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HTGR SPENT FUEL TREATMENT PROGRAM

HTGR SPENT FUEL TREATMENT DEVELOPMENT PROGRAM PLAN

PROGRAM STAFF

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ACRONYMS

AFR	away from reactor
AIST	advanced-isotope-separation technique(s)
AKUT	Off-Gas Treatment Facility for Aerosols, Krypton and Tritium
AR	at reactor
AVR	Arbeitsgemeinschaft Versuch Reaktor
BOG	burner off-gas
CFRP	Consolidated Fuel Reprocessing Program
DOE	Department of Energy
DOG	dissolver off-gas
EPA	Environmental Protection Agency
FIS	Federal Interim Storage
FRG	Federal Republic of Germany
GA	GA Technologies Inc.
GNS	Gesellschaft für Nuklear Service
HBK	Hochtemperaturreaktor Brennstoff Kreislauf
HEPA	high-efficiency particulate air (filters)
HETF	Hot Engineering Test Facility
HEU	high-enriched uranium
HLW	high-level waste
HOBE	Hochtemperaturreaktor Brennelement Gesellschaft
HTGR	high temperature gas-cooled reactor
HTR	German high temperature reactor (gas cooled)
ICPP	Idaho Chemical Processing Plant
ICT	Institut für Chemische Technologie
IFSF	Irradiated Fuel Storage Facility
INEL	Idaho National Engineering Laboratory
JFPD	Joint Fuel Processing Demonstration
JHPD	Joint Hot Fuel Processing Demonstration
JPHF	Joint Preconceptual Head-end Flowsheet

JPOF	Joint Prototype Off-Gas Treatment Facility
JPRF	Joint Prototype Refabrication Facility
JPWF	Joint Prototype Waste Facility
JUPITER	Jülicher Pilot Facility for Thorium Element Reprocessing
KFA	Kernforschungsanlage, Jülich GmbH (a German national laboratory)
KfK	Kernforschungszentrum, Karlsruhe (Institute of Neutron Physics and Reactor Engineering at Karlsruhe)
LEU	low-enriched uranium
LLW	low-level waste
LWR	light-water reactor
MILLI	Mineaturwiederaufarbeitungsanlage, millitonne (1 kg per day) heavy metal reprocessing facility at KfK
MRS	monitored retrievable storage
NRC	Nuclear Regulatory Commission
NWPA	Nuclear Waste Policy Act of 1982
ORNL	Oak Ridge National Laboratory
PIE	postirradiation examination
R&D	research and development
RD&D	research, development, and demonstration
SFT	spent fuel treatment
THTR	Thorium Hochtemperatur Reaktor [300-MW(e) Thorium High Temperature Reactor]

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1. INTRODUCTION

1.1. OBJECTIVES

This document is intended to establish a multiyear base line plan that addresses the critical near-term and long-term development needs for the management and treatment of high temperature gas-cooled reactor (HTGR) spent fuel to assure fuel cycle closure. The plan will provide the technology for treating spherical and prismatic low-enriched uranium (LEU) fuel discharged from an HTGR Lead Plant and follow-on plants and high-enriched uranium (HEU) fuel discharged from later plants. The plan also incorporates the cooperative agreement with the Federal Republic of Germany (F.R.G.) on HTGR spent fuel treatment development and provides for economic evaluation of spent fuel treatment alternatives.

1.2. SCOPE OF PROGRAM

The previous National Program Plan (Ref. 1) was directed toward development and demonstration of fuel reprocessing and refabrication only. This spent fuel treatment (SFT) program plan addresses spent fuel volume reduction, packaging, storage, transportation, fuel recovery, and disposal to meet the needs of the HTGR Lead Plant and follow-on plants. In the near term, fuel refabrication will be addressed by following developments in fresh fuel fabrication and will be developed in the long term as decisions on the alternatives dictate.

The formulation of this revised program plan considered the implications of the Nuclear Waste Policy Act of 1982 (NWPAA) which, for the first time, established a definitive national policy for management and disposal of nuclear wastes. Although the primary intent of the program plan is to address technical issues, the divergence between commercial and government interests, which arises as a result of certain provisions of the NWPAA, must

be addressed in the economic assessment of technically feasible alternative paths in the management of spent HTGR fuel and waste. A comprehensive report covering the economic basis for HTGR spent fuel treatment decisions has been prepared as a companion document to this program plan (Ref. 2). In effect, the primary economic concern, with respect to alternative methods of disposal of spent fuel, lies with the government, and the primary economic concern in fuel recycle lies with the private commercial sector. These factors are taken into account in the plan presented herein.

This new SFT program plan also incorporates a significant cooperative research and development (R&D) program between the United States and the F.R.G. The major objective of this international program is to reduce costs by avoiding duplicate efforts.

The program plan will take into account current HTGR market growth forecasts, SFT strategies which recognize the impact of NWPA provisions, and needs which are evident based on light-water reactor (LWR) experience.

1.3. BACKGROUND

Some of the SFT experience and problems that have already evolved in both the LWR and HTGR programs are reviewed below. The LWR experience is particularly useful because it identifies some of the problems that might be expected in the next 10 to 30 years for the HTGR.

1.3.1. Light-Water Reactor Spent Fuel Treatment Experience

Some of the LWR SFT difficulties stem from incorrect assumptions of the late 1960s and early 1970s involving recycle regulations, LWR growth, and U₃O₈ prices. Current LWR difficulties associated with SFT include the following:

1. Spent fuel congestion at reactor sites because of the lack of storage, disposal, and/or reprocessing facilities; this has been

the result of protracted deliberation of waste storage and disposal issues at the national level.

2. A currently low U_3O_8 price that reduces the incentive for recycle.
3. The lack of a good commercial-scale demonstration of current reprocessing technology.
4. Questions on how plutonium might best be used and regulatory restrictions on what will be permitted.
5. Uncertain licensing requirements and procedures and general instability in the regulatory process.
6. Policy matters involving the federal government, state governments, and industry.
7. Policy changes due to concerns on nuclear weapons proliferation.

Considerable disagreement exists regarding the economic benefit of LWR reprocessing with current U_3O_8 prices, but the present uranium price structure is generally agreed to be distorted by current market conditions. Perhaps the most serious near-term problem is the shortage of interim storage facilities for spent fuel either at the reactor site or at sites away from the reactor. However, the NWPA is supposed to alleviate this problem. Another source of concern is the uncertainty in U.S. government policies toward reprocessing, which makes future commitments for commercial reprocessing facilities risky and unattractive to private enterprise.

Many of the problems already facing the LWR industry will hopefully be resolved by the time that commitments are needed for closing the HTGR fuel cycle. Nevertheless, continuing R&D and policy planning for closing the HTGR fuel cycle must consider the LWR SFT experience.

1.3.2. HTGR Spent Fuel Treatment Considerations

Considerations in planning HTGR SFT strategies include the following:

1. HTGR growth projections.
2. Trends in U_3O_8 and enrichment costs.
3. Timing of availability of repository/monitored retrievable storage (MRS).
4. Timing of availability of reprocessing capability.
5. Cost of spent fuel volume reduction, storage, and transportation.
6. Costs of spent fuel and waste disposal.
7. Cost of reprocessing and refabrication.
8. Acceptability of HEU (U-235 and U-233) utilization.
9. Timing and cost of technology development and demonstration.
10. Degree of government participation in the development of alternative spent fuel management strategies.
11. Influence of the NWPB on the relative economic interests of the private sector versus the government in both the short term and the long term.
12. Relative costs for at-reactor (AR) and away-from-reactor (AFR) storage.
13. Degree and mode of international cooperation.

14. Possible large changes in related technologies (e.g., uranium mining and milling technologies and advanced-isotope-separation technologies).

These considerations can lead to uncertainties both in program direction and in the timing of technology transitions within a particular program. For these reasons, the decision process approach should be applied to the alternatives; this approach is described in detail in Section 2.

1.3.3. U.S./F.R.G. HTGR Cooperative Program

Prior to 1977, the U.S. and the F.R.G. conducted independent programs on gas-cooled reactor R&D. Realizing that total program costs could be reduced by a cooperative program, these governments put into effect in early 1977 a joint program document (Ref. 3), known as the "Umbrella Agreement."

The U.S. and F.R.G. SFT development programs have a common approach involving once-through disposal of whole spent fuel, optional volume reduction, and reprocessing. Both programs interface in the areas of head-end SFT (including volume reduction), spent fuel transportation and storage, waste stabilization, and materials control and accountability. The plan is revised yearly, depending upon the immediate and future requirements of each country.

Cooperative R&D in the areas of spent fuel element transportation and storage development include information exchanged on the F.R.G. salt mine project and related work. Design studies of interim surface storage for German high temperature reactor (HTR) spent fuel are being performed in the F.R.G. U.S. experience with Peach Bottom and Fort St. Vrain spent fuels obtained at the Idaho National Engineering Laboratory (INEL) will be shared with the F.R.G. Design and cost studies by GA Technologies Inc. (GA) on HTGR spent fuel storage facilities and transportation systems will also be provided to the F.R.G.

