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Research and Development Requirements for the Recycle of Bred Fuels in Uranium and Thorium Fuel Cycles

P. R. Kasten
R. G. Wymer
W. D. Burch
B. L. Vondra
A. L. Lotts
A. R. Olsen
W. L. Carter
R. H. Rainey
D. R. Johnson

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P. R. Kasten, R. G. Wymer, W. D. Burch, B. L. Vondra, A. L. Lotts,
A. R. Olsen, W. L. Carter, R. H. Rainey, and D. R. Johnson

Edited by

Lorraine S. Abbott
Engineering Physics Division

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FOREWORD

This report fulfills a commitment made under the Thorium Utilization Program in FY-1977 to provide the Thorium Assessment Program with estimates of the research and development (R&D) requirements associated with the commercialization of thorium fuel cycles in various reactor types. In providing such estimates, the R&D needs of various uranium fuel cycles were also included to place requirements under proper perspective. Thus, the technical requirements prior to the commercialization of fuel recycle are presented for uranium, thorium, and mixed uranium-thorium-based fuels as used in different reactors, with costs and schedules estimated in a relative, consistent manner. For a given reactor type, the estimated variation of R&D requirements as a function of fuel cycle should be significant because of the similarity of needs for the various cycles. At the same time, it is difficult to predict accurately the costs and times required to resolve problems involving R&D, and costs of demonstration facilities are highly uncertain without performing detailed design studies (and these were not carried out here). Because of this, ranges of fuel recycle development costs as a function of reactor type and fuel cycle are also presented, based on probable uncertainties in the estimates. Overall, this report provides an initial evaluation based on the limited information available at the time of this FY 1978 study; however, it does incorporate more recent cost estimates covering the fuel reprocessing areas.

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ABSTRACT

A summary is given of the 1978 status of fuel recycle technology, along with the research and development (R&D) which is required prior to commercialization of fuel recycle. The fuel cycles consider use of uranium, thorium, or mixed uranium-thorium-based fuels; the reactor types include Light Water Reactors (LWRs), Spectral Shift Controlled Reactors (SSCRs), Heavy Water Reactors (HWRs), High-Temperature Gas-Cooled Reactors (HTGRs), Liquid Metal Fast Breeder Reactors (LMFBRs), and Gas-Cooled Fast Reactors (GCFRs). Estimates of the schedules and costs for implementing the various fuel cycles in the different reactor types are given, and include those for demonstration/pilot plants. The technical areas cover fuel fabrication/refabrication, fuel reprocessing, fuel qualification, and waste treatment.

Based on this study, the cost (1978 dollars) for developing commercial recycle of bred fuel can vary from $1.3 to $3.6 billion. The uranium cycle in water reactors with recycle of plutonium is at the low end of the range, while the denatured-uranium-thorium (DUTH) cycle in all reactors is at the high end of the range. Developing the DUTH cycles for fast breeder reactors (FBRs) and for HTGRs will solve most of the R&D problems of fuel recycle development in general. The estimated lapsed time from initial development to commercialization of fuel recycle ranges from about 12 to 20 years, with thorium fuel cycles at the far end of the development time range.

SUMMARY

Research and development (R&D) requirements prior to the commercialization of fuel recycle are presented for uranium, thorium, and mixed uranium-thorium based fuels, along with estimates of the schedules and costs for implementing the various fuel cycles in different reactor systems. Principal technical problems which need to be addressed are discussed within the framework of present recycle technology, with status and development requirements addressed sequentially. The status and needed R&D of the uranium-plutonium cycle are discussed first for LWRs and then for HWRs and SSCRs; further R&D requirements for these three reactor types operating on denatured uranium-thorium (DUTH) cycles are then presented. Similarly, the status and R&D requirements of the uranium-plutonium cycle for FBRs are addressed prior to the R&D needs of DUTH cycles for those reactors. The status and development requirements for HTGRs, however, are discussed first for the thorium cycle (since that has been the reference cycle for HTGRs), followed by discussion of the additional R&D needed for developing DUTH cycles. The technological areas cover fuel fabrication/refabrication (fuel material preparation, rod fabrication, element assembly); fuel reprocessing (headend treatment, solvent extraction, product conversion, off-gas treatment); fuel qualification (irradiation performance testing and evaluation); and waste treatment (concentration, calcination, vitrification, radioactive-gas treatment).

In general the basic technology for the fabrication of uranium oxide pellet fuels exists today with the fabrication of LWR and HWR uranium fuels conducted on commercial scales. To date, Pu/U fuels have only been fabricated on a small, pilot-plant scale, and a significant amount of research and development is still required. Areas requiring further study include demonstration of:

(1) A pelletizing process to assure uniform product characteristics and performance;
(2) Methods for verifying and controlling the characteristics of the Pu/U fuels;
(3) Processes for the recovery of contaminated scrap;
(4) A reliable nondestructive assay system for powders, fuel rods, and wastes;
(5) The ability to operate a large-scale plant remotely, with hands-on maintenance (in the case where Pu/U oxides containing high quality Pu are being fabricated); and
(6) Satisfactory irradiation performance of Pu/U fuels produced in commercial-scale processes and equipment.

Relative to thorium-based fuels, for metal-clad fueled reactors the intense radioactivity of the decay daughters of the ^{232}U requires that the refabrication processes be remotely operated and maintained. Areas requiring further study are essentially the same as those for the Pu/U fuels except that additional efforts are needed for fuels as influenced by the need for remote maintenance, and this may lead to new fabrication methods. Further, additional R&D is required in fuel qualification of U/Th and Pu/Th fuels. For HTGR fuels, fabrication processes and equipment have been developed for refabricating fuel remotely. However, additional R&D is needed, particularly in the scaleup of refabrication equipment, the recycle of scrap material, the control of effluents, the assay of fuel-containing

materials, and the qualification of recycle fuel. Further development work will be required to fabricate DUTH fuels because of the requirement of a larger kernel for fissile particles.

Relative to fuel reprocessing, the basic technology exists for the reprocessing of LWR uranium and uranium/plutonium fuels using the Purex process. This technology is based on many years of reprocessing experience with low burnup fuels primarily; however, a commercial reprocessing plant that conforms to current U. S. federal and state requirements has not yet been operated. While reprocessing of LWR fuels in the NFS plant can be considered a significant step on the road to commercial reprocessing, the problems which have plagued subsequent plants emphasize that there still remain technical, regulatory, and institutional matters to be resolved. Specific areas that presently require additional development work and demonstration include the following:

(1) Operation and maintenance of the complex mechanical headend equipment;
(2) Methods for handling highly-radioactive residues that remain after the dissolution of high-burnup fuel;
(3) The technology for reducing radioactive off-gas releases (e.g., Kr-85, iodine and tritium) to conform to anticipated regulations; and
(4) Remotely operated and directly maintained conversion processes for plutonium from power reactor fuels.

The technology for reprocessing thorium-based fuels is less advanced than for uranium fuels. While irradiated thorium of low burnup has been processed in government plants, thorium has not been processed in a large-scale plant specifically designed for thorium processing, nor has fully irradiated thorium fuel been processed by the standard Thorex process in engineering-scale equipment. The high level waste from dissolution operations would contain fluoride and may contain large amounts of zirconium, and leads to additional R&D needs. Areas of development for thorium processing which differ from those for uranium processing and require additional development include the following:

(1) Product dissolution and separation from Zircaloy cladding;
(2) Feed adjustment and clarification of fully irradiated fuel;
(3) Technology for containing Rn-220 and other radioactive gases to conform to regulations;
(4) Recovery of fully irradiated thorium in large-scale facilities;
(5) Partitioning of fuel solutions containing U, Pu, and Th;
(6) Methods for handling high-level wastes which contain fluoride and possibly zirconium solutions; and
(7) In the case of graphite-based HTGR fuels which utilize thorium, additional development work with irradiated materials in the crushing, burning, particle separation operations, and off-gas treatment associated with the head-end of the reprocessing plant.

The R&D requirements for waste treatment involve development of the technology needed for immobilizing high-level, intermediate-level, and gaseous wastes, and include those for

concentration, calcination, and vitrification of wastes. The waste treatment requirements for the various fuel cycles are similar, but are somewhat more complex for the thorium cycles because of the presence of fluorides in the wastes.

Based on the technological requirements, preliminary estimates are made of the schedules and costs for carrying out the needed R&D for the implementation of commercial fuel recycle for the different reactors and fuel cycles. These estimates consider carrying R&D through the demonstration or pilot plant phase such that a commercial sized fuel recycle facility having acceptable operations could be built with assurance of successful operation. However, first-of-a-kind costs associated with large commercial-scale facilities are not included. The demonstration recycle plants considered here involve a fuel reprocessing capacity of 5 MT/day for uranium fuel cycles in LWRs, SSCRs, and HWRs, and assume use of the Barnwell Nuclear Fuel Plant (only add-on costs were considered); pilot plant reprocessing facilities are considered for thorium fuel cycles in water reactors and for FBRs and HTGRs with reprocessing capacities of 0.5 MT/day for the FBR and water reactor fuels, and 0.2 MT/day for HTGR fuels (the above are consistent throughputs for a given GW(e) nuclear industry for each reactor type since HTGR fuels have average exposures of 2.5-3 times the average fuel exposures of FBR and water reactor fuels). Fuel refabrication capacities are 0.2 MT/day for all reactor types except for the HTGR, where the capacity is about 0.1 MT/day. Fresh fuel fabrication demonstration plant capacities are about 2 MT/day except for the HTGR fuel, where the capacity is about 1 MT/day. The costs and schedules are estimated on the basis of those required to develop a given fuel cycle independently, so as to give a relative evaluation of inherent fuel cycle R&D requirements as a function of fuel cycle. At the same time, the results are not meant to imply that fuel cycle R&D would or should be carried out independently for the various cycles or reactors. Integration of fuel recycle R&D for the various fuel cycles and reactor types based on generic technology development would permit fuel recycle to be developed for several fuel cycles and reactor types with only incremental increases in costs above those for a single fuel cycle. In general, development of the more complex fuel cycles associated with FBRs, HTGRs, and DUTH fuels would encompass most of the R&D needs of the other fuels and reactor types. The specific integration to be employed, however, depends upon the importance given to developing the various fuel cycles in specific reactor types.

Based on the inherent requirements of the various fuel cycles in different reactors, the research, development and demonstration/pilot plant costs are estimated in a relative, consistent manner. At the same time, it is not possible to predict accurately the costs and times required to resolve problems involving research and development; further, the costs of demonstration and pilot plant facilities are highly uncertain without performing detailed design studies, and these were not carried out here. Thus, there are large uncertainties in the estimated costs. However, for a given reactor type, the variation of R&D costs as a function of fuel cycle should be significant and the trends should be accurate. Further, the relative costs between the various reactor fuel cycles having many generic similarities should be more accurate than the relative costs of HTGR fuel cycles involving unique problems.

In general, the lowest R&D costs are associated with reactors on the LEU throwaway cycle. Of these, the highest R&D and demonstration facility costs are associated with the HTGR and the LEU-fueled HWR, because of the need for constructing fresh fuel demonstration plants for those reactors. For the throwaway/stowaway fuel cycles, the R&D activities for all reactors are estimated to be completed in the period between 1984 and 1986. The fresh fuel fabrication demonstration plants are estimated to be operating in 1991. For the LEU cycle with recycle of uranium only, the total costs are highest for the HTGR followed by the HWR using slightly enriched uranium. For the Pu/^{238}U fuel cycle with recycle of bred fuel, total costs for R&D and demonstration/pilot plants are lowest for water reactors, highest for the FBR, with the HTGR intermediate. For the thorium fuel cycles with recycle of bred fuel, the HTGR and the water reactors appear to have relatively lower costs than do FBRs for R&D and demonstration/pilot plant facilities. The differences between FBR and HTGR costs are primarily due to the differences in pilot plant costs, and are associated with the lower HTGR fuel throughput required. The R&D for all reactors utilizing thorium fuel cycles could be completed within the period 1991 to 1996. The demonstration fuel recycle plant using thorium cycles would be first available about the year 2000. Demonstration fresh fuel fabrication plants involving thorium fuels could be operating about 10 years earlier. For the uranium fuel cycles, there is a significant difference in total costs for the different reactors; also, the total costs go up markedly in going from throwaway/stowaway cycles to cycles involving recycle of uranium only and on to cycles involving recycle of both uranium and plutonium. In general, the total costs for developing U/Pu fuel recycle appear to be less than those associated with thorium recycle systems. Of the thorium-based cycles, development of the DUTH cycle appears to have the highest total cost.

Integrated planning for fuel recycle development will have significant cost savings, particularly for facilities, such that development of several fuel cycles will cost much less than the sum of developing the individual cycles independently. With an integrated approach, however, development schedules would be extended because of the need for sequential development associated with specific reactors and fuel cycles. The specific integration to be carried out is dependent upon the economic performance of reactors and their fuel cycles.

Because of the uncertainty in the cost estimates performed, ranges of costs are presented for fuel recycle development. Based on this study, the total cost for developing fuel recycle to the point of commercialization (but not including first-of-a-kind costs for commercial facilities) can vary from $1.3 billion to $3.6 billion. The uranium cycle in water reactors with recycle of Pu is at the low end of the range, while the DUTH cycle in all reactors is at the high end. For all fuel cycles, however, there is much uncertainty in the R&D costs. Thus, in water reactors, the estimated range of R&D costs is $1.3-2.2 billion for U/Pu recycle development, and $1.9-3.1 billion for DUTH recycle development. For HTGRs, the corresponding ranges are $1.5-2.4 billion and $1.9-3.0 billion for U/Pu and DUTH recycle development, respectively; for FBRs the corresponding ranges are $1.8-2.8 billion and $2.2-3.6 billion, respectively. If a number of related cycles were

developed using the same generic facilities, the total costs could be only slightly higher than those associated with any one cycle, but the overall development schedule would be lengthened. Developing the DUTH cycle for FBRs and for HTGRs will solve most of the R&D problems of fuel recycle development in general.

For a given fuel cycle, the estimated lapsed time from initial development to commercialization of fuel recycle ranges from about 12 to 20 years, depending upon the initial technology status and the degree to which the R&D program steps are telescoped to save time. The thorium cycles would be at the far end of the development time range. An integrated program for developing several fuel cycles would increase the time for completing the overall schedule by perhaps 5 years over that for individual development, but would provide large savings in facility costs.

INTRODUCTION

This report discusses the research and development requirements for the recycle of denatured uranium-thorium fuels (DUTH fuels) and presents estimates of the schedules and costs for implementing DUTH cycles in various reactor systems. For purposes of comparison, and because reactors operating on DUTH cycles will almost certainly comprise a component of a symbiotic system that includes reactors operating on other cycles, similar schedules and costs are included for several additional fuel cycles that are being contemplated. It is to be emphasized that this report has been prepared without the use of projected reactor growth scenarios and without sufficient study to know with certainty whether all the problems associated with the establishment of commercial fuel cycle activities have been addressed. Thus, the discussion is largely limited to a delineation of the principal technical problems as they are currently perceived within the framework of the present recycle technology. While the time schedules and costs indicated to resolve these problems were in some cases derived from existing detailed R&D technology program plans, they are still largely based on engineering judgment and experience in many cases, and thus subject to rather large uncertainties.

