEX PROCESS. IF THE LATTER IS THE CASE, IT WILL BE FURTHER

NECESSARY TO DETERMINE THE OPTIMUM SPIKING LEVEL, WHICH COULD VARY AS MUCH AS A FACTOR OF A BILLION. A VERY BASIC QUESTION HANGS ON THESE DETERMINATIONS: WHAT IS TO BE THE NATURE OF THE RECYCLE FUEL FABRICATION FACILITIES? IF THE HOT, FULLY REMOTE FUEL FABRICATION IS REQUIRED, THEN A GREAT DEAL OF FURTHER DEVELOPMENT WORK WILL BE REQUIRED TO MAKE THE FUEL CYCLE FULLY COMMERCIAL.

On April 7, 1977 President Carter outlined a series of desires relating to nonproliferation policy.....

Decision

- The US should discourage nuclear weapons proliferation

Implementation

- Assure a supply of nuclear fuel
- Explore an international approach to the control of the spreading of nuclear weapons

Short Term Tactics (2 years)

- Defer commercial reprocessing
- Establish study programs (i.e. NASAP, INFCE)

(1)

ORNL Dwg 78-685R

-Nuclear Antiproliferation Act of 1977- {HR 8638, S 897}

It is the policy of the United States to -

1. Pursue establishment of international controls over transfer and use of nuclear materials, equipment and sensitive nonweapons technology to prevent proliferation,
2. Enhance the reliability of the U. S. as a nuclear fuel supplier to nations sharing our antiproliferation policies,
3. Encourage prompt ratification of Treaty on Non-Proliferation of Nuclear Weapons,
4. Aid Treaty nations with appropriate energy technology, both nuclear and nonnuclear,
5. Seek international safeguards permitting warning time of diversion comparable to LEU fuel cycle without reprocessing,
6. Assure world that U. S. exports will use and maintain internatioal safeguards and security guidelines at least equal to other nuclear supplier nations.

The RFCC study project outlined several advantages and disadvantages of fuel cycle centers .....

Advantages

- Reduction of incentives for National Plants
- Increased confidence in safeguardability
- Relief of national fuel storage space
- Reduction of safeguards costs
- Enhancement of public acceptance

Limitations

- Potential physical protection problem
- Technology transfer
- Takeover problems

The INFCE program has been broken down into major evaluation tasks.....

Tasks	Co-chairmen
Fuel and heavy water availability	Canada Egypt India
Enrichment availability	France Germany Iran
Technology, fuel, heavy water, services	Australia Philippines Switzerland
Reprocessing, Pu handling, recycling	Japan U K
Fast breeders	Belgium Italy USSR
Spent fuel management	Argentina Spain
Waste management	Finland Netherlands Sweden
Advance fuel cycle, reactors	Korea Rumania U S

The objectives of the nonproliferation alternative systems assessment program (NASAP) are to ...

- Identify preferred nuclear systems alternatives and recommend programs for implementation

- Identify options for institutional arrangements to enhance proliferation resistance