Testing and demonstration of head-end spent fuel treatment processes is under way with unirradiated fuels from both countries in a Joint Fuel Processing Demonstration (JFPD). This demonstration is to be followed by a Joint Hot Fuel Processing Demonstration (JHPD) with irradiated fuels. The JFPD has used the cold pilot plant at GA to treat a number of U.S. HTGR prismatic fuel elements containing two particle fuels and thousands of the F.R.G. HTR spherical fuel elements containing single-particle fuel. KFA, the F.R.G. nuclear research center at Jülich, is conducting a program in their Institut für Chemische Technologie (ICT) to demonstrate processing of irradiated spherical fuel from their Arbeitsgemeinschaft Versuchreaktor (AVR). Head-end processes will be demonstrated in the ICT hot cell. Solvent extraction and product purification will be demonstrated at the MILLI facility of the Kernforschungszentrum (KfK) in Karlsruhe.

Upon completion of the studies with AVR fuel, the JHPD will provide data on U.S. prismatic elements from the Fort St. Vrain reactor. Only the head-end processes will be demonstrated with Fort St. Vrain fuel. Products will be returned to the U.S. for use in stabilization studies of volume reduced spent fuel. These demonstrations will show the applicability and versatility of the processes and identify further development and testing requirements. Preparation of a Joint Preconceptual Head-end Flowsheet (JPHF) is a key element in the U.S./F.R.G. cooperative program.

Results and recommendations from the JFPD and JHPD will provide guidance for future research, development, and demonstration (RD&D) requirements of the JPHF. The versatility of the program allows for redirection to cover additional spent fuel treatment possibilities.

Specific technical issues of common interest have been jointly defined for the major systems of the head-end SFT processes, currently including fuel element size reduction; material handling and sampling; crushed fuel element burning and off-gas treatment; particle classification, crushing, and secondary burning; and analysis, materials control, and accountability. Requirements will be identified for HTR waste and high-level waste (HLW) from treatment of spent fuel, joint development plans, and other areas for

interaction. For example, F.R.G. has been conducting tests to characterize irradiated SiC-coated particles and hulls.

A design assessment of the Jülicher Pilot Facility for Thorium Element Reprocessing (JUPITER) (F.R.G.) and the Hot Engineering Test Facility (HETF) (U.S.) hot-engineering-scale SFT projects has been completed. The JUPITER project, now in the cold shakedown stage, and the JHPD project (F.R.G.) will provide much of the needed information that the now-abandoned HETF would have supplied.

Figure 1-1 shows the relationship of these elements and other potential elements of the cooperative program such as the Joint Prototype Waste Facility, the Joint Prototype Off-Gas Facility, and the Joint Prototype Refabrication Facility (JPWF, JPOF, and JPRF).

Fig. 1-1. U.S./F.R.G. cooperative program elements

2. STRATEGY

This section defines the decisions that must be made regarding the HTGR SFT alternatives. The considerations stated in this section and specific development requirements form the basis for the plan presented in Section 3. The strategy to be developed is strongly influenced by the NWPA, which defines government responsibilities for nuclear waste and/or spent fuel disposal in the back end of the fuel cycle. Although the long-term objective of the HTGR SFT program is to optimize fuel cycle costs for commercial operation of the HTGR systems, the near-term objectives must, of necessity, consider the comparative costs to the government of alternative waste/spent fuel management methods during the NWPA-dominated phase of HTGR development. Near-term objectives therefore emphasize minimizing these costs by doing the following:

1. Evaluating costs and technical benefits of alternative methods of spent fuel management.
2. Identifying significant development work necessary in order to implement the promising alternatives.
3. Defining the necessary scope and appropriate depth of pilot-plant programs to optimize the preferred spent fuel management program.

2.1. INFLUENCE OF NUCLEAR WASTE POLICY ACT

The NWPA, by providing for government responsibility for receiving and disposing of spent fuel or waste after 1998, creates a significant distinction between the decision bases for the near-term spent fuel disposal strategy and the long-term strategy involving fuel recovery. This distinction is particularly important in the economic analyses of alternative

processing routes, because of the basic difference between government and utility financing factors (Ref. 2).

This plan strategy recognizes that SFT-RD&D programs which provide input to near-term government decisions are more urgent than research for longer-term commercial decisions. Thus, the SFT-RD&D program initially emphasizes developing and testing technology for spent fuel shipping, volume reduction, and lower-cost spent fuel storage modes, as well as developing long-lead-time process technology. The longer-term requirements for optimization of the HTGR fuel cycle would, for the near future, be the subject of continuing studies and analyses to identify promising candidate processes for development.

2.2. PLANNING METHODOLOGY

Responding to an established need to recycle spent fuel, the previous National Program Plan (Ref. 1) focused on a single course of action, namely, reprocessing and refabrication. The program was a major element of the U.S. effort to improve the supply of nuclear materials by utilizing thorium in a thorium U-233 fuel cycle, which is the basis of HTGRs. This approach was predicated on a favorable foreseen HTGR market growth, the economics of uranium supplies and fuel recycle, and supportive government policies. Over the past few years, the philosophy of spent fuel treatment and management has evolved in response to changing external influences. These external factors included a delay in nuclear growth; the federal approach to non-proliferation, resulting in the decision to use LEU in the Lead Plant HTGR; lower natural uranium prices; and the impact on the fuel cycle from the NWPA. Thus, a different planning approach was shown to be necessary to accommodate the evolving alternatives for HTGR SFT.

The present HTGR SFT program will be closely coordinated with reactor technology development and aimed at supporting its fueling choices. Reactor concepts under consideration in the HTGR development program include modular plant designs in the range of 250 to 350 MW(t) and integrated plant designs in the range of 1000 to 1300 MW(t). Both prismatic and spherical fuels are

being considered in these reactor concepts. Since the necessary major decisions cannot be completely predicted at this time, the program is structured to address a variety of alternatives. Fortunately, the choices are limited and can be initially investigated with a modest program. Many of the long-term alternatives have development needs in common with the near-term alternatives, at least over the next few years until the commitment to the construction of the Lead Plant is made with the resulting fixing of a specific fuel design selection. Program elements have been identified which support the largest number of alternatives and the most critical needs and reflect the long lead requirements. These program elements are scheduled for development of the near-term priorities.

Rather than taking a single course of action, as used previously, the program plan is based on developing a decision tree for the SFT alternatives. Commitments to an alternative can be made at decision points at appropriate times based on all of the impinging technological, economic, institutional, and political factors. In the near term, studies and analyses will provide preliminary designs, costs, and the development requirements associated with each alternative. Concurrent development will provide additional input to these studies. This will be an iterative process until a logical decision can be made. This approach will reduce the chances of a costly program redirection.

2.3. DECISION TREE

The major decisions affecting the course of the HTGR Spent Fuel Treatment Development Program are shown on the decision tree in Fig. 2-1. The key decisions involve the utilization of (1) AFR or MRS storage, (2) volume reduction of spent fuel to reduce the costs of interim storage and/or repository disposal or as pretreatment to reprocessing, and (3) reprocessing to recover fuel values.

Many of the decisions on the course of the HTGR Spent Fuel Treatment Development Program are affected in turn by decisions regarding the use of HEU or LEU fuel. Both the Peach Bottom and Fort St. Vrain HTGR plants used

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Fig. 2-1. HTGR-SFT decision tree

an HEU/Th fuel. Several considerations not related to the SFT program, however, led to changing the fuel cycle to LEU/Th for the HTGR Lead Plant. First, because of the much slower nuclear growth than anticipated, current plans are limited by economics to a once-through fuel cycle until a clear HTGR growth is indicated. Second, political non-proliferation concerns associated with the large-scale use of HEU fuel led to a decision to use the LEU/Th fuel cycle for the Lead Plant. On these bases, therefore, direction for the Lead Plant is the LEU/Th once-through fuel cycle. However, because of lower fuel cycle costs and improved resource utilization, an important objective of the HTGR Reactor Program is the eventual change to the use of HEU fuel for both the once-through and recycle modes of operation. Therefore, the SFT program must address both the LEU and HEU fuel options. In addition, the use of the once-through LEU fuel cycle without thorium is under consideration for the Lead Plant if spherical fuel is chosen.

A decision must be made between disposing of the fuel as whole elements or as volume-reduced fuel. Either AR or AFR/MRS facilities can be used to store the whole spent fuel elements prior to shipment to a federal repository or a volume-reduction facility. Encapsulation of the fuel in some inert media (i.e., stabilization), in order to meet limits for leach rates and release of radioactive materials stored in a federal repository, must be considered for whole fuel elements and will probably be required for volume-reduced fuel.

After volume reduction and stabilization, the fuel could either be stored in the volume-reduction facility or in an AFR/MRS facility for required cooldown periods prior to repository disposal. Alternately, the volume reduction could be carried out at the repository.

If the decision is made to use HEU fuel with recycle, then the spent fuel can either be shipped directly to a reprocessing facility, held in AR storage, or shipped to an AFR facility. If AFR storage is used, then the fuel can be stored as whole fuel elements or as volume-reduced fuel. At the reprocessing facility, the fuel is recovered for recycle and the HLW is stabilized for disposal in a federal repository.