Much of the present fuel recycle technology has been developed for LWRs operating on the uranium-plutonium cycle. Since, except for the HTGR, the other reactors considered here also have been designed to operate on this cycle, the LWR U/Pu cycle is taken as the reference cycle from which the additional needs for DUTH cycles in non-HTGR-type reactors are addressed in stages. Specifically, the status and development requirements of the LWR U/Pu cycle itself are discussed first, after which the additional needs for HWRs and SSCRs to operate on the U/Pu cycle are considered. With the reference cycles thus established, the further requirements for all three of these reactor types to operate on DUTH cycles are discussed. Similarly, the status and development requirements of an FBR U/Pu reference cycle are addressed, with the additional needs for FBRs (LMFBRs and GCFRs) to operate on DUTH cycles discussed next. Finally, the status and development requirements of the HTGR thorium cycle utilizing highly-enriched uranium (which until recently was the reference cycle) are described, after which the additional work necessary to convert HTGRs to DUTH cycles is discussed. In all cases, reprocessing treats partitioning and recovery of the fuel components; thus, coprocessing and addition of spikants is not considered. This was done on the basis that fuel recycle would be conducted in secured energy centers. Thus, the R&D for developing coprocessing and fuels containing spikants was not specifically addressed. Nonetheless, such R&D is largely implicit in the work described, and including it specifically would not significantly influence the kind of R&D needed; however, use of radioactive spikants in fuel processes could increase recycle R&D costs significantly.

The R&D requirements and associated pilot plant and/or demonstration facilities are those needed prior to the construction of commercial fuel recycle facilities; fulfilling those requirements is to provide the information and experience needed to give assurance that commercial facilities can be built and operated successfully. The heavy metal throughput of commercial reprocessing facilities is considered to be about 5 MT/day for LWRs, SSCRs,

HWRs (10 MT/day for natural-uranium-fueled HWRs), and FBRs, and about 1.5 MT/day for HTGRs. The heavy metal throughput of commercial refabrication facilities is considered to be 1-2 MT/day. The demonstration or pilot plant facilities considered are of a size so as to provide operating experience with prototypical commercial equipment.

Throughout the discussion of the specific kinds of work needed for each of the above cycles, reference is made to the major steps common to all cycles. These steps and the primary operations comprising each of them are summarized in Table 1. Each operation is further categorized according to its stage of development or "scale of operation," using the terminology defined in Table 2. The scale of operation provides perspective and also an overview of the present level of experimental studies associated with the various fuel recycle operations for the different reactor types. In general the operations can be considered to be generic for classes of reactors and/or fuel compositions and thus by viewing them collectively the status and development requirements of the several cycles may be compared.

Following the discussion of the various fuel cycles, estimates are made of the schedules and costs for carrying out the needed research and development indicated for implementation of the cycles in the different reactors. The schedules consider the time intervals during which the research and development is carried out for reprocessing, fabrication/refabrication, and waste treatment and also for design, construction, cold checkout, and hot checkout of a demonstration fuel recycle facility, along with the corresponding costs. Finally, an integrated DUTH recycle development program that considers generic operations and facilities is outlined for assumed reactor development schedules.

Table 1. Fuel Recycling Steps and Operations

Recycle Step	Primary Operations Included
Fuel fabrication	Metal-clad fuels: powder and pellet preparation (or sphere-pac preparation); rod fabrication; element assembly.
	HTGR fuels: kernel preparation and loading, kernal carbonization, conversion, and coating; rod fabrication; element assembly; element carbonization.
Fuel reprocessing	Headend treatment; solvent extraction; product purification and conversion.
Fuel refabrication*	Same as for fuel fabrication (see above) except that the inclusion of radioactive fuel imposes special handling techniques.
Fuel qualification	Irradiation testing and evaluation of reactor fuels.
Waste treatment	Treatment of process wastes for permanent disposal (does not consider permanent disposal itself).

*Note: Fuel elements are assumed to be refabricated elements if the feed material arrives from a reprocessing plant rather than from a uranium enrichment plant or rather than being natural uranium. Thus all fuel elements containing ^{233}U fuel will be classified as refabricated elements.

Table 2. Scale of Operations Used to Describe Status of Fuel Recycle Technology Development

Term Denoting Scale of Operations[a]	Explanation
1. Cold laboratory	Operation performed with small-scale laboratory equipment; radioactivity not greater than tracer level; hands-on operations.
2. Hot laboratory	Operation performed with small-scale remotely-operated equipment; full-level radioactivity present.
3. Cold engineering	Operation performed with engineering-scale equipment; radioactivity not greater than tracer level; hands-on operations.
4. Hot engineering	Operation performed with engineering-scale remotely-operated equipment; full-level radioactivity present.
5. Cold prototype	Operation performed with equipment of size meaningful to commercial plant operation; radioactivity not greater than tracer level; equipment could be operated remotely.
6. Pilot plant[b]	Operation of integrated facility simulating certain parts of fuel recycle facility; equipment of size meaningful to commercial plant operation; full-level radioactivity present.
7. Demonstration facility[b]	Operation of integrated facility that provides recycle demonstration with full-scale or prototypic processes and equipment such as used in a commercial plant.
Developed[c]	Operation can be placed in commercial plant with confidence it will function successfully.

[a]The scale of operations is given in the general order followed in experimental development; also, e.g., if "hot engineering" is indicated, it is implicit that the cold laboratory, hot laboratory, and cold engineering modes of the operation have been generally completed, but that the hot engineering development has not been completed.

[b]In many cases these terms are used interchangeably, the objectives of both being similar. Pilot plants are normally the final phase of a test program, done at sufficiently large scale that the commercial-scale facilities which follow can be built with confidence. Demonstration facilities carry out the overall integrated operations in a way that licensing requirements are demonstrated. Commercial-size facilities provide the final demonstration.

[c]Status of development, rather than a scale of operation.

1. RESEARCH AND DEVELOPMENT REQUIREMENTS FOR URANIUM AND THORIUM CYCLES IN LWRs, HWRs, AND SSCRs

1.1 Status and Development Requirements of LWR U/Pu Recycle Technology

The basic technology for recycling LWR fuels containing uranium and uranium-plutonium exists. It is based on the Purex reprocessing process that has been used for many years in government-owned plants in the U. S. and other countries and on the fuel fabrication/refabrication experience of various countries and private organizations. However, neither a commercial reprocessing plant nor a refabrication plant that conforms to current federal and state requirements has been operated in the U. S. In fact, these requirements have not yet been fully defined. Fuel recycle plant licensing has been suspended, as has issuance of the Generic Environmental Statement on Mixed Oxides (GESMO) except for that part relating to safeguards. Thus the statement that the technology for recycle exists means that engineering-scale or pilot-plant-scale work has been successfully carried out on all important components of recycle. It does not mean that operability, reliability, licensability and costs of an integrated plant have been demonstrated. Development programs have been established in reprocessing (the Alternate Fuel Cycle Technologies Program at Savannah River Laboratory) and refabrication (at Pacific Northwest Laboratory) to address the remaining technical problems recognized in this cycle and are summarized briefly here. In addition, major programs to establish the waste handling and storage schemes for all fuel cycles including this one are in progress in existing DOE programs. Although additional work is needed, it is certain that an integrated plant can be built and operated.

Fuel Fabrication/Refabrication. The fabrication of the initial LEU fuel for LWRs is presently performed by a mature industry with the qualification of fresh fuel well established. Typically the procedure for fabricating LEU fuel is to prepare UO_2 powder from slightly enriched UF_6, process the UO_2 to solid pellets, carefully dimension the pellets by grinding, incorporate the pellets in sealed Zircaloy tubes, and assemble the tubes into complex fuel assemblies. The major plants that fabricate LEU fuel for LWRs built by the U. S. are listed in Table 3.

Table 3. Major U. S. LWR-LEU Fuel Fabrication Facilities

Company	Location	Estimated Capacity (tonnes/day)
Westinghouse	Columbia, SC	5-7
General Electric	Wilmington, NC	5
Babcock & Wilcox	Lynchburg, VA	3-5
Combustion Engineering	Windsor, CT	2-3
Exxon	Richland, WA	2-3

The refabrication of recycled fuel has not been commercialized in the U.S. and the development of the commercial processes is dependent in part upon a favorable decision by the Nuclear Regulatory Commission (NRC) and the President to permit plutonium to be recycled in power reactors. However, fuels made from mixtures of uranium and plutonium oxides (called mixed oxide or MOX fuels) have already been prepared in small-scale pilot plants operated in the U.S. and abroad, using high-grade plutonium. The usual procedure in mixed oxide fabrication plants is to prepare UO_2 powder (from natural uranium, recycled uranium, or slightly enriched uranium), to mix the UO_2 with PuO_2 powder (where the PuO_2 has been prepared from plutonium nitrate solution), and then to proceed through the same fuel fabrication operations as for fresh fuel. Thus the principal difference between fabrication and refabrication is that in refabrication plutonium is involved and because of its radioactivity, recycled fuel requires special considerations. Plutonium has to be contained with a high degree of integrity and shielding must be provided to protect workers from radiation. This in turn will necessitate that remote or semiremote handling techniques be developed. Refabrication experience with plutonium of the isotopic composition expected in recycle fuels is limited, and the full extent of the problems associated with MOX fuel refabrication will not be known until more experience has been gained. Further, to facilitate fuel dissolution during reprocessing, the MOX fuels may need to be made by means to insure homogeneity.

The qualification of fresh fuel for reactor use has, of course, been established. The qualification of recycle fuel has not been completed; present development has largely been based on fuel fabricated in laboratory- or engineering-scale facilities. Additional work is required to demonstrate that fuel refabricated in commercial facilities performs satisfactorily. Additional development work to clean and recycle most process rad waste streams appears required to reduce the release of plutonium from fuel refabrication plants.

The major U.S. refabrication plants are shown in Table 4.

Table 4. Major U. S. LWR-U/Pu Fuel Refabrication Facilities

Organization	Location	Recycle Capacity	
		tonnes/yr*	tonnes/day
		Existing	
B & W - Numec	Apollo, PA	20-25	0.1
Exxon	Richland, WA	∿ 20	0.1
Westinghouse	Cheswick, PA	20-25	0.1
		Planned	
Westinghouse	Anderson, SC	200	1.0
B & W - Numec	Apollo, PA	72	0.4

*Approximate capacity assuming 200 days per year.

Fuel Reprocessing. LWR fuel reprocessing operations include shearing the fuel, voloxidation, dissolving the fuel, feed clarification and adjustment, off-gas cleanup, recovering the fissile material, and then converting nitrate products to the oxide form for refabrication (see above). Significant U. S. commercial development has gone into LWR fuel reprocessing as evidenced by the operation of the Nuclear Fuel Services (NFS) plant

in West Valley, New York, during the period 1966-1971. Other plants intended for commercial operation have been built at Morris, Illinois, by General Electric, and at Barnwell, South Carolina, by Allied General Nuclear Services. The capacity and status of each of these plants are given in Table 5.

None of the U. S. plants listed in Table 5 are in operation today. Only the AGNS (Barnwell) plant is being considered for use, and plans for its startup are indefinite. The plant is in an advanced construction state, but fuel-conversion and waste-treatment facilities are still needed, as well as NRC approval. Extensive modifications would be required for the MFRP and NFS plants to operate. While the NFS plant provided commercial reprocessing experience, this experience might not be directly applicable to the more highly irradiated fuels anticipated for the future (up to 40,000 MWD/T), nor for the shorter cooling times. Further, the effluent control operations of the plant would not meet today's requirements, and neither would its design for earthquake and tornado resistance.

Table 5. Commercial-Type LWR Fuel Reprocessing Plants for LEU-Type Fuels

Plant and Site	Fuel Type	Capacity, U + Pu (tonnes/yr)	Oxide Fuel Processed (tonnes)	Status of Operation
Allied-General Nuclear Services (AGNS), Barnwell, SC	Oxide	1500		Has not started; startup dependent on NRC decision on Pu recycle and additional facilities.
Nuclear Fuel Services (NFS) West Valley, NY	Oxide	750		Shut down; startup dependent on relicensing by NRC and economic factors. Startup is unlikely.
Midwest Fuel Reprocessing Plant (MFRP), Morris, ILL	Oxide	300		Has not started; startup dependent on major revisions to plant and economic factors. Startup is unlikely.

The limited commercial experience with the NFS plant and the extensive work carried out at government installations has nevertheless provided a good understanding of reprocessing operations. With regard to the initial mechanical processing, development of a reliable, remotely maintainable fuel element shear is needed and is underway. Isolation of tritium is expected to be required in the future and completion of the development of the voloxidation process or an alternate retention scheme is needed. Dissolution of highly irradiated LEU fuels is straightforward, but mixed oxides are relatively less soluble, particularly if made by methods which have not insured homogeneity.

A highly radioactive residue in amounts which increase with increasing burnup remain when highly irradiated fuels are dissolved, and practical separation of the residue from

the solution may be difficult. Plutonium loss to this residue, while thought to be low, must be determined in plant practice. With regard to Purex reprocessing, no significant new problems are expected, even though experience with high-exposure fuels is limited.

In order to reduce radioactive releases from a reprocessing plant, considerable additional work needs to be carried out on off-gas treatment, with emphasis on the containment of ^{85}Kr, ^{14}C (as CO_2), ^{129}I, and tritium. Research and development which has been carried out on various separation processes for the above nuclides includes: cold (tracer) pilot-plant-scale operation of a fluorocarbon absorption process for ^{85}Kr removal, bench-scale studies of iodine absorption in nitric acid, and absorption of tritium on activated carbon and on molecular sieves. Removal of ^{14}C could be accomplished by fixation of CO_2 as $CaCO_3$.

Waste Treatment. In a fuel recycle plant waste treatment concentrates acidic aqueous wastes for interim storage followed by calcination and incorporation into vitrified materials for ultimate disposal. (The disposal itself is not considered here.) Cladding hulls, other alpha-containing wastes, and numerous low-level wastes from reprocessing and refabrication operations must also be treated for disposal. The radioactive off-gases mentioned above need to be collected and treated for storage. Waste-treatment operations would be largely associated with the effluents of the reprocessing operations of the recycle plant, but refabrication wastes cannot be neglected.

There is limited experience with treatment of high-level wastes from reprocessing reactor fuels. Idaho National Engineering Laboratory (INEL) has carried out engineering/pilot-plant and larger scale studies on calcination of high-level wastes; Batelle-Pacific Northwest Laboratory (PNL) has carried out extensive research and development acitivities on calcination and vitrification. The technology for handling wastes from Zircaloy clad removal operations is also limited. Also, modification of the fuel dissolution procedure to accommodate MOX fuels may add chemicals which make waste treatment more difficult.

1.2 Research and Development Required to Extend LWR U/Pu Fuel Recycle Technology to HWRs and SSCRs Operating on the U/Pu Cycle

The research and development fuel recycle needs of HWRs and SSCRs operating on the U/Pu cycle are basically the same as those for LWRs operating on the same cycle. Some additional effort will be needed because of the different design and enrichment requirements of fuel elements for HWRs and SSCRs, which would affect fuel fabrication/refabrication processes in detail and require additional fuel qualification testing and fuel reprocessing effort. Both HWRs and SSCRs would have lower fuel enrichment than LWRs, with HWRs having the lowest. Also, the diameter of HWR fuel pins is larger than LWR pins, and the length of the elements is much shorter, and while the elements have been commercialized in Canada for the HWR natural uranium fuel, converting to slightly enriched uranium fuel would require additional testing. Similarly, SSCR fuel fabrication methods would need verification, and the fuel fabrication and power cycling performance would have to be determined. In addition, differences in the concentrations of plutonium in the recycle

fuel for HWRs and SSCRs would require verficiation testing of fuel performance and demonstration that the refabrication processes produce an acceptable product.

In fuel reprocessing operations, different element designs would affect fuel chopping operations and the dissolution rate of the fuel itself. Since there are differences in fuel enrichments within the cores of the various reactor types, considerable attention must be given to fuel batching and inventory control if a common fuel reprocessing plant is utilized. Further, the irradiation exposure of the fuel would not be the same in the different reactors, and this may influence solvent extraction operations, partitioning requirements, and waste treatment requirements.