- Provide technical assistance to the Department of State in support of INFCE

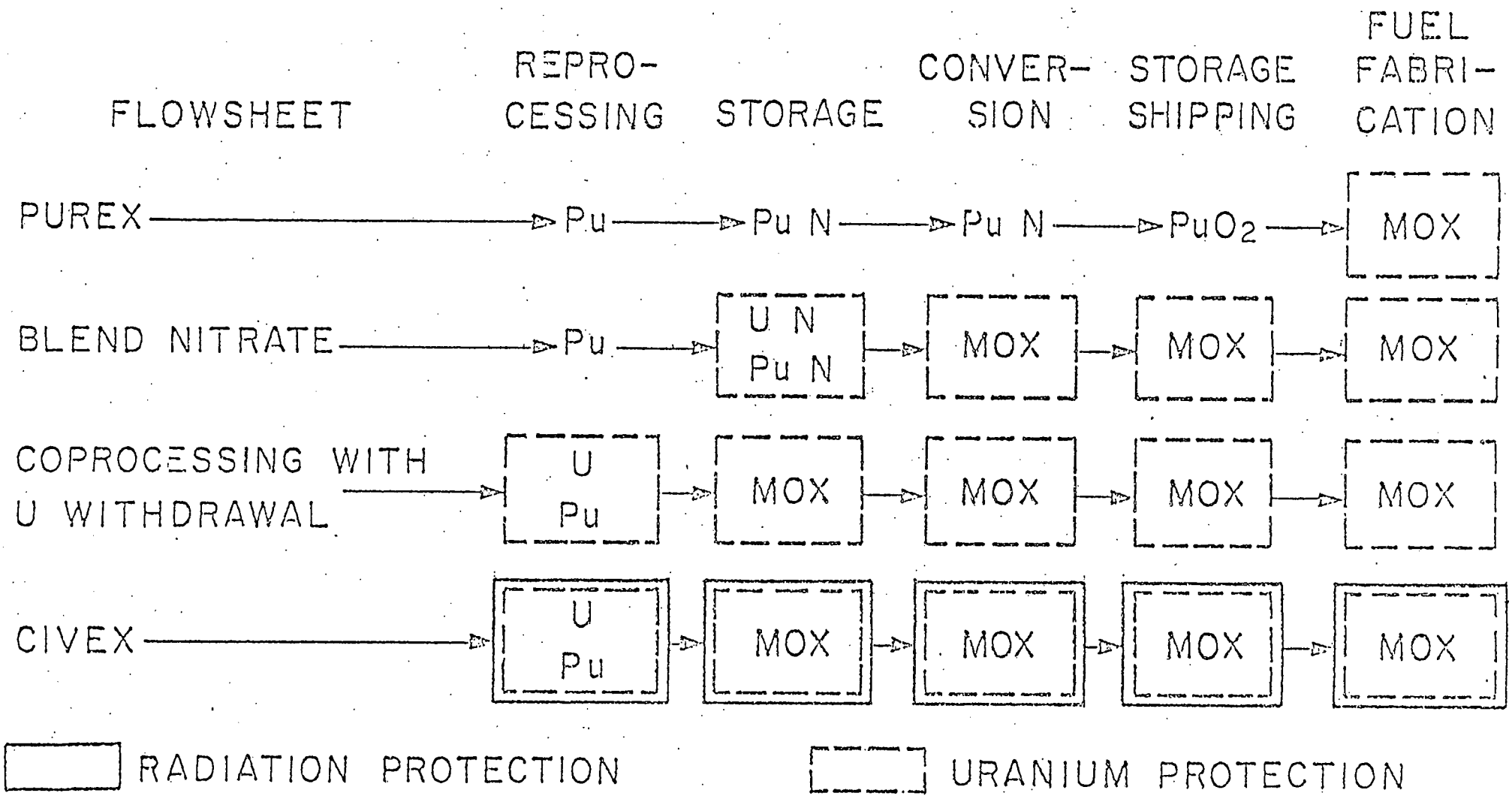
The BNFP applicability study will:

- Study proliferation-resistant flowsheets (e.g. co-recovery with spiking or Th-denatured U) and compatibility of the BNFP systems with such concepts;
- Address the institutional and international issues facing multinational (US-IAEA or UN-IAEA) fuel cycle center operations, using the BNF and site as a western hemisphere model;
- Discuss R & D on spent fuel management and safeguards technology/integrated systems for a multinational fuel cycle center;
- Describe possible nonreprocessing options for IAEA involvement in uses of the BNFP; and
- Study the procedures and technology involved in mothballing or decommissioning a multinational nuclear fuel cycle center, using the BNFP as a model.

R&D activities at the BNFP will be directed toward:

1. Assessment of spent fuel management functions;
2. Test and determination of performance for advanced safeguards components when integrated with process control systems;
3. Evaluating feasibility of reprocessing alternatives (e.g. spikes to deter diversion potential) for U-base LWR fuels;
4. Evaluating feasibility of comparable reprocessing alternatives for Th-base fuels; and
5. Facility/systems maintenance, technical training, and development of program to facilitate mothballing or decommissioning of a spent fuel reprocessing plant