The companion report to this program plan on the economic basis for HTGR spent fuel treatment decisions (Ref. 2) gives a thorough analysis of the impact of the reactor and fuel cycle choices on alternative spent fuel treatment strategies in relationship to both government and commercial decisions. The implications of this study are that the near-term SFT RD&D should be part of a unified SFT program leading to ultimate fuel recovery if the prismatic fuel block design is retained. If the modular pebble bed fuel design is selected, fuel packaging and disposal RD&D becomes a more significant element of the program.

For either a pebble bed or a prismatic fuel design choice, the incentive for volume reduction of the spent fuel to minimize spent-fuel costs is large since these design options, based on enhanced or passive safety features, involve lower power densities and/or shorter cycle burnups than was the case for the previous reference 2240-MW(t) design. As a result, waste volumes per GW(e)-yr are 30% to 115% greater than those for the 2240-MW(t) design. Therefore, spent fuel considerations need to be factored into the fuel design to prevent major handling problems. Suggested fuel design changes to simplify HTGR spent fuel processing are presented in the FY-84 report on volume reduction (Ref. 4).

3. PLAN

The principal objectives of the HTGR Spent Fuel Treatment Development Program are to (1) assure that adequate technology is available when needed to close the fuel cycles for the Lead Plant, follow-on plants, and HEU recycle and (2) support the ongoing U.S./F.R.G. cooperative program.

Facilities are available in the U.S. at GA, Oak Ridge National Laboratory (ORNL), and INEL where cold (unirradiated) and hot (irradiated) tests and storage studies can be conducted to develop the technologies of HTGR spent fuel management. The F.R.G. has several facilities and R&D centers which complement the facilities in the U.S. and are available under the international cooperative agreement. Appendix A describes the facilities of both countries in more detail.

Development of HTGR SFT technology requires (1) studies and analyses and (2) RD&D programs. Appendix B details the status and requirements of these areas of activity.

Activities are planned for the following specific areas:

1. Transportation.
2. Storage.
3. Volume reduction.
4. Packaging.
5. Disposal and economics.
6. Reprocessing.
7. Spent fuel characterization.

The highest priority is given to near-term requirements; however, many have continuing application to longer-range needs and, consequently, will evolve from near-term to long-range objectives.

Closing the LEU once-through fuel cycle for the Lead Plant necessitates that the highest priority be put on the following near-term tasks:

1. Spent fuel characterization.
2. Transportation and storage.
3. Volume reduction.
4. Packaging.
5. Disposal and economics.

3.1. SELECTION CRITERIA

The following factors were considered in selecting the near-term development program elements:

1. Extent to which the element supports the objectives of the HTGR Lead Plant.
2. Lead time required to perform the element.
3. Extent to which the element supports the U.S./F.R.G. cooperative program.
4. Extent to which the element verifies or establishes technical feasibility of fuel cycle options.
5. Degree of assurance the element provides in defining SFT costs.
6. Extent to which the element maintains a level of technical expertise for future needs.

3.2. NEAR-TERM PROGRAM SELECTION

The near-term program is arbitrarily defined as that work needed during the next five years (FY-85 through FY-89). This includes work to support a reference spent fuel management concept for the Lead Plant and critical

long-lead requirements. These activities also support critical elements of the U.S./F.R.G. cooperative program.

3.2.1. Reference Spent Fuel Management Concept for the HTGR Lead Plant

Figure 3-1 illustrates the reference concept and options for HTGR Lead Plant spent fuel management:

1. AR storage of whole spent fuel.
2. AR packaging of whole spent fuel for shipment.
3. Shipment of whole spent fuel in a Department of Energy (DOE) furnished cask to a repository for final packaging and disposal, or to a MRS facility. (Ownership of the spent fuel is transferred from the utility to DOE at the reactor site.)

To reduce spent fuel costs, the concept could also include a volume-reduction facility at the repository (or MRS site). Depending on the volume-reduction process, low-level waste (LLW) might also have to be shipped to a surface disposal site.

The reference concept was selected because it should impose a minimum, or at least reasonable, capital cost burden on the utility and is consistent with the requirements of the NWSA. The concept does not include AFR storage except for the potential surge storage which might be required by DOE at the optional volume-reduction facility. This decision was based on preliminary studies (Refs. 2 and 5) which show that the unit (dollars/fuel element) capital cost of an AR storage facility is considerably less than that of an independent AFR storage facility, whether built and operated by a utility or by the DOE. However, the AR storage capacity should be fixed at the minimum required by the most restrictive of the following considerations (i.e., the one which leads to the greatest amount of AR storage):

1. Potential repository operating delays.

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Fig. 3-1. Reference SFT concept for the HTGR Lead Plant

2. Potential problems with priorities for repository disposal under the NWPA or subsequent DOE-utility contracts.
3. Required cooldown for acceptance at repository.
4. Compatibility with packaging and optional volume reduction.
5. Emergency core unloading requirements, if any.

Packaging for disposal will have to meet proposed government regulations (10CFR60). To be consistent with the proposed treatment of LWR spent fuel, the reference concept assumes that chemical stabilization of whole spent fuel elements is not required to meet these regulations. This assumption will be validated in the near-term development program.

3.2.2. Studies and Analyses

The following studies are scheduled for the next five years to meet the needs of the HTGR Lead Plant and critical long-lead requirements:

1. Storage.
 - a. Determination of the best method for storage of HTGR spent fuel in whole and volume-reduced form.
 - b. Development of conceptual designs and cost estimates for storage facilities for whole and volume-reduced HTGR spent fuel by the method(s) selected in 1a.
2. Transportation.
 - a. Development of conceptual designs and cost estimates for rail and truck shipping systems for whole and volume-reduced HTGR spent fuel.
 - b. Initiation of Title I (preliminary) designs for rail and truck shipping systems for whole HTGR spent fuel elements.

3. Volume reduction.

- a. Development of conceptual designs and cost estimates for government and commercially financed volume-reduction facilities using the most feasible options.
- b. Evaluation of concepts and costs of candidate volume-reduction methods and selection of a preferred option.

4. Packaging.

- a. Evaluation of methods of packaging LWR spent fuel for applicability to whole and volume-reduced HTGR spent fuel.
- b. Definition of packaging RD&D requirements to establish a comparison with LWR fuels and to determine the needs for stabilization of whole and volume-reduced fuel for disposal.
- c. Development of designs for spent-fuel packages for repository disposal of whole and volume-reduced fuel and for near-surface disposal of emptied spent-fuel blocks; estimation of package costs.

5. Disposal and economics.

- a. Updating cost estimates for disposal of whole and volume-reduced HTGR spent fuel.
- b. Development of a conceptual design and cost estimate for an integrated universal waste package for storage, transportation, and disposal to ensure selection of an optimum waste form.

- c. Updating the Economics Basis Report as new information is developed in the HTGR reactor and spent fuel treatment programs.
- 6. Reprocessing. Evaluation of various options for improving the technology and economics of reprocessing. Include options to reduce the volume of C-14 generated or reduce the cost of C-14 fixation and disposal.
- 7. Spent fuel characterization. Preparation of a data base for the reference LEU/Th spent fuel, including radioactive release as a function of fuel element temperature, decay heat generation rates as a function of time, and radiation dose rates as a function of time.

3.2.3. Research, Development, and Demonstration

The following RD&D activities are scheduled for the next five years to meet the needs of the HTGR Lead Plant and critical long-lead requirements:

- 1. Volume reduction
 - a. Development, testing, and evaluation of candidate options for volume reduction, including off-gas treatment development as required by the option.
 - b. Identification, testing, and evaluation of safeguard methods for volume-reduced fuels.
- 2. Packaging.
 - a. Development and characterization of HTGR spent-fuel forms suitable to meet disposal requirements defined by studies and analyses.

- b. Development, testing, and evaluation of processes for stabilizing spent-fuel forms and associated process off-gas treatment.
- 3. Reprocessing. Development of long-lead items is limited to the crush/burn process for volume reduction of either prismatic or spherical spent fuel. The resulting volume-reduced spent fuel could be used for disposal studies or as pretreated spent fuel for head-end reprocessing.
- 4. Spent fuel characterization.
 - a. Characterization of LEU/Th elements from the Fort St. Vrain reactor to verify data base calculations and to determine the waste classification of the emptied fuel block.
 - b. Examination of spent fuel to establish fission product leachability, and to determine whether and to what extent fission products migrate into the fuel rod matrix and into the graphite block.

3.3. NEAR-TERM PROGRAM SCHEDULE

Figure 3-2 shows the development schedule. The major schedule elements are discussed below.

3.3.1. Storage

The conceptual designs and cost estimates for an HTGR spent fuel storage facility are scheduled to provide these designs and costs for storage of Lead Plant spent fuel in whole or volume-reduced form.