Overall, the research and development needs for HWRs and SSCRs operating on U/Pu cycles appear to be more of the verification type rather than of the new-process-development type; nonetheless, the effects of the above differences must be examined in detail as U/Pu cycles are developed for these reactors.

1.3 Additional Research and Development Required to Implement DUTH Fuel Cycles in LWRs, HWRs, and SSCRs

The technology for recycle of thermal reactor fuels containing thorium is generally less well developed than that for U/Pu fuels. It is, however, derivative from the LWR-LEU fuel recycle technology as extended and modified by limited demonstration of the Thorex (and Interim 23) process for thorium fuel reprocessing and the thorium fuel fabrication experience.

Fuel fabrication/refabrication operations in DUTH cycles will involve fuels having both higher uranium enrichment and higher radioactivity than the standard LEU fuel, and it is virtually certain that new plants specifically designed for DUTH fuel fabrication conditions would be needed, along with development and verification of those fabrication processes and equipment influenced by the fuel differences. Commercial fabrication experience for metal-clad thorium-based fuels has been limited to the initial $^{235}UO_2$-ThO_2 fuel and was obtained with engineering- and pilot-plant-scale equipment. (The reactor was subsequently converted to LEU fuel for economic reasons.)

Refabrication of DUTH fuels involves ^{233}U containing ^{232}U. Since the decay of ^{232}U leads to the emission of highly energetic gamma rays, extensive research and development must be carried out on remote refabrication operations in shielded facilities. Westinghouse has engineering-scale experience in fabricating ^{233}U/Th fuel elements at its Bettis Laboratory, but the ^{232}U content of the ^{233}U fuel was low (<10 ppm) compared with levels of 1000-2500 ppm in thermal reactor fuels. Even so, the radioactivity of the fuel imposed special precautions and equipment. Because commercial plants will require remote operations, refabricated fuels may be based on gel-sphere and sphere-pac technology, in which case research and development would be required for microsphere

formation and densification, sizing of microspheres, and loading of microspheres into metal tubes to form fuel rods.

Extensive research and development must also be carried out to qualify the performance of DUTH fuel. DUTH fuels will generate both ^{233}U and Pu during the irradiation process, and the associated power distributions during life can lead to a fuel performance different from that of U/Pu fuels. Thus, the research and development for fuel refabrication must include processes for fuel homogeneity control; scrap recovery and recycle processes and the demonstration of reliable nondestructive assay systems for fuel materials and wastes will also be needed. Fuel performance data needs include information concerning in-reactor densification and swelling behavior, heavy metal redistribution during irradiation, fission gas release, thermal conductivity of the fuel, and mechanical and chemical fuel-cladding interactions under various reactor operating conditions. Further, to obtain meaningful qualification, fuel used in the above testing must be fabricated with processes and equipment representative of commercial refabrication technology.

The DUTH fuel cycle introduces significant new requirements with regard to fuel reprocessing. For example, the shearing operation must be demonstrated with thorium-based fuels. Also, the dissolution of thoria in nitric acid is too slow to be practical unless fluoride ion is added, but the fluoride will attack the Zircaloy cladding of the fuel, and the resulting zirconium compound will complex the fluoride ion so that thoria dissolution will be retarded. Adding excessive fluoride would decrease the dissolution rate of thoria since thorium fluoride has low solubility; it would also increase equipment corrosion markedly. If practical, it would be desirable to remove the cladding before dissolving the thoria. This might be accomplished by chemical methods (e.g., Zirflex process), pyrometallurgical methods, or by mechanical methods, any one of which would require extensive research and development.

The removal of tritium from thoria fuels may be more difficult than from urania fuels. When thoria is heated in air it does not change in chemical form, and so in this case the voloxidation process may not be effective for tritium removal. This could lead to a significant impact on subsequent reprocessing operations inasmuch as tritium dissolution in aqueous streams would increase the problems of liquid-waste handling.

With regard to solvent extraction, the Acid Thorex process has demonstrated the separation of thorium and uranium from fission products for fuels of low irradiation exposure; however, DUTH fuels will have high fuel exposures ($\sim$40,000 MWD/MT) and will contain plutonium. In order to accommodate the extraction and separation of fuel products in the DUTH fuel cycle, significant modifications to the Thorex process appear to be required. Also, in the use of

products from the solvent extraction steps, care must be taken so that ^{220}Rn does not lead to radiation release problems. Radon gas forms from the decay of ^{228}Th, and while it decays relatively quickly to a solid daughter, off-gas treatment methods need to be developed for radon control.

New waste treatment requirements may arise because of the thoria dissolution problem. Wastes resulting from any chemical decladding of the Zircaloy (or from other treatment) would need to be handled and treated. Also, the presence of fluoride in the wastes from fuel dissolution will influence the choice of waste treatment process. A significant research and development effort appears needed in these areas.

2. RESEARCH AND DEVELOPMENT REQUIREMENTS FOR URANIUM AND THORIUM CYCLES IN LMFBRs AND GCFRs

2.1 Status and Development Requirements of FBR U/Pu Recycle Technology

The technology for recycle of FBR fuels based on the uranium-plutonium cycle is similar to that for LWR fuels on the same cycle, but important differences make FBR fuel recycle technology more difficult. The Advanced Fuel Recycle Program at ORNL has been addressing these problems for a number of years and has recently broadened efforts to include examination of reprocessing problems in other breeder fuel cycles. The program plan includes significant work on generic remote maintenance techniques and a major pilot-plant phase. This phase has many features which are identical to the demonstration phase described in other places in this document. Because the fuel recycle needs for LMFBRs and GCFRs are generally very similar, they are discussed here together. However, the presence of sodium on the cladding of LMFBR fuel elements, and possibly inside them, is an important difference requiring special considerations in the head-end treatment.

The considerations presented in Section 1 on the refabrication of plutonium in LWRs for the most part also applies to the fabrication of FBR fuels; however, the concentration of plutonium isotopes will be higher than in LWR fuel. As a result, FBR fuel refabrication operations may require additional shielding, or totally remote methods, which will complicate the operations, particularly since the design of FBR fuel elements is more complex than that of LWR elements. Further, the higher concentrations of plutonium require more concern about criticality situations.

It is important that the refabrication operations result in a product which meets licensing and reactor operations requirements. Thus, while significant fuel performance data have been obtained on fuel made in laboratory/engineering-scale equipment, substantial test data are still needed on fuel refabricated with prototypic processes and equipment.

In fuel reprocessing, a significant difference between FBRs and LWRs arises from the higher irradiation levels, the higher fission-product concentrations, the higher fissile contents, and the differently clad and constituted fuel elements associated with FBR fuels. Thus, areas that will require significantly more research and development include fuel shearing and maintenance of shearing equipment, dissolution (MOX fuels can be made fully soluble, but methods for insuring complete solubility are not clearly established), dissolver feed clarification (arising from the large amounts of insoluble fission products present in highly irradiated FBR fuels), and the first cycle of solvent extraction (arising from the large irradiation dose that the highly irradiated fast reactor fuels will give to the organic solvent systems). Associated research and development will be needed on solvent degradation behavior, plutonium chemistry, avoidance of criticality, and off-gas cleanup processes and their operating conditions (iodine is a special problem with FBR fuels). The above effort required (except for iodine) would be alleviated by processing blanket and core together. For the LMFBR, fuel cleaning for sodium removal is needed; also, if sodium logging of fuel elements is significant, sodium needs to be removed by voloxidation or other methods.

In the waste treatment area, the high concentration of fission products in FBR fuels may influence the calcination conditions of the high-level wastes. The fixation of solid wastes such as stainless steel hulls needs study, as does the isolation and fixation of effluents such as ^{14}C and tritium. A substantial part of fission product tritium may diffuse through fuel cladding into the coolant during reactor operation. However, the amount left in the fuel may still be sufficient to require removal prior to fuel dissolution during reprocessing operations. Maintaining low levels of plutonium in wastes is made more difficult by the much larger quantities present in process streams.

2.2 Additional Research and Development Required to Implement DUTH Fuel Cycles in LMFBRs and GCFRs

The technology for recycle of DUTH fuels (which involves either DUTH fuel in the core and thorium in the blanket, or DU fuel in the core and thorium in the blanket, the presence of thorium in the core depending on the permissible enrichment of DU) for FBRs is the least well developed of all technologies considered here. The difficulties are similar to those encountered in the recycle of DUTH fuels for LWRs but are more severe for many of the same reasons that fast reactor fuels in general are more difficult to recycle than thermal reactor fuels, especially LWR fuels. These relate primarily to the higher burnup and higher fissile content of fast reactor fuels. At the same time, use of stainless steel fuel cladding rather than Zircaloy cladding (as in LWRs) appears to simplify dissolution of thoria fuels from FBRs.

As in the case for LWRs, the refabrication of FBR fuels in the DUTH cycle requires remote operations in heavily shielded facilities. Extensive verification studies will be needed to ensure that refabrication of the complex FBR fuel assemblies can be carried out efficiently and practically. Emphasis would be on application of gel-sphere technology to either pellet or sphere-pac fuels. Also, while it might be expected that DUTH fuels will perform satisfactorily in FBRs, statistically significant fuel qualification must be carried out with fuel refabricated in facilities prototypic of those for a commercial refabrication plant. Fuel qualification testing will need to determine the densification characteristics of DUTH fuel during irradiation and its swelling characteristics, nuclide redistribution characteristics, and mechanical and chemical fuel-cladding interactions under various reactor operating conditions. Further, reliable nondestructive fuel assay systems that can be used during fuel refabrication operations must be demonstrated.

The research and development requirements for the processing and waste treatment of FBR DUTH fuels will be similar to those for LWR DUTH fuels; however, separate clad removal will not be necessary since dissolved stainless steel does not complex with fluoride ions added for dissolution of thorium. At the same time, significant differences in degree will exist in certain operations. For example, the concentration of fissile materials will be higher in FBR fuel than in LWR fuel, and this will require additional research and development

for the modified Thorex process which separates plutonium from thorium in the presence of uranium. In general, more information is needed on the operation of solvent extraction systems when uranium, plutonium and thorium are all present in the feed solution. Shearing equipment would be expected to be similar to the shearing equipment needed for FBR U/Pu fuels. Due to the different fission-product yield distribution in FBRs relative to LWRs, the feed clarification treatment and solids removal steps, as well as the waste treatment steps, may have to be modified. In addition, the higher fissile concentrations in FBR fuels could influence recycle equipment design to accommodate noncriticality criteria. Also, release of ^{220}Rn would need to be controlled in a manner similar to that for DUTH cycles in LWRs; however, the higher ^{220}Rn generation rates in FBRs must be considered.

3. RESEARCH AND DEVELOPMENT REQUIREMENTS FOR THORIUM AND URANIUM CYCLES IN HTGRs

3.1 Status and Development Requirements of HTGR Fuel Recycle Technology Based on the Standard Thorium Fuel Cycle

Although there is interest in utilizing the LEU throwaway cycle with HTGRs, until recently the reference fuel cycle for the HTGR has been the standard thorium cycle in which highly enriched uranium is utilized with thorium. Thus, the research and development carried out on HTGR fuel recycle has already considered a fuel system containing thorium; this work is being carried out under the HTGR Fuel Recycle Development Program sponsored by DOE.

The characteristics of HTGR fuel are quite different from those of the metal-clad fuels, since HTGR fuels are based on small microspheres of fuel coated with various layers of pyrolytic carbon and silicon carbide. The fabrication of HTGR fuels has been carried out in cold pilot plant operations at General Atomic (GA) and in engineering development operations at Oak Ridge National Laboratory (ORNL), GA, and Idaho National Engineering Laboratory (INEL). The fabrication/refabrication operations have included preparation of initial and makeup fuel kernels based on use of UC_2; preparation of recycle fuel based on uranium loading, drying, and conversion of weak-acid-ion-exchange resins to give UO_2-UC_2; preparation of fertile kernels based on sol gel technology to produce ThO_2; fuel particle coating; fuel rod fabrication; fuel element assembly; and fuel carbonization. Fuel performance has been qualified under accelerated test conditions based on fuel fabricated by processes and equipment prototypic of anticipated commercial units. Fuel refabrication processes and equipment have been studied in engineering-scale operations, with emphasis on the requirement that fuel be refabricated in shielded and remotely operated facilities because of the activity in the recycle fuel due to ^{232}U daughter products. In general, cold development of processes and equipment for fabrication/refabrication has taken into consideration scrap recycle, effluent control, and fuel assay requirements; also, testing of methods has been performed relative to fuel assay requirements. Additional research and development efforts are needed, however, particularly in the scaleup of refabrication equipment, the recycle of scrap material, the control of effluents, the assay of fuel-containing materials, and the qualification of recycle fuel. Finally, hot demonstration is required.

The headend treatment of HTGR fuel reprocessing consists in crushing the graphite element, burning the graphite, and dissolving the fuel then accessible to the leaching solution; fuel with SiC coatings is further crushed to expose the fuel kernel, followed by another burning operation to remove the graphite coatings and convert the fuel to oxide, with subsequent dissolution of the fuel. The above also permits separation of the fuels which were initially fissile and fertile in nature by separate recovery of the SiC-coated fuel. The above operations, with emphasis on primary burning, separation of fertile and fissile particles, fuel leaching, crushing of SiC coatings, secondary burning, and trans-

fer of granular and powdered solids, require additional research and development in prototypic equipment. To date, the crush/burn/leach operations have been demonstrated in engineering- to cold-prototype-scale equipment. The burning of the graphite generates large quantities of CO_2, which may have to be contained because of the ^{14}C content; carbon fixation as calcium carbonate is the preferred containment process at this time, and laboratory-scale tests indicate that fixation could be performed prior to Kr removal. The burning operation also has the potential of releasing tritium prior to aqueous processing, although the conditions for adequate release need further study, and some tritium will be released in the dissolver. Since the burner technology is relatively new, and has not been performed with radioactivity present, it may be expected that much development work will be required to demonstrate practical burner operations.

The solvent extraction operations for fuel separations and recovery make use of the Acid Thorex process for the fuel containing thorium and of the Purex process for the fuel containing only uranium. Thus, two separate solvent extraction lines are required. To date there has been fairly extensive cold engineering-scale testing of the Thorex process addressing the influence on separation operations of high zirconium concentrations and of silica and carbon content in the solvent. Additional work must be carried out to determine the influence of solvent diluent degradation and of long-term radiolysis effects on the efficiency of the Thorex process. With regard to the solvent extraction processing of enriched uranium using the Purex process, additional studies are required to ensure that the high concentrations of fission products from the highly burned fuels which are present do not decrease uranium recovery significantly.

Off-gas treatment work has considered processes for controlling the release of ^{220}Rn (by holdup to permit decay), of ^{14}C (by fixation), of ^{85}Kr (by Kr absorption in liquid CO_2), and of iodine and tritium. Engineering-scale work on the Kr absorption process has been completed. Removal systems for iodine and tritium would probably not be greatly different than those for other reactor fuels, particularly if fixation of the CO_2 were carried out first.

Additional research and development work is also required for the design, construction, and operation of a hot engineering test complex to test engineering-scale processes and equipment in the presence of ^{233}U (containing ^{232}U) and fission products; for the design, construction, and operation of selected cold prototype equipment for reprocessing and refabrication operations; for a fuel irradiation testing program to validate the performance of the product from fuel recycle operations; and for the design of a future recycle demonstration facility.

With regard to waste treatment, the presence of fluoride in the wastes causes corrosion of equipment (possibly to the off-gas systems also) and may complicate high-level liquid waste treatment and subsequent calcination and vitrification. Wastes which have to be treated include reflector blocks, SiC hulls, and waste SiC-clad fissile particles, as well as wastes from solvent-extraction and off-gas systems and from refabrication operations. Limited experience exists regarding the above.