ORNL Dwg 78-2530A



DIVERSION PROTECTION DURING FUEL CYCLE

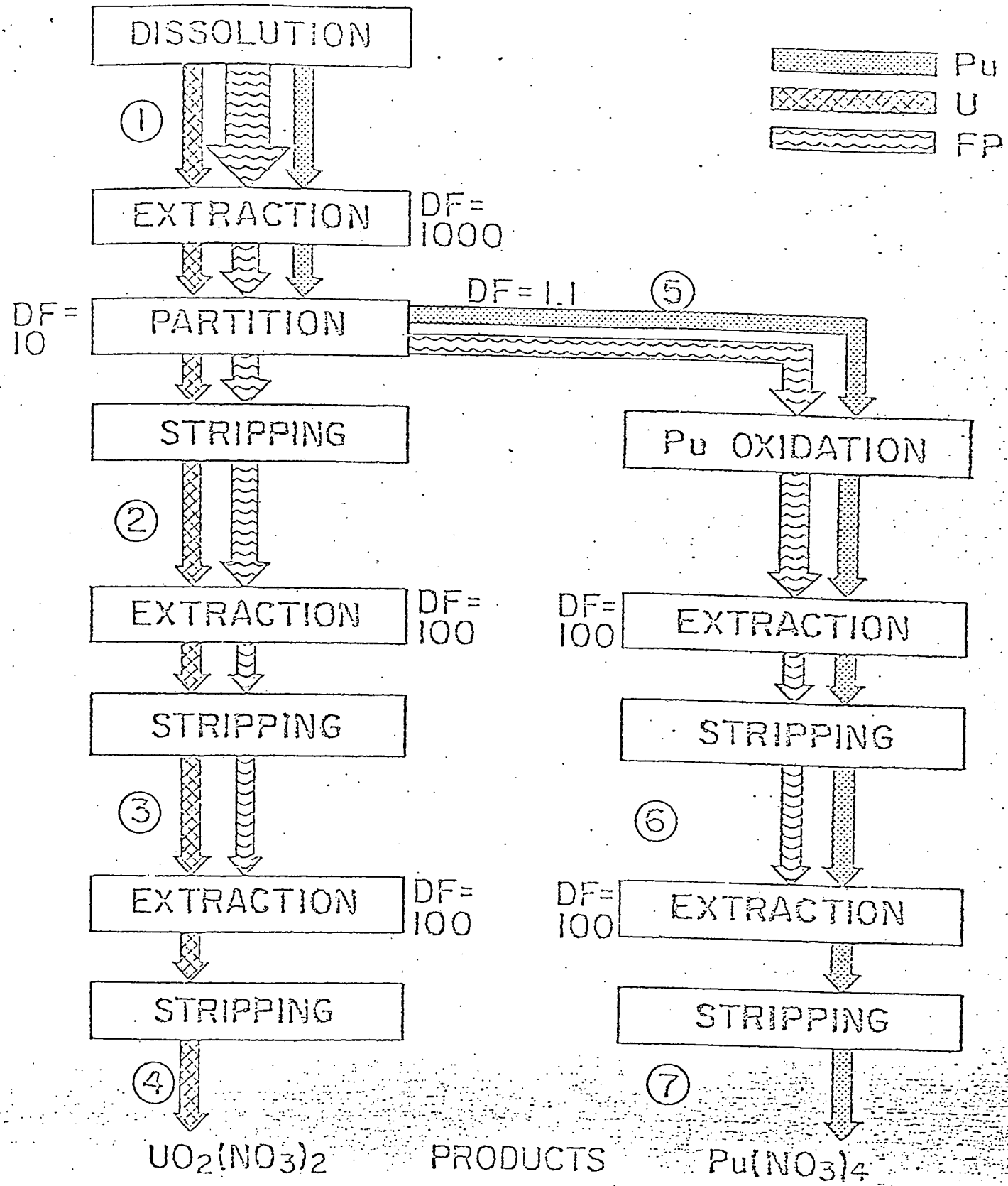
Levels of Radiation Deterrence

1. Easier detection	0.2–200 mR/hr
2. Delay making a weapon	0.2–200 R/hr
3. "Absolute" deterrence	200–100,000 R/hr

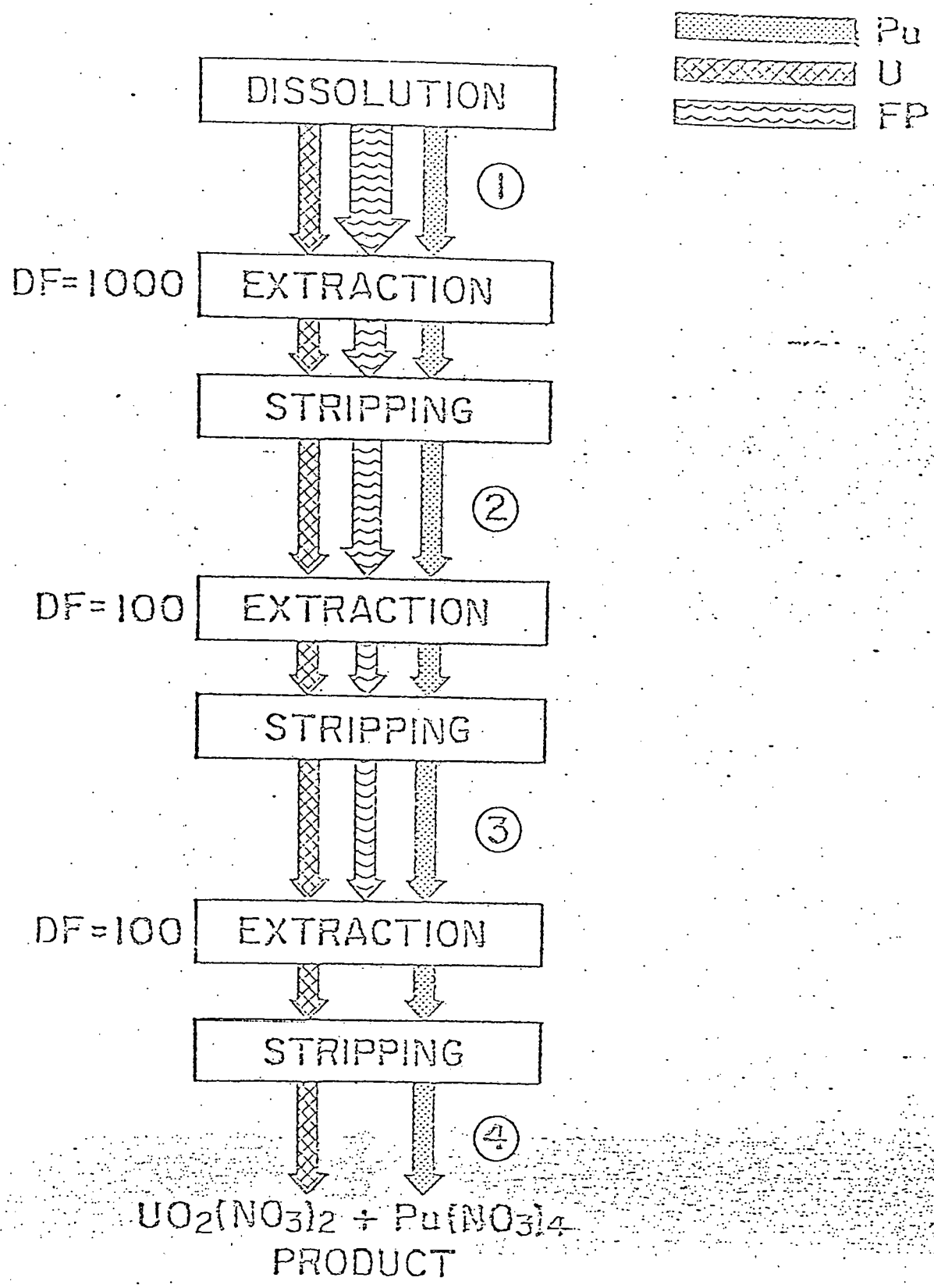
CALCULATED GAMMA RADIATION FROM FISSION PRODUCTS

ISOTOPE	HALF LIFE	TIME AFTER SHUTDOWN (years)		
		0	2	5
		DOSE RATE AT 1 ft. $\{R\ hr^{-1}\ (kg\ Pu)^{-1}\}$		
^{95}Zr	65 d	115,000	49	—
^{95}Nb	35 d	125,000	117	—
$^{106}Ru(Rh)$	368 d	11,200	2,800	355
^{110m}Ag	255 d	1,330	180	9
^{134}Cs	2.05 y	40,000	20,000	7,500
^{137}Cs	30.0 y	5,900	5,600	5,300
$^{144}Ce(Pr)$	284 d	5,900	1,000	70
^{154}Eu	16 y	760	690	600