Fig. 3-2. Near-term SFT development program schedule (sheet 1 of 2)

Fig. 3-2. Near-term SFT development program schedule (sheet 2 of 2)

3.3.2. Transportation

Title I designs of rail and truck shipping systems for whole spent fuel are scheduled to provide enough time for final design, prototype testing (if required), licensing, and construction prior to the first Lead Plant shipments. Conceptual designs are also scheduled to allow time for volume-reduced fuel shipping designs and cost estimates if volume reduction becomes desirable for Lead Plant spent fuel.

3.3.3. Volume Reduction

The schedule for volume-reduction development activities is conservatively based on obtaining an HTGR economy of 10 GW(e) by the year 2015 (Ref. 6). This requires that a full-scale volume-reduction facility, sized for 10 GW(e) capacity, be available around the year 2011. To accomplish the complex development required, the following major activities are planned:

1. Feasibility studies on available options.
2. RD&D of the most promising options identified in the feasibility studies, including demonstration of integrated burner/off-gas system for the crush/burn volume-reduction option.
3. Development of safeguards and non-destructive analyses techniques.
4. Conceptual design and cost estimate for reference process selection.

Near-term completion of these activities is critical to allow timely design and operation of cold prototype and hot pilot-plant facilities to be compatible with Fort St. Vrain and Lead Plant spent fuel utilization.

3.3.4. Packaging

Packaging activities are scheduled to support the transportation activities. Conceptual designs and cost estimates, RD&D activities on waste forms, product specifications, and stabilization processes schedules are planned for completion when Title I design of the Lead Plant shipping system begins.

3.3.5. Disposal and Economics

Disposal cost estimates and the Economics Basis Report updates are scheduled to support and guide related RD&D on whole and volume-reduced fuel disposal. Development of an integrated universal waste package design is scheduled to support the storage, transportation, and disposal activities.

3.3.6. Reprocessing

The only activity scheduled for reprocessing is to evaluate flowsheet options with the aim of reducing reprocessing costs.

3.3.7. Spent Fuel Characterization

Spent fuel characterization, including analysis of an irradiated fuel block after fuel rod removal to determine its waste category, is scheduled to coincide with discharge of LEU/Th elements from the Fort St. Vrain reactor.

3.4. LONG-RANGE DEVELOPMENT REQUIREMENTS

The long-range development requirements for the HTGR Spent Fuel Treatment Program are defined as that work starting no sooner than FY-90. These long-range requirements are derived by separating the near-term development activities from the overall program.

It is advantageous to prioritize the long-range R&D requirements because of the large number of work elements involved. Those work elements that support the HTGR Lead Plant are given the highest priorities.

3.4.1. Studies and Analyses

1. Preliminary (Title I) designs and updated costs of systems for transporting whole and volume-reduced HTGR spent fuel. These designs will be based on the conceptual designs completed in FY-86 and FY-88, respectively.
2. Final design and costs estimate for HTGR spent fuel shipping and disposal packages, based on final RD&D and systems integration results.
3. Designs and cost of hot pilot-plant and full-scale volume-reduction facilities for treating HTGR spent fuel.
4. Preliminary designs and updated costs of storage facilities for whole and volume-reduced HTGR spent fuel. These designs will be based on the conceptual designs completed in FY-88.
5. Preliminary designs of systems for transporting HLW and stabilized silicon carbide hulls.
6. Conceptual designs and cost estimates for disposal waste packages for HLW and stabilized hulls.
7. Repository disposal costs for HLW and stabilized hulls.

3.4.2. RD&D

1. Prototype testing (if required) and licensing of spent fuel shipping casks.

2. Completion of tests and evaluation of processes for stabilizing whole and volume-reduced HTGR spent fuel and completion of development of methods for special nuclear material control and accountability.
3. Participation in postirradiation examination (PIE) and characterization tests of LEU/Th test elements removed from the Fort St. Vrain reactor in 1991 and 1994.
4. Completion of cold and hot testing of preferred volume reduction method.
5. Prototype testing (if required) of storage facilities for whole and volume-reduced HTGR spent fuel.
6. Development and testing of dry head-end HEU reprocessing steps other than fuel element crushing and burning, including particle separation (if desired), solids transport, and particle crushing and burning. Specific requirements will depend on evaluation of reprocessing flowsheet options.
7. Development and testing of wet head-end HEU reprocessing steps including dissolution, hulls drying, feed adjustment, solvent extraction, and waste processing.
8. Dissolver off-gas (DOG) treatment development.
9. Product conversion to UO_3 and ThO_2 .

3.5. RD&D FACILITIES

Six types of facilities have been identified for testing and demonstrating the technology developed in the HTGR SFT Program:

1. Laboratory facility.
2. Cold pilot plant.
3. Cold prototype facility.
4. Hot cell.
5. Hot pilot plant.
6. Demonstration facility.

The culmination of this development testing is assumed to be the operation of commercial-scale facilities.

Both volume-reduction and HEU reprocessing technologies require hot demonstration of selected processes in full-scale facilities. A hot pilot plant for either technology will be needed earlier for process development, scaleup studies, optimization studies, remote-technology development equipment testing, and reliability testing. If the design capacity matches the spent fuel discharge rate of the HTGR Lead Plant (i.e., one core segment per year), then the hot pilot plant can also be used for processing spent fuel discharged from the Lead Plant, thus reducing total storage requirements for spent fuel. The hot pilot plant could also process Fort St. Vrain spent fuel, thereby increasing the spent fuel storage capacity at INEL. In planning a schedule for these facilities, the critical effects of major decisions should be recognized. Plans for a cold prototype facility and a hot pilot plant for spent fuel volume reduction and packaging will depend largely on (1) the HTGR commercialization schedule, (2) unit costs for options (volume-reduction versus whole fuel disposal), and (3) implementation of U.S. government policies on repository waste disposal. Reprocessing RD&D facilities beyond the existing U.S. cold pilot plant and the F.R.G. hot cell facilities at KFA, Julich, will depend on (1) U.S. government policies on nuclear fuel reprocessing, (2) the HTGR commercialization schedule, (3) introduction of the HEU/Th recycle option, (4) future uranium and enrichment

prices, and (5) unit costs for options (volume reduction versus reprocessing versus whole fuel storage and disposal). However, several program activities involving RD&D facilities must be initiated:

1. Cold pilot-plant development of volume-reduction methods (new) and reprocessing (on-going).
2. Cold prototype facility testing of a selected volume-reduction method and reprocessing (crush/burn).
3. Any required hot-cell studies for volume reduction and reprocessing.

For packaging spent fuel, RD&D is required in three types of facilities: hot laboratory, cold pilot plant, and cold prototype.

Because of the uncertainties about the technical approach and scope in the new areas of this SFT program (i.e., volume reduction and packaging) as well as the dependence of detailed program direction on decisions based on results of work yet to be done, a detailed schedule for RD&D facilities cannot be forecast at this time. The approach used in this plan provides a mechanism for dealing with these uncertainties. After the next five years, when work has been done to evaluate volume-reduction and packaging concepts and after the DOE has implemented more of the NWPA and more is known about the HTGR commercialization schedule, a more detailed schedule can and will be developed.

3.6. FACTORS AFFECTING DECISIONS

Choices between options will be based on technical, economic, institutional, and political issues. The following factors are involved in these issues:

1. Availability of MRS/repository facilities.
2. Availability of volume reduction/reprocessing facilities.

3. Federal versus private ownership and operation of facilities.
4. Facility capital and operating costs.
5. Packaging, storage, and transportation costs.
6. Disposal costs.
7. Fuel values.
8. Volume reduction/reprocessing costs.
9. HTGR installation schedules and market.
10. Licensing and regulations.
11. Federal nonproliferation policy.

The methodology to be used in making economic assessments among the alternatives is presented in a companion report written as part of the FY-84 development program (Ref. 2). Overall, the development program must provide the technological and economic basis for HTGR spent fuel management for the Lead Plant and follow-on plants and incorporate the U.S./F.R.G. cooperative program.

3.6.1. Nuclear Waste Policy Act of 1982

Under the NWPA, the responsibilities for spent fuel management between the commercial side and DOE are defined as shown in Fig. 3-3.

The commercial side is responsible for the following:

1. Interim storage prior to transfer of title of the spent fuel to the DOE for disposal.
2. Any primary treatment of spent fuel (e.g., volume reduction or reprocessing) desired by the commercial side for economic reasons.
3. Packaging, in accordance with DOE requirements, for shipping.
4. Loading the spent fuel shipping cask furnished by DOE.

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Fig. 3-3. Commercial/DOE responsibilities under NWPA (future plants)

The DOE is responsible for the following:

1. Shipping spent fuel or waste to an MRS facility for long-term storage or to a repository for disposal.
2. Any treatment, such as volume reduction, desired by DOE.
3. Other treatment as required and packaging for final disposal.
4. Long-term storage or disposal.

The NWPA requires DOE to begin receiving HLW or spent fuel for disposal by January 31, 1998. The commercial side effectively pays the entire cost for spent fuel management through an electric generation fee to the Nuclear Waste Fund.