3.2 Additional Research and Development Required to Implement DUTH Fuel Cycles in HTGRs

Since the original reference cycle for HTGRs was based on the standard thorium cycle, the previous section also largely discusses the research and development needs of the DUTH cycle. However, verification testing needs to be carried out for all the fuel recycle operations, processes, and equipment. Further, utilizing the DUTH cycle requires a more dense fissile fuel particle in order to accommodate the required reactor fuel loading; thus, extensive effort is required to develop and qualify dense UO_2-UC_2 as the recycle fissile particle and to develop practical kernel refabrication processes and equipment. Further, some modifications to other refabrication operations may be required to accommodate the required fuel loadings. Fuel qualification tests will require irradiation testing under simulated HTGR conditions with fuel fabricated with prototypic-type processes and equipment, along with postirradiation evaluations of fuel performance.

The original Thorex and acid-Thorex flowsheets have been run in pilot plant and full-scale operations with low burnup fuel containing only thorium and uranium. At the high fuel burnups expected in large HTGRs, the fission-product concentrations are so high that adjustments to the feed composition prior to solvent extraction might cause precipitation of some fission products. Modification to the first extraction cycle may be needed to avoid such precipitation, as well as additional modifications to the overall process to accommodate the separation of the Th, U, and Pu components.

Additional requirements of the DUTH cycle above those of the thorium cycle are associated with the leaching and classification steps (because of the different heavy metal loadings and different fission-product concentrations), the separation of fissile and fertile particles (the two particles may be more difficult to separate in the DUTH cycle), and with the waste treatment operations (the presence of plutonium in the wastes will probably influence the treatment required).

3.3 Research and Development Requirements for Uranium Fuel Cycles in HTGRs

The requirements for uranium-based fuel cycles are largely covered in the above discussions on the thorium cycles. The essential differences are associated with the uranium and plutonium recovery operations; both of these are simpler to develop for the uranium cycle relative to the thorium cycle, since fluoride is not needed for uranium dissolution, and solvent extraction involves the Purex rather than the Thorex process. The development of refabrication processes and equipment for plutonium-bearing fuels would be largely similar to those required for ^{233}U-bearing fuels.

4. ESTIMATED SCHEDULES AND COSTS FOR FUEL RECYCLE RESEARCH AND DEVELOPMENT

It is apparent from the preceding discussion that some of the steps in the various fuel cycles are very similar if not identical and thus that an integrated program to develop several fuel cycles simultaneously would be very effective in reducing total costs. As a result, the existing technology development programs have many generic characteristics and no matter which fuel cycles may eventually be developed, much of the ongoing work will prove useful. However, in order to provide relative information, the schedules and costs presented here assume that the cycles will be developed independently of each other.

In developing detailed planning for the individual fuel cycles, logic networks similar to that shown in Fig. 1 were used. With this logic network, the development of the recycle process would progress in the general order shown in Table 2. For certain portions of the cycle some of these steps may be bypassed. The resulting information for the various recycle steps would then be integrated and used to design, construct, and operate a fresh-fuel fabrication plant and/or a recycle demonstration plant. The plants would operate on a semicommercial scale and would contain all elements of the development program. They would also demonstrate the safety and licensing requirements of the commercial plants, as well as generate useful products. Because of the importance of installing prototypic processes and equipment in the plants, the schedule assumes that all research and development efforts will be completed prior to plant construction. With this approach there is less risk that the plants will require modification, although delays in the overall schedule will probably be experienced because of the timing of construction. The throughput of the demonstration plant for fresh-fuel fabrication would be 1-2 metric tons per day. The reprocessing plant costs for the water reactors on the uranium fuel cycles were based on modification and use of the Barnwell reprocessing facility with a reprocessing capacity of about 5 tons heavy metal per day; for thorium fuel cycles a pilot plant of 0.5 MT/day capacity was considered; for all the water reactor fuels a refabrication plant capacity of 0.2 tons per day was used. For FBRs and HTGRs, the recycle plant costs were based on a reprocessing capacity of about 0.5 and 0.2 tons heavy metal per day, respectively; the refabrication capacity was 0.2 and 0.1 tons per day, respectively.

Overall, the approach discussed above should give a valid relative evaluation of research and development schedules and costs for the various reactor fuel cycles, and takes into consideration that the major engineering-scale proof of the technology will proceed through a pilot-plant or a demonstration phase that would be closely integrated with the initial commercial-scale facility which follows. First of a kind costs associated with an initial commercial plant, however, were not included in this study.

4.1 Schedules and Costs for Individual Cycles

Using the above approach, research and development schedules and costs for each fuel cycle considered are broken down into the following broad categories: fuel fabrication, refabrication, reprocessing, waste treatment, demonstration facility for fresh fuel fabrication, pilot plant or demonstration facility for recycle, and fuel qualification. The

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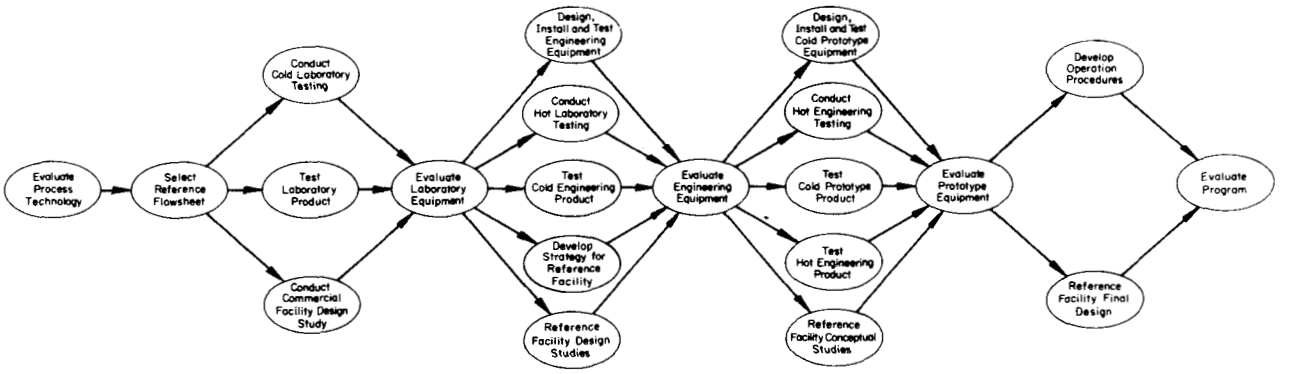


Fig. 1. Logic Network for Estimating Fuel Cycle Research and Development Program.

categories of fabrication, refabrication, reprocessing and waste treatment cover the conventional fuel recycle research and development areas. Fuel qualification provides acceptable proof that research and development has produced a fuel that meets commercial power reactor specifications, the proof having been obtained through appropriate fuel irradiation testing. Fuel qualification cannot proceed until fuel specifications and fabrication processes and equipment have been developed to at least an engineering scale. The time to complete a fuel qualification program has been estimated to be eight years after reasonably assured specifications are established. In some fuel cycles it will be appropriate to carry out capsule or small-scale fuel irradiation testing to establish specifications.

The pilot plant or demonstration facilities provide (for fresh fuel fabrication as needed, and for fuel reprocessing and refabrication) the step between research and development efforts and commercial facilities; due to the large capital investment and operating costs, such facilities should only be provided where clearly needed and for those cycles which are clearly expected to be commercialized. Furthermore, efforts should be made to accommodate several or all cycles chosen in a single facility. This requires much more study and analysis following some identification of the cycles to be developed.

The time required to place a fuel recycle demonstration facility on line is generally estimated to be 10 years, including three years for Title I and II designs, five years for construction, and two years for cold shakedown. A good engineering cost estimate for *such* plants can be made only after *a detailed conceptual* design is completed. For the schedules presented such information was *limited* and could not be developed with the resources available. Thus, the estimates are quite preliminary and are based primarily on *preconceptual designs in certain programs*, and on engineering judgment and experience.

Six fuel cycles are considered here: the LEU throwaway/stowaway cycle; the LEU cycle with recycle of uranium only; the Pu/^{238}U cycles with total recycle; the Pu/Th cycle with recycle of plutonium and thorium and the dispersal of uranium to other fuel cycles; the DUTH cycle with recycle of all uranium and thorium and with transfer of plutonium to storage; and the ^{233}U/Th cycle (HEU/Th) with recycle of all uranium and thorium. The two LEU cycles were limited to thermal reactors--LWRs, SSCRs, HWRs, and HTGRs. The remaining four cycles were considered for all these reactors plus FBRs. In the case of the LEU throwaway/stowaway cycle, HWRs were considered for two different fuel loadings, the natural uranium loading and a slightly enriched loading. In the case of the LEU cycle with uranium recycle, the HWR fuel was assumed to be slightly enriched.

The estimated time schedules and costs for research and development for the various fuel cycles in the different reactors are shown in Fig. 2 and summarized in Table 6. The solid lines in the bar graphs represent the times during which the research and development is carried out. For fuel qualification involving ^{233}U, the first part of the testing period largely utilizes ^{235}U as a stand-in fuel, followed by extensive testing of ^{233}U fuels. For the demonstration plant, the solid lines are associated with design, construction, and checkout of the facility; the dashed lines indicate the beginning of "commercial-type" operation. The duration of the dashed lines will depend upon the need for operating and design data and the need for fuel recycle services.

As has been pointed out earlier, it is difficult to predict accurately the costs and times required to resolve problems involving research and development. Further, the costs of demonstration facilities cannot be estimated very accurately without performing detailed plant design studies, and the time and resources available precluded this. Nonetheless, the schedules and costs (1978 dollars) were developed on a consistent relative basis and should be useful for overall guidance. At the same time, the large uncertainty in absolute costs needs to be emphasized. Thus, Table 6 also gives estimated ranges of R&D costs. The estimated ranges are roughly based on an uncertainty of -10% to +30% for base R&D costs, and of -10% to +50% for costs of fuel fabrication, refabrication, and reprocessing facilities and their operations. In addition, the ranges consider that the fuel for HWRs using LEU might be fabricated in present natural-uranium fuel fabrication facilities with relatively little modification to those facilities. These ranges are not intended to imply lower and upper limits, but are believed to be reasonable estimates based on probable uncertainties. The footnotes in Table 6 give detailed information on the capacities of the various fuel recycle facilities. The considerations that led to the estimates given in Fig. 2 are discussed below.

LEU Throwaway/Stowaway Cycle. For this fuel cycle, the waste treatment research and development refers to fuel element testing associated with the long-term storage of reactor fuel elements; it includes determination of containment performance, of heat removal methods and their adequacy, and of material compatibility under storage conditions. For the present LWRs, the only research and development requirement would be the fuel storage development efforts. The testing period specified is associated with resolving technical issues and does not consider long-term demonstration.

Table 6. Summary of Estimated Fuel Recycle R&D Costs and Schedules for Selected Reactor Types and Fuel Cycles

	Estimated Costs (Millions of Dollars)									Year of Completion		
	R&D					Demo. or Pilot Plant Facilities[a]					Demo. or Pilot Plant[c]	
Reactor Type	Fuel Qualification	Fabrication	Refabrication	Reprocessing	Waste Treatment	Fresh Fuel (Capital/Operating)	Recycle Plant (Capital/Operating)	Mean Total Costs	Estimated Range of Costs	R&D[b]	Fresh Fuel Fabrication Plant	Fuel Recycle Plant
LEU Throwaway Cycle												
LWR					50			50	40-70	1984	Available	
SSCR	30	10			50			90	80-120	1985	Available by adaption	
HWR (Nat U)					35			35	30-50	1984	Available in Canada	
HTGR	40	80			35	100/150		405	370-600	1986	1991	
HWR (LEU)	30	20			35	100/150		335	300-500	1985	1986	
LEU with Recycle of Uranium Only												
LWR				45(140)[e]	310		400/150	905	800-1300[f]	1984	Available	1985
SSCR	30	10		45(140)[e]	310		400/150	945	800-1300[f]	1985	Available by adaption	1986
HWR	30	20		45(140)[e]	310	100/150	400/150	1205	900-1800[f]	1985	1986	1986
HTGR	40	80		180	330	100/150	500/160	1540	1400-2200	1989	1991	1996
Pu/^{238}U with Recycle of Bred Fuel												
LWR	40		155	45(140)[e]	310		500/300	1350	1300-2200[f]	1989		1994(1991)[d]
SSCR	45		155	45(140)[e]	310		500/300	1355	1300-2200[f]	1989		1994(1991)[d]
HWR	40		190	45(140)[e]	310		500/300	1385	1300-2200[f]	1988		1994(1991)[d]
HTGR	50		150	180	330		610/310	1630	1500-2400	1989		1996
FBR	40		240	280	320		800/310	1990	1800-2800	1989		1995(1993)[d]
Pu/Th with Recycle of Bred Fuel												
LWR	60		200	220	350		750/320	1900	1700-2700	1993		2001
SSCR	60		200	220	350		750/320	1900	1700-2700	1994		2001
HWR	60		200	220	350		750/320	1900	1700-2700	1994		2001
HTGR	50		175	245	330		730/320	1850	1700-2700	1994		2000
FBR	70		250	350	340		950/330	2290	2000-3200	1996		2001
DUTH with Recycle of Bred Fuel (^{235}U in fresh fuel; ^{235}U and ^{233}U in Recycle Fuel)												
LWR	60		225	220	350	100/150	750/320	2175	1900-3100	1992	1989	1999
SSCR	60		225	220	350	100/150	750/320	2175	1900-3100	1992	1989	1999
HWR	60		225	220	350	100/150	750/320	2175	1900-3100	1992	1989	1999
HTGR	80		150	245	330	100/150	730/310	2095	1900-3000	1991	1988	1998
FBR	80		235	340	340	120/180	950/330	2575	2200-3600	1992	1989	1999
^{233}U/Th with Recycle of Bred Fuel (High-Enriched Uranium)												
LWR	60		225	210	340		700/300	1835	1600-2600	1992		1999
SSCR	60		225	210	340		700/300	1835	1600-2600	1992		1999
HWR	60		225	210	340		700/300	1835	1600-2600	1991		1999
HTGR	70		140	230	320		690/310	1760	1600-2500	1992		1998
FBR	70		235	330	330		900/320	2185	1900-3100	1992		1999

[a]Based on demonstration fresh-fuel fabrication plant capacities of about 2 MT/day heavy metal for all reactor fuels except those for the HTGR; for the HTGR fuels, the demonstration fabrication facility has a capacity of about 1 MT/day. The demonstration or pilot plant fuel recycle facilities for the water reactors consider use of the Barnwell Nuclear Fuel Plant (BNFP) [plus modifications] for reprocessing uranium-based fuel (LEU and Pu-U fuel cycles); the BNFP facility costs for these cases are the additional costs above those already incurred by BNFP; the BNFP heavy metal throughput capacity has a value of about 5 MT/day. For reprocessing the thorium-based water reactor fuels, pilot plant reprocessing facilities are considered, each having a capacity of about 0.5 MT heavy metal/day. For all water reactor and FBR fuels, the refabrication facilities consist of pilot plants having capacities of about 0.2 MT/day; for HTGR fuels, the refabrication pilot plant has a throughput of about 0.1 MT heavy metal/day. For reprocessing all the FBR fuels, pilot plant facilities having throughputs of 0.5 MT/day are considered; for the HTGR fuels, pilot plant reprocessing facilities have a capacity of 0.2 MT/day. The lower capacities associated with HTGR fuel fabrication and recycle facilities reflect the lower throughput required for a given GW(e) nuclear capacity, due to the high HTGR fuel exposure.

The operating costs for the demonstration or pilot plants consider 4 years of facility operation (dashed lines in Fig. 2), and R&D interactions.

[b]Latest time to complete R&D for reprocessing, fabrication/refabrication, waste treatment and fuel qualification, based on schedules in Fig. 2.