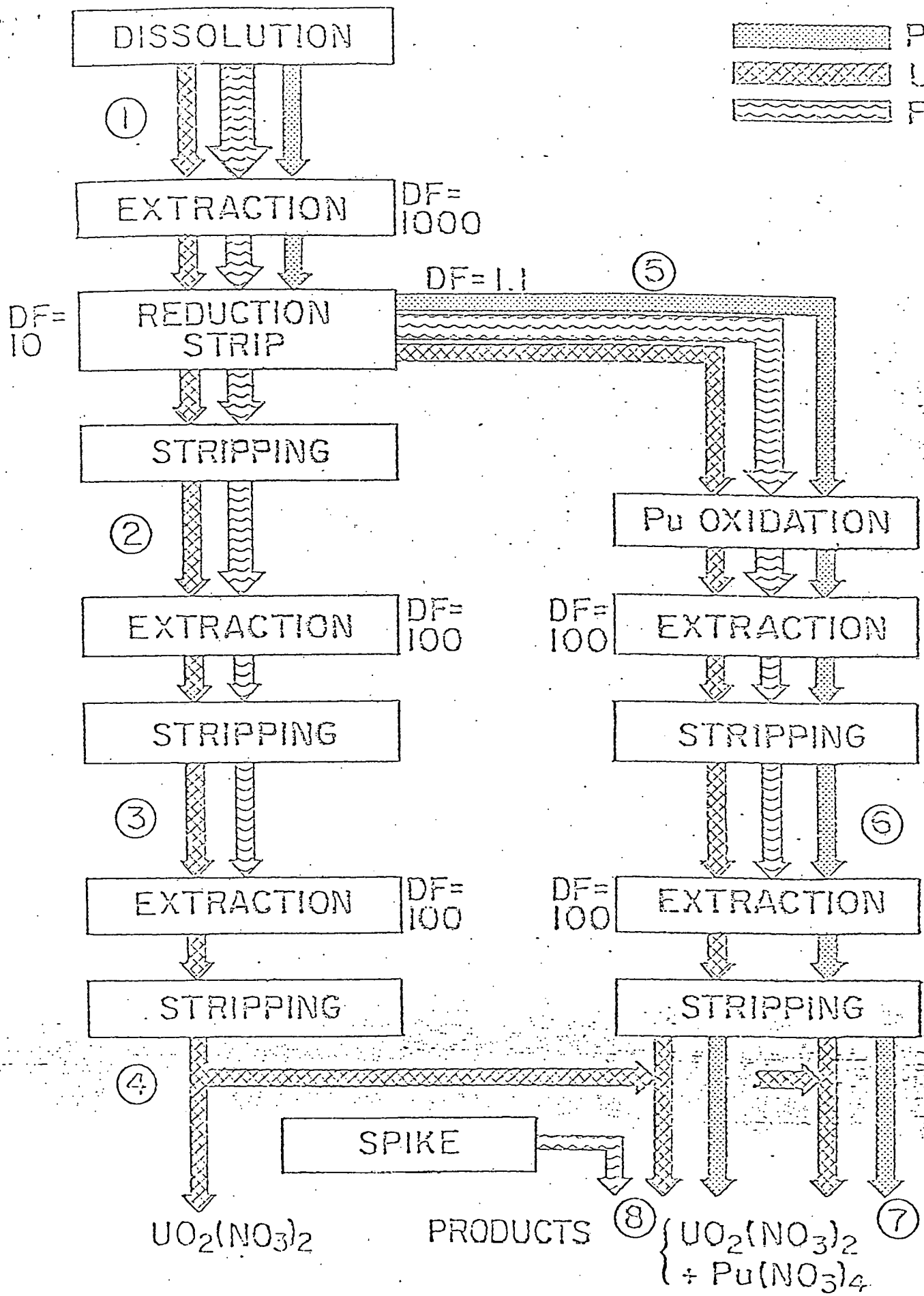
(a)



Flowsheet No-1. Purex.