In assessing the various HTGR fuel cycle options and the decision factors relevant thereto (discussed in this section and Section 3.7), several implications of the NWPA must be kept in mind:

1. The NWPA provides no financial incentive for the HTGR Lead Plant utility to do anything more than package the spent fuel for shipment to an MRS or a repository.
2. Although no specific words in the NWPA limit the type of reactor to which its provisions apply, the authors obviously had LWRs in mind.
3. Although the provisions dealing with Federal Interim Storage (FIS) of spent fuel required equitable distribution of the costs of FIS among the users of FIS services, the provisions relating to disposal of spent fuel require a flat assessment on all utilities based on electricity generated in nuclear power plants.
4. Although the costs of handling and disposal of intact HTGR assemblies is likely to be higher, on the basis of unit power

production, than LWR fuel, no provision in the NWPA would permit DOE to assess discriminatory fees against HTGR plants.

5. The higher cost, per unit power production, of disposal of HTGR fuel provides an incentive to DOE to consider volume reduction on HTGR fuel prior to disposal.
6. No provision in the NWPA, however, would authorize DOE to allow a credit against the Nuclear Waste Fund fee to a utility which carried out volume reduction of its spent fuel before turning it over to DOE.
7. The cost-benefit analyses of the various fuel cycle alternatives must therefore take into account the entity paying the cost and the entity receiving the benefit.

The specific implementation of the NWPA for an HTGR fuel cycle will evolve with time as the DOE Mission Plan is implemented, issues such as MRS are decided, and the feasibility and cost of alternatives become known. The intent of this program is to provide the technological and economic basis for overall HTGR spent fuel management to enable decision making and implementation when required.

3.6.2. Volume Reduction

A decision on volume reduction for once-through spent fuel handling prior to disposal in a repository has alternate approaches which depend upon favorable economics and the availability of facilities:

1. Volume reduction at the reactor site.
2. Volume reduction followed by storage at a stand-alone volume-reduction facility.
3. Volume reduction followed by storage in an AFR/MRS facility.

4. Storage in an AFR/MRS facility followed by volume reduction.
5. Volume reduction at a repository.

If fuel for eventual recycle is to be held in an AFR/MRS facility, then it could be volume reduced as a pretreatment step to reduce storage requirements. Rod pushout at one segment per year may be allowed at the reactor site. In any case, conducting the volume reduction at the reactor site would be subject to concurrence of the utility and provision for volume reduction in the operating license.

Decisions on volume reduction include those factors listed in Section 3.6, but must also consider the costs for a stand-alone facility and the alternative costs of handling whole spent fuel. These other costs include storage, packaging, transportation, and final disposal. These economics also depend on the specific process selected.

Technical issues will be important in selecting the method of volume reduction. One important issue will be the waste classification of the non-fuel-bearing materials.

3.6.3. AFR Storage

In addition to the factors listed in Section 3.6, the economic factors involved in decisions on AFR storage include (1) determination of the optimum capacity based on required storage and discharge of the facility, (2) the cost for a stand-alone facility, (3) whether the fuel is to be stored as whole elements or volume-reduced fuel, (4) the competing costs for AR long-term storage of fuel which is to be reprocessed at utility cost, and (5) the competing costs for storage at any spent fuel treatment facility.

3.6.4. Reprocessing

Decisions on reprocessing spent fuel depend on national policy as much as on economics. A key issue will be future concerns on nuclear weapons

proliferation and the capability for handling and assuring the accountability of nuclear material in the facility.

In addition to the factors listed in Section 3.6, the economic factors include (1) U_3O_8 and enrichment costs, (2) throughput, (3) the value of recovered U-233 in terms of its use and supply from other sources, (4) the acceptability of HEU (U-235 and U-233) utilization, (5) waste treatment, and (6) interim storage costs. The competing costs for once-through fuel disposal, both as whole elements and volume-reduced fuel, including all interim storage, packaging, transportation, and final disposal costs must also be considered.

Decision making on reprocessing could be affected by major improvements in uranium mining and milling and in advanced-isotope-separation techniques (AIST). Improvements could sufficiently reduce the price of U-235 to minimize the incentive to recycle. However, development of an efficient and economic AIST could eliminate the U-232 contamination of U-233, which is a barrier to contact refabrication processes, and refabrication costs would be reduced substantially.

3.7. FUEL CYCLE EVOLUTION

The initial fuel cycle direction for the HTGR Lead Plant is LEU once-through. Even with this cycle, decisions are required regarding the use of thorium and regarding the fuel storage capacity for the Lead Plant and follow-on plants. For the Lead Plant, the simplest option is to store the intact spent fuel elements at the reactor. Superimposed on this option is the economics of volume reducing the fuel prior to disposal.

Considering market commitments for follow-on HTGR plants, a second decision point requires choosing between storing the spent fuel from these reactors at the reactors or at AFR/MRS facilities. Again, the decision must be made whether to include a volume-reduction facility prior to interim storage or prior to disposal. Factors influencing these decisions include assumptions that (1) not more than one to five years AR storage will be

available, (2) follow-on plants will be added on the basis of a given market doubling time, and (3) a repository will be available in 1998; other factors are the economics of volume-reduced fuel storage and disposal versus whole element storage and disposal and whether the reactors are fueled with LEU or HEU.

Factors which affect the eventual transition from the LEU or LEU/Th fuel cycles to the HEU/Th fuel cycle include (1) fuel cycle economics, (2) progress on nuclear material safeguard procedures, (3) domestic and international policy directions, and (4) probably, experience with plutonium recovery and use. The qualifications of the HEU fuel and process development associated with handling and accountability of sensitive nuclear fuels could also be important factors in these decisions. Therefore, reasonable near-term development must be undertaken to provide the necessary background. Safeguards/accountability development is an ongoing activity in HEU fuel manufacturing for the Fort St. Vrain reactor.

With the operation of several plants using the HEU/Th fuel cycle, the introduction of reprocessing and refabrication becomes a consideration. This transition would depend upon a number of other factors such as the price of U_3O_8 , separative work cost, and reprocessing costs.

Because an economic incentive exists for using HEU fuel even with a once-through cycle, the RD&D expenses for this transition are relatively modest, and the economic incentive for recycle is greater after adoption of the HEU/Th fuel cycle. The preceding sequence of decisions assumed that transition from the LEU to the HEU once-through fuel cycle is prior to implementation of fuel recycle. However, the transition from the LEU once-through fuel cycle could go directly to HEU recycle if the price for U_3O_8 and/or separative work were sufficiently high and if whole element storage and disposal costs are high relative to reprocessing. This illustrates the advantage of using a decision process approach to program planning rather than a single course of action. Consideration of the entity paying the cost and the entity receiving the benefit will be paramount factors in the decision process.

Economic (and perhaps policy) incentives for recovering bred fuel from the relatively small number of LEU/Th fuel elements from the Lead Plant should also be investigated. These elements and the Fort St. Vrain spent fuel could also be used for hot reprocessing development until spent fuel containing the new reference HEU/Th fuel became available. Assuming that a net benefit could be shown for recovering bred fuel from the LEU/Th fuel cycle, then a decision on the recovery of plutonium from the fissile particles must also be made.

The benefits and costs of fuel in segregated particles also needs some review. Reprocessing without separation and the use of single-particle fuels are feasible. In LEU fuel, the low tolerance for fissile-to-fertile crossover is significant. In HEU fuel, the reduced penalty from a time-dependent buildup of U-236 in the first few generations of recycle should be considered. Segregation of the fissile and fertile particles within the fresh fuel initially may also be feasible.

The economics of fuel cycle selection including the question of reprocessing without particle separation are addressed in detail in the companion report to this program plan on the economic basis for HTGR spent fuel treatment decisions (Ref. 2). This report covers the important distinction between government and commercial decisions.

4. REFERENCES

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3. Agreement Between the United States Energy Research and Development Administration and the Federal Minister for Research and Technology of the Federal Republic of Germany in the Field of Gas-Cooled Reactor Concepts and Technology, signed February 11, 1977.
4. "HTGR Spent Fuel Volume Reduction Engineering Feasibility and Economic Evaluation," DOE Report GA-A17697, September 1984.
5. "FY-83 Unit Handling and Resource Cost Assumptions for Fuel Cycle Evaluations," GA unpublished data, April 13, 1983.
6. "U.S. Commercial Power," DOE Report DOE/EIA-0315, March 1982.

APPENDIX A PROGRAM RESOURCES

A.1. GA TECHNOLOGIES INC./OAK RIDGE NATIONAL LABORATORY

Reprocessing development activities throughout the United States are managed by ORNL under the U.S. CFRP. The primary objective of the CFRP is the development of technology directed toward the demonstration of breeder fuel reprocessing while also advancing the technology of LWR reprocessing. Moreover, some of the available facilities have been utilized to further HTGR reprocessing, and many of the development programs have applications to HTGR reprocessing. Current SFT development at GA is a part of the CFRP.

In June 1976, GA completed the construction of a cold engineering-scale head-end pilot plant. The purpose of the plant is to demonstrate the feasibility of SFT technology on an acceptable scale. Prior to this, the processes were developed in unit operations on a smaller scale. Since its completion, each system within the pilot plant has been used for qualification testing, for design verification experiments, and in sequential and some integrated operations of the pilot plant using both U.S. and F.R.G. fuels.