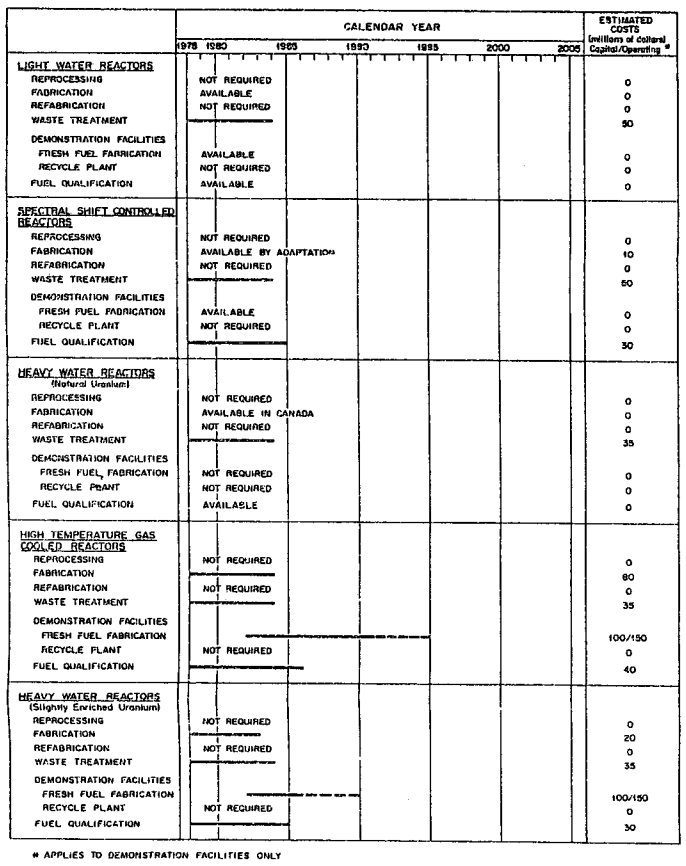
[c]Time at which facility starts operation with design throughput. Use of the Barnwell Nuclear Fuel Plant is considered for the water reactors operating on uranium fuel cycles.

[d]Based on use of pellet-type fuel only.

[e]The $140 million in parentheses refer to the R&D dollars associated with developing advanced reprocessing technology for use in future fuel recycle plants. The $45 million value refers to R&D for upgrading operation of the Barnwell Nuclear Fuel Plant.

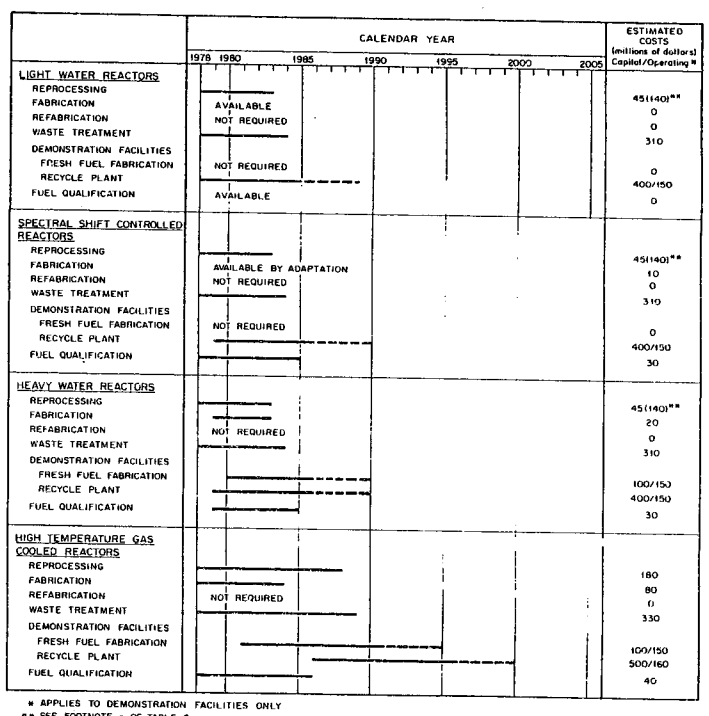
[f]For the LEU fuel cycle with recycle of uranium only, the BNFP facility can be utilized at an early date, and so the estimated range of costs do not include the R&D associated with developing advanced reprocessing technology. For the Pu-^{238}U fuel cycle, fuel refabrication and qualification schedules defer use of BNFP into the 1990s, and so there could be practical expenditures for advanced reprocessing technology development; the upper range of costs for this cycle thus includes R&D costs for advanced reprocessing development.

LEU, Throwaway Cycle



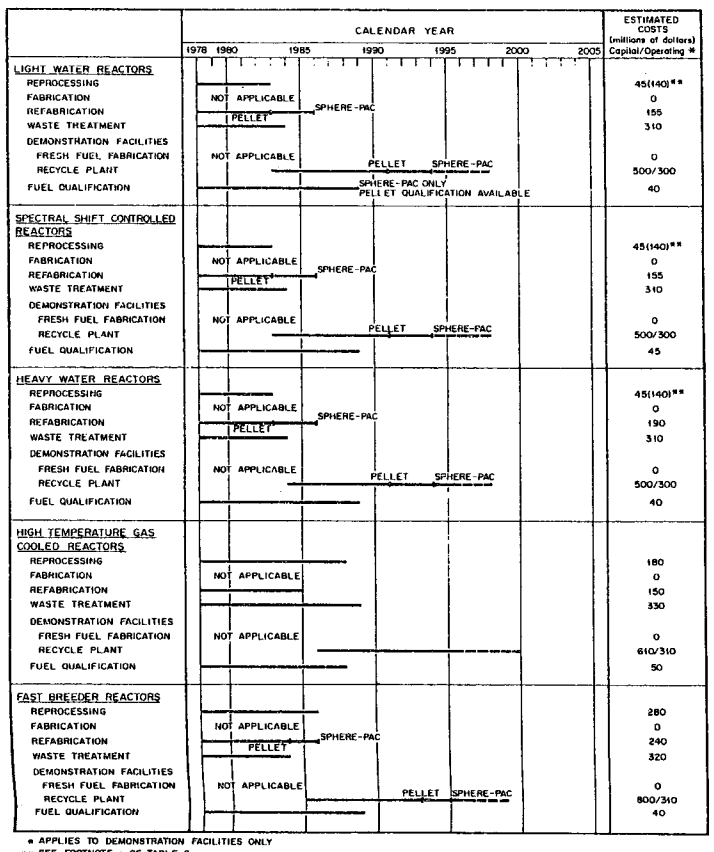
* APPLIES TO DEMONSTRATION FACILITIES ONLY

LEU, Recycle of U Only



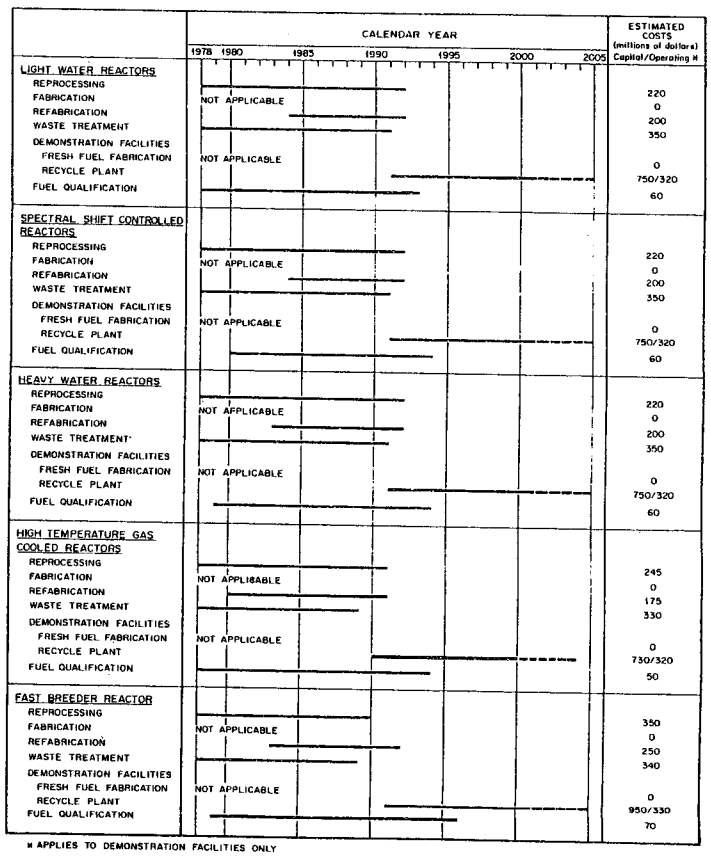
* APPLIES TO DEMONSTRATION FACILITIES ONLY
** SEE FOOTNOTE g OF TABLE 6.

Pu/^{238}U, Recycle of Bred Fuel



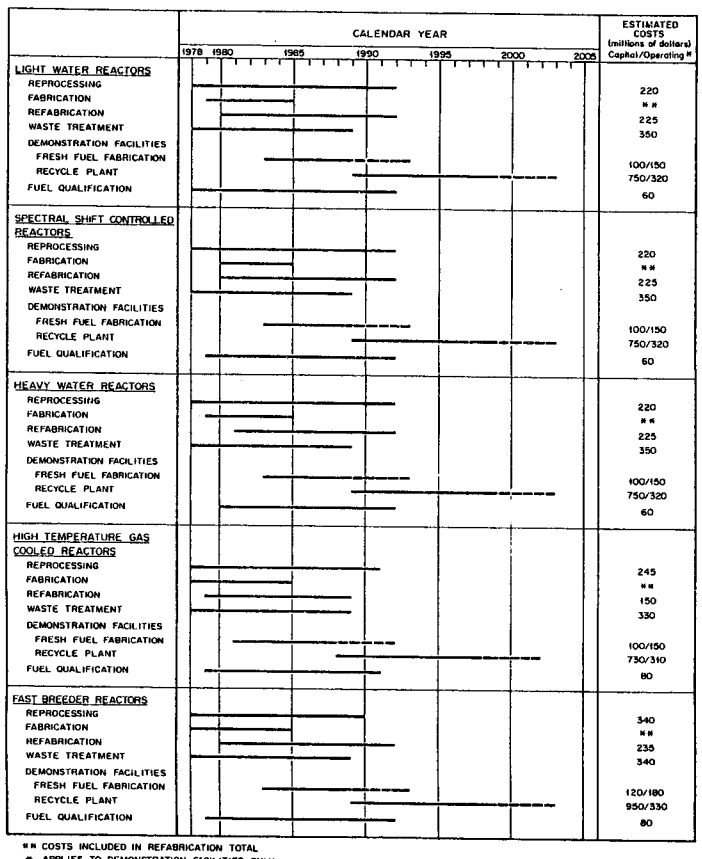
* APPLIES TO DEMONSTRATION FACILITIES ONLY
** SEE FOOTNOTE g OF TABLE 6.

Pu/Th, Recycle of Bred Fuel



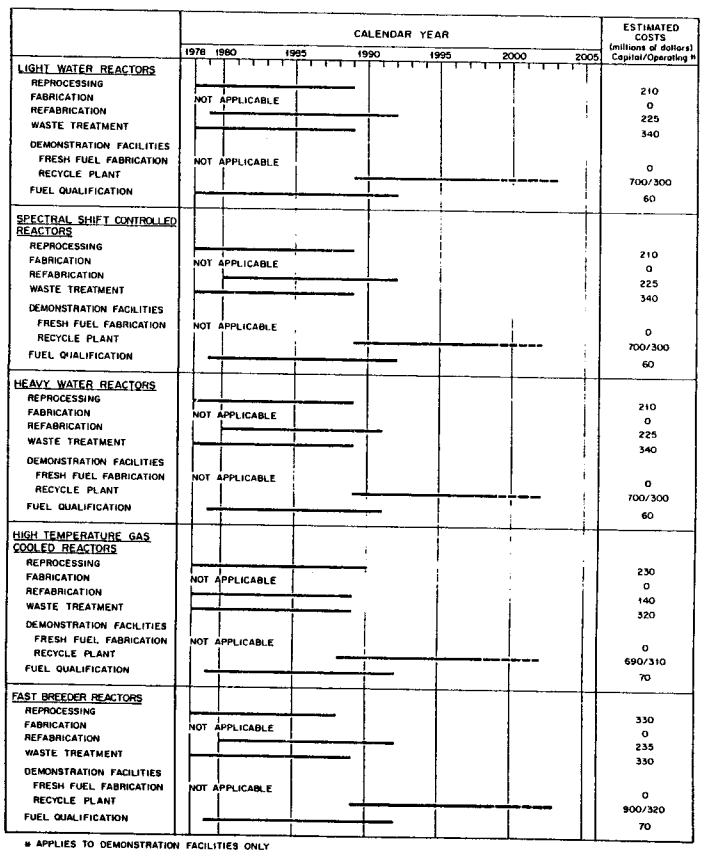
* APPLIES TO DEMONSTRATION FACILITIES ONLY

DUTH, Recycle of Bred Fuel



** COSTS INCLUDED IN REFABRICATION TOTAL
* APPLIES TO DEMONSTRATION FACILITIES ONLY

^{233}U/Th, Recycle of Bred Fuel



* APPLIES TO DEMONSTRATION FACILITIES ONLY

Fig. 2. Research and Development Schedules and Costs for Various Fuel Cycles in Thermal and Fast Breeder Reactors.

For the SSCRs, the LWR fuel fabrication technology would be largely available by adaptation; however, because the SSCR fuel enrichment would be lower and distributed differently and because the specific element design will probably not be exactly the same as for the LWR design, a small research and development cost is estimated for SSCR fuel fabrication. Waste treatment research and development is estimated to be essentially the same as for LWRs. Because the SSCR fuel would have different fuel enrichments and specifications than LWR fuels, fuel qualification testing is needed, but it would largely consist of verification studies. The schedule specified provides time to do full-life testing. The fresh-fuel fabrication plant available to LWRs was considered to be available to SSCRs by adaptation, and thus no cost was associated with fuel fabrication plants.

For natural-uranium-fueled HWRs, which are commercialized in Canada, the only research and development requirement would be that associated with long-term fuel storage. Because of the low-level heat source and fission-product inventory in such fuel elements, the cost of fuel storage research and development is estimated to be somewhat lower than that associated with LWRs. The fresh-fuel fabrication plants presently in Canada were considered to be available for manufacturing fuel, and so no demonstration plants were included.

For HTGRs, significant research and development effort is required for the fabrication of fuels based on the uranium cycle, since emphasis until recently was on thorium cycle fuels. Although UK experience is helpful, the use of prismatic graphite elements of GA design may require development of UC_2-UO_2 fuel kernels, along with associated fuel fabrication processes and equipment. Further, significant fuel qualification studies need to be carried out to assure that the product fuel performs adequately under commercial conditions. The fuel storage research and development requirements for the HTGR fuels consider the low-level heat source of the large HTGR fuel elements and are estimated to be the same as for HWRs. For the HTGR, a fresh-fuel fabrication demonstration facility would need to be built since there are no commercial facilities available. The costs for this facility are given in terms of capital costs and operating costs. The facility operating costs are those associated with operating the facility for four years, and operation for this period is considered to be part of the overall research and development program. That period is indicated by the dashed line associated with the demonstration facility. The demonstration plant may indeed operate for longer periods of time, depending upon the need for further operating experience or on commercial requirements, but that is not considered here. The capacity of the fabrication plant is considered to be a nominal 1-MT/day of heavy metal. The schedule for startup of the facility includes the time to design, procure equipment, construct and check out the facility.