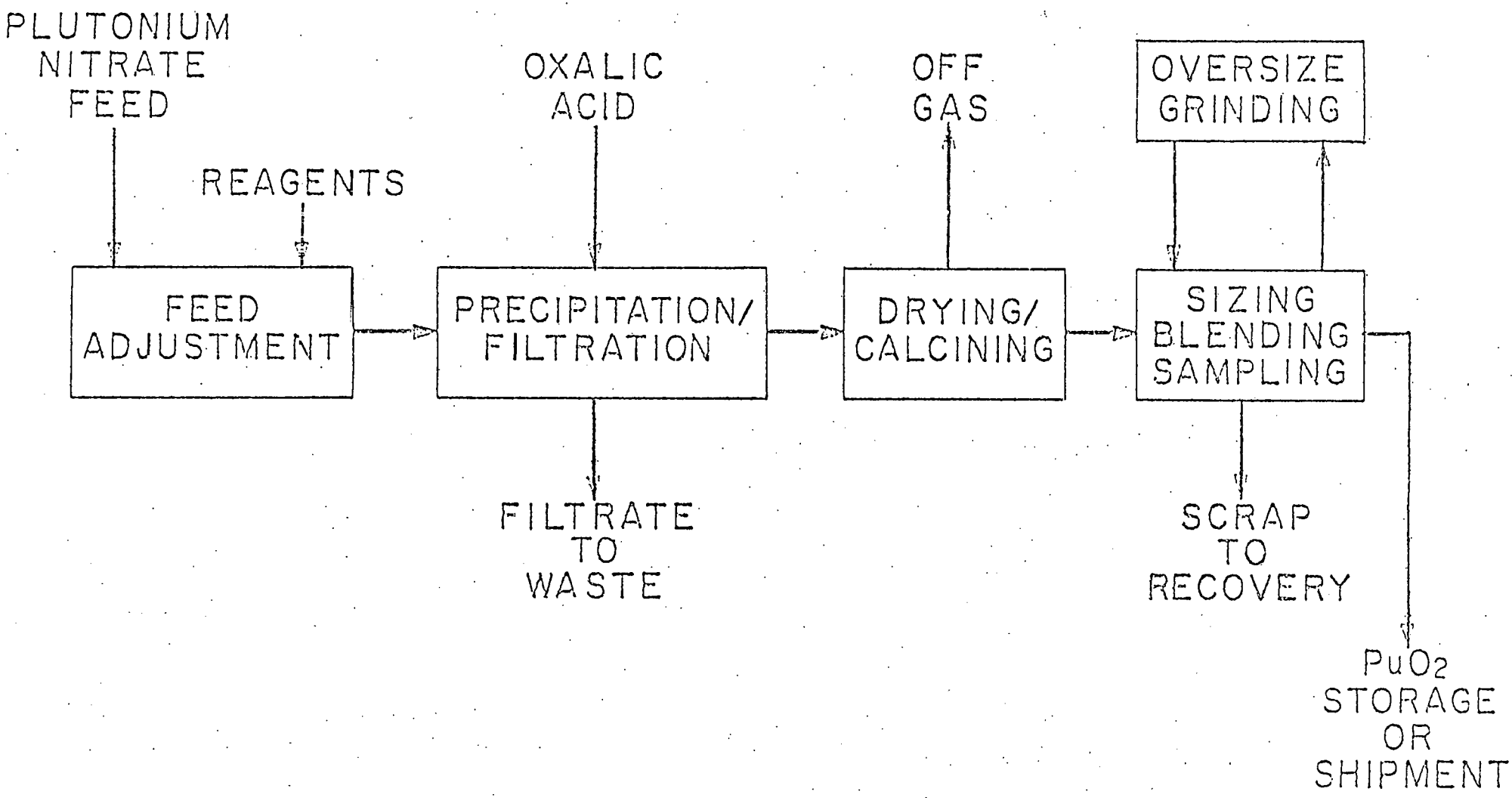


Flowsheet ~~No. 2~~. Total Coprocessing.



Flowsheet No. 3: Coprocessing with Uranium Withdrawal

ORNL Dwg 78-254



PLUTONIUM OXIDE CONVERSION PROCESS

41

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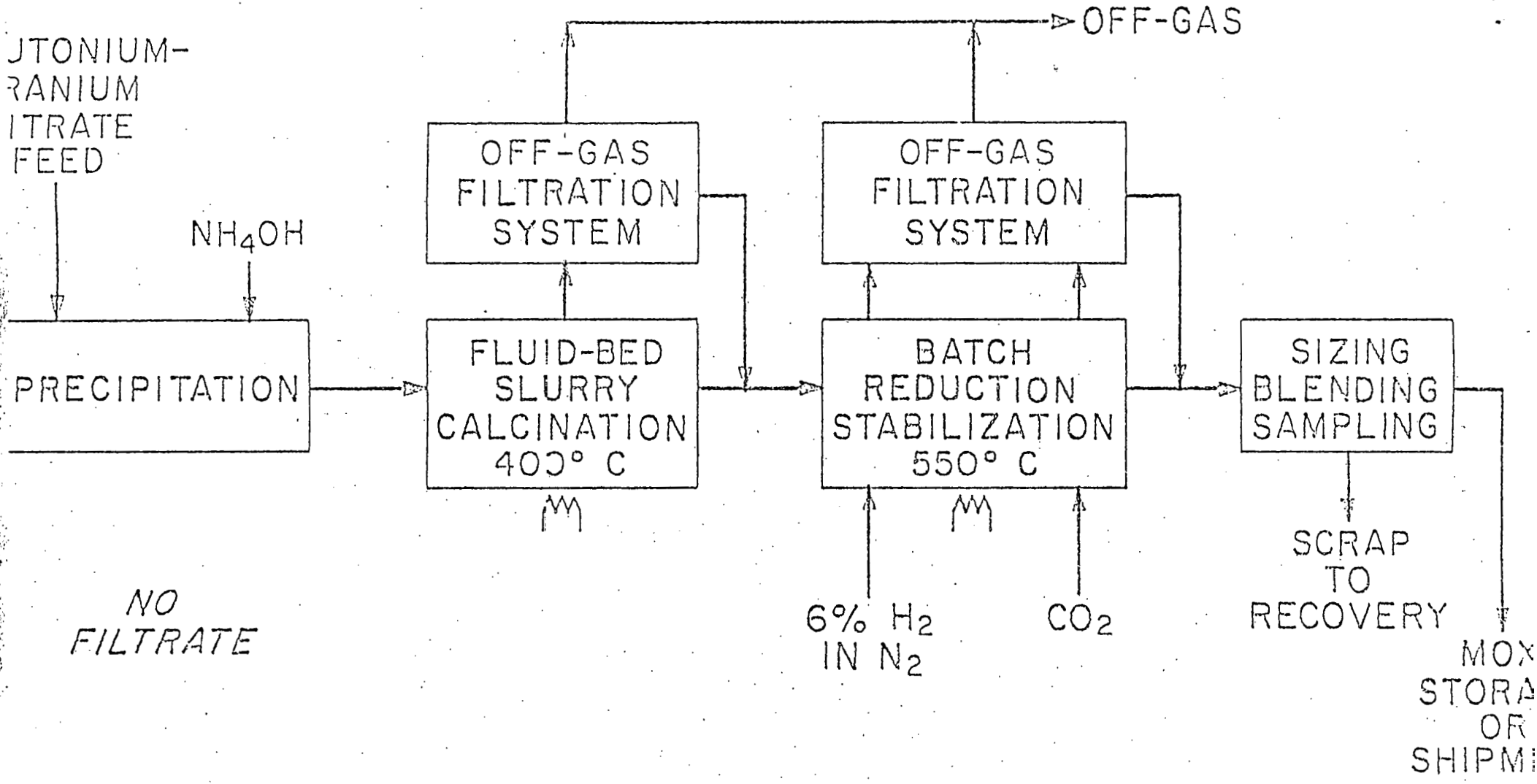