The cold pilot plant is divided into dry and wet head-end processes. The dry head-end processes consist of equipment to (1) crush the fuel elements to a size suitable for the subsequent removal of graphite by combustion in a fluidized-bed burner, (2) separate the fissile and fertile particles pneumatically, (3) crush the TRISO-coated particles to expose the inner carbon coatings, and (4) remove these coatings by combustion in a fluidized-bed burner. These systems are connected by pneumatic transport systems to move material from unit to unit. The wet head-end processes consist of equipment to (1) dissolve the heavy metals, (2) separate the soluble from the insoluble materials, and (3) separate the uranium, thorium, and fission products by solvent extraction. The pilot plant also has support facilities

to analyze and characterize the feed and product materials and to repair and modify equipment.

Within the cold pilot plant complex is also a cold engineering-scale off-gas treatment system to demonstrate this portion of the technology. This system will remove semivolatile fission products, radioactive gases, and chemical impurities contained in the off-gases from the burners and dissolver.

Uranium and thorium microsphere processing facilities at GA are capable of producing all types of uranium and thorium oxide and carbide fuels as feed for use in SFT RD&D facilities.

A computerized control system for storage and inventory of special nuclear materials for safeguards and accountability has been established for the HTGR fuel fabrication facility. This facility also has methods developed for the quality control of fuel to be used as feed material for SFT development.

GA has extensive experience in the design, licensing, manufacture, testing and operation of radioactive materials shipping systems. These include truck and rail systems for fresh and spent fuel and for HLW.

Remote technology support has been provided for more than 15 years for the Fort St. Vrain reactor project and for the fuel manufacturing and SFT programs. This technology has been expanded and incorporated into large spent fuel treatment plant designs that include spent fuel shipping and storage, head-end reprocessing, and remote repair facilities.

The hot-cell facility located at GA is comprised of both high- and low-activity cells. It is equipped to perform a wide range of investigations on the physical, metallurgical, and chemical properties of irradiated materials and to do mockup testing of remote equipment. The large shielded cell provides for radiation levels up to one million curies. Provisions allow remote operation of the machine shop and laboratory equipment in the cell to

prepare samples, disassemble irradiated components, and perform various physical, chemical, and metallographic examinations.

A.2. IDAHO NATIONAL ENGINEERING LABORATORY STORAGE FACILITY

Irradiated graphite fuels are currently stored in the Irradiated Fuel Storage Facility (IFSF) at the Idaho Chemical Processing Plant (ICPP) which is located at INEL. The IFSF is a canyon-type dry storage facility that was built as an addition to the ICPP fuel storage basin building to make maximum use of existing facilities and equipment. It is designed to provide safe storage for spent fuel from the HTGRs, Peach Bottom I and Fort St. Vrain reactors, and from the Rover Nuclear Rocket Program. Irradiated fuel has been stored at the IFSF since early 1975.

The spent fuel is stored in 636 carbon-steel canisters which are approximately 0.46 m (18 in.) in diameter and approximately 3.35 m (11 ft) long. For heat transfer and criticality reasons, the canisters are stored in an enclosed storage rack in a staggered arrangement. The decay heat is removed by a forced-flow, single-pass air system. Before entering the facility, the inlet air passes through roughing filters to remove dust and foreign materials. The exit air passes through prefilters and high-efficiency particulate air (HEPA) filters to remove any particulate matter, is monitored to detect activity, and is then discharged to the atmosphere through the facility stack.

To facilitate the required fuel handling and storage tasks, the storage facility is divided into several functional areas including a cask receiving area, a cask transfer pit, a fuel handling cave, a crane maintenance area, a control room, and a fuel storage area. The facility is equipped with a cask transfer car, a 15-ton crane, and a manipulator for performing specific fuel handling operations.

A.3. FEDERAL REPUBLIC OF GERMANY FACILITIES

Reprocessing activities in the F.R.G. are managed by the Hochtemperaturreaktor Brennstoff Kreislauf (HBK) project. The F.R.G. has several facilities and R&D centers which complement the facilities for HTGR SFT development in the U.S. Major ones include KFA, KfK, and the fuel manufacturing, development, and process engineering companies of Hochtemperaturreaktor Brennelement Gesellschaft (HOBEG) and NUKEM.

A 46-MW(t) research and power HTGR, the AVR, is located at the KFA. This reactor is powered by over 100,000 spherical graphite fuel elements containing uranium-thorium fuel. The ICT at KFA is constructing laboratory-scale equipment for the demonstration of the head-end processes for reprocessing spent AVR fuel. This facility, called AVR-VI, consists of cold equipment to check out process and remote operability and identical hot-cell equipment to demonstrate head-end processing operations with irradiated fuel. Head-end processes have previously been demonstrated with unirradiated fuel in other laboratory facilities located at the ICT.

For larger-scale demonstration, the KFA employs the JUPITER facility, and in conjunction with JUPITER, the AKUT facility (Off-Gas Treatment Facility for Aerosols, Krypton, and Tritium). This facility is currently being upgraded to demonstrate fully remote operation with unirradiated fuel.

Solvent extraction and product purification for reprocessing will be demonstrated in the MILLI facility of the KfK.

In addition to the AVR research reactor, the 300-MW(e) prototype Thorium Hochtemperatur Reaktor (THTR) is nearing startup. Although the reference fuel for HTRs in the F.R.G. is 10% enriched uranium fuel, both the AVR and THTR reactors will be operated with HEU/Th fuel. This requires the continuance of R&D activities for both high- and low-enriched SFT.

Since 1973, 75,000 spherical spent fuel elements from the AVR have been stored in special water basins at KFA. KFA is currently developing plans to expand this capacity.

As part of the interim storage test program, the spheres have been placed in leak-tight steel canisters. The THTR and AVR canisters will have capacities of 2100 and 1000 spheres, respectively. Testing of these canisters is already underway at KFA to monitor leakage of Kr-85 and tritium and to measure surface temperatures. In the storage facility, decay heat will be dissipated by convection, with cooling air vented to the atmosphere after filtration. The building has four steel storage cells with a capacity of 400 canisters stacked four high in a critically safe array. The central zone of the building contains operation areas and offices and is used for loading and unloading shipments. The building is constructed of concrete such that the effects of credible accidents are inconsequential. The canisters enter by rail and are placed in storage remotely.

Transnuklear and Gesellschaft für Nuklear Service (GNS) have each provided one cask for storage demonstration and tests on these casks are underway.

The process engineering company of NUKEM, founded in 1960, is active in nearly all parts of the nuclear fuel cycle including fuel element transport, storage, reprocessing, and radioactive waste treatment and solidification. NUKEM has designed and built critically safe, double-walled slab geometry liquid tanks, large stainless-steel tanks, and compact storage racks for LWR fuel storage. For pretreatment of radioactive wastes, NUKEM has developed flash evaporators and condensers for aqueous solutions and incinerators for solid wastes. NUKEM has also constructed a transportable cementing plant for solidification of low- and medium-radioactive wastes. NUKEM's subsidiary, HOBEG, manufactures the spherical fuel elements for high-temperature reactors such as the AVR and the THTR.

APPENDIX B RD&D ACTIVITIES

B.1. SPENT FUEL CHARACTERIZATION

B.1.1. Present Status

Characterization of irradiated LEU fuel elements simulating spent fuel from the HTGR Lead Plant is needed as a basis for development of spent fuel packaging, development of alternative methods of volume reduction, and design of storage and transportation systems for whole or volume-reduced spent fuel. In addition, HEU fuel elements need to be characterized for these modes of SFT as well as for reprocessing. Work was performed in FY-84 on an actual HEU spent fuel element from the Fort St. Vrain reactor. No work has been done on an actual LEU spent fuel element since none exists at the present time.

B.1.2. Program Needs

Three LEU HTGR test fuel elements are planned for fabrication and insertion into the Fort St. Vrain reactor in 1985. These test elements will also contain several fuel stacks of HEU fuel. Removal of these test elements for postirradiation examination (PIE) is scheduled at the rate of one fuel element for every two years of effective full-power operation. These spent fuel elements need to be characterized with respect to decay heat generation rates, fission product and other radioactive releases, fission product leachability, radiation dose rates, and surface temperatures. Similar work needs to be completed on spent HEU fuel elements from the Fort St. Vrain reactor. Characterization studies that might be required by the Nuclear Regulatory Commission (NRC) or the Environmental Protection Agency (EPA) should be identified and work undertaken to meet possible requirements for HTGR fuel disposal in a repository or for longer-range reprocessing

activities. In the area of determining the radionuclide content of the block, a determination needs to be made on actual spent fuel to classify whether the graphite is LLW or transuranic waste after removal of the rods from the block in order to confirm the economics of this volume-reduction method.

Studies of instrumented containers holding fuel rods or other forms of volume-reduced fuel should be undertaken. These studies would require the removal of fuel rods from a number of Fort St. Vrain spent fuel elements and some carefully instrumented experiments. The orientation of the rods might be an important consideration, both from the point of view of heat conductivity and a possible requirement for minimizing damage to the fuel rods that might result in further fission-product leakage.