For HWRs using slightly enriched uranium, some research and development would be needed for the fabrication of slightly enriched fuel which would go to higher fuel exposures (relative to natural uranium fuel). Because of the above, there would be research and development required on fabrication procedures and element design development. However, as shown in the chart, the estimated effort is small and would largely be associated

with verification studies. Research and development would also be required in fuel qualification to demonstrate that fuel elements using slightly enriched uranium fuel would perform adequately under commercial conditions. Fuel storage research and development for HWR fuel elements using slightly enriched uranium are estimated to be about the same as those for HWRs with natural uranium fuel since the heat removal requirements would be low in both cases and the element designs would be similar. The fresh-fuel fabrication demonstration plant schedule for this reactor is on the basis that present plants for fabricating natural uranium fuel would be converted to slightly-enriched uranium. The costs are for a 2-MT/day fresh-fuel fabrication facility in the United States.

LEU Cycle with Recycle of Uranium. For this cycle demonstration fuel reprocessing plants must be built, but since bred fuel is not recycled, the fuel fabrication plants need to manufacture only initial and makeup fuel. Thus, for a given reactor the fuel will be the same as for the LEU throwaway cycle. For LWRs, the reprocessing research and development has to consider the processing of fuels having exposures of 30 MWd/kg or greater. Specific needs have been discussed in previous sections, but in general include shear development, off-gas treatment to reduce effluent levels, solvent extraction of high exposure fuels, and product conversions. The estimated costs and schedules take into consideration the reprocessing technology status discussed in previous sections and the conversion and storage of plutonium product for future but undefined use. The waste treatment for this fuel cycle includes the concentration of liquid wastes, the calcination of high-level wastes and their vitrification, storage treatment of radioactive gases, and treatment of fuel refabrication wastes. The research and development cost estimates are based on a concentrated program consistent with present planning. Under demonstration facilities, the recycle plant considers use of the Barnwell Nuclear Fuel Plant (BNFP) with conversion facility additions; the schedule allows reasonable time for licensing issues to be resolved, for design, procurement of equipment, construction, and for check-out of the plant by 1985. The capital costs are estimated to be $400 million plus $150 million allocated for four years operation of the plant, with these costs being above present investments in BNFP. The capacity of the recycle plant is considered to be about 5 tons/day of heavy metal.

For the SSCR, the reprocessing and waste treatment requirements would be essentially the same as for LWRs. The same is nearly true for the demonstration fuel reprocessing plant; however, since the SSCR would have modifications in fuel enrichment and fuel element design relative to the LWR and the fission-product yields would be altered because of the neutron spectrum effects, some time would be needed to verify the direct applicability of the LWR reprocessing technology. Thus, an additional year was added to the schedule for startup of the SSCR reprocessing plant. The fuel qualification requirements of the SSCR for this case are the same as for the LEU throwaway cycle since the same fuel is employed.

The HWR considered for this cycle utilizes slightly enriched uranium. As for the SSCR, the reprocessing and waste treatment requirements of the HWR would be basically the same as for the LWR and are so indicated. Because of the slight enrichment of the uranium fuel, some effort is required in fuel fabrication and fuel qualification research and development; this is the same as that shown for the HWR with LEU throwaway fuel, and again a fresh-fuel fabrication demonstration plant is needed for the slightly enriched uranium fuel and is so shown. Four years operation of the plant is included in estimating demonstration plant costs.

The HTGR in this cycle requires considerable reprocessing development based on use of the uranium cycle with recycle of uranium; as indicated in previous sections, for that cycle there has been less research and development on HTGR reprocessing development than on that for LWRs. Much of the higher estimated cost for reprocessing of HTGR fuels relative to LWR fuels is associated with the HTGR headend treatment requirements. The HTGR fuel fabrication and fuel qualification research and development requirements are the same as those given for the LEU throwaway/stowaway cycle. The waste treatment requirements including the handling of SiC hulls and of large amounts of CO_2 containing ^{14}C, which increases the waste treatment costs slightly above those for LWRs. Both a fresh-fuel fabrication demonstration plant and a fuel recycle demonstration plant would be needed, the schedule for the former being the same as in the throwaway cycle; the schedule for the reprocessing plant considers that the reprocessing and waste treatment research and development would be essentially completed before plant construction. Because of the complicated headend treatment for HTGR fuels and the investment already made in the Barnwell plant, the cost of the reprocessing plant is estimated to be higher than that for water reactor plants.

<u>Pu/^{238}U Cycle with Recycle of U and Pu</u>. For the thermal reactors the fuel reprocessing needs for this fuel cycle are essentially the same as for the previous case. While in that case only uranium was being recycled, it was necessary to recover and store plutonium for future, although undefined, use. Thus the schedules and costs for fuel reprocessing research and development and for reprocessing plants are the same as given above. Since for this cycle, all fuel is refabricated fuel in the terminology used here, no fresh-fuel fabrication plant is required and the recycle plant includes both fuel reprocessing and refabrication. The recycle plant schedule is controlled by the refabrication schedule.

For the water reactors, the refabrication research and development for this cycle considers that both pellet and sphere-pac fuel technology will be developed. Hot laboratory refabrication of LWR Pu/U fuels has been carried out, but much work remains to be done with regard to developing/verifying the processes and equipment in larger equipment and in fuel rework and recycle operations. Relatively little work has been carried out

with sphere-pac fuels. The schedule and cost estimates for research and development refabrication are based on bringing pellet and sphere-pac fuels to the point of commercial use. With regard to fuel qualification in LWRs, U/Pu fuels have been largely qualified based on fuels fabricated in small-scale equipment; however, much testing must yet be done to qualify U/Pu sphere-pac fuels. The estimated schedule and costs consider the relatively long irradiation tests required to obtain commercial data; the costs do not include irradiation unit costs (if any) for testing fuels in commercial reactors.

In SSCRs, the research and development costs and schedules for fuel refabrication and qualification are estimated to be nearly the same as for LWRs. The differences in enrichment of SSCR fuels should not significantly change the time and cost for refabricating research and development since that development would specifically treat the SSCR fuel conditions. The slightly higher costs for SSCR fuel qualification are to accommodate the additional pellet fuel qualification needed for SSCRs.

In HWRs, the fuel refabrication research and development costs are estimated to be higher than those for LWRs since there has been relatively small effort on Pu/U fuels in such reactors. For HWR fuel qualification, the research and development costs are estimated to be about the same as for LWRs; although HWRs need effort in both pellet and sphere-pac fuel qualification for the Pu/U fuel cycle, it is estimated that qualification is more readily obtained in the shorter, larger-diameter fuel pins of HWRs.

For the water reactors, the waste treatment research and development costs for this cycle are estimated to be the same as in the previous (LEU uranium recycle) case since the same problems have to be solved. The costs of the fuel recycle demonstration plants are higher, however, because of the need to include refabrication facilities.

For the HTGR the reprocessing research and development needs would again be the same as for the previous case. More refabrication research and development will be required, however, to develop/verify that the processes and equipment for fabricating uranium fuels would be applicable to Pu/U fuels. The costs and schedule for HTGR fuel qualification consider irradiation testing of Pu/U fuels in the FSVR reactor (without costs for irradiation units); the higher costs relative to the LEU uranium recycle case reflect an estimated increased difficulty in qualifying Pu/U fuels. The schedule and cost of the fuel recycle pilot plant includes both fuel reprocessing and refabrication operations; the higher cost relative to that for LWRs reflects the high investment already associated with the Barnwell reprocessing facility (but not included here).

In constructing the costs and schedules for this cycle in FBRs, the specific FBR considered was the LMFBR; however, the costs and schedules for the GCFR should not be significantly different. The presence of sodium is a small complicating factor in LMFBR fuel reprocessing, and the use of vented fuel pins is a small complicating factor in GCFR fuel refabrication, but these tend to be compensating differences.

The costs and schedules for reprocessing highly burned FBR fuels consider the large amount of effort required for developing practical methods of headend treatment, of recovery of radioactive gases, of fuel recovery from solutions containing high concentrations of plutonium and fission products, and of product conversions. The much higher costs for FBR fuel reprocessing development compared to those for LWR fuels reflect the small reprocessing experience with FBR fuels relative to that with LWR fuels, the much higher fuel exposures associated with FBR fuel, the much higher fissile concentrations associated with FBR fuels, and the more complicated FBR fuel assembly.

As for the LWRs, FBR fuel refabrication research and development considers both pellet and sphere-pac fuels, with sphere-pac development as an add-on to pellet development. The higher costs for FBR fuel refabrication relative to that for LWR fuels is due primarily to the use of higher concentrations of plutonium and the more complex fuel geometry which make refabrication operations more difficult. The cost of FBR fuel qualification is estimated to be about the same as for LWR fuels, since pellet fuels are largely qualified, and the qualification tests for sphere-pac fuels would be very similar to those for corresponding LWR fuels (costs of irradiation units, however, are not included in these estimates). The cost of research and development for FBR waste treatment is estimated to be about the same as that for LWRs, with the small increase due to the higher activity of the FBR high-level wastes. The FBR facility cost is higher than that for LWRs because of the higher activity and fissile concentrations in FBR spent fuels, and the investment already placed in the Barnwell plant; it is higher than that for HTGRs because the capacity of the FBR plant is higher.

Pu/Th Cycle with Recycle of Plutonium and Thorium and Dispersal of Uranium. In this fuel cycle, the reactor fuel is Pu/Th at all times; thus, all fuel is refabricated fuel, and no fresh-fuel fabrication plant is needed. The use of thorium rather than uranium as fertile material has, in general, a large impact on fuel reprocessing requirements, particularly affecting headend research and development for those reactor fuels requiring dissolution of thoria in the presence of Zircaloy cladding; further, the thorium cycle complicates radioactive off-gas handling because of the buildup of ^{220}Rn.

For this cycle, LWRs, SSCRs and HWRs are all estimated to have approximately the same fuel recycle schedules and costs. This reflects the common status of development of the fuel cycle in these reactors and the very similar research and development and demonstration plant needs. Although specific research and development would be required for the individual reactors, it would be substitutive rather than additive, and in all cases would be similar. The high cost of fuel reprocessing research and development over that for uranium cycles reflects the low level of thorium cycle reprocessing development to date. Major needs leading to the increased costs are practical ways to: dissolve thorium from Zircaloy-clad fuel elements; remove tritium from thorium fuels prior to dissolution; handle the highly corrosive liquids containing acids and fluorides; effect solvent extraction of irradiated fuels containing thorium, uranium and plutonium; and contain ^{220}Rn. The higher cost of fuel refabrication research and development relative to Pu/U fuels reflects the higher fissile plutonium concentrations of Pu/Th fuels in

thermal reactors, and the need to handle thorium (either pellet technology or sphere-pac technology could be applied). The waste treatment research and development costs reflect the need to treat the wastes associated with Zircaloy dissolution and the complications of treating wastes containing fluorides. Because of these problems, the schedule for completing waste treatment research and development is extended relative to that given for the U/Pu cycle. The costs and schedule for fuel qualification research and development reflect the additional parameter which is introduced by the generation of another fissile fuel (^{233}U) during reactor exposure, which increases the number of parameters which require investigation. The costs and schedules of the demonstration recycle plant are also increased over those for the Pu/U cycle because of the more complicated requirements of fuel reprocessing and refabrication with Pu/Th fuels. The costs of the demonstration reprocessing plants are based on use of a pilot plant having a capacity of about 0.5 MT/day of heavy metal. The recycle plant schedules are limited by the schedules for R&D and for the demonstration fuel refabrication facilities. The above statements also apply to demonstration recycle plants for the DUTH and HEUTH cycles in water reactors; such cycles are discussed below.

For the HTGR, R&D for this cycle is estimated to be only slightly higher than that for the water reactors because of the substantial effort that has already been carried out on the standard HTGR thorium cycle, and because the scale of recycle equipment required for a given size nuclear power industry is generally smaller for HTGRs than for the other reactors. Nonetheless, significant effort is still required to complete the large-scale equipment testing needed. The fuel refabrication R&D reflects the application of processes and equipment already developed for the refabrication of thorium-based fuels, and also the possible need to extensively modify those processes and equipment to accommodate plutonium as the fissile fuel. The waste treatment R&D costs are slightly less than for the water reactors because there is no Zircaloy cladding present in HTGRs. The cost of the HTGR fuel recycle demonstration plant is slightly less than for the LWRs because the capacity of an HTGR plant is significantly less for a given GW(e) industry. The plant cost is higher than for Pu/U fuels because of the more complex fuel recycle requirements. The plant schedule reflects the R&D schedules. Fuel qualification R&D costs are estimated to be the same for Pu/Th as for Pu/U fuels because of the extensive results from irradiating thorium fuels; however, the time to qualify a fuel containing both Pu and ^{233}U (generated during irradiation) is estimated to be longer than that for qualifying fuel containing only plutonium.

For the FBR, the reprocessing R&D effort for this cycle is estimated to be significantly more than that for LWRs; even though stainless steel is the cladding rather than Zircaloy, this is more than compensated for by the higher fission-product concentrations and higher plutonium concentrations present in FBRs. Nonetheless, the elimination of Zircaloy clad is estimated to reduce the R&D time for FBRs relative to LWRs. Refabrication of FBR fuels would be similar to that for LWR fuels except that FBRs have a more complex element and higher plutonium concentrations; the refabrication R&D is thus estimated to be slightly more costly to FBRs. Waste treatment R&D costs would be comparable with those for other reactors; there would be no need to treat clad removal wastes, but very high

activities and probably flourides would be present. The FBR fuel recycle demonstration plant would need to fabricate complicated assemblies containing high fissile concentrations; this combined with higher reprocessing costs leads to higher pilot plant costs for the FBR relative to the LWR. Fuel qualification R&D for FBRs is estimated to be slightly more than for LWRs because of the higher fissile concentrations that would be present and the higher fuel exposures required.

DUTH Cycle with Recycle of Uranium and Thorium and Storage of Plutonium. In this DUTH cycle, it is assumed that all uranium and thorium will be recycled and that the plutonium will be recovered and stored for subsequent (but undefined) use in other reactors. The schedules and costs for reprocessing the fuels for the various reactors are similar to those for the Pu/Th fuel cycle except that the concentrations of plutonium are much lower in the DUTH cycle.

Denatured ^{235}U fuel (^{235}U-^{238}U/Th) will be the initial fuel in this cycle and therefore fresh-fuel fabrication will be required for all reactors. The introduction of ^{233}U as the recycle fuel (^{233}U-^{238}U/Th) leads to radioactive fuels due to ^{232}U daughter products; this radioactivity generally increases the time and costs for fuel refabrication research and development, except for the HTGR where the primary development to date has been based on ^{233}U-Th fuels. Even for the HTGR, much fuel refabrication research and development is still needed for the DUTH cycle. Comparison of this cycle with the Pu/Th cycle shows that the research and development cost estimates for the various reactors are nearly the same in the areas of fuel reprocessing and waste treatment, and that the costs of the fuel recycle plants are about the same. However, the recycle plants for the DUTH fuels are estimated to be completed sooner than those for the Pu/Th fuels, it being assumed that the essential research and development for fuels containing less plutonium will be completed earlier. The fuel refabrication development research and development costs are generally higher for the DUTH cycle in thermal reactors because of the radioactivity of the recycle fuel, except for the HTGR where significant refabrication development has been carried out to date for ^{233}U-containing fuels. For the FBR, refabrication could involve only $^{233}U/^{238}U$ fuel, and it is estimated that refabrication development for that fuel as a homogeneous product would be less costly than that for Pu/Th because more of the development effort could be carried out with $^{235}U/^{238}U$ as a substitute fuel. Fuel qualification research and development costs for the DUTH cycle are estimated to be the same as for the Pu/Th cycle in the water reactors, but higher for the DUTH cycle in HTGRs and FBRs. The latter DUTH cycle estimates are based on the increased ^{233}U fuel testing required in FBRs relative to plutonium fuel testing (already accomplished), and the relatively high buildup and burnout of plutonium in HTGR fuels compared to that in the other thermal reactors. For all reactors, the cost and schedule of the fresh-fuel fabrication demonstration plants would be about the same, except that the costs for the FBR would be slightly higher because of the high fissile concentration of the FBR fuel and the complex element assembly.