"COPRECAL" MIXED OXIDE CONVERSION PROCESS

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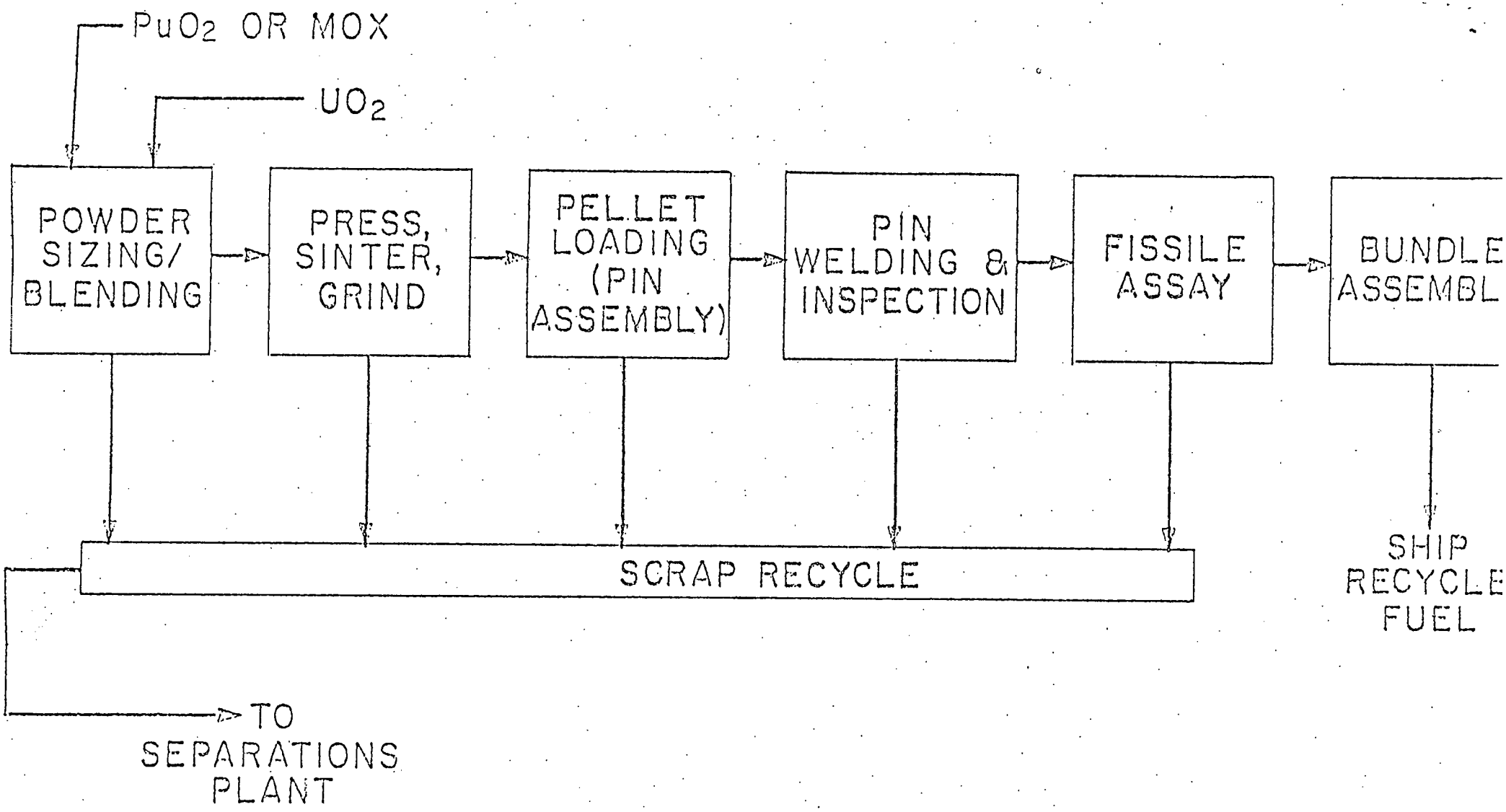
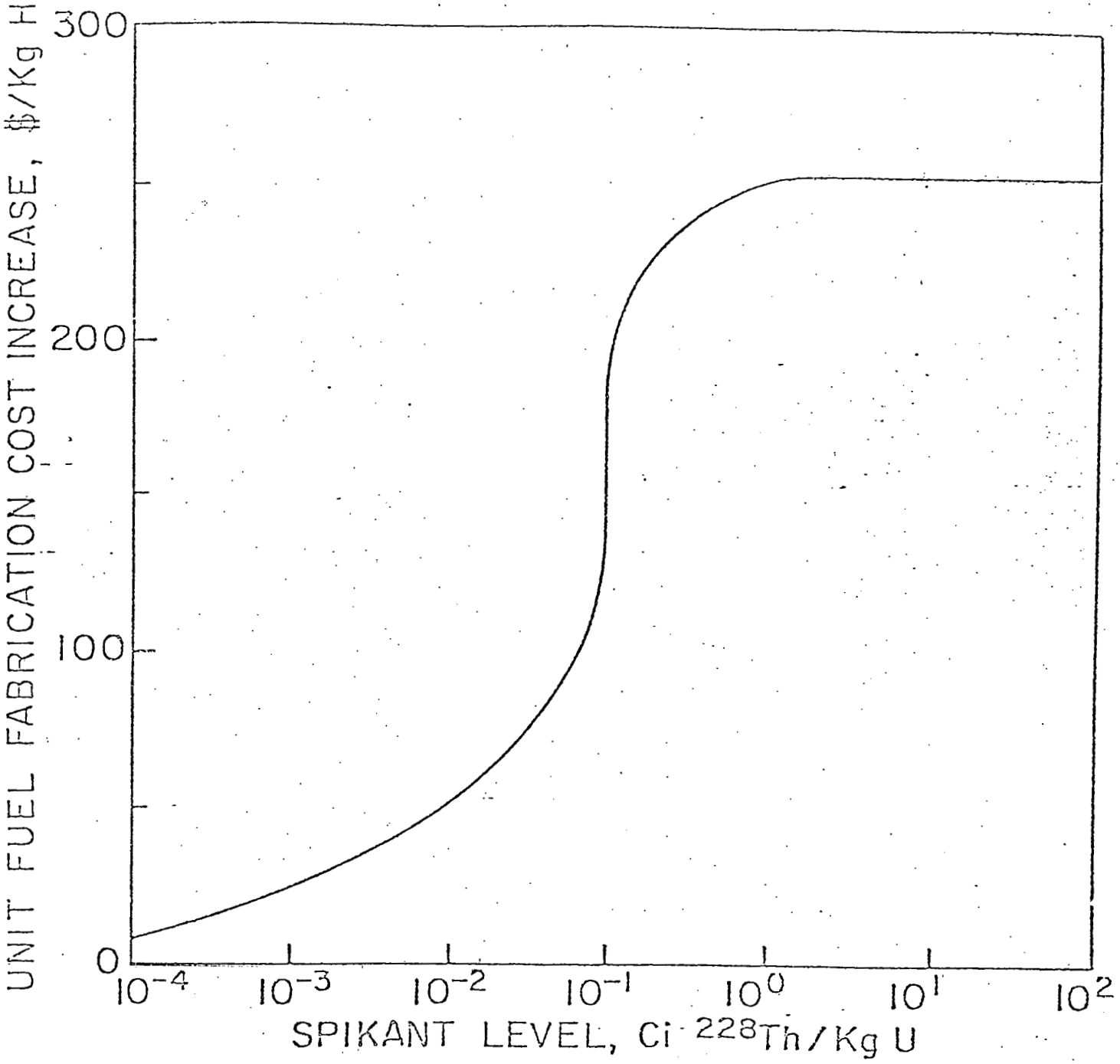


FUEL FABRICATION

ORNL Dwg 78-693



EFFECT OF SPIKING LEVEL ON INCREMENTAL FUEL FABRICATION COST

Ref. *"The spiking of special nuclear materials as a safeguards measure"* —BNL

"Hot" Fuel Fabrication Involves ....

1. Remote operation and maintenance

2. Interference with fissile assay system

3. Interference with mechanical inspection procedures
   - Possible de-rating of fuel

4. High projected cost

Summary .....

- ^{238}U-^{239}Pu fuel cycle is the most highly developed
- Pure ^{239}Pu is potentially subject to diversion
- Adulteration of the plutonium does not perturb the reactors
- Coprocessing alone costs relatively little — but is protection adequate?
- Coprocessing plus high-level spiking {CIVEX} will entail expensive hot fuel fabrication

(19)