As a longer-range requirement, identifying the amount of C-14 in other components of the fuel element, particularly the fuel rod matrix material and the outer-pyrocarbon coating of the fuel particles, may be useful. If a large fraction of the C-14 is found in these components, some other type of volume-reduction process, such as crush/separate or rod pushout, might be useful to remove these C-14 sources without a burning operation.

In summary, spent fuel characterization is critically important for both near-term SFT planning and the longer-range reprocessing strategies. While the longer-range needs are not urgent, the incremental difficulty of obtaining that information might be small in view of the on-going experiments required for the near-term program.

B.2. SPENT FUEL TRANSPORTATION AND STORAGE

B.2.1. Present Status

Design studies on truck and rail casks have begun. Three truck casks have been built for shipping Fort St. Vrain spent fuel and have been used successfully for some time. No experience is available on the shipping of HTGR LEU/Th spent fuel by either truck or rail.

Metal storage casks are currently being licensed for interim storage of LWR spent fuel. Concrete storage casks are the reference concept for storage of LWR spent fuel in an MRS facility. No experience is available on the long-term storage of HTGR spent fuel in metal or concrete casks.

B.2.2. Program Needs

More information is required on the following subjects:

1. The licensing difficulties and economics of rail shipping compared to truck shipping, as well as any actual and potential regulations and policies prohibiting rail shipment of spent fuel and HLW.
2. The shielding requirements for LEU/Th spent fuel versus those for HEU/Th spent fuel.
3. The potential cooling and shielding problems associated with the storage and shipping of volume-reduced HTGR spent fuel.
4. The behavior of HTGR spent fuel during long-term storage and the performance of the storage system to meet thermal and environmental criteria.
5. Monitoring methods for large dry storage facilities and storage units.

Much of the information required can be obtained from studies and analyses. However, the availability of the Fort St. Vrain casks may offer an opportunity to obtain more experimental information on shipping cask designs. In particular, shielding evaluations with spent LEU/Th fuel could be planned at the time of the LEU/Th test element discharges from Fort St. Vrain. Both shielding and cooling requirements for shipping casks to handle volume-reduced fuel might be evaluated with existing Fort St. Vrain cask equipment. These spent-fuel transportation RD&D needs will be determined from results of the transportation studies and analyses. Also, the need for prototype

model testing for the various shipping casks will need to be determined with respect to obtaining the NRC Certificate of Compliance. Prototype testing may also be required for storage facilities for whole and volume-reduced HTGR spent fuel. Storage experience at INEL and KFA will be valuable.

B.3. SPENT FUEL VOLUME-REDUCTION

B.3.1. Present Status

Some work has been performed on each of the potential methods for volume reduction of HTGR spent fuel: rod removal, crush/burn, and crush/separate processes. For the mechanical rod-removal method, an HEU spent fuel element from the Fort St. Vrain reactor has been examined for the feasibility of mechanically removing the fuel rods from the fuel element. The rods could be manually removed, and it appears that the resulting graphite block may be classified as LLW. However, determination of the waste classification of the graphite block from a LEU spent fuel element will not be known until an LEU spent fuel element is available from Fort St. Vrain tests in 1988.

As a modification for volume reduction of the reference reprocessing crush/burn head-end operation, circulating-bed combustion of finely crushed fuel elements is under consideration. Since particle breakage is potentially not a concern in volume reduction for disposal (as opposed to being of major concern in reprocessing), the block can be crushed to a fine product and burned in a circulating bed. This would lower the cost for volume reduction. In contrast, the gentle crushing and burning in a bubbling bed is intended to minimize particle breakage in reprocessing. Feasibility studies and preliminary tests of this modified crush/burn operation show promise. However, the effect of broken particles on stabilizing the volume-reduced spent fuel for disposal needs to be studied.

In crushing operations, some of the fuel particles tend to separate from the graphite. Crushing conditions that enhance this effect need to be investigated. Also, methods of separation need to be determined to

establish whether a reasonable portion of the graphite can be separated without excessive loss of fuel particles. Removal of heavy metal from the resulting graphite may be possible by gas leaching in order to qualify the graphite as LLW. The economics of this process appear favorable (see Ref. 4 of the main body of this report).

B.3.2. Program Needs

Studies and analyses will guide the development of volume-reduction technology. If the optimum process consists of sawing ends off the fuel blocks and pushing rods out, development work should include the handling and transport of the fuel blocks through the process line and the subsequent handling of the fuel rods and empty blocks. Sawing equipment should be developed, where necessary, with remote maintenance procedures receiving particular attention. The relative merits of various rod removal approaches should also be examined, including mechanical and pneumatic processes. Cold pilot-plant studies, augmented by appropriate hot-cell studies, should be planned to develop this technology. The process will need to be demonstrated on a pilot scale with irradiated fuel elements.

Experimental studies should also be undertaken to examine the ease of fuel rod removal as a function of clearance between the fuel rods and the graphite walls. Through interactions between the SFT development program and the fuel development program, the effect of the gap size on fuel performance temperatures should be examined. The development work should also include steps to handle irregular blocks where the fuel rods cannot be completely removed by the regular push-out techniques. Standardization of fuel rod stack heights should be studied in order to reduce the number of saw cuts required, thereby simplifying the rod removal process. Information from these studies should be fed back to studies and analyses to develop a better estimate of the economics.

For all alternative methods of volume reduction, the feasibility of each method needs to be determined; where feasible, input should be provided to determine development requirements and conceptual designs and cost

estimates. This would aid the studies and analyses work in the selection of a volume-reduction method. Fort St. Vrain spent fuel should be considered as a possible feed material for hot tests of volume-reduction methods.

Since only the crush/burn and crush/separate volume reduction technologies apply to spherical fuels, the development of these technologies, as well as the U.S./F.R.G. cooperative program, takes on added significance if spherical fuel is selected for fueling of the Lead Plant.

In addition, safeguards development will need to proceed on the volume-reduction process. The flowsheet will need to be defined for special nuclear materials control and accountability, and the measurement capability will need to be determined using various nondestructive assay methods. This will involve preparation of simulated waste forms from the volume-reduction and stabilization processes having known heavy metal contents. These results will also be used to develop the facility conceptual designs and cost estimates.

B.4. SPENT-FUEL PACKAGING

B.4.1. Present Status

Storage experience with Peach Bottom and Fort St. Vrain fuels at the ICPP facility indicates that stabilization and packaging requirements for whole HTGR spent fuel are minimal for interim AFR storage. The standard contract for disposal of spent fuel suggests that the requirements for LWR fuel packaging, for government acceptance, are also not extensive. However, only initial exploratory work has been done on the stabilization and packaging of whole and volume-reduced HTGR spent fuel for disposal.

B.4.2. Program Needs

The RD&D requirements for HTGR spent fuel disposal packaging will be developed based on evaluation of LWR methods as applied to HTGR needs. The initial issue that must be addressed is whether whole HTGR spent fuel

elements need to be stabilized before being acceptable for disposal; this determination will be based on results of the spent fuel characterization work described above. If stabilization is required, suitable disposal forms, such as glasses, metal matrix, and cements, will need to be developed for whole spent fuel elements and volume-reduced spent fuel. Also, consideration will need to be given to requirements for packaging the emptied graphite blocks for near-surface disposal as LLW if the rod push-out method or other nonburning method of volume reduction is selected and the residual graphite qualifies as LLW.

The developed disposal forms will need to be characterized with respect to leachability of fission products, combustibility, pyrophoricity, and other significant factors. These processes will be developed on a laboratory scale, then scaled up. Work also needs to be done in off-gas treatment of the stabilization process. Fort St. Vrain spent fuel should be considered as possible feed material for hot tests of stabilization processes.

B.5. REPROCESSING

RD&D activities associated with the development of HTGR reprocessing technology have assumed a variety of steps from the laboratory phase to an ultimate hot demonstration facility:

1. Laboratory tests.
2. Cold pilot plant.
3. Cold prototype.
4. Hot-cell tests.
5. Hot pilot plant.
6. Hot demonstration.

Much of the laboratory test development has been completed. A cold pilot plant has been built and operated at GA, giving much useful guidance to subsequent steps. Hot-cell tests are now underway, with the availability of AVR pebble-bed fuel from the German HTR plant and prismatic fuel from the Fort St. Vrain HTGR plant.

It should be noted that the RD&D needs for volume reduction for disposal and for reprocessing are similar for the fuel element crushing, burning, and off-gas treatment processes.

The present status and program needs of the reference reprocessing flowsheet are discussed in the following subsections. Before discussing these steps individually, some common RD&D requirements can be identified:

1. Definition and demonstration of satisfactory materials, mechanical systems, and lubricants suitable for long-term use in a high-radiation field.
2. Development and demonstration of reliable control and instrumentation systems both for process monitoring and nuclear-materials accountability.
3. Definition of potential process-safety hazards (e.g., dust explosions, pyrophoricity, criticality, etc.).
4. Demonstration of process operability under remote conditions.
5. Demonstration of acceptably low material accumulation and holdup.
6. Demonstration of the reliability of all systems and components in a radiation environment.
7. Demonstration of acceptable operation under anticipated off-normal conditions.
8. Development and demonstration of remote maintenance equipment and procedures for critical components.