Highly Enriched ^{233}U/Th Cycle with Recycle of Uranium and Thorium. This cycle assumes that ^{233}U is available from recycle and as needed from some other source not identified here. In the terminology used here all fuel is refabricated and no fresh fuel fabrication facility is required. The costs and schedules associated with the ^{233}U/Th fuel

cycle are very similar to those for the DUTH cycle, with the $^{233}U/Th$ cycle being simpler because no significant quantity of plutonium is bred or handled. As a result, the estimated R&D costs are slightly lower for this cycle than for the DUTH cycle, and the schedule for fuel reprocessing R&D is shorter. However, the schedules for completing the fuel recycle pilot plants for all the reactors were considered to be the same for the HEU/Th cycle as for the DUTH cycle because the overall differences in R&D costs and schedules between the two cycles were not considered to be significant relative to influencing pilot plant schedules.

Summary and Discussion. It is to be reemphasized that large uncertainties are associated with the costs summarized in Table 6, and this is illustrated by the estimated range of costs given in that table. Nonetheless, relative costs and schedules are meaningful in the sense that much of the uncertainty in costs is due to the licensing requirements, and the degree of technology development needed to meet those requirements. Thus, the costs of developing various fuel cycles are influenced in about the same way when going from one fuel cycle to another, and also (to a lesser degree) when going from one reactor to another. This summary discusses the relative costs given in Table 6 and is presented to indicate the relative status of the various cycles. As can be noted, the lowest costs are associated with reactors on the LEU throwaway cycle; of these the highest R&D and demonstration or pilot plant costs are associated with the HTGR and the LEU-fueled HWR. This is due primarily to the estimated need for constructing a fresh-fuel demonstration plant for those reactors. For the throwaway fuel cycles, the R&D activities for all reactors are estimated to be completed in the period between 1984-86. The fresh-fuel fabrication demonstration plants are either not needed or are estimated to be operating in 1986 for HWRs(LEU) and in 1991 for HTGRs(LEU).

For the LEU cycle and recycle of uranium only, the total costs again are highest for the HTGR and the HWR (using slightly enriched uranium). Again, this is due primarily to the estimated need for fresh-fuel demonstration plants which add $250 million to the total costs. The general R&D schedule requirements for the HTGR are higher than for the other reactors; as a result, the time to complete the fuel cycle R&D for the HTGR is estimated to be 1989 compared with 1984-1985 for the other reactors. The fresh-fuel fabrication demonstration plants for the HTGR and the HWR(LEU) systems are again estimated to be available in 1991 and 1986, respectively. The fuel recycle plants are estimated to be available in 1985 or 1986 for the water reactors and in 1996 for the HTGR.

For the $Pu/^{238}U$ fuel cycle with recycle of bred fuel, the total costs for R&D and demonstration or pilot plants are about $1.4 billion for the water reactors, and about $2.0 billion for the FBR; the corresponding costs for the HTGR are intermediate to these. The higher costs for the FBR are due primarily to the higher costs associated with fuel refabrication and reprocessing R&D (due to the relatively high Pu concentrations in the fuel, the complex fuel geometry, and because of the high activity associated with the spent fuel). R&D for this fuel cycle would be completed by 1988 to 1989 for all the reactors. The fuel recycle plants are estimated to be available in the period 1994-96 if both pellet and sphere-pac fuels are to be provided. If only pellet fuels are utilized, fuel recycle plants for metal-clad fuels are estimated to be available in the period 1991-93; fuel recycle plants for HTGRs are estimated to be available in 1996.

For the Pu/Th fuel cycle with recycle of bred fuel, the total estimated costs vary from about $1.9 billion for the HTGR to about $2.3 billion for the FBR, the total costs for the water reactors being intermediate to these. The lower costs for the HTGR largely reflect the lower capacity required of HTGR recycle plants for a given nuclear capacity. However, the differences between the total estimated costs for the different reactors are less than the accuracies with which the total costs can be estimated at this time. For this fuel cycle the R&D activities are estimated to be completed between 1993-94 for all the reactor types except for the FBR for which they will not be completed until 1996. The time of operation of fuel recycle demonstration plans for all reactor types is estimated to be 2000-2001.

For the DUTH cycle with recycle of ^{235}U and ^{233}U, the total estimated costs vary from about $2.1 billion for the HTGR to $2.6 billion for the FBR. Again the costs associated with the water reactors are intermediate to these. The lower costs for the HTGR largely reflect the lower capacity required of recycle plants for a given nuclear capacity. The time for completing R&D activities varies from 1991 to 1992 for all the reactors. The time at which the fresh-fuel fabrication demonstration plants will first operate is estimated to be between 1988 and 1989, while the fuel recycle pilot plants are estimated to first operate in either 1998 or 1999.

For the ^{233}U/Th cycle with recycle of bred fuel, the total estimated costs for the various reactors vary from $1.8 billion for the HTGR to $2.2 billion for the FBR, with the costs for the water reactors being in between. Again, the slightly lower costs for the HTGR largely reflect the lower capacity required of HTGR recycle plants for a given nuclear capacity. The higher costs for the FBR relative to water reactors reflect the higher concentrations of fissile material that have to be handled, the higher activity of spent fuel, and the more complex geometry of the fuel elements. The R&D efforts are estimated to be completed in 1991-92 for all reactors, and the fuel recycle pilot plants should start operation in 1998 or 1999.

From the above, while it appears that there are no significant differences in estimated relative costs for R&D and pilot plant facilities among the different reactors when thorium fuels are being utilized, the costs for FBR fuels tend to be higher. The total costs estimated are about $1.8-2.6 billion for all of the different reactors (1978 dollars). Further, the R&D for all the reactors utilizing thorium fuel cycles could be completed within the period 1991-96. Finally, the pilot plant fuel recycle facilities using the thorium cycles would be first available about the year 2000. Demonstration fresh-fuel fabrication plants involving thorium fuels could be operating about 10 years earlier.

For the uranium fuel cycles, there is a more significant difference between total costs for the different reactors; however, the total costs go up markedly in going from throwaway cycles to cycles involving recycle of uranium only and on to cycles involving recycle of both uranium and plutonium. In general, the total costs for developing uranium-plutonium fuel recycle appear to be slightly less than those associated with thorium recycle systems. Of the thorium-using cycles, development of the DUTH cycle appears to have the highest total costs.

4.2. Integration of Fuel Recycle Research and Development Program

As noted in the preceding sections there are generic areas of fuel recycle development which apply to several fuel cycles and reactor types. Thus, it would be possible to design an integrated fuel recycle development program in which several cycles were developed in a cost effective manner. The schedule is influenced by the timing of developing specific reactor types, as well as the selection of the fuel cycles to be used with those reactors. Thus, fuel recycle development programs must factor in information that is independent of fuel recycle technology in itself. Consider, for example, the development of a fuel recycle technology for LWRs. The development of a thorium fuel recycle technology subsequent to uranium fuel recycle technology would appear technologically logical; alternatively, the development of a thorium fuel recycle technology while deferring commercial uranium fuel recycle might have desirable fuel utilization features. On the other hand, if the once-through uranium cycle in LWRs is economically more attractive than the other fuel cycles for a number of decades, then the schedule for any commercial fuel recycle development for LWRs might be reasonably postponed.

When thermal reactors other than LWRs are considered (i.e., SSCRs, HWRs and HTGRs), the economic attractiveness of the other reactors relative to LWRs, including capital cost and fuel cycle cost factors, should influence the fuel recycle development program. If the throwaway/stowaway fuel cycle is emphasized over the next few decades in thermal reactors, the practical fuel cycles of interest are the uranium cycle in LWRs, HWRs, and SSCRs, and the thorium cycle in HTGRs. Thus, the water reactors would lead to plutonium in spent fuel, and the HTGR to ^{233}U in spent fuel. Since plutonium is a desirable fuel for FBRs, commercial recycle of plutonium could be deferred until FBRs utilize it. Recycle of ^{233}U would be desirable for all the thermal reactors, but HTGRs would constitute the only economic source; the recycle fuel could also be used in fast reactors. Fuel recycle R&D would desirably proceed at this time because of the lengthy time required for development to the commercial stage; but the emphasis could be on that for FBRs and on HTGRs, if HTGRs are emphasized as an economic source of stored ^{233}U. The above scenarios again illustrate some of the important factors to be considered in developing an integrated program involving reactor types and their fuel cycles. In any case, fuel recycle is likely to be necessary in the long term for a viable nuclear power industry to exist.

The discussion below points out certain ways that fuel recycle technology can be integrated, but as illustrated above, the integration which should be addressed is dependent upon the economic performance of reactors and their fuel cycles.

As for the case of singular development given above, integrated research and development for various fuel cycles in different reactors requires demonstration in a number of key areas; the technology must be demonstrated at a scale of operation commensurate with anticipated commercial practice, with appropriate materials, and with acceptable economics.

In addition, commitments to the different reactor types have to be made along with commitments to the fuel cycles. Such commitments involve large sums of money if they are carried out; thus, the strategy for fuel recycle development and its commercialization must be drawn carefully. The technical issues can usually be determined with the greatest confidence; what is needed is a flexible technical program which can be effectively modified as new information becomes available. In particular, insofar as practical, fuel recycle technology should be developed on a generic basis but should include the specific needs of reactor and fuel cycle combinations that show the most promise.

As is evident from the previous discussion of fuel recycle technology, generic elements exist in the various fuel cycles. For example, fuel cycles for LWRs utilizing Zircaloy-clad fuels and fuel for FBRs utilizing stainless-steel-clad fuels share common features. There is less generic technology between HTGR fuel cycles and that for the metal-clad reactors (thermal or fast), but some fuel recycle research and development work is generic to all the reactors. While commonality should not be the basis for fuel recycle development programs, recognition of commonality should be given in meeting reactor and fuel recycle program requirements. At the same time, many areas which need unique development for specific reactor types will remain, particularly with regard to fuel irradiation tests, fuel element assembly, and unique headend and refabrication operations.

Table 7 provides in a general way an overview of the processes for the fuel recycle operation in the different reactors and fuel cycles and indicates areas in which research and development could be carried out generically. Even when the work is generic, however, some problems associated with recycle of specific reactor fuels may need to be uniquely addressed. The following discussion, while not complete, does address some of the factors to be considered in a generic research and development program.

Table 7 shows under headend treatment that fuel shearing is common to all metal-clad fuels and leaching is common to all reactor fuels, but that Zircaloy-clad thoria fuels and HTGR fuels undergo unique processes. Leaching problems will, of course, be different for the different reactor fuel element designs, but common equipment might be used for all but the HTGR fuels, and even for the HTGR an understanding of all the fuel dissolution technology should be helpful in solving specific problems.

In the fuel separation operation, Table 7 illustrates there are three processes which apply; further, these processes should be amenable to development in a common facility designed to handle the most complicated one (Modified Thorex). At the same time, unique problems such as those associated with large variations in fuel activity (e.g., LWR vs FBR fuels) and with different impurity levels (e.g., HTGR fuels with dissolved carbon and silicon in leach solution) will need specific treatment; further, in combined programs, development schedules need to reflect the significant "clean-out" times and equipment modifications which would be associated with using a common facility.

Table 7. Overview Showing Commonality of Processes for Recycling Various Fuels

Reactor Type(s)	Fuel	Headend Treatment	Separation Process	Radioactive Off-Gas Treatment	Waste Treatment	Refabrication
LWR, SSCR, HWR	UO_2	Shear, leach	Purex	^{129}I, ^{3}H, ^{85}Kr, ^{14}C	Concentration, calcination, gas storage, Zr-clad hulls	Pellet (or sphere pac), rod bundle (low activity)
	$(U\text{-}Pu)O_2$	Shear, leach	Purex	Same as above	Same as above	Pellet (or sphere pac), rod bundle (medium activity)
	$(Pu\text{-}Th)O_2$	Shear, cladding separation, leach	Modified Thorex	^{129}I, ^{3}H, ^{85}Kr, ^{14}C, ^{220}Rn	Concentration, calcination, gas storage, Zr and fluoride wastes	Same as above
	$(DUTH)O_2$	Same as above	Modified Thorex	Same as above	Same as above	Pellet (or sphere pac), rod bundle (high activity)
	$(^{233}U\text{-}Th)O_2$	Same as above	Thorex	Same as above	Same as above	Same as above
FBR (core)	$(Pu\text{-}U)O_2$	Shear, leach	Purex	^{129}I, ^{3}H, ^{85}Kr, ^{14}C	Concentration, calcination, gas storage, SS clad hulls	Pellet (or sphere pac), rod bundle (medium activity)
	$(Pu\text{-}Th)O_2$	Shear, leach	Modified Thorex	^{129}I, ^{3}H, ^{85}Kr, ^{14}C, ^{220}Rn	Concentration, calcination, gas storage, SS clad hulls, fluoride wastes	Same as above
	$(DUTH)O_2$	Shear, leach	Modified Thorex	Same as above	Same as above	Pellet (or sphere pac), rod bundle (high activity)
	$(^{233}U\text{-}^{238}U)O_2$	Shear, leach	Purex	^{129}I, ^{3}H, ^{85}Kr, ^{14}C	Concentration, calcination, gas storage, SS clad hulls	Same as above
	$(^{233}U\text{-}Th)O_2$	Shear, leach	Thorex	^{129}I, ^{3}H, ^{85}Kr, ^{14}C, ^{220}Rn	Concentration, calcination, gas storage, SS clad hulls, fluoride wastes	Same as above
FBR (blanket)	UO_2	Shear, leach	Purex	^{129}I, ^{3}H, ^{85}Kr, ^{14}C	Concentration, calcination, gas storage, SS clad hulls	Pellet (or sphere pac), rod bundle (low activity)
	ThO_2	Shear, leach	Thorex	^{129}I, ^{3}H, ^{85}Kr, ^{14}C, ^{220}Rn	Concentration, calcination, gas storage, SS clad hulls, fluoride wastes	Same as above
HTGR	UO_2	Crush, burn, leach	Purex	^{129}I, ^{3}H, ^{85}Kr, ^{14}C (large)	Concentration, calcination, gas storage, $Ca^{14}CO_3$, SiC, spent SiC coated particles	Coated microspheres in graphite block (low activity)
	$(U\text{-}Pu)O_2$	Crush, burn leach	Purex	Same as above	Same as above	Coated microspheres in graphite block (medium activity)
	$(Pu\text{-}Th)O_2$	Crush, burn, leach	Modified Thorex	^{129}I, ^{3}H, ^{85}Kr, ^{14}C (large), ^{220}Rn	Concentration, calcination, gas storage, $Ca^{14}Co_3$ fluoride wastes, SiC, spent SiC coated particles	Coated microspheres in graphite block (high activity)
	$(^{233}U\text{-}^{238}U)C_2\text{-}(^{233}U\text{-}^{238}U)O_2, ThO_2$	Crush, burn, leach	Modified Thorex	Same as above	Same as above	Same as above
	$^{233}UO_2\text{-}^{233}UC_2$, ThO_2	Crush, burn, leach	Thorex	Same as above	Same as above	Same as above

Under "Radioactive Off-Gas Treatment" the gases of most importance are generally the same for the different reactors and fuel cycles, with the thorium cycles having ^{220}Rn as an additional item. Further, the quantity of CO_2 which has to be handled in controlling ^{14}C is much larger for HTGRs than for the other reactors. Under "Waste Treatment" there is common research and development associated with all the reactors and fuel cycles relative to concentration of wastes, calcination of high-level wastes, and gas storage treatment. Differences exist in the activity of the high-level wastes (e.g., LWR vs FBR fuels), in the amount of wastes (e.g., Zr-clad UO_2 fuels would have less wastes than corresponding Zr-clad ThO_2 fuels), and in the amount of fluoride present (wastes from ThO_2 fuels would contain significant fluoride concentrations). The wastes associated with cladding hulls from different reactors may also require unique treatment, and spent silicon-carbide-coated fuel microspheres need to be treated for HTGR cycles. Further, HTGRs have a special waste due to the relatively large amounts of low-activity $CaCO_3$.