B.5.1. Fuel Element Crushing

B.5.1.1. Present Status. Unirradiated prismatic and spherical HTGR fuel elements have been successfully crushed in a full-scale, three-stage crusher. The product was reduced to a size suitable for feeding the graphite burner, demonstrating the adequacy of the basic design.

B.5.1.2. Program Needs. Work needs to be done to ensure that particle breakage is at an acceptably low level for HEU reprocessing. Adequate fission product confinement needs to be demonstrated, and the off-gas composition needs to be determined.

B.5.2. Fuel Element Burning

B.5.2.1. Present Status. The graphite from crushed unirradiated prismatic and spherical fuel elements has been successfully burned in fluidized-bed burners up to 0.4 m in diameter, yielding a burner ash of low residual carbon content.

B.5.2.2. Program Needs. The optimum operating conditions need to be determined with respect to graphite burning rate, fines generation rate, fines recycle subsystem design, and minimizing particle breakage. Also, work needs to be done to quantitatively determine the semivolatile fission products evolved from the fuel element and fuel particle burners and to demonstrate an acceptable means of removing them.

B.5.3. Particle Separation

B.5.3.1. Present Status. An acceptable separation of unirradiated whole fissile and fertile particles by pneumatic classification has been demonstrated on an engineering scale for HEU fuel reprocessing. It should be noted that it probably would not be necessary to separate fissile and fertile particles in reprocessing for some time after a reprocessing plant starts up. This is covered in the companion Economics Report (Section 4.5 of Ref. 2 in the main body of this report) to this Program Plan.

B.5.3.2. Program Needs. The feasibility of separating the SiC hulls and fertile particle kernels by pneumatic classification needs to be determined.

B.5.4. Particle Crushing and Burning

B.5.4.1. Present Status. Unirradiated TRISO-coated fuel particles have been successfully crushed and burned in engineering-scale equipment.

B.5.4.2. Program Needs. The optimum operating conditions with reference fissile and fertile particles need to be determined with respect to crushing efficiency and rates, burner operating time cycles, and the amount of unburned carbon in the product from the graphite fuel element burner. Also, adequate particle crushing needs to be demonstrated with a feed containing the anticipated quantity of particles from separation crossover.

B.5.5. Solids Transport

B.5.5.1. Present Status. In the dry head-end portion of an HTGR reprocessing facility, systems for the transport of the solids from one process step to another are required. Crushed fuel elements, fuel particles, and particle burner ash have been successfully transferred in engineering-scale pneumatic transport systems operating at subatmospheric pressure. The operated systems contained bunkers for solids storage.

B.5.5.2. Program Needs. Means for minimizing particle breakage in transport systems preceding particle separation need to be determined and demonstrated. Also, design solutions need to be determined and demonstrated for problems such as valve jamming, seal and packing leaks, sampling, and line plugging.

B.5.6. Off-Gas Treatment

B.5.6.1. Present Status. Experimental work on off-gas treatment is divided into burner off-gas (BOG) treatment and dissolver off-gas (DOG) treatment.

Most components of both BOG and DOG treatments have been successfully tested in cold engineering-scale equipment. Preliminary integrated burner/off-gas testing has also been performed.

B.5.6.2. Program Needs. Catalyst poisoning by off-gas constituents needs to be evaluated; and extended, integrated (with the burner and dissolver) operation over the range of anticipated off-gas compositions needs to be demonstrated. Laboratory-scale work also needs to be done on the fixation and packaging of C-14 for disposal, if required. The off-gas system work will also include development of any off-gas treatment required in volume reducing and packaging HTGR spent fuel.

B.5.7. Dissolution

B.5.7.1. Present Status. Fuel dissolution has primarily emphasized methods to improve the dissolution rate of ThO_2 kernels resulting from the burning of BISO-coated fertile particles. This work has been successful. Dissolution of fissile particle burner ash has also been carried out successfully in the cold pilot plant at GA. Dissolver solutions containing hulls were successfully transferred to a continuous centrifuge and clarified.

B.5.7.2. Program Needs. Acceptable time cycles need to be demonstrated for the total dissolution of ThO_2 kernels in the presence of SiC hulls for various batch sizes. The specifications need to be defined for the products from the particle crushing and burning process that will allow acceptable dissolution. Of particular interest is a quantitative determination of the insoluble fission product content in the dissolver product. Integration between HTGR fuel design and SFT programs to develop ThO_2 kernels with good dissolution capability would be beneficial.

B.5.8. Hulls Drying

B.5.8.1. Present Status. Experimental work on the drying of SiC hulls in a fluidized bed has been carried out in pilot-plant-scale equipment. The

dryer performance has not been fully satisfactory. Preliminary work with a rotary-screw dryer is promising.

B.5.8.2. Program Needs. Alternative dryers and dryer feeders need to be evaluated. The specification needs to be defined for the particle crushing and burning product that will allow acceptable hulls drying. The limiting salt content in the residual solution needs to be determined. Also, the radionuclide content of the SiC hulls resulting from the dissolution of irradiated fuel needs to be characterized.

B.5.9. Feed Adjustment

B.5.9.1. Present Status. The continuous feed adjustment of Thorex dissolver solution was successfully demonstrated in cold pilot-plant-scale equipment.

B.5.9.2. Program Needs. The effects on feed adjustment, dissolution, and hull rinsing caused by the presence of the soluble neutron poison required to maintain subcriticality need to be determined.

B.5.10. Solvent Extraction

B.5.10.1. Present Status. Solvent extraction has been extensively used for the decontamination and separation of plutonium and uranium contained in irradiated nuclear fuels. Experience has also been gained in the processing of irradiated thorium fuels for the recovery of bred U-233 and thorium. Experiments to define flowsheets for solvent extraction processing of HTGR fuel have been carried out in cold pilot-plant equipment. Sufficient work has been completed to provide design information for a hot demonstration.

B.5.10.2 Program Needs. The specification needs to be defined for the particle burner ash regarding allowable carbon content that will allow acceptable performance in the solvent extraction step.

B.5.11. Product Conversion

B.5.11.1. Present Status. Well demonstrated technology exists for converting a uranyl nitrate solution to UO_3 and plutonium nitrate to PuO_2 . The technology for converting thorium nitrate solutions containing relatively high concentrations of Th-228 to ThO_2 is much less developed.

B.5.11.2. Program Needs. The system needs to be defined for converting UNH from HEU fuel to UO_3 . The product specification for the UO_3 recovered from the reprocessing of HEU fuel needs to be defined. Also, the process and equipment for converting thorium nitrate to ThO_2 for storage and the related storage system need to be defined.

B.5.12. Waste Processing

B.5.12.1. Present Status. A considerable amount of development work has been done on the conversion of the high-level liquid waste resulting from the reprocessing of LWR fuel into a solid form suitable for repository disposal. Because of the similarity of high-level liquid waste from HTGR fuel reprocessing to that from LWR fuel reprocessing, the basic waste solidification process should be applicable. Concentration of HLW, waste storage, and nitric acid fractionation and recycle have been carried out at spent fuel reprocessing plants for many years.

B.5.12.2. Program Needs. The effects of any residual carbon fines on waste concentration and solidification need to be defined and the maximum allowable residual carbon concentration determined. Suitable methods for stabilizing SiC hulls need to be developed and demonstrated for disposal in a repository. Methods need to be defined for packaging and disposing of constituents removed in off-gas processing.

The path of fluorides through the waste concentration, nitric acid fractionation, and waste solidification steps needs to be determined. Also, the possible formation of organic acids from residual carbon in the waste concentration and solidification steps needs to be determined. If organic

acids are formed, their path through the nitric acid recovery system and the effects on the solvent extraction system will need to be determined. In addition, a C-14 fixation system will need to be demonstrated (if C-14 fixation is required) on an engineering scale including product packaging.

B.5.13. Fuel-Materials Safeguards

B.5.13.1. Present Status. The Peach Bottom and Fort St. Vrain HTGR plants have made use of the HEU/Th fuel cycle. Thus, considerable experience is available with the handling of HEU fuel. In the interest of avoiding licensing risks for the HTGR Lead Plant, it was decided to use an LEU or an LEU/Th fuel cycle. It is an objective, however, to utilize the HEU/Th fuel cycle in the long range. Hence, any and all safeguard problems associated with the use of reactor-bred fuels and HEU feed fuels (in this case bred U-233 as well as highly enriched U-235) should receive a high priority to allow a transition to the more efficient HEU/Th fuel cycle.

B.5.13.2. Program Needs. HEU safeguards development is an on-going activity of HEU fuel manufacturing at GA for the Fort St. Vrain reactor. As planning for the reprocessing hot pilot plant develops, the flowsheet will need to be evaluated for special nuclear materials control and accountability. Suitable nondestructive assay methods will need to be determined and demonstrated on representative fuel forms containing special nuclear materials. Safeguards studies have been carried out as part of the U.S./F.R.G. cooperative program on the reprocessing dry head-end and will continue on the wet head-end, as required in future stages of reprocessing development and demonstration.