As indicated in Table 7, the metal-clad fuels have common design features which permit some of the refabrication research and development to be generic. The technology required, however, varies with the activity of the fuel, and so the generic efforts may be restricted to specific activities. In general, it appears that sphere-pac fuel technology can be developed generically more independent of activity level than can conventional pellet fuel technology. However, pellet fuel technology might also be based on microsphere technology in part by using common material preparation technology. Of the different reactor fuels, the HTGR fuel refabrication research and development is the most unique, and largely requires independent development; the one generic area involves microsphere production, with microspheres developed for HTGRs having generic features with microspheres for use in sphere-pac fuels.

While the economic incentives for near-term recycle of plutonium in LWRs are marginal, fuel recycle technology requires long times for development to commercial scale, and R&D needs to proceed to provide it in a timely fashion. At this time, a major portion of a reprocessing complex exists in the AGNS plant at Barnwell. It may be desirable to use the Barnwell facility to develop and demonstrate in a timely manner that fuel recycle can be handled safely in an environmentally acceptable manner and with adequate guarantees for safeguards and proliferation resistance.

The Alternate Fuel Cycle Technology Program has addressed problems for LWR fuel reprocessing, such as improvements in fuel separations processes and better emission control of gaseous fission products. This program and others help in the long-term development of fuel recycle. However, more comprehensive programs are needed and are underway to solve the more complex set of problems of recycling advanced fuels whether from breeders or from thorium-fueled converters; these programs include pilot-plant demonstration of fuel cycles before these cycles are implemented on an industrial scale. Versatile pilot plant demonstrations are particularly appropriate for integrated fuel recycle research and development. Due to the generic nature of much of the research and development as discussed above, development and demonstration of fuel recycle technology for several reactors and

fuel cycles could be carried out to a significant degree in common pilot facilities. However, it would be necessary to structure the fuel recycle research and development programs and to phase the pilot-plant programs consistent with the timing and implementation of the different reactor concepts of interest. The large pilot plants, as envisioned, could accomplish many of the same functions as a demonstration reprocessing facility for a number of cycles. Reprocessing at commercial scale might follow such a pilot plant program.

Relative to an integrated program for fuel reprocessing research and development for the various reactors and fuel cycles, Fig. 3 provides a schedule based on the above considerations. While not discussed here, the schedule is based on studies of concepts, arrangements, layouts and flowsheets concerning flexible reprocessing facilities for carrying out integrated research and development. While the work can be pictured as independent efforts on each cycle, use of an integrated pilot plant facility permits similar fuel types to be examined concurrently. The work would emphasize generic areas as discussed above and include remote operations and maintenance research and development.

As shown in Fig. 3, the route to industrial-scale reprocessing of LEU-LWR fuels could proceed without a pilot-plant program by making use of the Barnwell facility. The schedule would be improved in such a scenario. For other fuel cycles and reactor types, use of the pilot-plant route is shown; the order in which the various fuel cycles would be developed is not yet established. If thorium fuels were emphasized in water reactors, these fuels would be first routed through the pilot plant. FBR fuels for uranium-plutonium cycles might be next, followed by breeder-thorium cycle fuels.

While a pilot plant could be designed with sufficient versatility that alternate fuels could be handled on a two- to three-month campaign basis, there seems to be little incentive for this. Instead, the facility is conceived to examine specific fuel cycles over a period of a few years depending upon the reactor types and fuel cycles of most immediate interest. Down time between research and development for different fuels need not be longer than three to six months. As one possible phase schedule, LWR fuels with conventional uranium-plutonium cycles might initially be reprocessed in the first two years of operations during initial shakedown tests, beginning about 1990. This would demonstrate much of the generic technology of reprocessing. With the more complex fuel cycles an additional three to five years of pilot plant R&D might be required. Following this, or alternative to developing thorium cycles in LWRs, the facility could be switched to R&D on breeder fuel cycles. As indicated in Fig. 3 and in the previous discussions, HTGR fuel recycle R&D has many unique aspects which make it difficult to utilize a common pilot plant which includes HTGR development.

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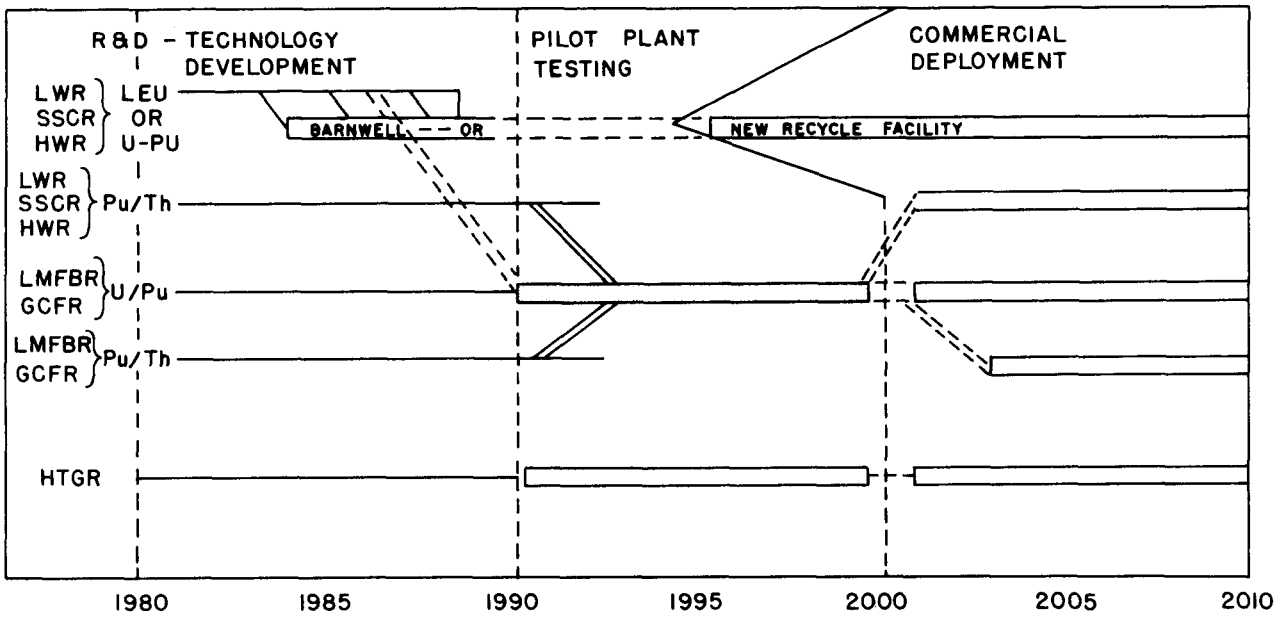

Fig. 3. Scenario for Integrated Program of Reprocessing Development-Deployment in U.S.

The present technology status, combined with the required lead times for implementing such a major facility, makes operation of an integrated pilot plant before 1990 highly improbable. This places the full-scale implementation of advanced fuel recycle in the general time frame of the year 2000 and beyond. Such a time frame is consistent with the practical development of advanced reactor types. It is most important that the timing and development of reactor types and their fuel recycle be carried out in a consistent, comprehensive fashion.

Examination of the research and development requirements for the divers individual fuel cycles shows that while certain research and development is fuel cycle specific, much of it is generic. For example, the major reprocessing efforts for the metal-clad reactors are applicable to more than one cycle. In headend equipment development and emission control, well over 50% of the effort appears applicable to the various fuel cycles. This means that development of several cycles will not cost as much as the sum of the individual cycles, particularly with regard to the cost of facilities. Specifically, substantial savings result by structuring a program utilizing a common pilot plant facility. The capital costs for such a facility are estimated to be at least $500 million in present dollars, based on a reprocessing pilot plant handling 0.25-0.5 tonnes/day of heavy metal. Cycle-specific equipment, other than the original pilot plant complement, might cost several tens of millions of dollars, but it is clear there are substantial capital cost savings in an integrated program, where applicable. Development schedules, in general, however, would be extended because of the need for sequential development associated with specific reactors and fuel cycles. In the area of waste treatment, a common program would be very efficient, with the most extensive research and development program discussed previously simultaneously solving most of the waste treatment problems for all the above fuel cycles.

Integrated planning for fuel refabrication development is also expected to show cost savings. For example, and as indicated previously, sphere-pac fuels are applicable to all the metal-clad reactor fuels, and the microsphere forming operations are applicable to HTGR fuels. Thus, a gel sphere-pac fuel program can be integrated in a meaningful way. Such a program would include common development of refabrication processes and equipment and an irradiation test program. Work could proceed logically through cold laboratory and hot laboratory development and consider ThO_2, UO_2 and ThO_2-UO_2 in parallel with PuO_2 and UO_2-PuO_2. Spiked fuels could be included in the generic research and development program. Since the bulk of the research and development is generic, this approach allows proceeding with development of cold engineering equipment while pursuing the development of flowsheets for PuO_2-containing fuels and would shorten the time required to reach the stage of engineering-scale operation with coprocessed UO_2-PuO_2. Figure 4 illustrates an integrated program which might be followed in developing sphere-pac reactor fuels. It would, of course, be necessary to develop and test fuels which were reactor specific, and this is not shown in Fig. 4; however, the figure does illustrate the kind of integrated fuel refabrication research and development which is possible. Similar integartion of refabrication research and development could be developed for pellet type fuels. At the present time, pellet type fuel development is in a more advanced stage than sphere-pac fuel development.

4.3. Overview of Costs and Schedules for Fuel Recycle Development

The foregoing sections have presented scoping-level estimates of the costs for developing alternative fuel cycles. Table 8 presents an overview based on the estimated cost ranges and shows that, depending on the cycle selected, the total costs for developing a closed cycle with recycle of bred fuel could vary from $1.3 billion to $3.6 billion. The LWR/$^{238}U$ cycle would be at the low end of the range, while the DUTH cycle and the cycle for FBRs would be at the high end. Table 9 presents the R&D cost ranges in terms of reactor types and fuel recycle cases; as shown, there is a significant cost uncertainty for each reactor type and fuel cycle, although as discussed previously, for a given reactor type the trend in costs as a function of fuel cycle is significant. If a number of related cycles were developed in the same facilities, the total cost would be only moderately higher than that associated with any one cycle, but the overall development schedule would be lengthened. Since the DUTH cycle implies a system of symbiotic reactors (^{233}U producers and DUTH consumers), such an approach is likely to be attractive if a decision were made to develop the DUTH cycle.

The estimated lapsed time from initial development to commercialization of fuel recycle for a given cycle ranges from about 12 years to 20 years, depending on the initial technology status and the degree to which the research and development program steps are telescoped to save time. An integrated program for developing several fuel cycles would increase the time required for completing the overall schedule by perhaps about 5 years. The thorium cycles would be at the long end of the development time scale; however, pilot-scale facilities able to serve several reactors would be in operation prior to operation of the commercial-scale plant.

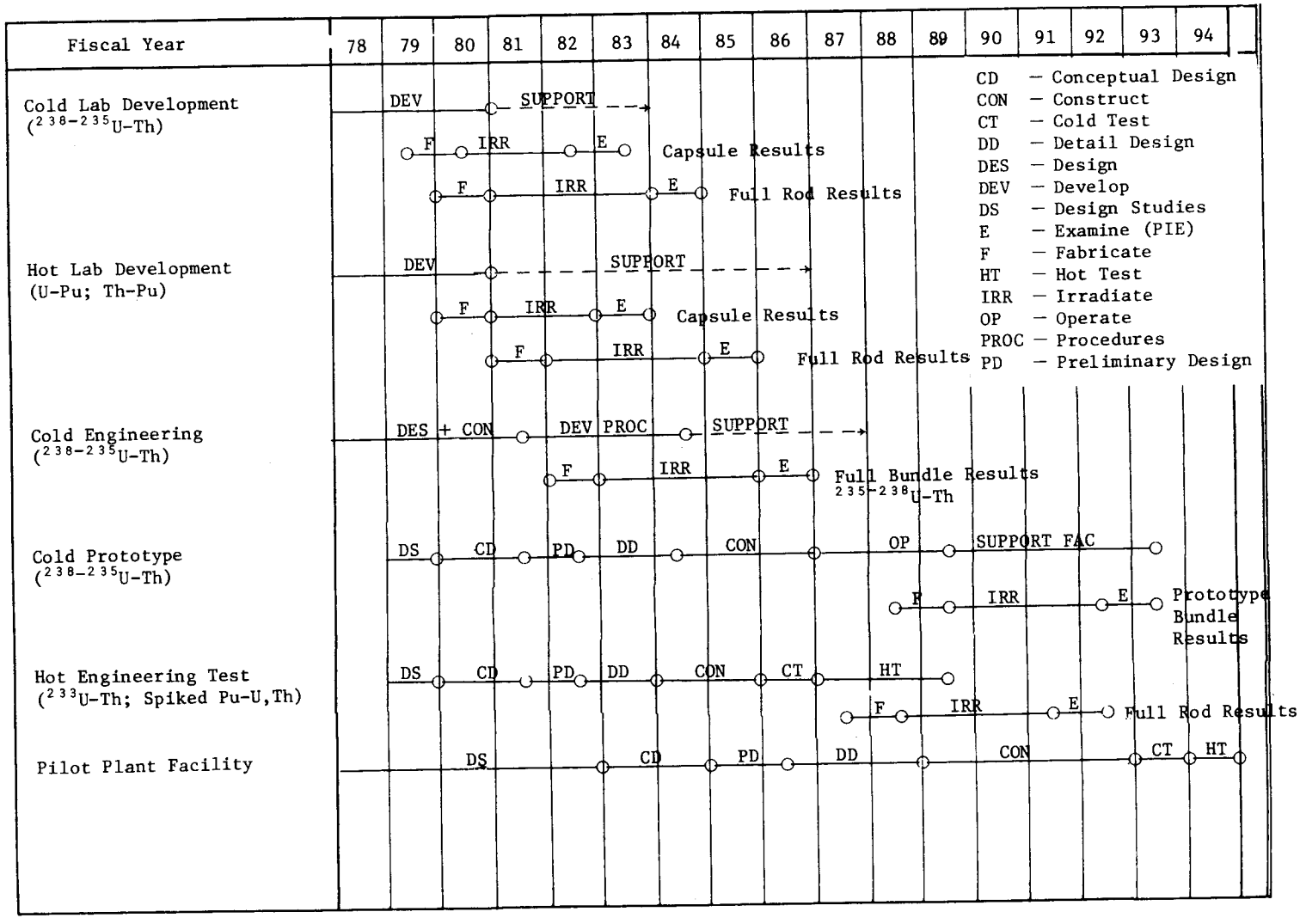

Fig. 4. Thermal Reactor Fuel Refabrication Program Schedule.

Table 8. Summary of Estimated Fuel Recycle Research and Development Costs

	$ Million
Base Reprocessing R&D	100 - 500
Base Refabrication R&D	150 - 300
Base Fuel Qualification R&D	50 - 100
Base Waste Treatment R&D	300 - 400
Demonstration Plants and/or Pilot Plants	700 - 2300
Total	1300 - 3600

Table 9. Estimated Range of Fuel Recycle R&D Costs
For Various Reactors and Fuel Cycles

Reactor Type	Fuel Recycle Case (Costs, $ Million)			
	U/Pu	Pu/Th	DUTH	HEUTh
Water Reactors	1300-2200	1700-2700	1900-3100	1600-2600
HTGRs	1500-2400	1700-2700	1900-3000	1600-2500
FBRs	1800-2800	2000-3200	2200-3600	1900-3100

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